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REPORT SUMMARY

This report documents a 2011 workshop on thermal discharge issues that examined recent developments and future trends. Thermal discharge issues are receiving increased attention from government agencies and electric power companies; consequently, the report will be of particular value to power company environmental staff, government regulators, water resource managers, and the general public.

Background

In October 2011, more than 100 people met at Great River Energy headquarters in Maple Grove, Minnesota, for an Electric Power Research Institute- (EPRI-) sponsored workshop on Section 316(a) of the Clean Water Act (CWA). This section of the CWA regulates the thermal effluents of steam electric power plant cooling systems. It provides for variances from both technology-based limits and water quality standards if a plant can demonstrate that its thermal discharge "will assure the protection and propagation of a balanced, indigenous population of shellfish, fish, and wildlife in and on that body of water."

Objective

- To report on current status and future trends regarding thermal discharge research and regulations presented at the workshop

Approach

Over two days, attendees heard presentations on Section 316(a) from technical, legal, and regulatory perspectives. The workshop also included a poster session where seven posters were presented. The poster presenters summarized their posters prior to the attendees breaking into a more informal setting where the posters were discussed in a one-on-one or small group setting. Among the technical topics covered in the presentations and posters were the development of water quality and thermal standards, thermal response characterization, thermal modeling, case studies, the use of thermal imagery to optimize cooling lake performance, and methods to estimate forced evaporation from surface waters.

Results

All presenters at the Third Thermal Ecology and Regulation Workshop were asked to prepare a paper on their presentations. In total, 25 papers were received and are contained in this EPRI report.

EPRI Perspective

Although the Clean Water Act has not changed in 40 years, the world has and continues to do so. Water issues, such as thermal discharge, impingement and entrainment, total maximum daily loads, effluent guidelines, water availability, and climate variability, are converging. The workshop provided an opportunity to bring together a concerned community of power plant employees, regulators, consultants, researchers, professors, and students to consider a mixture of

employees, regulators, consultants, researchers, professors, and students to consider a mixture of old and new thermal-discharge-related research and regulatory topics that call for creative scientific, technical, and policy solutions. The workshop was a follow-up to two previous EPRI-sponsored workshops on Section 316(a) issues held in 2003 in Columbus, Ohio (see EPRI report 1008476), and in 2007 in Westminster, Colorado (see EPRI report 1016809).

Keywords

316 (a)
Aquatic populations
Cooling technologies
Regulations
Research
Thermal discharge

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INTRODUCTION

In October 2011, over 100 people met at Great River Energy in Maple Grove, Minnesota (Figure 1-1) for a workshop sponsored by the Electric Power Research Institute (EPRI) to discuss new developments concerning technical, regulatory, and legal perspectives on Section 316(a) of the Clean Water Act (CWA). This section of the CWA regulates thermal effluents (typically referred to as “once-through non-contact cooling water”) and provides for a variance from both technology-based limits and water quality standards if it can be demonstrated that the thermal discharge “will assure the protection and propagation of a balanced, indigenous population of shellfish, fish, and wildlife in and on that body of water”. The 316(a) program was very active in the 1970s as thermal dischargers conducted studies to determine whether they might qualify for a variance.

Figure 1-1
Great River Energy’s facility in Maple Grove, Minnesota

During the course of this two-day workshop, there were over 35 presentations and posters on 316(a) and related topics, including legal and regulatory perspectives, water quality and thermal standards, thermal response characterization, thermal modeling, use of thermal imagery to optimize cooling lake performance, forced evaporation, and the impacts of CWA 316(b) regulations on 316(a) assessments. The keynote speaker, Chuck Coutant, discussed how thermal issues are still with us, despite strong regulatory pressure to use closed-cycle cooling for new power stations (many existing stations still use once-through cooling), despite five decades of focused thermal-effects research and analysis, and despite four decades of 316(a) demonstrations showing no harmful impact. A primary reason for the continuing focus on thermal issues is that 316(a) demonstrations face increasing scrutiny for showing a Balanced Indigenous Community that matches what would have existed in the absence of the thermal discharge. Confounding these demonstrations are highly variable year-to-year population densities in Representative Important Species; state thermal standards based on laboratory experiments; and unsettled concepts about community ecology as used in the CWA and state regulations.

Dr. Coutant's remarks hit home as many of the presentations focused on site-specific approaches to demonstrate or achieve regulatory compliance. These approaches typically included monitoring, modeling, or a combination of both. For example, a combination of modeling and monitoring was used to demonstrate compliance of the Indian Point Energy Center's thermal plume with New York's thermal criteria in a permit renewal process. Craig Swanson of Applied Science Associates discussed this demonstration, which included a field program consisting of an extensive fixed instrument array to monitor river temperatures and currents over a 2-year period. Also, a hydrothermal model was used to evaluate the extreme environmental conditions that have the largest influence on river temperature. The result was a highly credible analysis that demonstrated compliance with thermal criteria. The model was ultimately used to define a thermal mixing zone for use in a draft permit.

A combination of monitoring, river temperature forecasts, and hydrothermal modeling has been used at the Browns Ferry Nuclear Plant to make crucial decisions regarding the combined operation of the power plant and upstream dams. Paul Hopping of the Tennessee Valley Authority discussed how hydrothermal models are run regularly to provide predictions of water temperature at the plant, over both the short-term and long-term. These models are used in making operational decisions to meet water quality goals. TVA's recent experience trying to provide reliable generation and meet thermal criteria under severe weather conditions during the summer of 2010 resulted in power production derates and ultimately lead to the decision to increase the capacity of the plant's recirculating cooling system.

In addition to being used to meet water quality goals, modeling and monitoring are also used at power stations to more directly evaluate the effects of thermal discharges on the biological community. Monitoring and modeling were used in a study to evaluate the potential individual and interactive effects of Peach Bottom Atomic Power Station's thermal discharge and Muddy Run Pumped Storage Station operations on migration of American shad (both pre-spawning and post-spawning). Kimberley Long of Exelon Generation Company described how hydrothermal modeling was used to delineate the extent and magnitude of the upstream dispersion of the thermal plume due to pumping and the hydrological conditions under which it occurs. This modeling effort, in combination with radio telemetry studies, suggested that operations of the two stations individually or jointly contribute little, if any, to the failure of a high proportion of upstream migrating American shad to utilize the Holtwood Fish Lift. At Brayton Point Station, USEPA examined multiple discharge scenarios using a hydrodynamic model and chose the scenario that would assure protection of winter flounder nursery habitat. Phil Colarusso of USEPA presented how temperature effects on species avoidance and attraction and potential changes in predator-prey dynamics were considered in this study. Ultimately, the plant was required to reduce its thermal discharge by approximately 95%, which resulted in installation of cooling towers at Brayton Point Station. Monitoring alone was used at Quad Cities Nuclear Station, where a shellfish monitoring program was established to investigate whether an alternate thermal standard would affect a federally endangered freshwater mussel (unionid) species, which occurs a few miles downstream of the thermal discharge. In her presentation, Heidi Dunn of Ecological Specialists showed results of this study which demonstrated no impact to the species. Results were used to develop a proposed Habitat Conservation Plan (HCP) that combines a monitoring program with existing data to detect any changes in unionid communities that might occur due to operation under the proposed alternate thermal standard.

Site-specific approaches for demonstrating thermal compliance often rely on species thermal tolerance data. A number of presentations at the workshop focused on laboratory research to further define species thermal tolerances. Mussels in particular were identified as a potentially sensitive species where minimal research has been done in the area of thermal tolerance. Alissa Ganser of the University of Wisconsin discussed how the complex mussel lifecycle makes them especially sensitive to temperature changes and presented her laboratory research on development of thermal criteria for mussels based on physiological and reproductive traits. Determining whether sediment provides a buffer to thermal stress and identifying thresholds of sublethal stress were the focus of mussel research presented by Jennifer Archambault of North Carolina State University. The thermal tolerances of aquatic macroinvertebrates and fish were the focus of laboratory experiments presented by John Jackson and Willy Eldridge of the Stroud Water Research Center. In these experiments, the sensitivities of aquatic macroinvertebrates and fish to various rates of temperature change and maximum daily temperatures were examined. Results indicate that any temperature change can be stressful, but effects will depend upon species, magnitude of the change, duration at high or low temperatures, and proximity to thermal limits.

At one site in southwestern Colorado, species thermal preferences and population data have been successfully used to reclassify a stream as warm water, resulting in less stringent thermal limits. Historically in Colorado, stream use classification was based on expected fish communities. In their presentations on this study, conducted on the San Miguel River near Nucla, Colorado, Chantell Johnson of Tri-State Generation and Transmission and Steve Canton of GEI Consultants discussed how instream temperatures and fish community composition data were not sufficient to reclassify the stream. In addition, they used benthic invertebrate densities and thermal tolerances to establish the new warm water classification of the river segment. Also, it was determined that habitat limitations, such as low flow conditions, high summer temperatures, and wide, shallow riffle habitat, rather than Nucla Station's discharge, are the driving factors in shaping the aquatic community in the San Miguel River.

Overall, the presentations at the workshop illustrate progress being made in the area of thermal ecology and regulation, but they also indicate that there is much more to be done. One study in particular spoke to the need for continued research. Studies at the Diablo Canyon Power Plant in central California illustrate the difficulty in predicting changes in complex biological communities as a result of altered temperature regimes. Chris Ehrler of Tenera Environmental presented these studies, which are unique in that they have an extended pre-operational baseline of data. This, combined with a comprehensive study design, increased the ability to detect changes due to the thermal discharge. Laboratory studies on thermal tolerance of Representative Important Species identified at the site were used to make several predictions of the spatial extent and magnitude of discharge impacts. After several years of operation, the changes detected from sampling were compared with the predictions and showed that the spatial extent and magnitude of the changes generally exceeded the predictions. Reasons for this included the predictions did not account for algae losses due to high temperatures cascading through the community and a prolonged period of warm ocean temperatures that started at the same time the study began. This study highlights the complexity of biological communities and the need for continued research to further understand their reaction to thermal stressors.

Returning to the words of Dr. Coutant, that despite five decades of focused thermal-effects research and analysis and despite four decades of 316(a) demonstrations, the workshop demonstrated that in the area of thermal ecology and regulation there is still much to be learned. Some topics identified for further research are as follows:

- New applications of 3-dimensional hydrothermal models.
- Improve methodologies to measure thermal tolerance and identify ecological factors that influence thermal sensitivity.
- Increase understanding of thermal effects at all spatial scales, from molecular to whole community and ecosystem.
- Improve methods to evaluate indirect responses of biological communities to temperature changes.
- Improve methods to forecast water temperatures in order to make reliable predictions several weeks into the future.

This document presents the proceedings from the Third Thermal Ecology and Regulation Workshop. Each of the 36 presenters was asked to prepare a paper on their presentation. In total, 25 papers were received and are contained in this EPRI report. Copies of the presentations themselves can be obtained from EPRI’s eTherm website at http://www.epri.com/etherm.

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ARE WE STILL IN “HOT WATER” OVER THERMAL ISSUES AT POWER PLANTS?

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Abstract

Thermal ecology research and analysis are far from passé. Despite the trend toward use of closed-cycle cooling at new thermal power stations, issues of thermal effects remain important for the electric power industry. Opponents of new facilities now target warm-water blowdown discharges for their potential thermal effects, as exemplified by the permitting of the Vogtle nuclear power station’s two new units. In such cases, thermal modeling and biological assessments are required even though the discharges are small and in-stream water temperature standards are met. Once-through cooling at existing facilities still must meet water temperature standards in the water body or obtain a Clean Water Act (CWA) §316(a) alternative thermal limitation (variance). Temperature standards in many states need improvement with better scientific basis in fundamental thermal-effects data for aquatic species. Demonstrations for §316(a) alternative thermal limitations face increasing scrutiny for showing a Balanced Indigenous Community (BIC) that would have been there in the absence of the thermal discharge and for “no prior harm” that includes long-term trends in Representative and Important Species (RIS) populations. With permit renewals usually on a 5-year cycle, the repeated biological surveys need to improve understanding of the local thermal ecology under the previously permitted discharges as well as tally current populations. The science of community aquatic ecology has yet to mesh well with the regulatory criteria for “balanced.” Lastly, enhanced understanding of thermal ecology in relation to thermal discharges needs to be more effectively communicated among relevant parties: regulators, educators, consulting firms, company personnel, and opposing groups.

Introduction

Thermal issues are still with us in the electric power industry. Although the Environmental Protection Agency (EPA) requires all new power stations be equipped with closed-cycle cooling, existing power stations still use once-through cooling systems with waste heat discharges at temperatures above the ambient source water (thermal discharges). It will likely be many decades before these existing facilities are decommissioned. Thermal effects issues continue to be raised at many of these facilities despite about five decades of laboratory and field research, monitoring, and analysis focused on thermal effects and development of biological criteria, about four decades of demonstrations of “no prior harm” under §316(a) of the CWA, and about four decades of related environmental impact assessments under the National Environmental Policy Act (NEPA), primarily for nuclear plants. In a comprehensive compilation of studies of the ecological effects of thermal discharges through the late 1980s, Langford concluded in his 1990 textbook: "The research and surveys have not borne out the dire predictions of disaster [found in the 1960s and early 1970s]." [1]

Why are thermal issues still with us? There are several reasons, some regulatory, some scientific, and some social. There is increased regulatory attention to CWA §316(a) demonstrations of lack of harm by EPA and the states to which EPA has delegated authority. Stringent state water temperature standards, based heavily on laboratory data or undocumented opinion, tend to be unattainable thus forcing generators to seek §316(a) alternative limitations. NEPA requires the Nuclear Regulatory Commission (NRC) to evaluate thermal discharges in Environmental Impact Statements (EIS), especially if temperature-related contentions are filed by interveners. The science of community ecology is often inadequate to define clearly what is required in the §316(a) statute and its implementing regulations (e.g., "balance," "diversity," and "sustainability"). Opponents of existing or new generating facilities (or other facilities with thermal discharges such as paper mills) seize on any issue, including thermal effects, to press their opposition, often reverting to the "dire predictions" of earlier years cited by Langford [1].

In this paper, I discuss these reasons, with primary emphasis on the current state of increased regulatory attention. With knowledge of what is currently being required, industries that must defend their thermal discharges can be prepared to submit the most appropriate information, particularly in §316(a) demonstrations. First, however, I give a brief review of the regulation of thermal discharges as background.

Regulatory Review

Federal Water Pollution Control Act of 1965

This federal legislation mandated water quality standards for pollutants in water bodies (receiving waters), including temperature. It initiated in-stream, water-quality-based pollution control. Water temperature standards were to be developed by the states under guidance of the federal authorities (initially the Federal Water Pollution Control Administration and later the EPA). Guidance first took the form of the 1968 "Green Book," the *Report of the Committee on Water Quality Criteria* [2]. The Green book was supplanted in 1973 by the "Blue Book," *Water Quality Criteria 1972*, which was commissioned by EPA from the National Academy of Sciences and National Academy of Engineering [3]. There have been subsequent guidance documents that essentially perpetuated the guidance in the Blue Book.

State water temperature standards are in place in every state. They generally include maximum temperatures (sometimes seasonal) for water bodies having specific use classifications, maximum temperature elevations above ambient, and sometimes a maximum rate of temperature change. Implementing regulations allowed a mixing zone to be established close to the discharge within which the standard would not apply. If a thermal discharge with its designated mixing zone can meet the temperature standards, then aquatic life is assumed protected. This continues to the present.

National Environmental Policy Act of 1970 (NEPA)

This federal legislation mandated environmental review for any major federal action, including issuance of licenses. The (then) Atomic Energy Commission, later the NRC, was required to prepare EISs for licensing of nuclear power plants. Initially interpreted to mean radiological impacts, the mandate was expanded to include thermal discharges (and other cooling system impacts) by the Calvert Cliffs decision. By interagency agreement, primary responsibility for cooling system impacts was later assigned to EPA through the National Pollutant Discharge Elimination System (NPDES) although the NRC must still consider cooling system impacts, especially when interveners in the licensing process raise contentions related to thermal discharges.

Federal Water Pollution Control Act of 1972 (amended in 1977 as the Clean Water Act)

Federal pollution control took a major change in direction in 1972 with implementation of technology controls over pollutant discharges, although water quality controls remained. Closed cycle cooling was deemed the best technology for power stations, which was to essentially eliminate thermal discharges except for blowdown (the small discharge necessary to minimize buildup of salts in the recirculating cooling water). However, one section [§316(a)] provided for alternative thermal effluent limitations (often called a variance) for existing discharges exempting them from closed cycle cooling and any other thermal limitations (e.g., in-stream temperature standards) on demonstration of a "balanced indigenous population of shellfish, fish, and wildlife" in or on the water body. This demonstration was to be part of the application for a NPDES pollutant discharge permit to be issued by EPA or a state to which EPA has delegated NPDES permitting authority. Since many power stations and other thermal dischargers cannot readily meet temperature standards in the receiving waters, §316(a) demonstrations have been, and still are, the predominant means for obtaining thermal limitations under NPDES permits.

Implementing Regulations for §316(a)

Federal regulations were developed to implement §316(a): 40 CFR 125.70–125.73 (called "Subpart H: Criteria For Determining Alternative Effluent Limitations Under Section 316(a) of the Act"). These regulations clarified the "Balanced Indigenous Population" (BIP) of the Act to mean a BIC, and defined the BIC as a *"biotic community typically characterized by diversity, the capacity to sustain itself through cyclic seasonal changes, presence of necessary food chain species and by a lack of domination by pollution tolerant species."* It also included other important requirements and caveats, such as providing for designation of RIS for detailed analysis in lieu of exhaustive species lists. Subpart H remains as the focal regulation for §316(a) demonstrations.

Interagency 316(a) Technical Guidance Manual (1977)

Jointly prepared by EPA and NRC, the manual was prepared to be a practical guide for biologists preparing §316(a) demonstrations and thermal effects sections of nuclear facilities' EISs [4]. It gave guidance for conducting field investigations, predictive assessments in advance of a facility's operation and "no prior harm" demonstrations for an operating facility. Although issued only as a draft, the 1977 guidance manual has been the continuing practical guide for surveys and assessment criteria, although the decision regarding issuance of a permit is ultimately up to the "Administrator." The more specific assessment criteria augmented those in Subpart H.

Key Administrative Decisions ~1976–2010

Many early §316(a) demonstrations were litigated leading to many clarifying decisions. Additional practical decision criteria were established, such as the importance of the magnitude of effect (not just that there was an effect), whether the water body as a whole was affected (as opposed to any single place in it), and that trends in species population abundance over time in the whole water body should be considered. This body of precedents continues to evolve and shapes what analysts need to consider and what regulators see as the relevant decision criteria.

Regulatory Attention

What's Currently Happening?

EPA headquarters has recently given special attention to regulation of thermal discharges. In 2008, a memo was sent to EPA regional offices outlining what headquarters expected. This memo resulted in more detailed regional EPA review and evaluation of §316(a) demonstrations approved by states. As a consequence, there are more strict requirements being placed on BIP/BIC demonstrations. These requirements include:

- Emphasis on *renewal at about 5-year intervals*, consistent with the original intent for NPDES permits. Many thermal "variances" had been continued uncritically for decades.
- Requirement of *full biological demonstration studies at each renewal*, rather than cursory review and update for discharges that had been permitted in the past. Subpart H specifically designated the degree of detail in renewals to be at the discretion of the Administrator.
- Strict *adherence to Subpart H BIP/BIC criteria* of diversity, sustainability, food chain species, and lack of domination by pollution-tolerant species. Many demonstrations had used the criteria in the EPA/NRC Guidance Manual exclusively without referring to the criteria in the basic federal regulations.
- Inclusion of *all trophic levels* (biotic categories) in the demonstration. These are: phytoplankton/periphyton, zooplankton, shellfish (macroinvertebrates), fish and wildlife. Many demonstrations had focused on fish as the primary group of concern with little or no attention to other trophic levels/biotic categories. Even when a biotic category is considered "low potential impact" per the EPA/NRC guidance, it must still be discussed and the rationale for low impact spelled out.
- Interpretation of a BIP/BIC as *what would have been there without the thermal discharge* (not just "a" BIC). This is a relatively new interpretation based, in part, on the EPA Environmental Review Board review of the Brayton Point (BP) plant litigation [5].
- Emphasis on *cumulative impacts*, such as regional fish population trends that may be affected by the thermal discharge. Although a Subpart H criterion, this interpretation has been given new emphasis by the (BP) decision.
- Emphasis on *indigenous species* except for historically non-native species introduced in connection with management or species whose presence results from irreversible prior modifications (a requirement in Subpart H).

- Strong *scrutiny of RIS* selected as indicators. Subpart H specified that this selection was to be by the Administrator, although often the applicant selected the species on the list with little critical evaluation.
- Despite RIS, insistence on a *full community analysis* in support of the Subpart H criteria.
- Examination of *thermal effects in the plume* (mixing zone) to ensure that any effects there would not affect the broader water body (e.g., plume entrainment mortality, zone of passage). Often, the mixing zone was considered exempt from a BIC study.
- Stronger *regional EPA oversight* of states with delegated authority. Audits had indicated that such oversight was lax.
- Detailed *review and approval of BIP/BIC study plans* by both the state and EPA region prior to initiation of the studies by the applicant. In the past, reviews were conducted by the state with no formal review by the EPA region, if done at all. EPA clearly wants better oversight.
- EPA or the state may *set an alternative effluent limitation* that is different from the one proposed by the applicant, which may lead to limitations that cannot be met by the present discharge. Although always true in principle, the "variance" was usually given in the form proposed by the applicant. The (BP) decision strengthened the role of EPA or the state in setting the alternative limitation.

Staying Out of Regulatory "Hot Water"

First, the option of meeting in-stream water temperature standards needs to be carefully evaluated. If the thermal discharge structures and the approved mixing zone can be configured to enable the in-stream temperature standards to be met outside of the mixing zone, then further consideration of thermal effects is not necessary for the NPDES permit. There are a variety of discharge diffuser designs that can rapidly reduce temperatures in a small mixing zone by enhancing mixing with ambient water. Selection of the mixing zone's dimensions is often the most demanding task, and one that requires good-faith negotiations between the discharger and the regulator. With adequate understanding of the biological features of the vicinity (e.g., migratory patterns fish, drift patterns of planktonic organisms) the mixing zone can often be located so that there is essentially no biological impact on the main water body.

When a §316(a) Demonstration is necessary, it needs to give careful attention to regulations, guidance, and communication as it seeks to demonstrate no prior harm. The demonstration will be more favorably received when:

- There is agreement ahead of conducting any studies about what the permitting authorities in the state or EPA region expect. This includes obtaining an explicit approval of biological and thermal plume study plans. If there are opposition groups, it is helpful to include them in an advisory role as plans are developed. Including their concerns in a study plan may alleviate their opposition. Multi-organizational technical advisory committees have been used by several utilities to craft study plans that have met diverse expectations.
- Data compilations and draft evaluations from the on-going study are shared with the relevant regulators and a technical advisory committee (if assembled). This way, the

applicant, its advisors and the regulators develop understanding together before the final product is presented.

- The demonstration presents information in terms of meeting specific regulatory criteria. Because regulators are apt to review a demonstration by reference to a criteria checklist, it is helpful to present the information with clear statement of the criterion that is being addressed. This should include explicit citation of Subpart H, including quotation of its main criteria and other considerations it lays out, as well as specific decision criteria from the EPA/NRC guidance document and relevant administrative decisions (specifically cited, if possible).
- There is dialog with regulators over the findings, conclusions, and alternative limitations when the demonstration is submitted. Rarely are ecological studies of any kind cut and dried.

Temperature Standards

An operator of a thermal discharge can either meet in-stream temperature standards or seek a §316(a) alternative effluent limitation. As noted above, meeting temperature standards generally obviates the need for extensive biological studies. The temperature standards are developed and approved by states with the assumption that they are protective of aquatic life.

In-stream temperature standards can be quite restrictive, however, often forcing a thermal discharger to seek a §316(a) alternative limitation. Many state standards were developed quickly in the 1960s based on the temperature-change (allowable rise above ambient) recommendations of the "Green Book" [2], which considered temperature only briefly and relied on a sparse history of thermal-effects research (and did not document the scientific sources for its information, relying instead on professional opinion of the task force that developed it). In response, the EPA commissioned the national academies in 1971 to prepare the "Blue Book" [3], which extensively documented its conclusions for all the water quality criteria. In the case of the Heat and Temperature chapter, emphasis was changed to meeting the temperature requirements of species and life stages of aquatic organisms found at a site. While that approach was more scientifically credible than an allowable temperature rise above ambient, much of the available information was from laboratory studies, which dominated the technical literature at that time.

The restrictiveness of current temperature criteria and standards needs to be re-evaluated in light of numerous field studies that have been conducted since the early 1970s. Many of these studies have been scientifically rigorous, whereas others have been of a monitoring nature or less rigorous §316(a) studies. As Langford stated, many of the dire predictions of thermal effects have not been found in the field [1]. Many normal biological functions can explain the differences: species assemblages and life stages change naturally with the seasons, organisms select temperatures suitable for them while avoiding potentially damaging temperatures, locally adapted species respond differently than the same species for which data in the literature were obtained elsewhere, habitat characteristics often dominate the more subtle thermal influences, the most thermally-sensitive species regionally (that might drive the standard) may normally be rare at the site, species normally do not function at the most favorable (optimal) temperatures in nature, and so on. Considering that most field studies of the past three decades were not included in the criteria of the 1970s, a reassessment surely seems in order.

Limitations of Community Ecology

The science of community ecology has yet to mesh well with the statutory criterion of "balanced" or the Subpart H regulatory criteria of diversity, sustainability or dominance. In the strictest scientific sense, there is no such thing as a balanced aquatic community, for assemblages of aquatic organisms are in constant flux depending on such factors as changing environmental conditions and cyclic predator-prey relationships. The caveats of Subpart H (e.g., excluding irreversible alterations of habitat by other developments) are just the beginning of uncertainties.

There are many examples of uncertainty. For example, community ecology has spent much scientific effort developing various diversity indices that are potentially applicable to Subpart H's criterion of diversity, but which ones are best for a §316(a) demonstration is not clear (to be safe, some demonstrations use multiple indices). The most appropriate evidence for sustainability through seasons in Subpart H is not clear. Must the species always be there (not appropriate for migratory species) or is evidence of seasonal reproduction more appropriate? What percentage of a community composition is considered domination? Is any shift in percent composition considered a trend toward domination? How similar to a reference site does a thermally influenced community need to be, when all communities differ to some extent? The statutory limitation to "indigenous" species seems somewhat out of date considering that most aquatic systems have acquired species whose ranges have expanded since pre-European times, both naturally and by human alteration of habitats and migratory routes even though they are not specifically managed (as stated in Subpart H). Even the stipulation that thermal discharges should not foster nuisance species is vague, since one person's nuisance species is another's game species. Although Subpart H calls for evaluation of the cumulative impact of the thermal discharge and other influences, the ecological baseline for cumulative impact is not clear (some opposing groups insist, for example, that evaluation of a discharge to an impounded river must use a baseline of the pre-impoundment, free-flowing river). Although the administrative guideline that the biotic community of the thermally influenced receiving water should be the same as it would have been without the thermal discharge seems appealing, what state of a pre-thermal-discharge environment is the correct one for comparison? When experience with thermal discharges indicates that most changes at operating facilities are extremely subtle outside a mixing zone, these details can become very important when regulators or others press for increasingly stringent thermal requirements.

Despite the emphasis of the statute and regulations on community ecology, the final decision on a §316(a) demonstration often boils down to impacts to a few key species of special interest. This may be because of the inherent limitations of community ecology, but it may simply reflect social pressures to protect or enhance certain desirable species.

NEPA Considerations

Although the regulation of thermal discharges has largely been assigned to EPA and the states under the NPDES system, NEPA still comes into play for NRC review for nuclear power plant licensing. This is especially true when an intervening group files a contention related to the thermal discharge. Nuclear generation is experiencing a revival, and new units and entirely new sites are being considered. Even though new cooling systems are mandated to use closed cycle cooling, there remains a blowdown flow that is generally warmer than the ambient receiving water. For NEPA EISs by the NRC, a scientifically credible analysis of potential thermal plume and biological effects needs to be carried out. NEPA requires an independent analysis, not just certification that EPA or the relevant state has approved. For example, in the licensing proceeding for constructing two new units for the current 2-unit Vogtle nuclear plant (Georgia), thermal plume modeling and biological analyses were necessary for the NRC impact statement and were contested by interveners in hearings before the Atomic Safety and Licensing Board. For those contemplating a nuclear plant, selection of a closed-cycle cooling system is not the end of the story.

Communication, Education and Opponents

Many of the dire predictions about thermal discharges that were prevalent in the 1960s live on, particularly when there is an opportunity for facility opponents to use them to their advantage. These predictions need to be countered with credible data and analyses. In hindsight, there has been a failure to adequately educate the public and regulatory staffs about thermal discharges, the biological criteria and engineering options available for facilities to minimize ecological hazards and the many studies and monitoring programs that protect the environment from thermal damages.

Reputable reference documents are needed to summarize the history of thermal discharge analyses, regulations, and results for the educated lay public and students who may take jobs in water pollution regulation or work for firms doing §316(a) demonstrations. Langford’s 1990 textbook is a good example, but it needs to be updated with the many field studies and §316(a) demonstrations that have been carried out since then. The EPA/NRC guidance manual for §316(a) demonstrations could stand updating based on decades of experience with thermal discharges since 1977, including results of studies, the history of administrative decisions, and current thinking. In 1977, the focus of the guidance was largely on predictive analyses for proposed power stations; today it is on regulating existing discharges via demonstrations of a BIP/BIC in the already affected water body. Such information resources would not necessarily exonerate all thermal dischargers, but they should allow a better ability to recognize those situations where tightened effluent limitations are warranted and where they are not.

Conclusions

Thermal ecology research and analysis are still needed. This is largely because existing thermal discharges are facing increased scrutiny from regulators, largely at the insistence of EPA headquarters. Although meeting water temperature standards is an option, field studies to prepare a §316(a) demonstration of a balanced, indigenous community often must be conducted. Fundamental thermal ecology studies are needed to refine thermal criteria for temperature standards and to better align the understanding of community ecology with the community-oriented requirements of the statute and regulations. Better education of the lay public and students in pollution-control curricula is needed on the topic of thermal effects in aquatic ecosystems.

Facility managers need rigorous, relevant data from laboratory and field studies that are analyzed specifically for their site to address the §316(a) criteria for identifying and quantifying any undesirable thermal impacts, whether specifically for §316(a) demonstrations, NEPA analyses, or countering opposition. When §316(a) demonstrations are prepared, they will be more easily reviewed and readily accepted when study plans and findings are related specifically to criteria listed in the statute, regulations, guidance and administrative decisions.

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3

RECENT DEVELOPMENTS IN POWER PLANT THERMAL DISCHARGE REGULATIONS, THERMAL EFFECTS, AND STRESSORS

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Introduction

Section 316(a) of the Clean Water Act (CWA) regulates thermal effluents and provides for a variance from both technology-based limits and water quality standards if it can be demonstrated that the thermal discharge “will assure the protection and propagation of a balanced, indigenous population of shellfish, fish, and wildlife in and on that body of water”. In 2009, the Electric Power Research Institute (EPRI) [1] published a paper on §316(a) issues that discussed the following: (1) how the §316(a) regulation and temperature standards are evolving at the national, regional, and state levels; (2) what research is being done to better understand and address impacts of thermal discharges on aquatic species; and (3) the potential future stressors on thermal discharge compliance. This paper updates that information. In the past two years, no action on §316(a) regulations or guidance has been taken at the federal level, but a few states have completed amendments to their thermal standards and a few others have begun modifications. To provide another perspective on thermal standards in the U.S., the use of thermal standards internationally is presented. Thermal effects research has progressed, with an emphasis on further defining the effects of heat shock, looking at the effects of temperature in combination with other environmental stressors, and identifying the role of thermal pollution in life cycle assessments. Finally, potential stressors on thermal discharge compliance are discussed. Total Maximum Daily Loads (TMDLs) for temperature continue to be a potential stressor, and new threats discussed are rising water temperatures, reduction in water availability, and the potential for urban surface runoff to increase water temperatures.

Regulations

Temperature standards are at the heart of managing thermal discharge compliance; dischargers are required to meet them or demonstrate that a less stringent standard is applicable in their situation. This section describes activities at the federal and state levels regarding development and application of thermal standards. The development and use of thermal standards internationally are also discussed, focusing on the European Union and Canada.

Federal

Federal regulations and guidance with respect to CWA Section 316(a) remain unchanged since the 1980s; a summary of these is provided in EPRI [1]. The Environmental Protection Agency

(EPA) has been considering revising the federal regulations, and the process was initiated in 2008. However, other priorities, such as dealing with permits for ocean going vessel discharges and new pesticide enforcement issues, have sidetracked their effort on addressing §316(a) issues. While EPA recognizes that §316(a) is a potentially significant issue relative to climate variability and impacts on water availability, they have no plans to revisit the §316(a) regulations at this time [2].

State

In 2008, a survey was conducted to determine the latest revision date of thermal standards for each state. At that time, five states had adopted new standards since 2000: Colorado, Oregon, Washington, Idaho, and Massachusetts. The details of those revisions were provided in EPRI [1]. Also, Wisconsin, Illinois, and New Jersey were in the process of updating their standards, also described in EPRI [1]. Since that time, the Wisconsin standards have been approved, and they took effect on October 1, 2010. Illinois standards continue to be a subject of controversy and hearings before the Illinois Pollution Control Board (IPCB) continue into 2011 (this is summarized later in this section). In New Jersey in November 2009, new temperature criteria were adopted for both trout and non-trout waters to replace the “natural background” criteria for Trout Production waters with numeric criteria [3]. The new rules include a lower daily maximum temperature and a running seven-day average of the daily maximum temperatures to protect fish species from elevated temperatures occurring during the summer months.

Another survey of state offices was conducted in 2010 to get the latest information on activities related to thermal standards in the remaining states. Figure 3-1 was developed from this information and shows the time period in which each state’s existing temperature standards were adopted for the 48 contiguous states. Nine states are currently in the process of revising their temperature standards: Illinois, New Mexico, Arkansas, Georgia, Mississippi, Nevada, Texas, Vermont, and Virginia. Two of these states are making significant revisions to their temperature standards: Illinois and New Mexico. A detailed description of the revisions from these two states is presented below. The other seven states are making minor clerical changes or changes to site-specific water bodies (since these updates are minor, Figure 3-1 does not show these states as having recent updates to their temperature standards). Five of these states, Arkansas, Georgia, Nevada, Texas, and Virginia, are making site-specific adjustments for a limited number of waterbodies in the state. The current temperature standards will remain in effect for all of the other waterbodies in the state. The other two states, Mississippi and Vermont, are updating or clarifying certain wording and definitions in their current temperature standards. In 2009, Connecticut proposed significant revisions to their thermal standards but these were not adopted. A description of the proposed revisions is provided below.

Additionally, the Ohio River Valley Water Sanitation Commission (ORSANCO) revised their temperature standards for the Ohio River in 2010 [4]; these new standards were adopted for the Ohio River in the affected states, which include Illinois, Indiana, Kentucky, New York, Ohio, Pennsylvania, Virginia, and West Virginia. These temperature standards are based on an approach using 20 years of site-specific data to statistically derive an endpoint based on two measures of community health: species richness and the Index of Well-Being (IWB). This approach, which demonstrates the value of a long-term, site-specific biological data set, was described in a poster at the EPRI Thermal Workshop held in October 2007 [5].

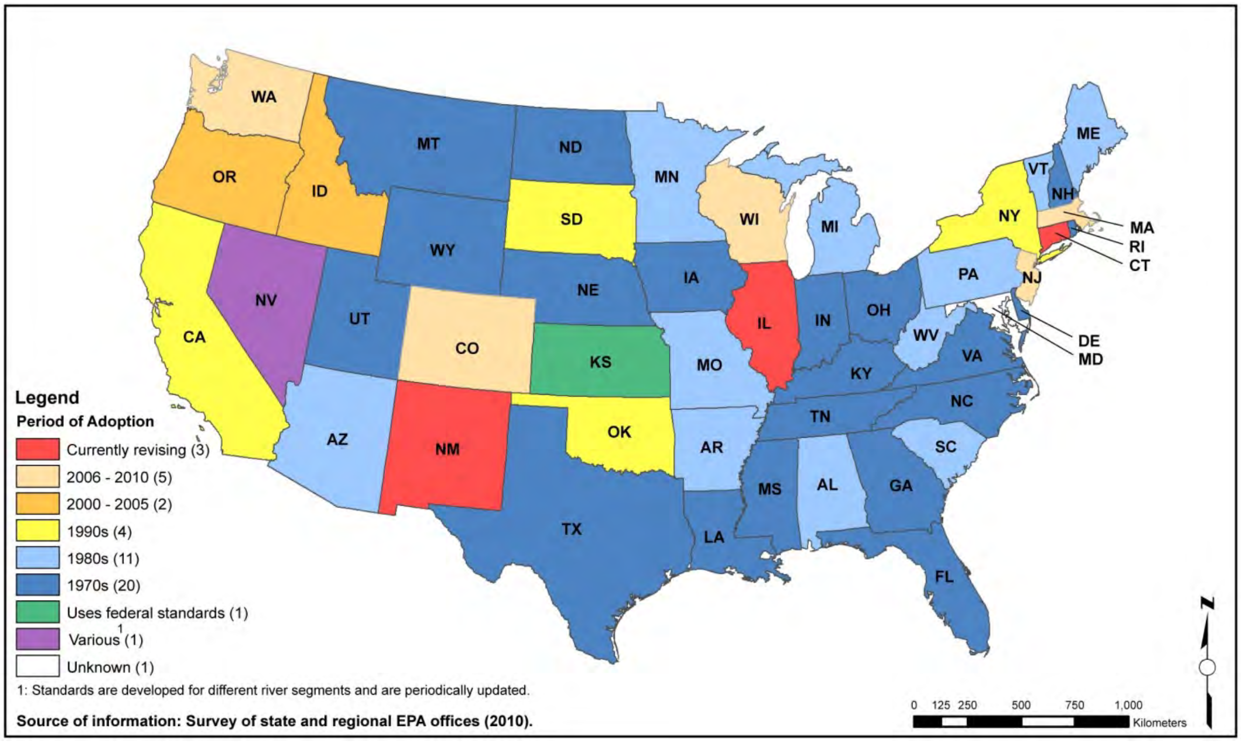


Figure 3-1
Time period in which current temperature standards were adopted for the 48 contiguous states

Connecticut

In 2009, Connecticut proposed revisions to its temperature standards. The proposed revisions to Connecticut's temperature standards are designed to 1) address short term, average and incremental thermal exposures using the EPA model adapted to species commonly found in Connecticut and 2) address the three major fish community groups, coldwater, coolwater, and warm. For freshwater, the thermal criteria are based on the thermal tolerance data and model in EPA's *Temperature Criteria for Freshwater Fish: Protocol and Procedures* [6], and are as follows:

- For coldwater communities, the average weekly temperature cannot exceed 46°F during the spawning period (October through March) and 66°F during the growth period (April through September) and the allowable maximum daily temperature is specified as 56°F (spawning period) and 74°F (growth period).
- For coolwater communities, the average weekly temperature cannot exceed 49°F (spawning period) and 72°F (growth period) and the allowable maximum daily temperature is specified as 66°F (spawning period) and 77°F (growth period).
- For warm water communities, the average weekly temperature cannot exceed 68°F (spawning period) and 85°F (growth period) and the allowable maximum daily temperature is specified as 79°F (spawning period) and 88°F (growth period).

- Additional criteria apply for waterbodies stocked with trout: average weekly and allowable maximum daily temperatures are 66°F and 74°F, respectively, for all fish communities.
- The temperature cannot be raised by more than 4°F.

Separate criteria are specified for marine or estuarine waters:

- The maximum daily mean cannot exceed 82°F.
- The allowable hourly maximum is specified as 83°F.
- The temperature cannot be raised by more than 2°F.

All criteria apply outside a zone of influence for a discharge, which is established on a site-specific basis. A full description of the proposed revisions to Connecticut's temperature standards and supporting documentation are available [7, 8].

These proposed revisions were withdrawn after the public comment period on the standards, and were not included in the Water Quality Standards Revision on February 25, 2011. Before moving forward, CTDEP recognized the need to further document conditions specific to Connecticut and establish implementation protocols.

New Mexico

The proposed revisions to New Mexico's temperature standards add magnitude, duration, and frequency to their current standards. The magnitude, duration, and frequency were added in the form of 4T3 and 6T3 temperature-related definitions. The "4T3 temperature" means the temperature not to be exceeded for four or more consecutive hours in a 24-hour period on more than three consecutive days. The "6T3 temperature" means the temperature not to be exceeded for six or more consecutive hours in a 24-hour period on more than three consecutive days. These revisions were made to improve aquatic life protection and for more effective criteria implementation, as New Mexico's Environment Department has shifted to using continuously recording thermographs, which allows the straightforward assessment of magnitude, frequency, and duration of water temperature. The proposed revisions to the thermal standards also include the addition of a maximum allowable temperature that is not to be exceeded at any time and a maximum allowable increase above ambient. The exact numbers for these standards are waterbody-specific and mixing zones are allowed under certain conditions. Additionally as part of their thermal standards revisions, New Mexico has also added a "coolwater" stream designation to their classifications (previously just coldwater and warmwater) and revised the classification for some stream segments that fit this classification. These proposed revisions became effective for state purposes as of December 1, 2010 and were approved by EPA for federal Clean Water Act purposes as of April 18, 2011. More information on the new standards and their status is available on New Mexico's Water Quality Standards website [9].

Illinois

As a result of two Use Attainability Analysis (UAA) reports, Illinois EPA (IEPA) is considering new thermal standards for NE Illinois. Five power plants are located in the area in question and all would be greatly affected by the proposed thermal standards. The proposed rules have been the subject of hearings before the IPCB for the past four years, and the hearings will continue into 2012. There are two main issues in these proceedings: (1) what are the proper uses for the various waterbodies and (2) what thermal limits are necessary to protect these uses? Both sides (i.e., the regulated community and IEPA) agree that the attainable aquatic life uses are driven by the physical habitat in the area. However, they disagree with regard to the quality of the habitat. IEPA believes that a portion of the area minimally meets CWA goals and more stringent thermal standards are necessary. The regulated community believes that none of the area meets CWA goals and therefore less stringent thermal standards should apply. Intensive assessments were conducted to support the contention that the habitat will not support a “healthy” fish community (i.e., one consistent with CWA goals). Earlier this year, testimony was presented demonstrating the severe habitat limitations in the area and on how Asian carp are likely to impact the resident fish community. The standards phase of these proceedings is expected to begin in early 2012.

The regulated community also strongly disagrees with the process by which IEPA established the proposed thermal standards. IEPA is proposing to use a “model” in which the endpoints for various categories (e.g., upper lethal temperature, avoidance temperature, etc.) are ranked from most to least sensitive. The upper lethal temperature for the most sensitive species becomes the short-term thermal standard. At hearings in 2012, the regulated community will point out several flaws with this procedure, including not adequately checking the database, and present an alternative approach to establishing thermal endpoints. This approach uses 20 years of site-specific data to statistically derive an endpoint based on two measures of community health: species richness and the IWB. The first iteration of this approach, which demonstrates the value of a long-term, site-specific biological data set, was described in a poster at the EPRI Thermal Workshop held in October 2007 [5].

States That Recently Considered Future Revisions

Five states are currently or have recently discussed plans to revise their temperature standards. In Kansas, where the federal standards are used, there was discussion regarding revising the thermal standards, but revisions are no longer being considered. Iowa also recently considered updating their temperature standards as part of their triennial review process, but ultimately decided not to. They have been challenged by several environmental groups for not properly implementing their current temperature standards; therefore they are working on new implementation procedures. South Dakota is planning to release new thermal standards in the coming months and expects them to be finalized and approved in 2012. Pennsylvania will also be issuing new draft temperature standards within the next few months and expect the revision process to take a few years. These standards are based on recently completed studies by the Stroud Water Research Center [10]. Finally, New Hampshire is planning to revise their temperature standards within the next two years.

Recent Actions Concerning §316(a) and NPDES Permits

Recent actions in the Midwest are making it harder for power plants to get thermal discharge permits. The Indiana Department of Environmental Management (IDEM) continues to push for updated Section 316(a) demonstrations. In 2009, they had informed the BP Whiting Refinery that an updated §316(a) demonstration would be needed. In response to a preliminary study plan submitted by BP in 2010, IDEM responded with a letter asking for a 10-fold increase in the number of data loggers to be used to gather data for a thermal plume model. They also emphasized that collection of new biological data, including data on phytoplankton and zooplankton, was necessary. This request for information on lower trophic level organisms is not consistent with how §316(a) demonstrations have been conducted recently on freshwater systems. Follow-up discussions persuaded IDEM that only fish needed to be studied. In July 2011, a §316(a) sampling program began at the Whiting Refinery that includes electrofishing, gill netting, and trawling. The Indiana Utilities Group submitted sampling guidance in 2008 but to date, IDEM has not accepted it.

IDEM has also renewed its efforts to establish more stringent thermal limits on Turtle Creek Reservoir, which is owned and managed by Hoosier Energy. IDEM maintains that the decline in the reservoir's largemouth bass population is solely the result of high temperatures. Hoosier Energy acknowledges that temperature may play a role in what has happened to the largemouth bass population, but that other factors are also likely involved. Hoosier Energy is sponsoring a variety of studies to better determine what factors are involved in the decline in the lake's bass population, including tracking bass during the spawning season. In July 2011, 36 temperature loggers were deployed in Turtle Creek Reservoir to provide data to refine a thermal model and determine how large a mixing zone (MZ) would be necessary to comply with the state's thermal standard.

EPA Region V recently rejected the thermal limits proposed for the Stuart Station on the Ohio River. One of the main points of contention is whether the lower portion of Little Three Mile Creek (LTC) represents the plant's discharge canal and therefore the discharge point is where the creek meets the Ohio River or whether the discharge point is where the heated effluent first enters the creek. When the plant was built roughly 50 years ago, the lower mile of the creek was straightened and dredged for the purpose of conveying the discharge water to the river. Thus, Dayton Power and Light (DP&L) contends that this section of the creek always was and continues to be a discharge canal and no balanced indigenous community can be expected to reside there. DP&L is conducting biological studies to determine the usage of the creek during the winter and early spring.

On the East Coast, recent controversies have resulted in the reduction of thermal discharges at several power plants. A new modified NPDES permit for the Mirant-Kendall cogeneration station located along the Charles River in Massachusetts reduces the allowable heat load to the Charles River by 95 percent. The station will be installing a back pressure steam turbine and an air cooled condenser to generate more steam which will be sold to a nearby hospital. Thus, the plant will use less river water for cooling; the discharge will be reduced from 70 MGD to 3.2 MGD [11, 12, 13]. In Delaware, NRG Energy's Indian River Plant has been the subject of recent attention, with its discharge permit up for renewal. In 2008, NRG Energy agreed to shut down two of its oldest units, which reduced its thermal effluent. In 2010, NRG Energy agreed to shut down a third unit in 2013, which will reduce water use by the plant by 86 percent. One unit will remain at the facility, which uses a cooling tower. [14] At the Merrimack Station in New Hampshire, EPA released a draft permit that would require Public Service of New Hampshire to install a closed-cycle cooling system, which would withdraw significantly less water from the Merrimack River and lower the temperature of the plant's discharge by 99 percent. The draft permit must still go through a public hearing and comment period. [15]

In contrast to the more restrictive actions for thermal discharges described above, in December 2009, the Vermont Supreme Court affirmed Entergy's Vermont Yankee permit that includes a variance that allows for a temperature increase in the receiving water. This has been the subject of controversy since 2006, when the Vermont Agency of Natural Resources (ANR) granted a discharge permit to Entergy Vermont Yankee that allowed Entergy to increase the river temperature at Vernon an additional 1°F by bypassing the cooling tower system between June 16th and October 14th annually. In 2008, this decision was appealed and the dates were revised to be between July 8 and October 14. The primary concern is the impact on American shad, which has seen a dramatic decline in numbers of shad returning to the river upstream of the location of the power plant that has occurred since 1991, which is the same time Vermont Yankee received its last thermal variance. Besides the thermal discharge, there are a number of potential causes for this decline, including dam passage and predation by striped bass. [16] This issue continues to be a subject of controversy, as Vermont Yankee is currently operating under an administratively-extended permit, and in 2011 the Connecticut River Watershed Council filed a petition asking ANR to fully revisit Entergy's application for a renewed variance. [17]

International Temperature Standards

With world-wide attention on a water shortage and potentially increasing water temperatures, many countries are beginning to re-evaluate their thermal standards. Dallas [18] compares thermal standards in a number of countries, with the conclusion that baseline data on water temperature and the thermal requirements of aquatic organisms are scarce for some areas, particularly in the Southern Hemisphere, which makes it difficult to adequately manage aquatic ecosystems in those areas. In order to get a perspective on how international temperature standards compare with U.S. standards, thermal standards for the European Union and Canada are explored.

European Union Temperature Standards

Protection and management of water throughout most of Europe is managed by the European Union (EU). The EU has created a system of laws that apply in all Member States. Included in these laws are the Fish Water Directive (FWD) and Shellfish Water Directive (SWD). The FWD includes thermal standards for freshwater as shown in Table 3-1.

Table 3-1
Freshwater thermal standards for the European Union

Standard	Caveat
The temperature measured downstream of a point of thermal discharge (at the edge of the mixing zone) must not exceed the unaffected temperature by more than the following: Salmonid: 1.5ºC Cyprinid: 3ºC	Sudden variations in temperature should be avoided
The following temperatures should not be exceeded at the edge of the mixing zone, for more than 2 percent of the time: Salmonid: 21.5ºC Cyprinid: 28ºC	Species that require cold water for reproduction are protected by an upper limit of 10ºC during the breeding season

Source: [19]

Variances may be granted that are limited in geographical scope if the relevant authority can demonstrate that there are no harmful consequences for the balanced development of the fish population. Member states are responsible for designating which waters the temperature standards will apply to (i.e., which are capable of supporting fish and are in need of protection and/or improvement) and designating waters as salmonid or cypronid. These standards only apply to water bodies that are receiving thermal discharges.

The SWD provides a guideline of a limit of 2°C rise in temperature. Although it is not a formal standard, member states are obliged to try to observe this guideline value.

The FWD and SWD will be replaced in 2013 by the EC Water Framework Directive (WFD). The WFD was established in 2000 to provide a legislative framework for water protection and management. One of the key aims of the directive is the setting of ambitious objectives to ensure that all waters meet "good status" by 2015. The WFD must provide at least the same level of protection to fresh waters and shellfish waters as their respective current directives. As part of the WFD, a definition of classes for fish communities was developed, as shown in Table 3-2.

Table 3-2
Summary of normative definitions for communities of fish

Level	Description
High	The expected fish species are present and their abundance is consistent with undisturbed conditions.
Good	There are slight deviations in the expected abundance of species, or the expected community structure. For example, some age classes may be under-represented.
Moderate	There is moderate disturbance; some of the expected species are absent or present in reduced abundance.
Poor	The communities deviate substantially from those normally associated with the water body. Key species may be absent.

Source: [19]

In anticipation of the repeal of the fish and shellfish water directives, the United Kingdom Technical Advisory Group (UKTAG) has proposed a set of temperature standards for the WFD [19]. These standards (see Table 3-3) are expressed as boundaries between high, good, moderate, and poor. The proposed boundary between the high and good status is the upper limit of the temperature in which most fish will spend 2/3 of their time (+/-2°C of the preferred temperature). The boundary between the good and moderate status is the upper limit of the temperature in which most fish will spend all of their time (+/-5°C of the preferred temperature). The boundary between moderate and poor status is the lower limit of the range in estimates of lethal temperatures for species. The proposed standards are values at the edge of the mixing zone that must be achieved for 98 percent of the time.

Table 3-3
Proposed WFD temperature boundaries

	Temperature (°C) (Annual 98th percentiles)			
	High	**Good**	**Moderate**	**Poor**
Cold Water	20	23	28	30
Warm Water	25	28	30	32

Source: [19]

Additionally, UKTAG proposes a limit of +/-3°C temperature change except for waters of high ecological status where a +/- 2°C limit is proposed. Furthermore, a maximum 10°C limit during spawning season in cold water bodies is also recommended.

Canadian Temperature Standards

In Canada, the Canadian Council of Ministers of the Environment (CCME) has set guidelines for temperature as part of their Canadian Environmental Quality Guidelines (CEQG). The CEQGs are nationally endorsed; however, provinces and territories may develop their own guidelines, objectives, or standards, which may be implemented within their respective jurisdictions. Ultimately, except for federal lands, the legislative authority for implementation of temperature standards lies with each province or territory.

The CCME freshwater guidelines for temperature are as follows [20]:

- For protection of drinking water, the maximum temperature shall not exceed 15°C.
- For recreational use, the maximum temperature shall not exceed 30°C.
- For protection of aquatic life:
    - Thermal Stratification: Thermal additions to receiving waters should be such that thermal stratification and subsequent turnover dates are not altered from those existing prior to the addition of heat from artificial origins.
    - Maximum Weekly Average Temperature: Thermal additions to receiving waters should be such that the maximum weekly average temperature is not exceeded.
    - Short-term Exposure to Extreme Temperature: Thermal additions to receiving waters should be such that the short-term exposures to maximum temperatures are not exceeded. Exposures should not be so lengthy or frequent as to adversely affect the important species.

The CCME marine guidelines for temperature are as follows [20]:

- Human activities should not cause changes in ambient temperature of marine and estuarine waters to exceed ±1ºC at any time, location, or depth.
- The natural temperature cycle characteristic of the site should not be altered in amplitude or frequency by human activities.

- The maximum rate of any human-induced temperature change should not exceed 0.5ºC per hour.
- These are interim guidelines.

CCME states that these guidelines should not be used as blanket values for environmental quality across Canada. They recognize that the guidelines may not be appropriate at all locations, particularly where there are sensitive species, and recommend site-specific guidelines be developed where appropriate. To assist with this, CCME prepared a guidance document to provide scientific and technical guidance on the development of site-specific water quality objectives [21].

To illustrate how these temperature guidelines have been implemented in individual provinces, two examples are provided: British Columbia and Alberta.

In British Columbia, extensive water quality guidelines for temperature were adopted in 2001 and are summarized in Table 3-4 and Table 3-5 [22]. Water quality guidelines for streams where the fish distribution is known are based on optimum temperature ranges for specific species present. Guidelines for streams where the fish distribution is unknown are also provided. These guidelines are considerably more specific than the CCME guidelines with the exception of the guidelines for marine waters, which are the same as the CCME guidelines. These guidelines are used to set ambient water quality objectives in the preparation of waste management plans, pollution prevention plans, waste management permits, orders or approvals. The objectives are set on a site-specific basis (e.g., [23,24,25]) to protect the most sensitive designated water use in a particular body of water.

In contrast to British Columbia thermal guidelines, Alberta’s thermal guidelines are simpler. Alberta’s freshwater guidelines for temperature state that the temperature must not be increased by more than 3°C above ambient temperature [26]. Until recently, Alberta has been relatively inactive in developing site-specific water quality objectives. However, in 2009, Alberta developed a *Water for Life* action plan [27] that includes the following goals:

- Define criteria and identify critical and significantly impacted aquatic ecosystems (by 2012).
- Maintain or improve the health of critical and impacted aquatic ecosystems through legislation, watershed and regional planning, and conservation organizations (by 2015).
- Monitor, report, and adjust, where necessary, to ensure the health of aquatic ecosystems are maintained or improved (by 2019).
- Establish science-based methods and tools to determine ecological requirements for a healthy aquatic environment, including completing the Alberta fish community index for assessing watershed health (by 2012).

One of the strategies used in the *Water for Life* initiative is to develop partnerships with watershed planning and advisory councils and other organizations to help move Alberta toward its goals. These partnerships can assist in developing site-specific thermal standards (e.g., [28]).

Table 3-4
Summary of water quality guidelines for temperature

Water Use	Recommended Guideline
Drinking Water Supply	15°C maximum
Freshwater Aquatic Life (Streams with bull trout and/or Dolly Varden)	Maximum Daily Temperature is 15°C Maximum Incubation Temperature is 10°C Minimum Incubation Temperature is 2°C Maximum Spawning Temperature is 10°C
Freshwater Aquatic Life (Streams with known fish distribution)	+ or - 1°C change beyond optimum temperature range as shown in Table 3-5 for each life history phase of the most sensitive salmonid species present Hourly rate of change not to exceed 1°C
Freshwater Aquatic Life (Streams with unknown fish distribution)	MWMT = 18°C (Maximum Daily Temperature = 19°C) Hourly rate of change not to exceed 1°C Maximum Incubation Temperature = 12°C (in the spring and fall)
Freshwater Aquatic Life (Lakes and impoundments)	+ or - 1°C change from natural ambient background
Marine and Estuarine Aquatic Life	+ or - 1°C change from natural ambient background the hourly rate of change up to 0.5°C see narrative in footnote
Wildlife and Livestock Watering Irrigation and Industrial Water Supplies	+ or - 1°C change from natural ambient background the hourly rate of change should not exceed 0.5°C
Recreation and Aesthetics	30°C maximum see narrative in footnote

Notes:

1. The MWMT, mean weekly maximum temperature is defined as the average of the warmest daily maximum temperatures for seven consecutive days.

2. The natural temperature cycle characteristic of the site should not be altered in amplitude or frequency by human activities.

3. The thermal characteristics of waters used for bathing and swimming should not cause an appreciable increase or decrease in the deep body temperature of bathers and swimmers.

Source: [22]

Table 3-5
Optimum temperature ranges (°C) of specific life history stages of salmonids and other coldwater species for guideline application

Species	Incubation	Rearing	Migration	Spawning
Salmon				
Chinook	5.0–14.0	10.0–15.5	3.3–19.0	5.6–13.9
Chum	4.0–13.0	12.0–14.0	8.3–15.6	7.2–12.8
Coho	4.0–13.0	9.0–16.0	7.2–15.6	4.4–12.8
Pink	4.0–13.0	9.3–15.5	7.2–15.6	7.2–12.8
Sockeye	4.0–13.0	10.0–15.0	7.2–15.6	10.6–12.8
Trout				
Brown	1.0–10.0	6.0–17.6	—	7.2–12.8
Cutthroat	9.0–12.0	7.0–16.0	—	9.0–12.0
Rainbow	10.0–12.0	16.0–18.0	—	10.0–15.5
Char				
Arctic Char	1.5–5.0	5.0–16.0	—	4.0
Brook Trout	1.5–9.0	12.0–18.0	—	7.1–12.8
Bull Trout	2.0–6.0	6.0–14.0	—	5.0–9.0
Dolly Varden	—	8.0–16.0	—	—
Lake Trout	5.0	6.0–17.0	—	10.0
Grayling				
Arctic Grayling	7.0–11.0	10.0–12.0	—	4.0–9.0
Whitefish				
Lake Whitefish	4.0–6.0	12.0–16.0	—	greater than 8.0
Mountain Whitefish	less than 6.0	9.0–12.0	—	less than 6.0
Other Species				
Burbot	4.0–7.0	15.6–18.3	—	0.6–1.7
White Sturgeon	14.0–17.0	—	—	14.0

Source: [22]

Summary

In reviewing the thermal standards of the EU and Canada, some similarities and differences between those countries and the U.S. can be observed:

- The thermal standards in Canada and the EU tend to contain the same elements as in the U.S., such as an absolute maximum temperature limit and a limit on the temperature rise above ambient.
- Like in the U.S., in both Canada and the EU, thermal standards are moving toward species-based standards in which the thermal standards are based on the species, or types of species, present in the water body.
- Similar to the U.S., in the EU, a provision for a variance is available if it can be shown that there are no harmful consequences for the balanced development of the fish population. It is unknown whether variances are allowed in Canada.
- Similar to the U.S., the responsibility for setting standards lies with the individual members of the EU and provinces of Canada. Also similar to states in the U.S., some Canadian provinces have set species- and water body-specific standards, while others have general guidelines that apply to all waters.
- The federal government of Canada and the EU have or are planning recent actions regarding updating the thermal guidelines. This is in contrast to the U.S., where the federal government has been inactive on this topic for several decades.

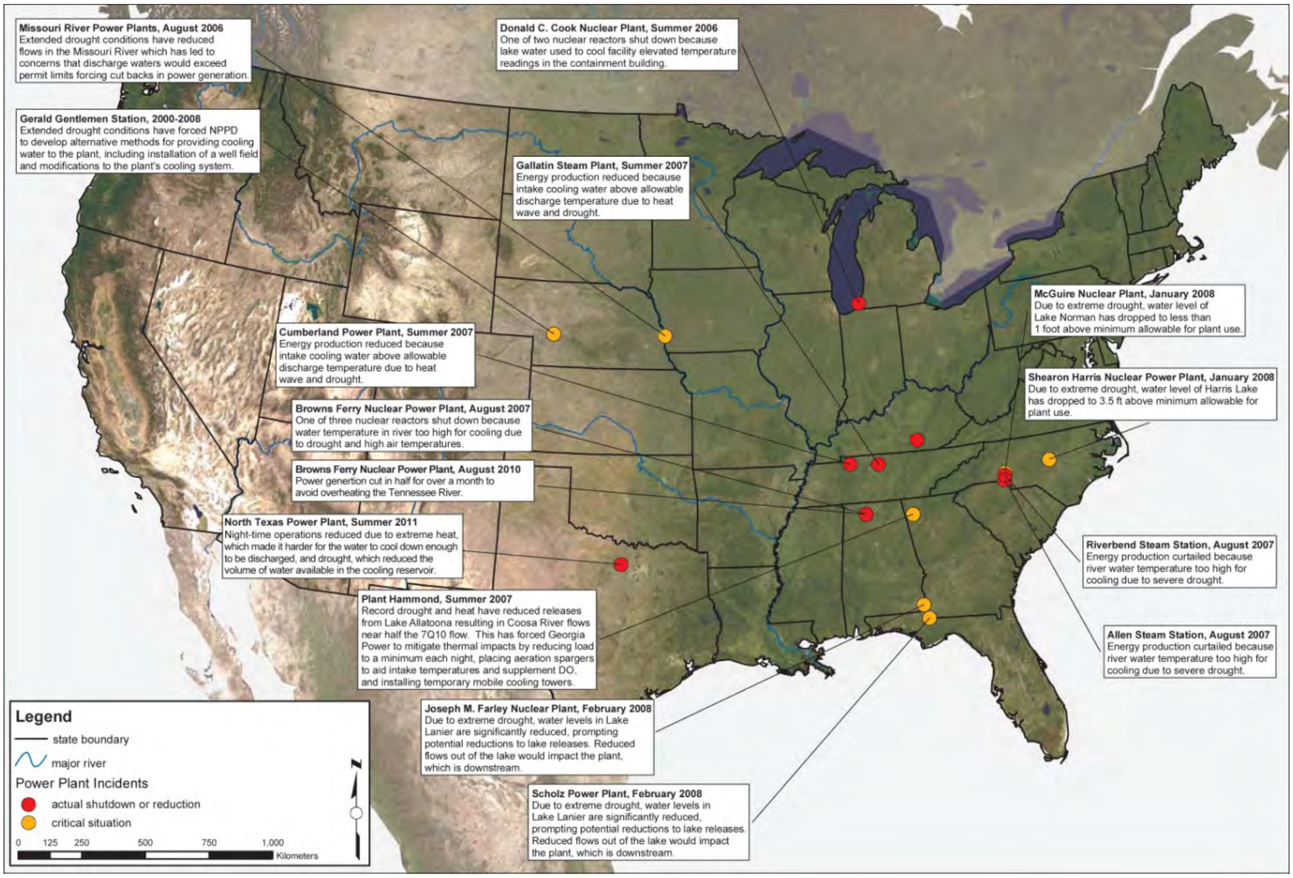
While the thermal standards themselves (i.e., actual numbers) may not be relevant in the U.S. due to different water body types and aquatic species, insight into how the standards are applied in these countries can offer reinforcement for the methods used to apply thermal standards in the U.S. and provide ideas for possible new methods.

Current and Future Stressors on Thermal Discharges

A reduction in water levels in a power plant’s receiving water can impact the plant’s ability to meet thermal discharge criteria. The National Energy Technology Laboratory (NETL) recently released a report on *Impact of Drought on U.S. Steam Electric Power Plant Cooling Water Intakes and Related Water Resource Management Issues* [29], which concluded that some power plants may be at risk of having to curtail or shut down operations in case of moderate or severe drought because of shallow intake depth. While the focus of this report was to examine impacts to power plants as a result of a drop in water levels below power plant submerged cooling water intakes, this report touches on a number of issues that are important for thermal discharges. First, there really is no time when some area within the United States is not experiencing at least some level of drought. Second, competing uses for water, such as cities and municipalities, industrial water supply, irrigation, navigation, and maintenance of the ecological health of the water body, are already causing tension in many areas and the demands for water will likely increase in the future. In a separate report [30], NETL evaluates the vulnerability of coal-fired power plants to water demand and supply issues and identifies specific plants that may be particularly at risk. Third, future climate variability will exacerbate drought conditions and conflicts over water demands. Finally, the NETL report concludes that even before the water level falls below the level of the intake, the elevated temperature of the receiving water may cause disruptions to power production.

Elevated water temperatures, not reduced water levels, are the cause of most recently reported cases where power plants have had to curtail or shut down operations. Specifically, in the Great Lakes, lower water levels and increased air temperatures has caused elevated water temperatures within the lake system, and the addition of heated cooling water from the power plants has reduced dissolved oxygen levels below levels needed for sustaining the local ecology [29]. The Tennessee Valley Authority (TVA) was severely impacted by the drought in 2006–07 and continues to be so today. In the summer of 2010, TVA’s Browns Ferry nuclear plant reduced operations by 50% for several weeks due to elevated receiving water temperatures. As a result of continued problems at this plant, additional cooling towers are being constructed. TVA has had similar issues with its Colbert, Cumberland, and Gallatin plants. Thermal concerns for Cumberland and Gallatin will likely increase due to a current Army Corps of Engineers’ project that will lower the pool levels on the Cumberland River [31]. In the Susquehanna River system, there has been one instance where a power plant was required to reduce operations because the temperature of the water was too warm to be able to achieve the cooling needed to run the plant at full capacity [29]. A prolonged drought in Texas has caused at least one power plant to reduce nighttime operations in order to operate fully during the daytime, when power is needed most. The extreme heat made it harder for the water to cool down enough to be discharged, and the drought reduced the volume of water available in a reservoir that would have helped reduce the temperature of the discharged water. [32,33] Figure 3-2 illustrates other recent critical situations where power plants have had to curtail or shutdown power production (or concerns about the potential to do so have arisen), most of which are related to elevated receiving water temperature.

Recent studies on stream temperature trends (e.g., [47]) indicate that river temperatures have been increasing over the past 50 years. Primary reasons for these increases include increasing air temperature and changes in riparian vegetation and river channelization. Morrill et al. [48] asserts that air temperature is one of the most important influences on stream temperature, and shows that for the 41 streams studied, water temperatures increased by 0.6–0.8°C per degree in air temperature increase. However, recent studies have focused on the importance of stream temperature increases due to urbanization, particularly related to the influence of heated stormwater runoff on streams resulting from stormwater contact with heated surfaces such as asphalt and rooftops. In a modeling study of runoff from an asphalt lot in Minnesota, Herb et al. [49] concluded that for most storm events, stormwater runoff is not a significant contributor to thermal pollution. However, under certain conditions heated stormwater runoff can have a severe impact on the temperature of cold-water trout streams: when air temperatures are higher than stream temperatures, rainfall events are preceded by full or partial sun, and the watershed has a high percentage of impervious surfaces. Further, stream temperatures increased 3.5°C on average and dissipated over about 3 hours in a study by Nelson and Palmer [50], where empirical relationships between seasonal temperature shifts and land use and between temperature surges and local rainstorms were developed for urban streams. These temperature surges briefly increased the maximum stream temperature by greater than 7°C and occurred frequently at the most urbanized sites. In another study that analyzed runoff temperatures and heat export rates for a variety of terrestrial land covers and aquatic surfaces, runoff temperatures from pavements, commercial rooftops, bare soil, wet detention ponds, and lakes/reservoirs were all found to be high enough to significantly impact stream temperature [51].



Missouri River Power Plants, August 2006
Extended drought conditions have reduced flows in the Missouri River which has led to concerns that discharge waters would exceed permit limits forcing cut backs in power generation.

Gerald Gentlemen Station, 2000-2008
Extended drought conditions have forced NPPD to develop alternative methods for providing cooling water to the plant, including installation of a well field and modifications to the plant's cooling system.

Donald C. Cook Nuclear Plant, Summer 2006
One of two nuclear reactors shut down because lake water used to cool facility elevated temperature readings in the containment building.

Gallatin Steam Plant, Summer 2007
Energy production reduced because intake cooling water above allowable discharge temperature due to heat wave and drought.

McGuire Nuclear Plant, January 2008
Due to extreme drought, water level of Lake Norman has dropped to less than 1 foot above minimum allowable for plant use.

Cumberland Power Plant, Summer 2007
Energy production reduced because intake cooling water above allowable discharge temperature due to heat wave and drought.

Shearon Harris Nuclear Power Plant, January 2008
Due to extreme drought, water level of Harris Lake has dropped to 3.5 ft above minimum allowable for plant use.

Browns Ferry Nuclear Power Plant, August 2007
One of three nuclear reactors shut down because water temperature in river too high for cooling due to drought and high air temperatures.

Browns Ferry Nuclear Power Plant, August 2010
Power genertion cut in half for over a month to avoid overheating the Tennessee River.

North Texas Power Plant, Summer 2011
Night-time operations reduced due to extreme heat, which made it harder for the water to cool down enough to be discharged, and drought, which reduced the volume of water available in the cooling reservoir.

Riverbend Steam Station, August 2007
Energy production curtailed because river water temperature too high for cooling due to severe drought.

Plant Hammond, Summer 2007
Record drought and heat have reduced releases from Lake Allatoona resulting in Coosa River flows near half the 7Q10 flow. This has forced Georgia Power to mitigate thermal impacts by reducing load to a minimum each night, placing aeration spargers to aid intake temperatures and supplement DO, and installing temporary mobile cooling towers.

Allen Steam Station, August 2007
Energy production curtailed because river water temperature too high for cooling due to severe drought.

Joseph M. Farley Nuclear Plant, February 2008
Due to extreme drought, water levels in Lake Lanier are significantly reduced, prompting potential reductions to lake releases. Reduced flows out of the lake would impact the plant, which is downstream.

Scholz Power Plant, February 2008
Due to extreme drought, water levels in Lake Lanier are significantly reduced, prompting potential reductions to lake releases. Reduced flows out of the lake would impact the plant, which is downstream.

Figure 3-2
Examples of recent power plant critical incidents and situations [34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46]

Rising stream temperatures may lead to an increase in the number of TMDL evaluations required for temperature. A recent NETL report [52] discusses the impacts of TMDLs on power plants using three 3 river systems in the eastern U.S. as case studies. The study primarily focused on chemical pollutants, though temperature and thermal modifications were listed as causes of impairment in two of the three systems and were discussed briefly. One of the main conclusions from the report is that in light of the recent focus on water quality and the power industry, existing TMDLs may be revised to be more stringent and new TMDLs are likely. This conclusion can be drawn not only for chemical pollutants but for thermal as well. An EPRI TMDL Program Advisory Committee identified heat and temperature as one of seven pollutants most likely to affect the power industry. Furthermore, EPRI recently released a report that provides an approach to help guide electric power companies through the technical and strategic aspects of a TMDL review [53]. While this report is not pollutant-specific, it identifies TMDLs for temperature as a potential future issue for power plants because of climate variability and the fact that many thermal variances are due to expire.

Figure 3-3 shows the water bodies with TMDL listings for temperature on a U.S. map. As shown on the map, the most highly concentrated area of temperature TMDLs is in the Pacific

Northwest. Also shown on the map are the coal-fired power plants that use once-through cooling, which are concentrated in the eastern half of the U.S. There appears to be some overlap between power plant locations and temperature TMDLs, though information on specific TMDLs involving power plants was unavailable. In the eastern U.S., TMDL listings for temperature are most prevalent in Wisconsin, Ohio, Virginia, and New Jersey. These are also states where there have been recent revisions to thermal standards or recent actions regarding thermal limits.

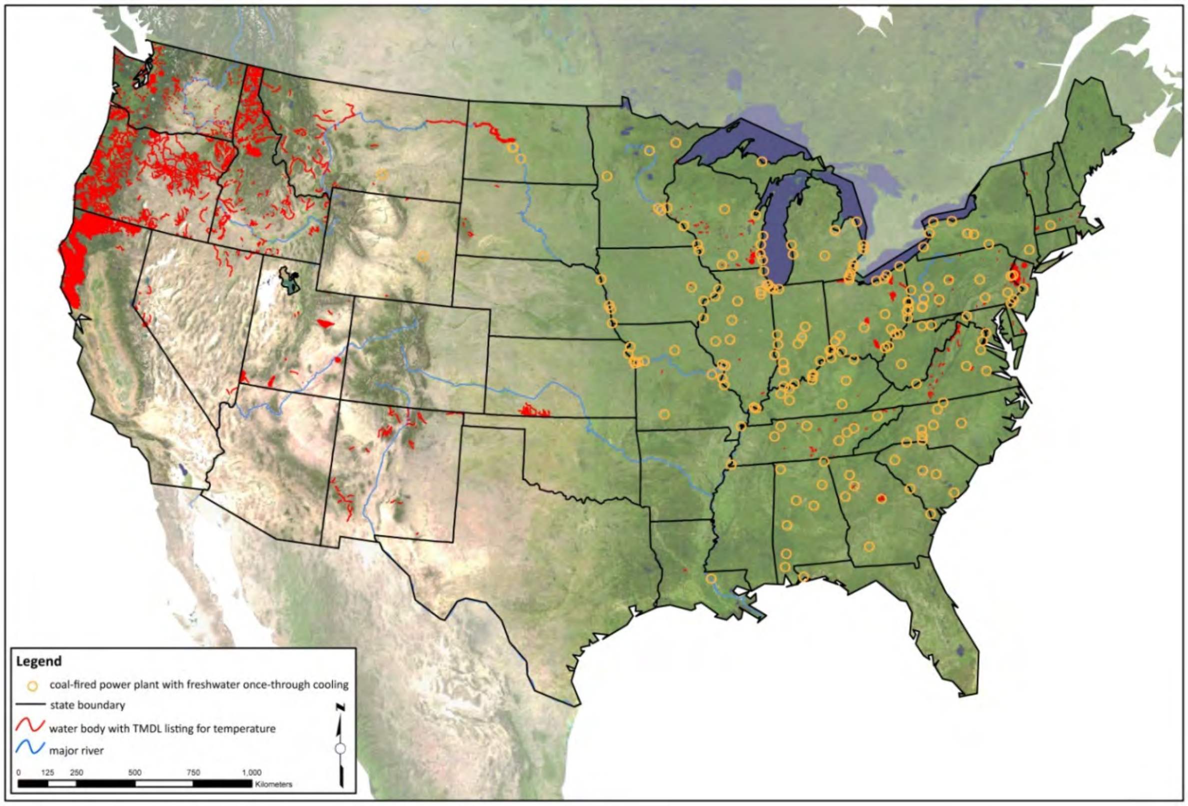


Figure 3-3
Water bodies with TMDL listings for temperature [54]

Thermal Effects Research

There has been an increase over the past decade in thermal response research, as evidenced by an increase in publications related to fish and water temperature (Figure 3-4) [55]. Figure 3-4 illustrates the interest in thermal effects research in the 1970s due to increased hatchery development and passage of the Water Quality Act in 1965, followed by decreasing interest in the late 1980s and early 1990s, and then resurgence in research in the late 1990s through today. The recent increase is likely driven by an interest in endangered species recovery and a better understanding of the physical processes of heated water bodies combined with concerns about climate variability [55]. Recent research continues to expand the database of laboratory research and field studies on the response of specific species to temperature increases as well as address the need for advancements in field studies. Furthermore, three topics that have received recent attention in the literature are thermal shock, interactions between multiple stressors, and impacts of thermal discharges in life cycle assessments. A summary of this recent research is provided below.

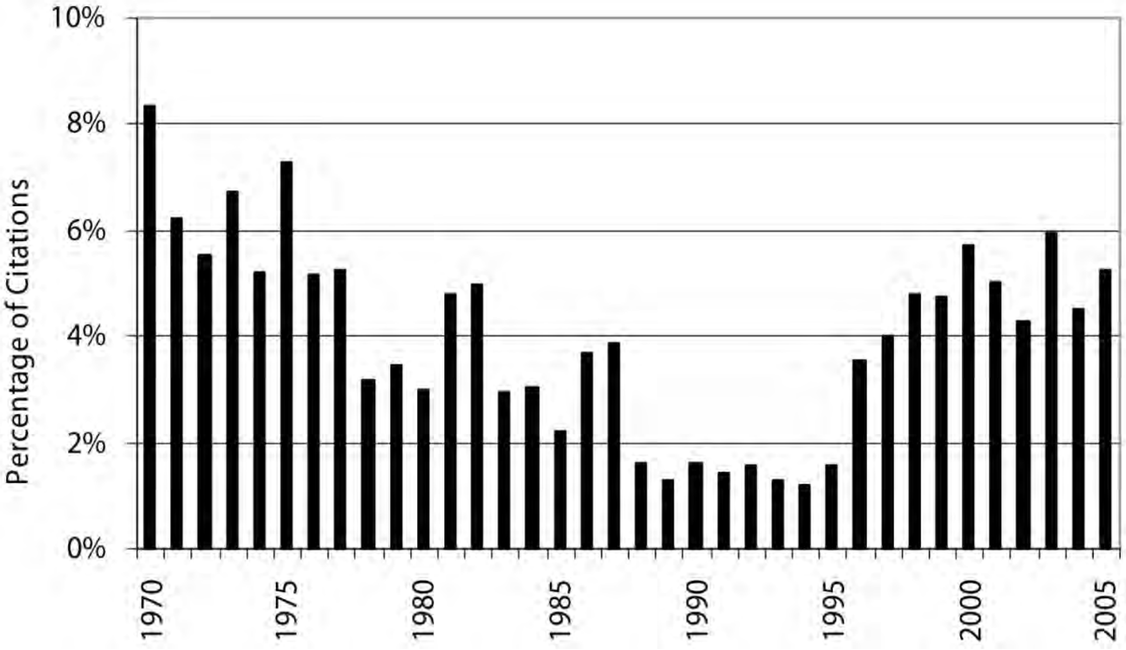


Figure 3-4
Search results from the 2006 Fish and Fisheries Worldwide database tabulating the annual proportion of freshwater fish citations that were key worded with "water temperature" [55]

Laboratory and Field Studies

Several laboratory studies on the thermal response of aquatic organisms were recently published. Bellgraph et al. [56] studied the laboratory response of fall Chinook salmon to a temperature increase of 15°C, simulating the change in temperature at the confluence of the Clearwater and Snake rivers, which are affected by hydropower, when fall juvenile salmon are emigrating. Results of the study show surprisingly low mortality rates but behavioral changes that may cause increased predation of juvenile fall Chinook in the wild following a thermal stress event. The effects of water temperature on growth and survival of juvenile Shovelnose sturgeon was examined in Kappenman et al., [57], with the goal of helping to refine thermal protection standards in the Missouri River basin. Doucet-Beaupre et al. [58] examined the thermal sensitivity of two closely related species of freshwater mussels located at two different latitudes; the two species demonstrated differences in their metabolism.

Recent field studies on thermal effects tended to be performed on thermal discharges to unique environments. Vandysh [59] studied the effect of a power plant thermal discharge on zooplankton in a subarctic water body. Teixeira et al. [60] looked at the impact of a power plant thermal discharge on fish communities and habitat structures in tropical rocky shores in Brazil. The effect of a power plant thermal discharge on phytoplankton in the Baltic Sea, where the water is brackish and the biota are adapted to seasonal variation (an icy winter and a moderate summer), was examined in Ilus and Keskitalo [61].

A recent EPRI study [62] endeavors to advance understanding of field research on thermal plumes. This study summarizes both conventional and innovative technologies to measure the effects of thermal discharges on fish in the field, and contends that new telemetry techniques, such as biotelemetry, will provide the best insight into the behavior and responses of fish to thermal discharges in their native environment. Further, a conceptual design for a study of fish behavior in the field is proposed with three tiers of assessment. Tier I uses existing information (or relatively inexpensive methods if new data are needed) to estimate the bounds of the thermal plume and characterize the community of potentially affected fishes. The results of Tier I indicate whether there are sufficient populations to justify proceeding to Tier II and, if so, which and how many fishes to tag. Tier II employs biotelemetry to assess the interactions of selected species with the plume, collecting data on the thermal exposures and behaviors of fishes such as competition, predator avoidance, prey availability, and habitat utilization. The results of the Tier II examination can be used to select a subset of individual fish for field-based physiological response research in Tier III. Tier III utilizes physiological monitoring telemetry to evaluate metabolic responses of tagged fishes exposed to thermal plumes, such as energy expended and recovery rates of fishes. Electromyogram (EMG) telemetry tags are used to provide critical information on the relationship between stress and thermal gradient exposure in the field.

Heat Shock

Several recent studies have addressed the concept of heat shock. When subject to heat stress in the environment, many fish and other organisms induce heat shock proteins that help protect cells from heat-induced damage. Fowler et al. [63] looked at the heat shock response (HSR) of juvenile versus adult rainbow trout by measuring the synthesis of a heat shock protein. The authors compared the levels of heat shock proteins in several tissues of both juvenile and adult rainbow trout. The study showed that the induction of a heat shock protein in the heart of juveniles was greater compared to adult fish. This enhanced HSR may contribute to greater thermal resistance in juveniles. A second study [64] reviews heat shock response literature to support the hypothesis that organisms that live in environments with either stable or highly variable temperatures are more susceptible to adverse effects from an increase in temperature than those that live in environments with only moderate temperature variation. The author shows that species experiencing a very narrow thermal range either do not have the HSR or rarely activate it, thus making them vulnerable if the temperature increases. Also vulnerable are species from high temperature variability environments because they can and do activate the HSR within the upper range of temperatures they experience; therefore, any further increase in temperature will push these fish beyond their thermal tolerance range. Species that live in moderate environments are most capable of handling an increase in temperature because they rarely induce the HSR and only at temperatures above those they commonly experience.

Interactions between Multiple Stressors

Another topic of recent research is the interactions between multiple stressors, one being temperature, and how they affect organisms. Sokolova and Lannig [65] investigate the interactive effects of temperature and metals on the metabolism of aquatic ectotherms. The authors review literature related to temperature-pollutant interactions and their effect on ectotherm physiology to better understand the mechanisms of these interactions. Environmental stressors can have effects on the oxygen supply (impaired uptake and delivery to the tissue), mitochondrial function (reduced efficiency), and energy demand of an organism, and exposure to one of these stressors sensitizes an organism to the other. In particular, the impairment of energy metabolism plays a key role in the synergistic effects of these stressors, as a stressor that requires an elevated energy demand or negatively effects the energy supply in an organism can make that organism more vulnerable to other stressors. Sokolova and Lannig put forth that much research is needed in the area of interactions of multiple stressors, especially in the areas of effects on the energy budget of the organism, the effects of fluctuating temperatures (as opposed to constantly elevated), and across more levels of biological organization (i.e., from molecular to organism to population) and stressors (i.e., salinity or food availability).

In another study, Chuang et al. [66] investigated the interactive effects of elevated water temperatures and chlorination. Power plant discharges often contain residual chlorine, as chlorine is used as a biocide for controlling fouling organisms in cooling systems. Chuang et al. looked at the effects of elevated water temperatures and residual chlorine from a thermal discharge at a coastal nuclear power plant on the biomass and productivity of periphyton and phytoplankton in subtropical Taiwan. Results of the study showed clear seasonal effects of chlorination on phytoplankton productivity, with the effects of chlorination greater in winter than summer. However, at high levels of residual chlorine (> 0.2 ppm), phytoplankton productivity was significantly decreased regardless of whether the temperature was elevated or not. By contrast, periphyton productivity was directly influenced by the water temperature itself, and residual chlorine concentration (< 0.5 ppm) had little effect.

Life Cycle Assessments

A new topic in thermal effects research is looking at the impact of thermal discharges in life cycle assessments. In life cycle impact assessment (LCIA), characterization factors are developed for environmental emissions that reflect the fate (environmental residence time) and effect in the environment and quantify the potential environmental damage. Verones et al. [67] applies this concept to the effect of thermal discharges on aquatic ecosystems. In this study, a method to derive characterization factors for quantifying the potential disappearance of freshwater aquatic species due to thermal discharges was developed. A 1-dimensional steady-state model was used to calculate the fate factor, which represents the residence time of heat emissions in the river. The effect factor specifies the loss of species diversity per unit of temperature increase and is based on a species sensitivity distribution (SSD) of temperature tolerance intervals for various aquatic species. To illustrate this approach, the characterization factors were calculated for the thermal discharge from a nuclear power plant in Switzerland; results from this study indicate that thermal discharges are a significant contributor to the overall environmental impact for aquatic ecosystems compared to other stressors. While the method presented was intended for widespread applicability, the authors recognize the fact that it would be enhanced with regional or site-specific data, particularly in areas where sensitive species are present or where there are other upstream influences on water temperature.

Areas for Future Research

McCullough et al. [55] reviewed the literature in thermal biology with the goal of suggesting areas where further research is needed. The authors provide insight into the most promising recent developments in thermal biology and identify some of the remaining unanswered questions. These developments are categorized into five topics areas: molecular level, organism level, population/species level, community and ecosystem levels, and policy implications. Figure 3-5 presents these categories along with the main topics in each that the authors consider important and specific questions that need to be addressed with future research. These questions emphasize scientific uncertainties and areas of controversy, and are intended to further our understanding of the potential of fish populations to sustain themselves and maintain their ranges in aquatic communities stressed by rising temperatures from a combination of anthropogenic and climatic sources.

Summary

Activities related to CWA Section 316(a) are and will continue to be of concern to power plants with thermal discharges. EPRI [1] summarized the history behind the development of the §316(a) regulation and current activities in regulations, thermal effects research, and stressors on thermal discharge compliance. EPRI also continues to maintain a website, eTherm, on issues related to thermal discharges (http://www.epri.com/etherm). This site contains information on permits and variances, including examples of completed §316(a) studies; state thermal standards; thermal plume assessment and modeling; thermal TMDLs; and research and emerging issues related to §316(a) such as evaporative losses and climate variability. This paper summarized the recent developments related to regulations, thermal effects research, and stressors on thermal discharge compliance.

In the area of temperature regulations and guidance, the federal government continues to be inactive, while a few more states have revised their standards. There is continued legal and regulatory activity in several states that is making it increasingly harder for power plants to get thermal discharge permits and has resulted in reductions in thermal discharges. Internationally, activities related to water protection and management are occurring due to a looming water shortage and potentially increasing water temperatures; in particular thermal standards have been or are recently being revised in Canada and the European Union.

The power industry continues to encounter stressors on thermal discharge compliance. In particular, water shortages and increased water temperatures are straining the water bodies to which heated effluent is discharged. Heated stormwater runoff may also be adding stress to the system. TMDLs continue to be a source of concern, as many discharge permits will be up for renewal in the coming years.

Advancements in thermal effects research continue, as a forecasted increase in water temperatures due to climate variability and anthropogenic causes has fostered interest in learning more about the effects of elevated temperatures on aquatic organisms. Recent focus has been on advancing the knowledge of heat shock response of fish, the synergistic effects of multiple stressors (temperature and metals; temperature and chlorine), and the role of thermal discharges in life cycle assessments. Further research is needed in these areas and at all scales of study, from molecular to whole community and ecosystem.

Acknowledgements

The author would like to thank Greg Seegert of EA Engineering, Science, and Technology, Inc. for his contributions to this paper. Mr. Seegert contributed to this paper on state standards in Wisconsin and Illinois and recent actions regarding §316(a) demonstrations in the Midwest. The author would also like to thank Rob Reash of American Electric Power for his input on thermal effects research.

Topic Area	Specific Topic	Key Research Questions
Molecular	Genetic adaptation in temperature tolerance	Can understanding the molecular and physiological processes of temperature tolerance improve prediction of a fish's ability to adapt to higher temperatures? Do negative genetic correlations among traits and the resulting selective trade-offs explain the resistance to change in thermal tolerance?
	Physiological indicators of thermal adaptation	What is the biological response to temperature at an organism level and how does it vary by sex, size, season, and water chemistry (e.g., dissolved oxygen, ammonia concentration, etc.)?
	Application of biomarkers	How can we discriminate between biomarkers that signal heat stress and those that signal thermal acclimation in the absence of stress? Can biomarkers effectively be used to readily compare field and lab results using a common yardstick other than mortality or growth, both of which are difficult and costly to measure, and difficult to interpret unambiguously?
Organism	Lethal effects: thermal tolerance	Is a single metric, such as average or maximum daily water temperature, adequate to predict fish production? In addition to simple daily cyclic effects, exactly how does a variable time series of daily minimum and maximum water temperatures affect acclimation, performance, and stress?
	Sublethal effects: growth	Have we cataloged all of the important sublethal effects that arise from thermal exposure? In bioenergetic modeling, what are the trade offs between energy devoted to activity and digestion? Can we use bioenergetic modeling with input from both laboratory and field studies to better understand the physiological processes interacting with temperature and food to control growth rates? Do the existing bioenergetic or fitness models adequately explain differences in thermal preference between the sexes, and have we carefully examined thermal tolerance limits by sex?
	Sublethal effects: reproduction and intergenerational effects	Can we isolate intergenerational effects from fertilization effects? Do intergenerational thermal effects explain a portion of the annual variability in egg-to-fry or fry survival not accounted for by annual temperature regime effects imposed in the egg-to-fry stages? To what extent can intergeneration effects be traced to parental exposure during early gametogenesis vs. later thermal exposure prior to or during spawning?
	Behavior movement and migration	Do salmonids use behavioral thermoregulation to decrease the variation in temperatures that they experience? How do the following factors act singly and in combination to trigger fish movement: water temperature, temperature change, weight or condition factor, streamflow, turbidity, fish density, availability of cover, photoperiod, presence of thermal refuges, fishing pressure, and other (potentially independent) movement stimuli? What are the mechanisms necessary or sufficient to trigger movement to and from thermal refuges?
Population/ Species	Adaptation in thermal tolerance	Why do thermal tolerances of stream fishes not show more evidence of rapid genetic adaptation to elevated temperatures? Why does adaptation often involve variation in growth rates or life-cycle timing?
	Adaptations in seasonaltiy	Is it true that timing (i.e., seasonal events) is typically an easier target of selection than thermal tolerance? If so, why? Is it the case that fish populations such as anadromous salmonids that are in decline are faced with demographic factors preventing genetic adaptation to such a degree that they are headed for extinction?
	Effects of fitness on the population	How can we adequately integrate information on an individual fish's response to water temperature to understand and predict physiological, behavioral, and abundance or productivity responses of populations at a watershed scale?

Figure 3-5
Areas for future thermal effects research as identified by McCullough et al. [55]

Topic Area	Specific Topic	Key Research Questions
Community and Ecosystem	Interaction among fish species	What is the vulnerability of prey at different sizes to predator attack? What are the general conditions where prey vulnerability could be minimized by modifying the temperature in a riverine system?
	Food web dynamics	Will changes at lower levels in the stream food web associated with temperature tend to be compensated at higher trophic levels of the food chain, or might there be complex interactions that propagate through food webs that confound simple interpretations? Is it possible to develop "rules of thumb" about how complex food webs function as governed by water temperature?
	Disease and parasites	What are the effects of elevated water temperature on disease in wild fish populations, and can these effects be quantified by both temperature and exposure duration?
Policy Implications	Development of thermal standards	Are all significant biological effects effectively considered? Are there long-term effects not well described by IULT tests, growth studies, or field distribution that must be incorporated into criteria? Will beneficial uses be maintained in the long term by application of thresholds or other criteria? Given a coldwater beneficial use to protect, can biological criteria and physical potential of a drainage both be used to ensure that cumulative effects do not cause long-term shifts in species distribution and community composition?
	Effects of habitat alterations on temperature	What is the shading effect of patchy or thinned riparian vegetation? What is the extent of thermal recovery as a stream passes downstream into a shaded reach? What is the influence of alterations to channel geomorphology on thermal patterns? What are the processes involved in loss of thermal refugia? What is the behavior of thermal minima with respect to land use alterations?
	Thermal heterogencity	What is the cost to fitness associated with a stream system where cold refuges exist within a warmed matrix which creates trade-offs in biological functions as the organism tries to satisfy multiple biological needs? What makes an effective thermal refuge for coldwater fishes?
	Interactions of water quality and flow with temperature	How can we put temperature in perspective with other variables that influence fish populations? Do we need more specific or different water-quality standards to better protect streams with cumulative stressors like high temperature and low dissolved oxygen?
	Application of new technology to study of thermal pattern and fish use	How can we predict the abundance and distribution of thermal refuges not associated with obvious tributaries? Can we develop a time budget of swimming speed relative to water velocity, food availability, and temperature distribution?

Figure 3-5 (continued)
Areas for future thermal effects research as identified by McCullough et al. [55]

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4

OUTLINE OF REGULATIONS AND RESEARCH ACTIVITIES REGARDING THERMAL ISSUES (ONCE-THROUGH COOLING SYSTEM OF POWER PLANTS) IN JAPAN

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Abstract

Outline of regulations, recent issues and research activities regarding thermal discharge of the once-through cooling system of power plants in Japan are described in this paper. Most fossil fuel and all nuclear power plants in Japan are located at the seaside and have employed the once-through cooling system using seawater. All utility power plants licensed after 1980 have employed 7°C or under as the temperature rise between intake and outlet, although some plants licensed before 1980 employed more than 7°C. Mainly because Environmental Impact Assessments (EIA) and mitigation measures based on scientific findings have been enforced, serious impacts on marine environments and organisms such as fishery resources have not been reported in Japan, so far. Scientific research indicates that impacts of impingement and entrainment on fishery resources would be relatively small, compared to impacts of fishery activities and the natural mortality of eggs and larvae. Changes in species composition of algae have been reported only near the outlet, where it is almost always covered with the thermal effluent of over 2-3°C higher than the environment. Assembling of warm water species only near the outlet has also been reported. Some fishermen and environmentalists, however, are still anxious about possible impacts of power plants on fishery resources, local endangered species, the ecological ”hot spot,” and other issues. Development of EIA methods applicable to the marine ecosystem and effective mitigation measures for macrophyte beds, tidal flats and coral reefs has been conducted.

Introduction

Most of fossil fuel and all nuclear power plants in Japan are located at the seaside and have employed the once-through cooling system. In the 1970’s, there were severe arguments about possible impacts on marine fishery resources due to the thermal discharge of large-scale nuclear power plants under construction among the fishery industry, the power industry, relating scientific societies and national agencies. Much research has been conducted to elucidate the impacts of thermal discharge on fishery resources by national and local government laboratories, the fishery industry, and the power industry, including the Central Research Institute of Electric Power Industry (CRIEPI) and the Marine Ecology Research Institute (MERI). An outline of regulations, recent issues and research activities regarding thermal discharge from the once-through cooling system of power plants in Japan is described in this paper.

Regulations and EIA Procedures in Japan

Basic EIA procedures are established by the Environmental Impact Assessment Law, and the detailed procedures are described in regulations of the competent authorities. The power plant EIA procedure is shown in the guideline edited by the Nuclear and Industrial Safety Agency (NISA), Ministry of Economy, Trade and Industry, Japan. The water pollution control law of Japan lists “heat discharge” as one of its regulation targets. No law or regulation, however, for heat discharge has been enacted, so far. The water temperature rise between intake and discharge of power plant, and the design of intake and discharge facilities are proposed by each proponent (each power plant) in accordance with the guideline of NISA, and are examined and licensed by NISA. The EIA is conducted in the following order,

1. Screening (determination of the projects to which EIA is applied)
2. Scoping (determination of the assessment method)
3. Survey, forecast, and evaluation of the environmental impacts, and consideration of the measures to protect the environment
4. Examination and authorization of draft environmental impact statement by NISA
5. Reflecting the assessment results in the project

Key Characteristics of the Japanese Power Plant Cooling System

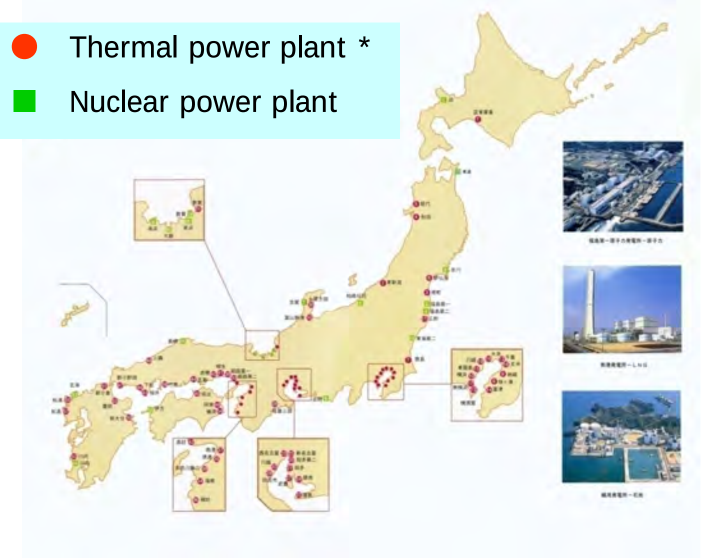
The following are the key characteristics needed to understand Japanese power plant cooling systems.

- Coastal site
- Once through cooling system
- ΔT of 7°C or under
- Envelope covering 1°C or higher thermal plume area
- No residual chloride at the outlet

These items are not legal requirements. These are proposed by power companies based on the guideline of NISA. Compensation of fishing rights for fishermen’s corporatives is required for the coastal development. This may be one of the unique characteristics in Japan.

Coastal Site and the Once Through Cooling System

As shown in Figure 4-1, all nuclear power plants and almost all thermal power plants owned by power utilities are located at the coastal sites. Only 2 smaller thermal plants are located on the riverside at present. The purpose of the coastal siting is to have a great enough volume of water available for cooling. The amount of freshwater available is limited in Japan, so it is not easy to prepare enough volume of freshwater even for cooling tower operation. Therefore, all utilities have employed the once through cooling system using seawater. Cooling towers are employed only by some smaller power plants belonging to steelworks, chemical factories and so forth.



* Thermal plants of more than 900 MW

Modified a pamphlet of the federation of Electric Power Companies of Japan

Figure 4-1
Thermal and nuclear power plant sites in Japan

ΔT of 7°C or Under

All utility power plants licensed after 1980 have employed 7°C or under as the temperature rise between intake and outlet, although some plants licensed before 1980 employed more than 7°C. The 7°C envelope was selected as a result of severe discussion of the generation efficiency and the impacts on fisheries resources among the power industry, the fisheries industry and the three related national agencies, the then Environment Agency (EA), the Fisheries Agency (FA), and the Agency of Natural Resources and Energy (ANRE), in the early 1970s.

Envelope Covering 1°C Higher Thermal Plume Areas

The concept of the thermal discharge envelop in Figure 4-2 [1] might be a unique concept of Japan. The envelope covering the thermal plume areas of 1°C higher than the environment temperature predicted in different tidal and weather conditions is prepared for the EIA of the thermal discharge. Then, whether any possible environmental impacts would be expected or not in the enveloped area is examined. The enveloped area is also a rough standard area for the compensation for fishing rights.

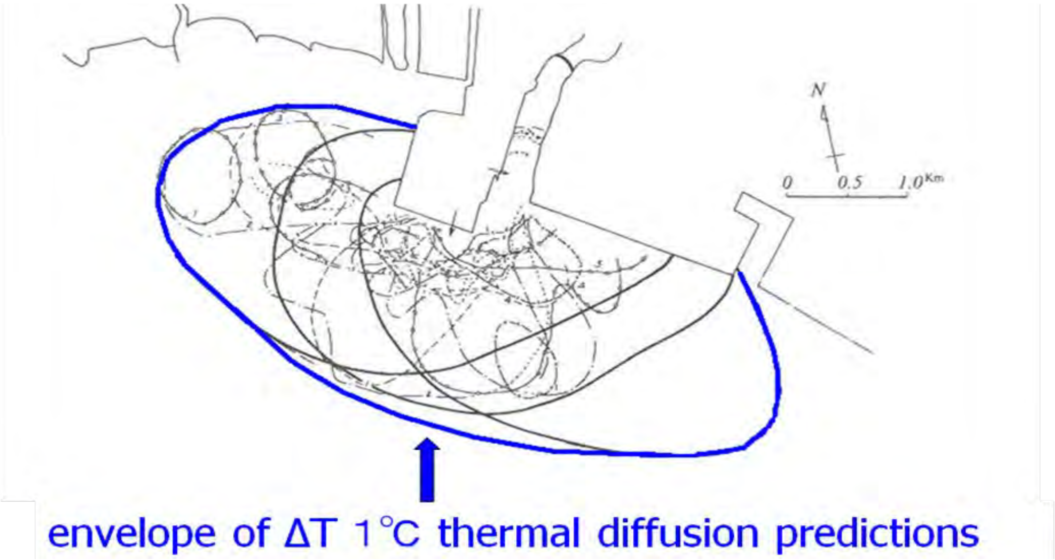


Figure 4-2
Concept of the envelope of thermal diffusion

The reason why a 1°C temperature rise area has been selected as a standard area for EIA is based on a science report [2] describing that 1°C rise might be harmful to the growth of red laver, *Porphyra*, which is one of the major seaweeds cultured in Japan.

No Residual Chloride at the Outlet

Chlorination is one of the main anti-biofouling methods also in Japan. “The water quality criteria for aquatic culture,” edited by the Japan Fisheries Resource Conservation Association [3] requires no residual chloride in water for aquatic culture. Residual chloride concentration at the outlet is required to be under the detection limit.

Compensation of Fishing Rights

Along almost the entire coastline of Japan, fishing rights for fishermen’s corporative have been established. Therefore, compensation of fishing rights is required for the coastal power plant construction and operation. This is one of the very peculiar subjects of Japan. “Temperature rise of 7°C or under,” “EIA targeting the envelope areas covering 1°C higher thermal plume,” and “no residual chloride at the outlet” are results from negotiation with the fishermen’s cooperatives. Fishermen’s cooperatives would be one of the tough stakeholders in Japan.

Understandings of the Impacts of Thermal Discharge

Up-to-date general understandings of the impacts of thermal discharge on the marine environment and organisms such as fishery resources in Japan are summarized below [4]. EIA and mitigation measures based on scientific findings have been enforced; therefore, serious impacts on marine environments and organisms have not been reported in Japan, so far. Scientific research indicates that impacts of impingement and entrainment on fishery resources would be relatively small, compared with impacts of fishery activities and the natural mortality of eggs and larvae as shown in Table 4-1 [5–7]. Changes in species composition of macrophyte have been reported only near the outlet [8, 9], where is almost always covered with the thermal effluent of over 2 - 3 higher than the environment. Assembling of warm water species near the outlet [10–13], and water exchange promotion due to cooling water intake or discharge in some smaller bays and harbors [14–16] are also reported.

Table 4-1
Estimations of intake effects on fish eggs and larvae

Species Stage	Target Power Plant	Impact Estimation	Reference
Pollack: egg/larva	A nuclear plant Open ocean site	The entrained / the total spawned is 1/2,000 (0.2 %)	Fukataki 1983 [5]
Salmon: young	2 plants, 42 and 312 m^2/s intake	The impinged / the seedlings released Is 0.01~0.87 %	Fisheries agency 1991 [6]
Whitebait: egg/larva	A plant 312 m^2/s intake	Entrainment mortality 0.1~2 % is smaller than the natural one 70%	Fisheries agency 1991 [6]
Whitebait: adult	A plant 312 m^2/s intake	Impinged mortality 0.01~0.1 % is smaller than the mortality due to fisheries activities 28%	Fisheries agency 1991 [6]
Rockfish: larva	2 plants , 75 and 230 m^2/s intake	Impinged ratio 0.2~4 % is smaller than the natural monthly mortality 10%	Fisheries agency 1991 [6]
Launce: juvenile	Adjacent 1 thermal and 2 nuclear plants	The entrained / fishery catching amount is 0.03~1.02 %	Yokota 2005 [7]

Mitigation measures widely conducted, so far are “avoidance of key biotopes such as macrophyte beds, tidal flats and coral reefs,” “water intake below the thermocline,” “decrease in intake water velocity,” and “underwater discharge.” “Discharge direction change to avoid biological susceptible areas,” “construction of offshore intake facilities,” “seasonal alternation of the discharge area,” and “development of algal beds” are also carried out at some specific sites based on EIA results or by the request of local stakeholders including fishery industries.

Recent main issues

As shown above, impacts of thermal discharge on the marine environment and organisms such as fishery resources are considered not so serious, there are, however, still several issues. Recent main issues are as follows,

- On the EIA process improvement, the following items have been proposed by the Ministry of the Environment, Japan, and both have been under review in the government circles.
    - Application of a Strategic Environmental Assessment (SEA) to the power plant EIA procedure.
    - Simplification of procedure for EIA in a case of the thermal power plant facilities replacement resulting in reduction of pollutant emission. Replacement of the conventional plant to the combined cycle plant would be an expected example.

- On the EIA technology, improvement of the following is requested, because the environment protection law amended in 1999 requires EIA on the natural environment, organisms, such as endangered species, and the ecosystem rather than on the fishery resources.
    - EIA methods applicable to the marine ecosystem
    - Mitigation measures for macrophyte beds, tidal flats and coral reefs
    - Management of warm water species going up north followed from the temperature rise of surface seawater, which may cause the ecological disturbance.
- Some fishermen and environmentalists are still anxious about possible impacts of power plants on fishery resources, endangered species, the ecological "hot spot," and other issues.

Research activities on biological impacts of thermal discharge

Much research has been conducted by national and local government laboratories, the fishery industry, and the power industry to elucidate the impacts of thermal discharge on fishery resources. For the past 30 years, mainly CRIEPI and MERI both have been working on research related to EIA of thermal discharge. CRIEPI has been responsible mainly for research on thermal diffusion and MERI has been responsible mainly for research on biological impacts. Research facilities and activities of MERI are shown below.

What's MERI?

MERI is an independent and non-profit research organization and was established in 1975 in agreement with the fishery industry and the power industry, under management of three national agencies (the then EA, the FA, and the ANRE) to elucidate the impacts of thermal discharge on marine fisheries resources. MERI has been requested to prepare scientific information of environment impacts of thermal discharge for the government, the power industry and the fishery industry (Figure 4-3). MERI has managed two marine laboratories, the Central Laboratory on the Pacific Ocean and the Demonstration Laboratory on the Japan Sea. The Central Laboratory was established in 1979, where abundant clean sea water is available for experimental works. The Demonstration Laboratory was constructed in 1984 adjacent to the Kashiwazaki Nuclear Power Plant, and actual thermal effluent from the nuclear power plant is available for experiments. In two laboratories, more than 100 species including fishes, invertebrates and algae have been cultured and used for a variety of basic and demonstrational experiments.

Besides the thermal discharge project, MERI has been also involved in various projects such as toxicological studies of chemical substances including chloride, monitoring surveys of marine environment radioactivity, ecological surveys of marine organisms including mussels and jellyfish, impact assessment of CO_2 ocean sequestration and storage, and macrophyte bed management [17].

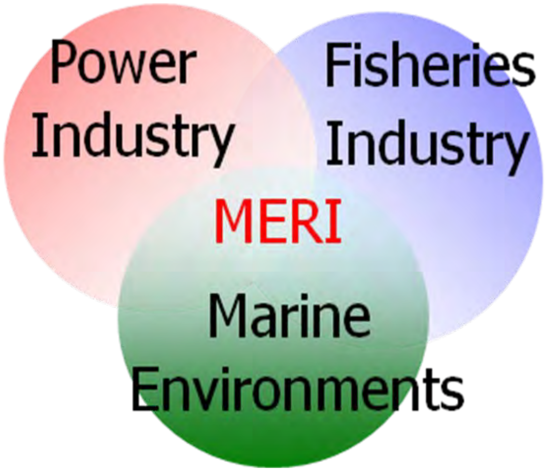


Figure 4-3
A concept of MERI position

Research Activities of MERI on the Thermal Discharge

MERI has conducted several laboratory experiments concerning thermal impacts and field surveys in and around the plume area to elucidate the impacts of thermal discharge mainly on marine fishery resources under contracts with the national agencies and power companies (Figure 4-4).

Thermal tolerance of 112 major marine species such as eggs and larvae of fish [18–20], invertebrates [21–30] and algae [31–38] have been studied, so far. Impacts of impingement and entrainment on fisheries resources would be relatively smaller, comparing with impacts of fishery activities and the natural mortality of eggs and larvae as shown in Table 4-1.

Demonstrational experiments of fish behaviour (preference and avoidance) to the elevated temperatures were conducted on juveniles [39–42] of several fish species in experimental tanks designed to reproduce the thermally stratified conditions and on adult fishes [43] using fish culture pens (12 m diameter) settled in and out of the actual plume of a nuclear power plant (Figure 4-5). Comparison between fish behaviors in the two pens was carried out. Japanese amberjack, *Seriola quinqueradiata*, mainly swam in the warmer surface layer in winter, while they preferred the cooler deep layer in summer. Salmon tracking survey around the thermal plume area of a nuclear plant was also conducted. Electron transmitters were used to track Chum salmon *Oncorhynchus keta* behavior. In this area, Chum salmon avoided the plume area, but could reach the mother river by swimming beneath the thermal plume.

Laboratory experiments [31] indicate that 28°C is the upper critical temperature for *Eisenia bicyclis*, a major kelp species in Japan. A series of intensive field surveys [9] also showed that *Eisenia bycyclis* was not observed near the outlet where temperature of over 28°C was measured. This area is almost equivalent to the area of 2°C higher than the environment.

To cope with recent public concern focusing on the preservation of the marine ecosystem, MERI has given higher priority also to the technology development [44, 45] of power plant impact assessment on the coastal ecosystem including macrophyte beds, tidal flats and coral reefs.

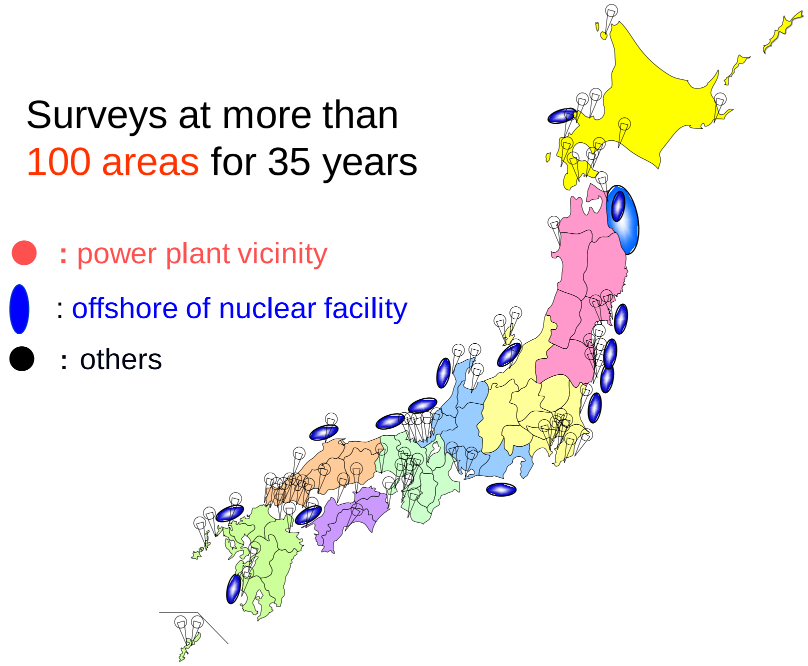


Figure 4-4
Areas where MERI has conducted field surveys for the past 35 years

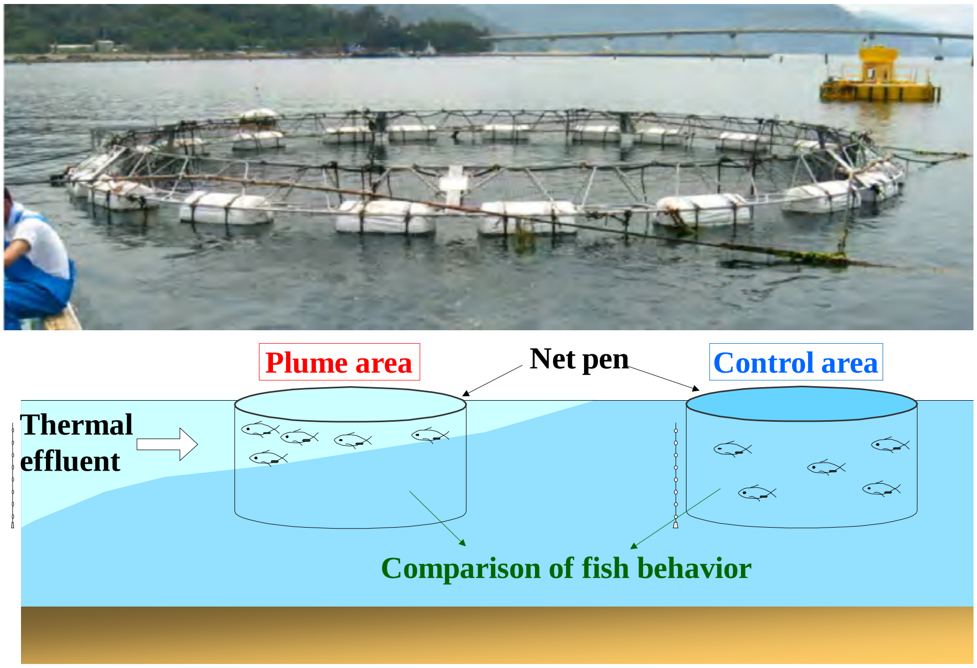


Figure 4-5
Schematic diagram of a fish behavior experiment using fish culture pens [43]

Conclusion

To address the recent issues described above, the following subjects should be emphasized for improvement of the power plant impact assessment in MERI in the near future.

- Development of EIA supporting tools for consensus formation among the public, the power industry and the fishery industry
- Development of practical technologies for quantitative impact assessment on the marine ecosystem, especially on the function of the marine ecosystem such as the material flow
- Technology development for adaptive management of the marine environment

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* Written in Japanese (the title and journal name are tentatively translated to English.)

** Written in Japanese with the English abstract

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5
BALANCED INDIGENOUS POPULATIONS?

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Abstract

When §316(a) of the Clean Water Act (CWA) was enacted in 1972, the U.S. Environmental Protection Agency (EPA) was charged by Congress to develop a regulatory structure to achieve the scientifically nebulous goal of ecological balance. At that time, the concept of ecological balance largely was undefined but likely was influenced by the historical concept of “the balance-of-nature,” which had theological origins. This paper recounts the history of the concept of “balance of nature” and relates it to the present regulatory framework for evaluating the protection and propagation of a balanced indigenous population (BIP) or community (BIC), the statutory requirement for granting a §316(a) variance from otherwise applicable thermal water quality standards. The §316(a) regulatory framework is briefly described, and relatively recent examples of its application to National Pollutant Discharge Elimination System (NPDES) permit renewals for four generating facilities are provided. It is concluded that, despite the still elusive concept of ecological balance and the scientific vagaries of the statute, the regulatory framework has been successful at preventing ecological degradation due to thermal discharges. As of 1992, a total of 679 facilities were operating under §316(a) variances. While EPA has indicated its intent to re-examine §316(a) variances in upcoming permit renewals, any attempt to define the BIC concept would have to deal with confounding issues, including unrelated species-management effects, species introductions and competition, ecosystem succession, and global environmental changes, among others.

Introduction

At the time Congress passed the Federal Water Pollution Control Act Amendments of 1972 (Public Law 92-500) which added Section 316(a), the need to regulate thermal discharges was viewed as a more urgent priority than it is today due to two factors. First, in the near term the demand for electricity was expected to rise exponentially. Midway through the 1970s the Nuclear Regulatory Commission estimated that generating capacity in the United States would need to nearly triple by 2000 [1]. The amount of surface water required for condenser cooling was expected to show a similar trend. Goodyear and Fodor estimated that cooling water withdrawals in 2000 would exceed two million cubic feet per second, a flow greater than the average freshwater discharge of the 48 contiguous states [2]. Although these projections of electricity demand and cooling water use ultimately were not realized, they were at least based on available data and reasoned analysis. Unfortunately, some projections of the potential effects of this water use were not. A good example is found in a college-level environmental science textbook of the era, which contained the admonition "Unless steps are taken to find alternate means of dispersing or utilizing this [waste heat from power generation], there is a distinct possibility that all major rivers in the United States will reach the boiling point by 1980 and then evaporate entirely by 2010!" [3]

The second factor determining the perceived need for regulation of thermal discharges was that very little was known about their ecological effects. The relatively small generating stations that were common before the 1970s certainly affected the water bodies into which they discharged waste heat. However, except when these discharges occurred to very small water bodies, they typically would not have substantially altered the ecology outside of the immediate plume, and systematic studies of the local or far-field effects had not been conducted. Coutant's 1962 study of the effects of a thermal discharge on benthic invertebrates in the Delaware River is one of the earlier efforts [4]. Power stations built during the 1960s and 1970s, particularly the nuclear stations, had much larger generating capacities than the older stations, and therefore those with once-through cooling systems discharged much more heat energy to the aquatic environment, with higher potential for environmental degradation.

The actual and projected increase in size and number of generating stations, coupled with the rising public perception of environmental issues at that time, combined to impel Congress to include §316(a) in the 1972 amendments. Congress took a minimalist approach by setting out what are essentially policy goals that require thermal discharges to maintain "balanced indigenous populations" (BIP). Congress wisely left it to the recently formed Environmental Protection Agency (EPA) to craft regulations to meet these goals. At the time, it seemed that these goals represented appropriate targets for the rulemaking process. Here, we focus on the problems in regulating to achieve a BIP, particularly with respect to how "balance" can be defined and measured. During implementation of §316(a), BIP has been interpreted to be “balanced indigenous community” or BIC, believed to be the original intent of Congress.

The concept of a BIP or BIC could have arisen from the historical concept of the “balance of nature”, which may have been an underlying vestigial, but fundamental, paradigm during the infancy of modern ecological research and theory.

History of Balance as an Ecological Concept

Antiquity

Balance-of-nature has a long history [5]. One of the earliest expressions of ecological balance came from the Greek philosopher Herodotus in the 5th century B.C. A foundation of Greek science at that time was the belief that nature was constant and harmonious. Herodotus hypothesized that the reproductive capacities of prey species, such as the hare, and predators, such as winged serpents (presumably now extinct) and lions, were set by Divine Providence so that the numbers of both would be stable. He also inferred the inherent balance in nature from the symbiotic relationship of crocodiles and the plovers that enter their open mouths to feed on parasitic leeches.

Plato's late 4th century B.C. *Dialogues*, particularly the Protagoras myth, held that at the time the god Epimetheus created the different species of animals, he endowed them with traits to escape their enemies, protect them from the weather, and find food. All species, including man, were providentially equipped with the means for continued survival.

Aristotle (384-322 B.C.) focused more on the physiological and behavioral aspects of individual species in *Historia Animalium*, but still recognized the interaction of traits that produce some balance in nature:

> The eagle lays three eggs and hatches two of them... though occasionally a brood of three has been observed. As the young ones grow, the mother becomes wearied with feeding them and extrudes one of the pair from the nest. At the same time the bird is said to abstain from food, to avoid harrying the young of wild animals....

These early concepts of balance-of-nature were not limited to the Greeks, but are also found in Roman philosophy. Cicero (106 - 43 B.C.) drew upon Herodotus and Plato in *De Natura Deorum* to reach the view that balance was maintained through differential reproductive rates, habitats, physical traits, and mutual relationships among species:

> In order to secure the everlasting duration of the world-order, divine providence has made most careful provision to ensure the perpetuation of the families of animals and trees and all vegetable species.

17th Century

Although the balance-of-nature concept persisted after Cicero, there was little documented advancement or elaboration until after the Middle Ages. The widespread Christian worldview of a constantly supervising God did not require elaborate built-in mechanisms to maintain balance of the natural world. Advancement of the concept began after the Protestant Reformation in the 17th century, which brought a renewed interest in the details of how both nature and society were governed. However, as would be expected, the theological underpinnings were maintained. One example of this comes from Sir Matthew Hale in *The Primitive Origination of Mankind* (1677):

> That yet these Motions of Generations (births) and Corruptions (deaths) .... are so wisely and admirably ordered and cotemperated, and so continually managed and ordered by the wise Providence of the Rector of all things, that things are kept in a certain due stay and equability: And though the Motions of Generations and Corruptions, and the Instruments and Engins therof are in a continual course, neither the excess of Generations does oppress and over-charge the World, nor the defect thereof, or prevalance of Corruptions doth put a Period to the Species of things, nor work a total Dissolution in Nature.

Hale explicitly added daily and seasonal heat fluctuations, physical factors rather than biological, to the mechanisms that maintain the balance.

The accumulating 17th century evidence of fossil animals that bore little resemblance to known living species posed a problem for the prevailing providential ecology paradigm because it suggested that species may have gone extinct. John Ray, an English clergyman known for his work on natural theology, a theological interpretation of natural history, dismissed this view since the fossil species could still be extant in unexplored regions of the world. Ray, in *The Wisdom of God Manifested in the Works of the Creation* (1691) explained the hydrologic cycle, a physical phenomenon that certainly could influence the natural balance, but did not tie it directly to biological processes.

18th Century

Although the influence of theology on natural science began to wane during the 18th Century, it was nevertheless still apparent in the writings of William Derham, another English clergyman and protege of John Ray. Derham was the first to use the word "balance" in this ecological context in *Physico-Theology* (1714):

> The Balance of the Animal World is, through all Ages, kept even, and by a curious Harmony and just Proportion between the increase of all Animals, and the length of their Lives, the World is through all Ages well, but not overstored.

Richard Bradley, an 18th century horticulturist, was able to generalize from a wealth of empirical observations how populations, particularly insect pest populations, are kept in check. Bradley observed that "every Herb has its peculiar Insect" and "the insects which nature has designed to prey upon the Flower of a Plant will not eat the Leaves." Bradley's overall conclusion, expressed in *A Philosophical Account of the Works of Nature* (1721) was that:

> all Bodies have some Dependance upon one another; and that every distinct Part of Nature's Works is necessary for the Support of the rest; and that if any one was wanting, all the rest must consequently be out of Order.

Carl Linnaeus, a Swedish professor of natural history, most known for establishing the binomial system of plant and animal classification, published *Oeconomia Naturae* in 1749, which both laid the framework for the science of ecology and gave a name to the balance-of-nature concept. Linnaeus' work seems influenced by the "supraorganismic" concept in which all parts of nature are fitted together as are the organs and limbs of single organism. All work together for the benefit of the (supra) organism.

The 18th Century also brought significant challenge to the balance concept. Georges-Louis Leclerc, Comte de Buffon, a French aristocrat, explorer, naturalist and mathematician, published a 44-volume encyclopedia of natural history, *Histiore naturelle*, in which he challenged the prevailing thinking about age of the earth (6000 years) and constancy of nature. Buffon raised again the issue of the extinction of species suggested by fossil evidence. With continued explorations of unknown regions, Ray's explanation was becoming increasingly untenable. But Buffon also supported the balance concept by offering theories about the forces in nature, such as reproductive capacity, weather, predation, and competition for food, which restore balance if populations become too abundant or too rare. Bernardin de Saint-Pierre wrote about the extreme ecological disturbance on the island of Mauritius from introductions of imported species, thus explicitly challenging the view that nature can always maintain a balanced state.

19th Century

By the 19th century, scientists had moved away from providential ecology and natural theology enough to tackle seriously the issues of constancy of nature, extinctions, species immutability, and how they relate to the balance-of-nature. Contributions came from Lamarck early in the century, although his ideas of rapid change within a species largely served as a foil for others. de Candolle was an early champion of competition as a factor determining plant species distributions, which would suggest that balances may shift in time and space. Nearly all of the pillars of biological and geological sciences of the time made contributions, including von Humboldt, Lyell, Cuvier, Wallace, and Darwin.

In *Vestiges of the Natural History of Creation* (1844) Robert Chambers, an amateur naturalist, attempted a synthesis involving the balance of nature in a changing world. The work was so unorthodox that it was attacked from both religious and scientific fronts, yet was wildly popular, requiring 10 editions by 1853.

With the publication of Darwin's *Origin of Species* (1859), the balance-of-nature concept became somewhat less compelling, particularly over long time spans. Darwin's theory that natural selection of favorable traits led to gradual changes in species and eventually resulted in species replacement seemed diametrically opposed to the balance-of-nature concept. However, Darwin's observations that, at any point in time, the high reproductive potential of species is held in check by a variety of mortality factors, is inherently a mechanism for balance-of-nature. Because he did not directly address the issue, Darwin's work had less impact on balance-of-nature than it should have had.

Based primarily on limnological observations, Forbes reinvigorated balance-of-nature in his address "The Lake as a Microcosm" (1887):

> Perhaps no phenomenon of life in such a situation is more remarkable than the steady balance of organic nature, which holds each species within the limits of a uniform average number, year after year, although each one is always doing its best to break across boundaries on every side....and yet life does not perish in the lake, nor even oscillate to any considerable degree, but on the contrary the little community secluded here is as prosperous as if its state were one of profound and perpetual peace.

Although Herodotus and Plato would have attributed this stasis to divine providence, Forbes' mechanism was the stabilizing effects, in the short term, of natural selection. Through the end of the century, the reasons for balance-of-nature were open for debate, but its existence was not seriously questioned.

20th Century

Early in the 20th Century, Clements in *Plant Succession* (1916) put forth the supra-organismic-community concept in which the climax plant community is considered an "organic entity":

> the climax formation is the adult organism, the fully developed community, of which all initial and medial stages are but stages of development. Succession is the process of the reproduction of a formation, and this reproductive process can no more fail to terminate in the adult form of vegetation than it can in the case of the individual plant.

These ideas had both supporters and critics. Elton was perhaps the most direct of the critics:

> ‘The balance of nature' does not exist, and perhaps never has existed. The numbers of wild animals are constantly varying to a greater or less extent, and the variations are usually irregular in period and always irregular in amplitude. Each variation in the numbers of one species causes direct and indirect repercussions on the numbers of the others, and since many of the latter are themselves independently varying in numbers, the resultant confusion is remarkable. [6]

Through the middle years of the century, ecologists debated the validity of the concept directly, and indirectly, through such topics as whether population abundances are controlled by density-dependent or density-independent factors. Defenders of the balance-of-nature included Allee et al. in *Principles of Animal Ecology* (1949):

> the community maintains a certain balance, establishes a biotic border, and has a certain unity paralleling the dynamic equilibrium and organization of other living systems. [7]

Equally prominent ecologists, such as Andrewartha, Birch, and Erlich have posed counter-arguments.

One of the most useful statements of the concept was provided by Carrington Williams in *Patterns in the Balance of Nature* (1964):

> The pattern of relative abundance is thus an expression of the momentary balance which has been set up among all the species of the association, and it is important to find out whether, as time passes, the fundamental pattern changes, or if the species move in their relative abundance within a more or less stable pattern. This is the approach to the problem of the 'balance of nature' from the point of view of quantitative synecology. [8]

The above historical summary comes from Egerton's much more complete analysis of the evolution of the concept [5] in 1973, which is about the time §316(a) came into existence. The debate has continued since that time, with the result that the concept has fallen further out of mainstream ecological thought since then [9, 10].

Regulating for a BIP/BIC

Although the balance-of-nature had been a component of the prevailing worldview throughout most of recorded history, the scientific acceptability of "balance" as an operative biological construct was clearly in decline, though perhaps not entirely gone, at the time Congress passed §316(a) with the goal of maintaining "balanced indigenous populations." Therefore, the EPA was charged to develop the regulatory structure to achieve a scientifically nebulous goal. Given the difficulty of that task, their technical guidance manual prepared in the mid-1970s [11] must be viewed, in light of the scientific uncertainty about the validity of the goal, as a reasonable and logical attempt to achieve the statutory standard.

The interagency task force that wrote the manual considered the various ecosystem components that would contribute to a balanced indigenous community such as phytoplankton, zooplankton, meroplankton, habitat-forming species, shellfish and other macroinvertebrates, and fish and other wildlife. The mere presence of these components was not sufficient. These community components or “biotic categories” also needed to display diversity and the ability to sustain themselves through cyclic seasonal changes. Additionally, they could not be dominated by pollution-tolerant species. Although the BIC typically was characterized as the locally desirable species of fish, shellfish, and wildlife, it also included biota at other trophic levels that were necessary as a part of the food chain or otherwise ecologically important. The BIC could include species not historically native if they resulted from major modification of the water body, such as damming a river, or deliberate introduction. Species or communities that are primarily of scientific or aesthetic value could be part of the BIC.

The regulatory scheme included specific criteria for each of the biotic categories considered to have low potential for thermal impacts, and therefore would require less data to determine whether that component of the BIC would be maintained. Rather than study every species within the potential zone of impact, a set of representative important species (RIS) could be established as the focus of study. The RIS would be commercially or recreationally valuable, threatened or endangered, critical to structure and function of the ecosystem, potential nuisance species, necessary in the food chain, or representative of the thermal requirements of other important species.

In regulating thermal discharges, criteria typically are established for measurable physical attributes, such as temperature or temperature rise of the discharge flow, extent of the thermal plume, and rates of temperature change, which, if met, provide presumptive evidence that the BIC will be maintained. However, in many cases, one or more of the criteria are not met. In those instances the generating facility may submit a request for a variance, which would establish alternative, less restrictive, criteria for the discharge that would still maintain the BIC. Stone & Webster estimated that in 1992, 679 facilities, comprising 32% of total United States generating capacity, operated under §316(a) variances [12]. Of Maryland facilities subject to §316(a), 7 facilities met all the water quality criteria and therefore did not need a variance, 4 facilities failed to meet one or more of the criteria and were required to request alternative criteria, i.e. request a variance, and 1 facility requested a variance due to an unusual flow regime in the receiving water [13].

Demonstrating that the BIC is or will be maintained can be problematic since no operational definition of "balance" has been provided, and no quantitative standard for balance has been proposed. In practice, demonstration of balance for existing discharges has often required:

1. No significant trends in abundance of RIS that would be attributable to the discharge
2. Different biotic categories are present in expected proportions (ideally illustrated in Figure 5-1)
3. Nuisance species such as blue-green algae or heat-tolerant fish species do not dominate the community
4. Conditions in the plume are not lethal

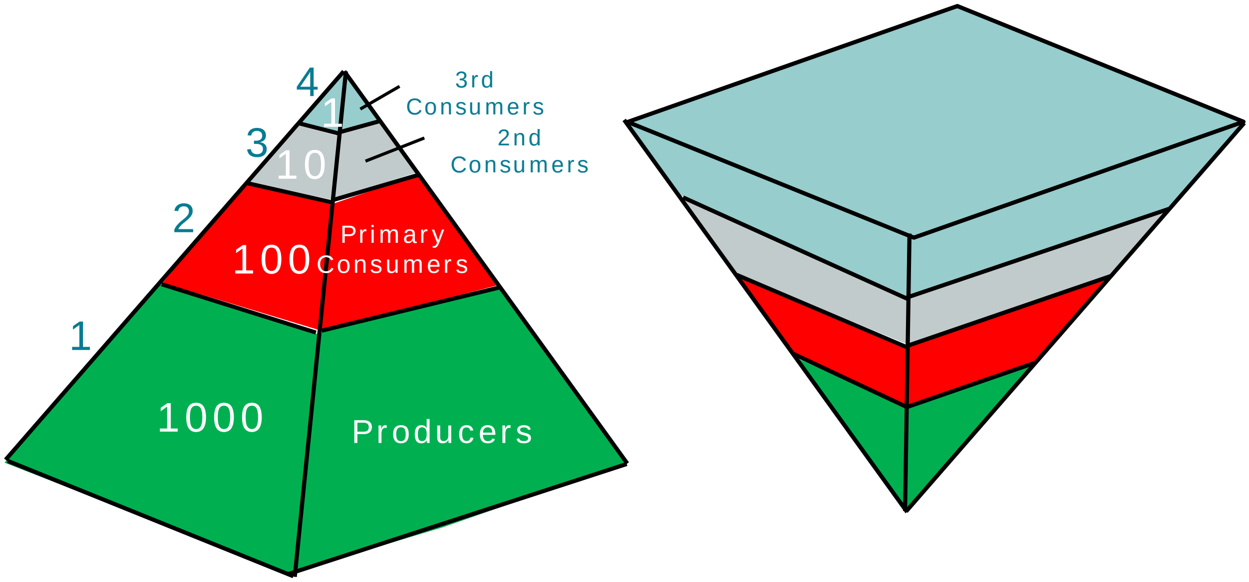

Figure 5-1
Balanced (left) and unbalanced (right) trophic levels

This common-sense approach to BIC generally has worked well in practice because the necessary information can be derived from standard fisheries and limnological sampling programs. However, regulation of thermal discharges under §316(a) is done in concert with regulation of the intake effects under §316(b), thus entrainment and impingement effects are typically included when considering whether the BIC is being maintained. This duality of the analysis has led to disputes between the regulatory agencies and the generating industry over technology requirements. Particularly at issue is the question whether closed-cycle cooling, which would nearly eliminate both the intake and discharge effects once it is installed, could be imposed if it was not necessary to meet §316(a). Some members of industry have argued that since closed-cycle cooling is not an intake technology, it cannot be imposed under §316(b).

Examples of BIP/BIC determinations

In the 40 years since §316(a) was enacted, EPA and state agencies have made thousands of determinations of what conditions are necessary to protect and maintain a BIC in the receiving water bodies. In many, if not most cases, variances have been granted to establish alternative criteria. Selected examples of successful and unsuccessful variance requests are provided.

Labadie

The Labadie Power Plant, near St. Louis, Missouri, consists of four 600 MW coal-fired generating units constructed in the early 1970s. The plant draws up to 856,000 gpm for once-through cooling from the Missouri River. The station's initial NPDES permit issued in 1975 required that closed-cycle cooling be implemented by 1981, and limited discharge temperature to 118°F. However, a §316(a) variance was requested, and approved in 1977, which dropped the requirement for closed-cycle cooling and discharge temperature limit, but limited heat rejection to 10.63 billion BTU/hr (full generation operation).

When the permit issued in 1987 was to expire in 1992, the facility submitted an analysis of electrofishing data from 1974-1976 that were used in the original variance request, additional data collected in 1980-1984, and ancillary data collected from 1982-1991 on fish species composition, to demonstrate no prior harm to the BIC.

The 1992 submittal [14] demonstrated an overall increase in fish abundance in the river between the 1974-1975 and the 1980-1984 programs (Table 5-1), although abundance within the discharge canal and downstream of the station was lower than abundance upstream. Species richness showed similar temporal and spatial patterns. Gizzard shad were the dominant species in both sampling programs (45.7% and 58.9% of the total catch, respectively), with freshwater drum, river carpsucker, goldeye, common carp, and shortnose gar as the other common species. The ancillary data, collected monthly from 1982-1991, demonstrated that forage fish, rough fish, and recreational and commercial species all continued to be represented and total species collected annually ranged from 17 to 28 for the years that were sampled in every month. The §316(a) variance was granted and it remains in effect currently.

Table 5-1
Fishery sampling metrics used to evaluate BIC for the Labadie Power Plant in 1992

Site	Upstream		Discharge Canal		Downstream	
Period	**1974–1975**	**1980–1984**	**1974–1975**	**1980–1984**	**1974–1975**	**1980–1984**
Mean CPUE[1]	0.88	2.76	1.28	0.85	0.33	1.61
Number of Species	14	30	12	15	9	24

[1] CPUE = Catch per unit effort

Mercer

Mercer Generating Station, located in Mercer County, New Jersey, has two fossil-fueled steam-electric generators (311 MW each) that were constructed in the early 1960s. Cooling water is withdrawn from the Delaware Estuary at the rate of 240,000 gpm for each unit. The cooling water is returned to the Estuary through a discharge canal.

Mercer Generating Station submitted a §316(a) demonstration [15] to renew their variance in 2000, using thermal modeling to assess compliance with the criteria, and a biothermal assessment to demonstrate the maintenance of the BIC. The biothermal assessment used both predictive and retrospective analyses. In the predictive analysis, low potential for appreciable harm was demonstrated for all biotic categories and for the RIS, which included 10 fish and 2 macroinvertebrate species.

Retrospective evaluation of RIS populations and the fish community confirmed the prediction that the station's thermal discharge did not harm these biotic categories. Indices of annual abundance of the RIS, obtained in field sampling from 1985 to 1999, indicated an increasing trend (blue crab, American shad, white perch, striped bass) or no trend (alewife, spottail shiner, bluegill, channel catfish) in abundance of the RIS in the estuary, tidal river, and upper tidal river except for blueback herring. A declining trend for blueback herring was mirrored all along the Atlantic coast. There was no evidence that the station's thermal discharge excluded the endangered shortnose sturgeon from available habitat or interrupted its reproductive migrations past the station. The operation of the station had not caused a simplification of the fish community since no reduction in species richness and species density was found in trawl sampling (1998–1999), compared to individual years sampled during 1970 to 1972 (Table 5-2). The fish community near Mercer remained diverse, with 49 species sampled in 1998-1999, after more than 35 years of station operation. The species comprising the fish community near Mercer are also found in freshwater tidal areas of nearby estuaries, and the community had not become dominated by any nuisance species. Shifts in species abundance that occurred between the early 1970s and late 1990s were hypothesized to be due to improving water quality and increases in abundance of large predators, which also have led to enhancement of the recreational fishery near the station. The New Jersey Department of Environmental Protection renewed the §316(a) variance.

Table 5-2
Fishery sampling metrics used to evaluate BIC for the Mercer Generating Station in 2000

Site	200 Yards Upstream to 1.25 Miles Downstream			Intake and Discharge Transects
Year	1970	1971	1972	1998-1999
Mean CPUE[1]	46.3	14.5	22.6	15.3
Number of Taxa	20	20	20	26
Unique Taxa	7 (not present in 1998-1999)			8 (not present in 1970–1972)
Mean Taxa per Haul	2.5	2.0	2.3	2.0

[1] Catch per unit effort

Merrimack Station

The Merrimack Station is a 470 MW coal-fueled facility located on the Merrimack River in Bow, New Hampshire. The station has a once-through cooling system capable of withdrawing 287 MGD. The discharge permit for the station issued in 1992 granted a §316(a) variance and required the station to use cooling towers to reduce the discharge temperature whenever ambient river temperature exceeded 20°C. The permit expired in 1997 and it has since been administratively continued.

In the Second Electric Power Research Institute (EPRI)-sponsored Thermal Workshop, Hutchins presented data that the station would use to demonstrate that the BIC has been maintained [16]. It included:

1. Analysis of RIS trends - Electrofishing data from 1972-1974, 1995, and 2004-2005 indicated no trends in a control zone, the thermally influenced zone, or in the pool where the discharge is located for 5 of 6 resident fish species and 1 anadromous species. Only 1 species, pumpkinseed, exhibited a statistically significant decrease in the thermally-influenced zone and pool, although it was stable in the ambient zone. Species richness exhibited no trends.
2. A zone of passage was maintained for out-migration of Atlantic salmon smolts.
3. Thermal exclusion based on the ultimate incipient lethal temperature (UILT) and avoidance temperature was only for a limited area within the plume.
4. The thermal environment within the plume would not be lethal or cause appreciable changes in growth rates.

The EPA and New Hampshire Department of Environmental Services issued a draft discharge permit for Merrimack in 2011. The agencies disagreed with the industry analysis [17] based on the following:

- ...the evidence as a whole indicates that Merrimack Station’s thermal discharge *has* caused, or contributed to, appreciable harm to Hooksett Pool’s BIP
- The Hooksett Pool fish community has shifted from a mix of warm and coolwater species to a community now dominated by thermally-tolerant species

- The abundance for all species combined that comprised the BIP in the 1960's has declined by 94 percent
- The abundance of some thermally-sensitive resident species, such as yellow perch, has significantly declined
- ... did not demonstrate that its proposed alternative thermal discharge limits.....would reasonably assure the protection and propagation of the BIP
- ....did not demonstrate that thermal discharge limits would be more stringent than necessary to assure the protection and propagation of the BIP

EPA's conclusion about harm to the fish is specific to Hooksett Pool, i.e., the immediate vicinity of the discharge. EPA presented no conclusions about passage of migratory fish, or about effects further downstream, but mandated closed-cycle cooling:

> EPA has found that Merrimack Station's thermal discharges have contributed to the deterioration of fish populations in the Hooksett Pool. In addition, EPA has determined that upgrading Merrimack Station's decades-old open-cycle cooling system to a closed-cycle system is the best available technology for reducing the facility's discharges of waste heat. Therefore, the Draft Permit includes monthly and yearly limits on the amount of heat that Merrimack Station can discharge to the Hooksett Pool based on the levels achievable by a closed-cycle cooling system. These limits apply year-round and would reduce the facility's thermal discharges by 99.6%. [17]

It is notable that EPA did not specify numerical limits on heated discharges that would maintain a BIC, but simply required that the heat discharged be no more than would be discharged if a closed-cycle cooling system were used year-round. EPA also determined that closed-cycle cooling was the Best Technology Available (BTA) for the intake, but only from April-August. However, the more stringent requirements imposed under §316(a) render this distinction moot.

Brayton Point

Brayton Point Station is a 1,600-MW fossil fuel generating station located on Mount Hope Bay in Somerset, MA and is the largest fossil fuel station in New England. The station had a once-through cooling system, discharging 951 MGD of thermal effluent on average. The station has four units; Unit 4 was converted from closed-cycle cooling to open-cycle cooling in 1984-1985. When the NPDES permit was due to expire in July 1998, a permit renewal application was filed based on water quality standards. However, in 2001 a renewal application, including a §316(a) and (b) demonstration, was submitted to seek a §316(a) variance. In October 2003, EPA Region 1 issued a permit renewal, which had stricter thermal discharge limits than earlier permits. The station appealed this permit to the EPA's Environmental Appeals Board (EAB) in November 2003, but the EAB upheld the permit. Subsequently, the station appealed the EAB ruling to the Federal Court in the Fourth Circuit. In December 2007, an agreement was reached with EPA to end litigation and to implement fully the limits specified in the October 2003 permit, specifying a 95% reduction in flow and heat rejection from the current operation.

In reviewing the station's §316(a) demonstration, EPA concluded that the limits proposed in the station's permit application would not be protective of the BIC in Mount Hope Bay. EPA observed that the Mount Hope Bay community showed signs of cumulative stress [18], and in particular the winter flounder population, which had declined 100-fold from historic levels. In addition to thermal impacts, EPA cited overfishing, predation, water quality, and entrainment and impingement at the station as other sources for fish mortality. Sixteen of 20 finfish populations dramatically declined in abundance since 1985, coincident with an increase in thermal discharges. In addition to declining stocks of finfish species, several arguments for evidence of thermal impacts on the overall community in the bay were made by EPA, including:

- Absence of a normal winter-spring phytoplankton bloom;
- Appearance of nuisance algal blooms;
- Overwintering of the predacious ctenophore *Mnemioposis leidyi*;
- Overwintering of striped bass and bluefish in the discharge canal;
- Increased abundance of more thermally-tolerant fish species, e.g., smallmouth flounder;
- Multiple large impingement events; and
- Thermal avoidance of the bay by adult winter flounder.

EPA concluded that the thermal discharge impacts would inhibit or prevent recovery of the system, which otherwise might be realized from measures being taken to improve water quality in the bay and to manage the fisheries to recovery. Imposition of cooling towers was intended to provide relief under both §316(a) and §316(b). The thermal limits imposed in the final permit were a maximum of 1.7 TBTU of heat input per year (0.14 TBTU per month) and a maximum discharge temperature of 95°F, which was considered by EPA to be §316(a) variance [18].

Conclusion

The examples provided show that whether a §316(a) variance request is granted or denied depends, as it should, on site-specific data. However, due to the inexactness of the legal standard, the amount of data required, and the interpretation of it may differ depending on which EPA region or state agency is evaluating it.

In 1991, Congress considered removing the variance provisions from §316(a), which would have resulted in over 600 generating stations needing to find a way to operate within the thermal criteria, install closed-cycle cooling, or cease operating. The possible consequences of that regulatory change would have been many stations, primarily older and smaller stations, shutting down, at least during periods when criteria would not be met, and expenditure of $23-$29 billion (1992 dollars) to install closed-cycle cooling, and an additional $1-$5 billion to replace lost generating capacity due to lower efficiency [19]. Such a legislative change, like the initial passage of §316(a), would have been an example of environmental regulation being out of synchrony with the prevailing science. Veil stated:

> The power industry has spent millions of dollars on demonstrating that the requirements of Section 316 are met at their generating stations. One direct benefit of the hundreds of studies is that knowledge of ecosystem dynamics and of the life histories, abundance, and distribution of aquatic organisms has been advanced substantially. As information accumulated from the Section 316 studies, it was generally recognized that thermal impacts on biota were less significant than originally thought. [19]

Veil was not the first to reach this conclusion. In a lengthy review of the aquatic impacts of power generation, Langford realized that the intensive research effort had generally supported a relative lack of observed degradation due to thermal discharges as early as 1983:

> It is doubtful if true thermal effects could be detected in biological terms over more than a few thousand hectares in the world, at a cost in research, legislation, alleviation and monitoring, of millions of dollars per hectare. [20]

As of 1990, Langford maintained his opinion about the severity and insignificance of thermal impacts:

> In conclusion, it seems clear that the prediction of the effects of thermal discharges from the new breed of power stations or other industries, need not be subject to the irresponsible extrapolation and exaggeration which was found in the 1960s and early 1970s. The research and surveys have not borne out the dire predictions of disaster much of which came from academic and political ambition. It is also clear that some of the legislation rushed through in some countries as a result of the high media and political profile of the issue was hasty and ill-conceived. ... There is no substitute, even in the field of applied ecology, site assessments or prediction, for sound objective science with high academic credibility. [21]

Despite the lack of a close linkage of the §316(a) statute to contemporary ecological science, the regulation has been successful at preventing ecological degradation due to thermal discharges. This success though, is not clearly a product of the regulatory provisions. The extensive studies conducted since §316(a) was enacted have demonstrated the robustness of the aquatic ecosystems and the conservativeness of the thermal compliance criteria. Given that as of 1992, a total of 679 facilities were operating under variances, clearly the EPA and state regulatory agencies have recognized this conservativeness.

EPA has indicated its intent to re-examine §316(a) variances in upcoming permit renewal activities [22], but has proposed no new regulations, which is probably the correct strategy. Any new regulations attempting to define the BIP/BIC concept more precisely would need to deal with many confounding issues. In particular, many aquatic ecosystems are subject to the continual change, both natural and anthropogenic, that affects the populations and communities living there. Natural changes may occur as a result of ecosystem succession, competition, and climate variations. Anthropogenic changes can arise from improved water quality, due to the other provisions of CWA, which may allow a richer community to replace a pollution-tolerant community. In other places, structural modification of the habitat, species introductions, consumptive water use, or fishery management actions may alter the community independent of, or in concert with, the effects of thermal discharges. The existing regulatory structure, and past agency interpretations, have in general been sufficiently protective to achieve Congress' goals, yet usually flexible enough to avoid imposing unnecessary excess costs on the generating industry. Although the effectiveness of EPA's future implementation of §316(a) is yet to be seen, past regulation has been a success in spite of the scientific vagaries of the statute.

Acknowledgments

The single citation of the work of F. N. Egerton in the historical perspective on balance-of-nature does not adequately express his contribution to this section. Readers with interest in the history should go to this source for a much more complete coverage of the topic.

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6
A REVIEW OF THE THERMAL TOXICITY LITERATURE

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Abstract

Several states have reviewed or are in the process of reviewing their thermal standards and utilities and others with thermal discharges have recently been required to prepare revised §316(a) demonstrations. Setting state, regional, or site-specific thermal standards is problematic because although well established procedures are in place for deriving criteria for most water quality parameters, clear guidance has not been established for deriving temperature criteria. In response to this recent regulatory activity, a literature review of upper lethal thermal limits for freshwater fishes was conducted with an emphasis on two issues: (1) the quality of the database that can be used to derive thermal criteria and (2) the factors that affect endpoint estimates. Because of its size, the database was divided into three categories: coldwater species (primarily salmonids), coolwater species (esocids and some percids), and warmwater species (most of the remaining freshwater fish families). It was found that with a few notable exceptions most investigations followed standard test protocols and, as a result, the quality of the database was good. Investigators typically derived short-term lethal estimates using either the incipient lethal temperature (ILT) method or the critical thermal maximum (CTM) method. The ILT method consists of acclimating fish to a particular temperature, then plunging them into a series of higher temperatures and recording the time to death. The CTM method also consists of acclimating fish to a particular temperature, then heating them at a predetermined rate until physical disorganization (most often measured by loss of equilibrium) occurs. The CTM method is now the method of choice but produces more problematic values generally due to either insufficient numbers of fish tested, different heating rates, and variable endpoints.

Coldwater species had the lowest upper endpoints. Salmonids had very similar endpoint estimates, usually around 25°C for the upper ILT (UILT) and 29-30°C for the CTM. The endpoints for coolwater species overlapped rather broadly with those for warmwater species, indicating that this designation is largely artificial and certainly not rigorously defined by temperature tolerance. Among warmwater species, all ictalurids, centrarchids, and most cyprinids and darters are fairly tolerant. Within the warmwater group, some of the more thermally sensitive species include northern hog sucker, redhorse, and especially white sucker; the UILT for white sucker is about 30°C.

Because of inherent differences in the endpoints estimated by the CTM and ILT methods (UILT values are usually about 5°C lower than CTM estimates for the same species), it is important that endpoints be adjusted or standardized when used to develop thermal criteria. Similarly, it was found that acclimation temperature greatly affects upper endpoint estimates. For warmwater species, endpoint estimates can vary by 10°C or more depending on acclimation temperature.

Again, adjustment or standardization of data is necessary before they are used to develop temperature criteria. Adjustment is particularly important if the only data available were derived from fish acclimated to temperatures well below the upper lethal temperature for that species.

Introduction

Several states including Colorado, Illinois, Pennsylvania, and Wisconsin have either recently reviewed or are in the process of reviewing their thermal standards and the Ohio River Valley Sanitary Commission (ORSANCO) also recently completed a thermal review for the Ohio River. Similarly, utilities and others (e.g., the British Petroleum Refinery in Whiting, Indiana) have recently been required to prepare revised §316(a) demonstrations. Setting state, regional, or site-specific thermal standards is problematic because although well established procedures are in place for deriving criteria for most water quality parameters (U.S. Environmental Protection Agency, 1985), clear guidance has not been established for deriving temperature criteria.

Although the manner in which thermal standards have or will be developed will differ among states and other regulatory agencies, the “raw material” for developing standards will be thermal endpoint data. Most of these will be acute endpoints calculated from either the traditional experimental procedure for deriving upper (and lower) incipient lethal values (Fry, 1947; 1967) or the procedure for developing critical thermal maxima (Hutchinson, 1961; Becker and Genoway, 1979; Paladino et al., 1980).

In contrast to other water quality parameters, most of which had criteria documents developed by U.S. Environmental Protection Agency (EPA) in the 1980s and 1990s and whose databases underwent a quality review as part of the development process, no such data compilation or quality control review has been done for temperature. Thus, poor quality temperature data has found its way into the existing databases. The objective of this review was to critically review the scientific foundation of the thermal toxicity literature and to evaluate its applicability for establishing thermal standards. To make the results broadly applicable and ecologically relevant, the freshwater dataset was divided into three groups (coldwater, coolwater, and warmwater) based on each species’ thermal preference.

Using existing literature reviews and data compilations (Brown, 1976; Brungs and Jones, 1977; Talmage and Opresko, 1981; Wismer and Christie, 1987; Smale and Rabeni, 1995; Beitinger et al., 2000) as well as searches of the literature from 1995 through 2010, a group of 400 or so titles was considered. Based on each title and the species tested, this initial list was reduced to about 60 papers. Each of these papers was reviewed and appropriate information extracted. In some cases, the selected papers did not provide usable information.

It is important to understand that this paper is not a review of the entire voluminous thermal literature database. Instead, a critical review of species or species groups at the sensitive end of the thermal tolerance spectrum was conducted and included species that were approximately in the most sensitive 10 percent for each of the three temperature categories. Emphasis at the sensitive end of the spectrum is appropriate because in most cases, water quality standards, including those for temperature, are based on protecting sensitive species. Thus, sensitive species are given extra weight. For example, EPA’s procedure for deriving water quality standards for most toxicants is based primarily on the four most sensitive species with the remaining species having little effect on the resultant standard (EPA, 1985). Some methodologies for deriving thermal standards only use the most thermally sensitive species (Yoder and Emery, 2004; Yoder, 2008). Given that criteria are usually based on thermally sensitive species, it was decided to concentrate on such species. As a result, we purposely did not review papers on thermally tolerant species such as common carp (*Cyprinus carpio*), bluegill (*Lepomis macrochirus*), largemouth bass (*Micropertus salmoides*), channel catfish (*Ictalurus punctatus*), and gizzard shad (*Dorosoma cepedianum*).

Issues Affecting Thermal Endpoints

Upon reviewing the literature, it became apparent that there were several issues that were important regardless of the species tested. These issues are particularly important for determination of short-term (acute) endpoints, but some are broadly applicable to all thermal endpoint determinations. These generic issues are discussed below.

Methods to Determine Acute Thermal Endpoints

Upper (and lower) temperature tolerances of fishes have been quantified in the laboratory via three different experimental approaches: the Fry or incipient lethal temperature (ILT) method, critical thermal maximum (CTM), and chronic lethal maximum (CLM) methodologies. Although these three laboratory approaches generate endpoints that are (1) quantitatively expressed as a temperature, (2) determined experimentally with random samples of fish acclimated to specific temperatures, and (3) involve both time and temperature as major test variables, they do not quantify the same response (Beitinger et al., 2000). Thus, endpoints can vary by as much as 5°C for the same species tested at the same acclimation temperature (Beitinger et al. 2000, Wagner et al. 2001). In the ILT method, a temperature lethal to 50 percent of a fish sample is determined by plunging groups of fish from a specific acclimation temperature into a series of constant test temperatures near the estimated upper (or lower) temperature limits of a species (Fry, 1947). For this review, I dealt exclusively with upper temperature maximums, which are referred to as the upper incipient lethal temperature (UILT). In this report, the term ILT refers to the test methodology and UILT is the upper (=U) endpoint estimate. In ILT tests, mortality is the endpoint and is recorded over time. An estimate of the temperature tolerated by 50 percent of a sample for various exposure time intervals, usually 4-7 days, is made from a regression of percentage mortality on test temperature. It was the method of choice through at least the 1960s.

The critical thermal methodology or maximum (CTM) has replaced the ILT as the method of choice since about 1990. This preference for CTM appears to have less to do with any scientific superiority associated with the CTM but more because fewer test organisms and less time are needed to conduct CTM tests. In fact, a CTM can be (and has been) generated from a single fish. In this methodology, individual fish are heated at a constant rate (0.3°C/min is a commonly recommended rate, Becker and Genoway 1979) until physical disorganization (e.g., loss of equilibrium or onset of muscle spasms) occurs. The value reported is usually the arithmetic mean of individual tests. Also, the CTM requires less investigator effort than the ILT method. Once the acclimation period is over, an ILT test typically takes several days because the resistance time (i.e., time to death) of each test fish needs to be measured whereas the CTM test takes only an hour or two, depending on the rate of heating. Kilgour and McCauley (1986) developed a formula that can be used to estimate CTM values from ILT values and vice versa.

To obtain an accurate estimate of the CTM, the rate of temperature change must be slow enough so that a fish's core temperature does not significantly lag behind water temperatures, and rapid enough so test fish do not have time to thermally re-acclimate during a trial. If the rate of temperature change is either too rapid or too slow, the measured CTM values will be biased towards higher temperatures. In practice, some acclimation is likely to occur during most CTM tests unless the heating rate is extremely rapid or the acclimation temperature is close to the upper lethal temperature.

Neither method is particularly representative of conditions that are likely to be encountered in the field. In the case of the ILT method, fish are plunged directly from their acclimation temperature into a series of constant test temperatures. The temperature differential (ΔT) associated with this might be as much as 20 to 25°C. Although a few power plant discharges can generate ΔTs of this order, it is difficult to imagine a fish swimming from ambient temperatures of say 10°C into a plume (perhaps to grab a prey item) with a centerline temperature of 30 or 35°C and remaining there for more than a few minutes. For the CTM method, test fish are heated at a constant rate. The rate most commonly used is 0.3°C/min (18°C/hr). Again, it is difficult to imagine a fish staying in an area for an hour during which the temperature increases by 18°C.

To address some of the issues associated with the ILT and CTM methods, a relatively new method has emerged, referred to as either the chronic lethal method (CLM) or the slow heating method. Note, however, that the traditional CTM method is sometimes also referred to as the slow heating method because the heating rate is slow relative to the ILT method. In the CLM, test fish are exposed to very slow increases (usually about 1°C/day) or decreases until mortality occurs. This slow rate of change allows organisms to acclimate to each succeeding higher or lower temperature. Thus, in theory, the endpoint should approximate the ultimate upper ILT (UUILT), which is the highest temperature an organism can withstand regardless of acclimation temperature. The rate of temperature change during the CLM method likely approximates changes that temperate fishes go through on a daily basis each season and therefore appears to provide more realistic estimates of upper (and lower) temperatures. The principal drawback of the CLM method is that, depending on acclimation temperature, each test might take up to three weeks to complete. Likely for this reason, it is the least frequently used method but it has been occasionally applied (Fields et al., 1987; Currie et al., 1998; and Reash et al., 2000).

Acclimation Temperature

Aside from possibly the test methodology as discussed above, the most important factor affecting temperature tolerance is acclimation temperature (Beitinger et al., 2000). For those species tested over a wide range of acclimation temperatures, a 10°C or greater change in the upper lethal temperature has been observed for some species. If CTM temperatures are plotted against acclimation temperatures, the slope of that line represents the relationship between these two factors. This relationship is linear for most species (Bietinger et al., 2000). The slope represents how much the upper thermal maximum changes for each degree change in acclimation temperature. Bietinger et al. (2000) reported that the average slope for 20 species ranged from 0.27 to 0.50 with a mean of 0.41. In other words, the upper lethal limit changes by 4°C for each 10°C change in acclimation temperature. This means that regulatory limits developed from endpoints based on fish acclimated to temperatures well below their upper temperature limit, regardless of how that limit is calculated, will be overly restrictive because the temperature tolerance of such fish will be underestimated.

CTM Endpoints

In Section 2.1, it was noted that there are three methodologies to derive acute thermal endpoints, one of those methods being the CTM. The CTM has been defined as *"the arithmetic mean of the collective thermal points at which locomotory activity becomes disorganized and the animal loses its ability to escape from conditions that will promptly lead to its death when heated (or cooled) from, a previous acclimation temperature at a constant rate just fast enough to allow deep body temperature to follow environmental test temperatures without a significant time lag"* (Cox, 1974). Note that exact criteria for identifying the point of locomotory disorganization are not specified. The most commonly used endpoint is loss of equilibrium; however, other endpoints are often used such as the onset of muscle spasms (Matthews and Maness, 1979), flaring of the operculars (Middaugh et al., 1975), non-reaction to prodding with a glass rod (Heath et al., 1994), cessation of opercular movements (Bettoli et al., 1985), and even combinations of the above (Hassam and Spotila, 1976).

Thus, the CTM value at a particular acclimation temperature for a particular species reported by one group of researchers might differ from that reported by a different group of researchers simply because they were using different CTM endpoints.

Minimum Number of Fish to be Tested

Because the ILT methodology is based on transferring fish from an acclimation temperature to a series of test temperatures and multiple organisms are needed to establish resistance times (i.e., time to death) at each test temperature, a moderate number of test animals is required. However, for the CTM method, an estimate of the endpoint is established for each organism tested. Thus, a CTM can be established based on testing one organism. A review of two related studies indicates that endpoints based on only a few test organisms can be common. Reuter and Herdendorf (1975, 1976) calculated CTMs for 33 freshwater fishes. They conducted tests under various seasonal regimes and reported the highest CTM for each species (Reutter and Herdendorf, 1976). Of the 33 species tested, 17 CTMs reported were based on testing a single fish, and most of the rest were based on testing two to three individuals per species.

Results

Based on the literature review, a number of species or species groups in each of three categories of fishes (i.e., coldwater, coolwater, and warmwater) were established for detailed review. As discussed previously, the main criterion for selecting species or species groups was whether they were near the sensitive end of the thermal tolerance range for each category. In deciding which species to review, I also considered the size of the geographic area occupied by species and the type of habitat in which it occurs and gave preference to species that are reasonably well distributed (e.g., occupies most of the Atlantic drainages or occurs throughout the Southeast) as opposed to those that occupy small ranges (say small portions of one or two states). Preference was also given to species likely to be encountered near power plant sites (e.g., medium to large freshwater and tidal rivers, the Great Lakes) as opposed to fishes restricted to small streams or springs. Clearly, species with restricted ranges or life history characteristics that keep them away from power plant discharges may be important in developing thermal standards at the state or regional level. However, widely-distributed, large waterbody species would play similar roles but in more places. Based on these criteria, species and species groups were selected as discussed below.

Coldwater Species

Although a few other species or groups (e.g., burbot, some sculpins, and most coregonids) are typically considered to be coldwater species, this category is dominated both numerically and especially in terms of political importance by the various trout, char, and salmon species. Because of their considerable recreational and commercial importance, this group (which I will hereafter refer to as the salmonids) has been widely tested. Information concerning the acute thermal tolerance of 11 salmonids representing four genera (*Oncorhynchus, Salmo, Salvelinus,* and *Thymallus*) is provided in Table 6-1. Some of these species are widespread and many have high recreational and/or commercial value. Although more data are available than that presented in Table 6-1, most of the other endpoint estimates were based on lower acclimation temperatures or on salmonids with limited distributions (e.g., Apache trout, *Oncorhynchus apache*). Examination of endpoints for the selected salmonids reveals several things. First, UILT values are consistently 4-5°C lower than CTM values for the same species tested at similar acclimation temperatures. Second are the remarkably similar UILT values across the salmonid species and genera and the equally similar CTM values among species and genera. For eight species representing three genera, UILT values ranged only from 23.5 to 25.1°C, a difference of only 1.6°C: UILT estimates for Chinook salmon (*O. tshawytscha*), coho salmon (*O. kisutch*), sockeye salmon (*O. nerka*), and grayling (*T. arcticus*) were virtually identical (25.0 to 25.1°C, Table 6-1). Similarly, with one exception, CTM estimates for eight species representing four genera ranged from 27.4 to 30.0°C, with most values being between 29 and 30°C. The only exception was Atlantic salmon *(Salmo salar)* whose single CTM value was 32.7°C (Table 6-1).

Although the range covered by the estimates was small, it appears that bull trout (*Salvelinus confluentus*) is slightly more sensitive than its relatives, while Atlantic salmon is somewhat more thermally tolerant compared to other salmonids. The consistency of the salmonid endpoint estimates supports the hypothesis of Myrick and Cech (2000) that, except for a few species restricted to high altitude, all salmonids have similar thermal tolerances irrespective of origin. This interpretation of data was echoed by Beitinger et al. (2000) who stated that “based on this finding” (i.e., very similar CTM values), “the upper thermal tolerance in this group is phylogenetically conservative”. I reviewed all but three of the studies cited in Table 6-1 and determined that they were well conducted and included reasonable sample sizes. Thus, as a practical matter, assuming that the derivation process is appropriate and that protection of salmonids is appropriate (i.e., the waterbody in question is a coldwater stream and does in fact support salmonids), then similar criteria will likely result regardless of which salmonid(s) is(are) to be protected.

Table 6-1
Salmonid acute upper lethal endpoints using two test methodologies

Species	UILT* (Acclimation)	CTM* (Acclimation)	Reference
Rainbow trout	--	29.8 (20)	Currie et al., 1998
Rainbow trout		29.8 (20)	Currie et al., 2004
Rainbow trout		29.0-29.7 (14)	Rodnick et al., 2004
Rainbow trout		28.4-28.8 (15)	Galbreath et al,. 2004
Rainbow trout		29.3 (20)	Lee and Rinne, 1980
Chinook salmon	25.1 (24)	--	Brett, 1952
Coho salmon	25.0 (23)	--	Brett, 1952
Coho salmon	--	28.7-29.7 (15)	Becker and Genoway, 1979
Coho salmon		29.1-29.2 (15-17)	Konecki et al., 1995
Sockeye salmon	25.0 (20)	--	Brett, 1952
Chum salmon	23.8 (23)	--	Brett, 1952
Brook trout	25.0	--	Fry et al., 1946
Brook trout	--	28.0-28.9 (15)	Galbreath et al., 2004
Brook trout		29.8 (20)	Lee and Rinne, 1980
Brown trout	--	27.4-29.0 (depending on strain) (12)	Carline and Machung, 2001
Brown trout		29.0-29.3 (15)	Galbreath et al., 2004
Brown trout		29.9 (20)	Lee and Rinne, 1980
Atlantic salmon	--	32.7 (20)	Elliott and Elliot, 1995 (as cited by Beitinger et al., 2000)
Cutthroat trout	23.5-24.3 (18)	29.4-30.0 (18)	Wagner et al,. 2001
Cutthroat trout	24.2 (18)	--	Johnstone and Rahal, 2003
Grayling	25.0 (20)	29.3 (20)	Lohr et al., 1996
Bull trout	23.5 (20)	28.9 (20)	Selong et al., 2001

*All values in °C.

Although the coldwater focus in this review is on salmonids, it appears that other coldwater species have very similar endpoints. Edsall and Colby (1970, as cited in Brungs and Jones, 1977) reported an UILT of 26°C for lake herring (*Coregonus artedi*) acclimated to 25°C, which is nearly identical to the endpoints for the trout and salmon that have been tested (Table 6-1). Tests on sculpins (*Cottus* spp.), another mostly coldwater group, but one not closely related to salmonids, yielded results very similar to those in Table 6-1. Otto and Rice (1977) reported that the CTM of slimy sculpin (*Cottus cognatus)* acclimated at 20°C was 29.4°C. They reported that UILT temperatures were 2.5 to 5.0°C lower than the CTMs at equivalent acclimation temperatures, again very similar to the differentials seen for salmonids (Table 6-1). Lastly, they calculated an ultimate upper ILT (UUILT) value of 26.5°C for slimy sculpin. Kowalski et al. (1978) reported a CTM of 30.9°C for mottled sculpin (*Cottus bairdii*) acclimated to 15°C. Thus, it appears that coldwater fishes have narrow endpoint ranges, with CTM values of about 29-30°C and UILT values of 24-25°C.

Coolwater Species

As mentioned in the preface of the proceedings of the "*Selected Coolwater Fishes of North America*" conference (Kendall, 1978), *"[t]he term 'coolwater fishes' is not rigorously defined, but refers generally to those species which are distributed by temperature preference between the 'coldwater' salmonid communities to the north and the more diverse, often centrarchid-dominated 'warmwater' assemblages to the south."* The species covered by that symposium were all members of the esocid (pike) and percid (perches) families. As was the case with the above-cited symposium, this review concentrates on five coolwater species that have major recreational and commercial value: walleye (*Sander vitreus*), sauger (*S. canadensis*), yellow perch (*Perca flavescens*), northern pike (*Esox lucius*), and muskellunge (*E. masquinongy*). I am not aware of tests that have determined the upper thermal tolerance of the other two North American esocids, redfin pickerel (*E. americanus*) and chain pickerel (*E. niger*); however, given their geographic distributions (Page and Burr, 2011), both are likely to be less thermally sensitive than either muskellunge or especially northern pike, both of which have more northerly distributions. Yellow perch, sauger, and walleye are all members of the family Percidae. Numerically, this family is overwhelmingly dominated by darters. Although there are nearly 200 species of darters (Page and Burr, 2011), less than 10 of them have been tested to determine their thermal tolerance (Beitinger et al., 2000). Of those that have been tested, CTM values are comparable to or slightly higher than those of the larger percids. Thus, I included the darters in the warmwater group rather than the coolwater group.

Northern Pike

Despite being a popular game fish throughout much of North America, little testing has been done to establish the thermal tolerance of northern pike. Hokanson et al. (1973) reported that, when acclimated to 17.7°C, the 7-day upper TL50 increased from 25.0 to 28.4°C from the time of hatch to the free swimming stage. They also reported that the optimum range for hatching ranged from 6.4 to 17.7°C and that hatching rates were poor at temperatures greater than 20°C. Cvancara (1975, 1977) tested juvenile northern pike collected from the Mississippi River. Upon capture, the young northern pike (average length of 116 mm) were placed in 60 liter aquaria with the initial temperature corresponding to the ambient temperature at which they were captured, 24 to 33°C. The temperature of the experimental tank was raised at a rate of 2 to 4°C per hour to the desired series of test temperatures. Mortality was then monitored for 48 hr and a 48 hr TL50 was calculated. There were 20 fish in each test and control group. Cvancara (1975) reported a TL50 of 30.8°C for juvenile northern pike. The test method of Cvancara yields values that would best be described as UILT values. Because no acclimation period was provided, stress may have affected the resultant TL50 estimates. For example, Cvancara (1975) reported TL50s of 28.5°C for both bluegill and gizzard shad, temperatures well below the tolerance values reported by others (Talmage and Opresko, 1981, Beitinger et al., 2000) suggesting that at least some of the TL50 results reported by Cvancara (1975) are low. Also, Cvancara (1975) reported that the northern pike tested were collected at ambient temperatures as high as 33°C indicating that they can tolerate this temperature for at least brief periods. Similarly, Scott (1964), as reported by Brown (1976), found that young northern pike acclimated to 30°C had an UILT of about 33°C. Horning (as cited in Hokanson et al., 1973), found that he could not maintain adult northern pike in the laboratory for more than one month at 29°C. Thus, depending on investigator and life stage tested, the upper lethal of northern pike varies from about 29 to 33°C.

Muskellunge

Hassan and Spotila (1976) determined CTM values for muskellunge fry that had been reared at 14°C. During transportation to the test facility, water temperature dropped to 8°C. Fry were to be tested at 25°C and were brought up to this temperature at a rate of 2°C per hour. This fairly rapid increase would not allow fry to acclimate to 25°C. Periodically over the next 19 days, six fry were heated at the rate of 1°C/min, to determine their CTM. This fast heating rate likely overestimated the CTM. Depending on the day on which the fry were tested, CTM ranged from 33.2 to 36.1°C. Control mortality was a problem by Day 13 of the test so the CTM values from Days 13 to 19 (33.2 to 34.2°C) appear to be compromised by the condition of the fry. Hassan and Spotila (1976) stated that the lower CTMs on Days 9 through 19 were *"probably due to the deteriorating condition of the fry."* The CTM was lower (34.8°C) on Day 1 than on Days 3 through 7, probably because the fry hadn't fully acclimated to 25°C. Based on this study, a reasonable estimate of the CTM for muskellunge acclimated to 25°C would be 35 to 36°C, the values measured during Days 3 through 7.

Sauger

Smith and Koenst (1975) evaluated the effects of temperature on the hatchability of sauger eggs, growth of sauger fry, and survival of fry. They found that the UILT for juvenile sauger acclimated to 26°C was 30.4°C, a value that is likely low (Hokanson and Koenst, 1986).

During studies to determine the effect of monochloramine on various fishes, Seegert et al. (1979) were able to hold juvenile sauger (average length = 81 mm) at 30°C for at least two months indicating that the UUILT for this species is greater than 30°C.

Walleye

Walleye is one of the most popular gamefish in the U.S. and Canada and supports substantial commercial fisheries in Canada. Smith and Koenst (1975) determined effects of various temperatures on walleye eggs, fry, and juveniles. Major findings were:

- Independent of fertilization temperature, the greatest percentage hatch was at incubation temperatures of 9 to 15°C
- An incubation temperature of 21°C appears to be lethal to walleye eggs regardless of the temperature at which they were fertilized
- Walleye fry growth was higher at 25°C than at 16 or 21°C
- Optimum temperature for growth was 22°C
- Walleye fry grew at 28°C, but growth was minimal
- Sudden changes (ΔTs as high as 17°C) in temperatures had little effect on walleye fry
- The TL50 at the highest acclimation temperature (26°C) was 31.6°C

Hokanson and Koenst (1986) attempted to reconcile the upper lethal of 34°C reported for walleye from experimental stream channels (Wrenn and Forsythe, 1978) with the lower upper lethal value (31.6°C) reported in a laboratory setting (Smith and Koenst, 1975). Hokanson and Koenst (1986) used a slow heating method (0.5°C/day) and reported UUILT values for walleye of 33.0, 34.1, and 34.1°C at acclimation temperatures of 22, 26, and 28°C, respectively. The latter two values are 2.5°C higher than the upper lethal reported by Smith and Koenst (1975). Hokanson and Koenst (1986) concluded that slow heating at less than 1°C/day with little or no handling of test organisms yields the best estimate of the upper lethal limit of fishes, whereas the ILT and the CTM methods, which both involve transferring fish from acclimation tanks to test tanks, stress the fish and result in lower upper endpoint estimates. Based on this finding, one would conclude that estimates derived from both the CTM and ILT methods often underestimate the thermal tolerance of fishes.

Peterson (1993) tested juvenile walleye from distinct populations in Iowa and Mississippi using the CTM methodology. Fish were acclimated to 23°C for 7.5 months, then individual fish were heated in 5 liter flasks at 1°C/min. Fifteen fish from each population were tested. Endpoints were loss of equilibrium (LOE) and onset of spasms (OS). For both endpoints, there was no significant difference between the two populations. Values for LOE were 34.8 to 35.0°C, whereas values for OS were about a degree higher (35.8 to 35.9°C).

Yellow Perch

Yellow perch is an important recreational and commercial species that has been tested regularly. Cherry et al. (1977) determined the upper lethal temperature of hatchery-purchased yellow perch. Following acclimation, groups of 10 fish each were tested at a series of test temperatures which were reached by raising the temperature from the acclimation temperature (either 21 or 24°C) to the test temperatures (24 to 27°C) at the rate of 1°C/day. They calculated a 7-day upper lethal temperature that was defined as *“the highest temperature at which no mortality occurred during a 7-day period.”* Based on this methodology, they reported a 7-day upper lethal of 26°C, well below that reported by others. In contrast to the low upper lethal temperature reported by Cherry et al. (1977), McCormick (1976) reported that the upper lethal temperature for young-of-year (YOY) yellow perch was between 32 and 34°C. Brooks and Seegert (1977) were able to maintain YOY yellow perch at 30°C for more than a month during tests to determine the sensitivity of this species to residual chlorine.

Brett (1944) reported that the UILT of yellow perch was 30.9°C and Hart (1947) reported that the UILT for yellow perch acclimated to 25°C was 29.7°C and the CTM for similarly acclimated yellow perch was 33.4°C based on an increase rate of 1°C/hr (0.017°C/min) from the acclimation temperature. Black (1953) reported that the 24-hr UILT for yellow perch was 29.2°C. However, this value is not suitable for criteria development (EPRI, 2011).

Warmwater Species

The large majority of North America's freshwater fish fauna (~900 species; Page and Burr, 2011) falls into the warmwater category. This includes members of the most speciose families: Centrarchidae (sunfishes), Cyprinidae (minnows), Catostomidae (suckers), Ictaluridae (catfishes), and to some extent, Percidae (perches). As described below, many members of these families have not been tested to determine their thermal tolerance. A summary of what is known about each of these families follows. I had earlier indicated that this review concentrated on thermally sensitive species. Because of the number of warmwater species, two additional factors were considered, distribution and waterbody type. Widespread species were given preference over species with local distributions and waterbody type was considered because most of the nation's power plants that use freshwater as a cooling water source are located on either large lakes/reservoirs or large rivers. Therefore, species found primarily in these habitats were given preference while those restricted to small streams, springs, or swamps were excluded.

Centrarchidae (Sunfishes)

Sunfishes include many widespread and recreationally popular species such as bluegill, redear sunfish *(Lepomis microlophus)*, crappie (*Promoxis* spp.), and the black basses (*Micropterus* spp.) that have been widely tested. For example, Beitinger et al. (2000) reported bluegill CTMs from five groups of researchers. Centrarchids are among the most thermally tolerant species. At acclimation temperatures of 20°C or greater, all *Lepomis* and *Micropterus* tested had CTMs greater than 35°C, many species had CTMs in the upper 30s, and two species had CTMs greater than 40°C. Although none of the centrarchids are particularly thermally sensitive, a few are somewhat sensitive or are thought to be sensitive.

Smallmouth bass *(Micropterus dolomieu)* is sometimes thought to be thermally sensitive; however, a review of the literature reveals this is not the case. Smale and Rabeni (1995) determined CTM values for 34 fish species from the Ozark region of Missouri. All fish were acclimated to 26°C. Twenty-two species were found to be more thermally sensitive than smallmouth bass. In fact, even largemouth bass, a species widely considered to be thermally tolerant, had a lower CTM value (36.3°C) than smallmouth bass (36.9°C). Wrenn (1980) held juvenile smallmouth bass in outdoor channels for nearly a year to monitor growth. During the summer, maximum temperatures in these channels were near or above 35°C for 70 days. He reported that no smallmouth bass died at these temperatures and that they grew at temperatures as high as 32°C. He concluded that *"the smallmouth bass is as tolerant of elevated temperature as the largemouth bass, even at the southern limits of the smallmouth bass' native range."* Similar endpoint values for smallmouth bass are cited in Brungs and Jones (1977), namely 38°C for larvae (Larimore and Duever, 1968) and 35°C for juveniles (Horning and Pearson, 1973). Cherry et al. (1977) reported that the 7-day UILT for smallmouth bass acclimated to 33°C was 35°C.

Crappie (*Pomoxis* spp.) are thought to be among the most thermally sensitive centrarchids. Brungs and Jones (1977) cited an upper lethal value of 33°C for juvenile white crappie *(P. annularis)* acclimated to 29°C, a value that is based on unpublished data so details are not available to assess the validity of the cited value. Brungs and Jones (1977), citing the same authors, reported that the upper lethal (33°C) for juvenile black crappie *(P. nigromaculatus)* acclimated to 29°C was identical to the upper lethal for white crappie. Baker and Heidinger (1996) determined upper lethal temperature for three sizes of Age 0 for black crappies. UILT values for black crappies acclimated to 24°C ranged from 31.5°C for black crappie that averaged 75 mm in total length to 35.1°C for those averaging 46 mm in total length. Baker and Heidinger (1996) did not provide exact CTM estimates; however, based on the data they provided, CTMs were 38 to 39°C for the two smaller size groups at each acclimation temperature (24, 30, and 32°C). CTM values for the largest specimens (75 mm TL) ranged from about 35°C when acclimated to 24°C to 37 to 38°C for those acclimated to 30 and 32°C. The fact that black crappie could be acclimated to 32°C indicates that their long term tolerance is greater than 32°C. Based on the collective results, both crappie species appear to be slightly more sensitive to temperature compared to other centrarchids but only marginally so, and are less sensitive than many other warmwater species.

Cyprinidae (Minnows)

Cyprinidae is the most speciose family, both globally and in the United States. There are about 300 cyprinid species in North America, not including Mexico (Page and Burr, 2011). Although the thermal tolerance of about 40 cyprinids has been measured, many are small stream species not likely to occur near power plants. Others like common carp and goldfish *(Carassius auratus)*, are highly tolerant and therefore were not considered for this review. Identified five smaller cyprinids (red shiner, *Cyprinella lutrensis;* plains minnow, *Hybognathus placitus;* Arkansas River shiner, *Notropis girardi;* fathead minnow, *Pimephales promelas:* and bullhead minnow, *P. vigilax)* that are found in large waterbodies but that had CTM values of 38.6°C or greater (Beitinger et al., 2000). Smale and Rabeni (1995) calculated CTM values for 16 cyprinids acclimated to 26°C. Although the majority of these are small stream species, five species are known to occur in larger waterbodies and therefore could be exposed to power plant discharges. Sand shiner *(Notropis stramineus)*, fathead minnow, and golden shiner *(Notemigonus crysoleucas)* were eliminated from further review based on high CTMs. Two species—rosyface shiner *(Notropis rubellus)* and bluntnose minnow *(Pimphales notatus)*—tested by Smale and Rabeni (1995) were considered further, as was emerald shiner (*N. atherinoides*), a widely occurring large river and large lake form that is somewhat thermally sensitive.

Rosyface Shiner

The literature contains upper thermal endpoints for "rosyface shiner" from three localities; however, rosyface shiner *(Notropis rubellus)* was recently split into four species (Page and Burr, 2011). Specimens from two of the three sites are still referable to as rosyface shiner; however, the specimens reported as rosyface shiner by Smale and Rabeni (1995) are now known as carmine shiner *(N. percobromus)*. Because rosyface and carmine shiners are morphologically indistinguishable and occupy similar habitats, I considered the thermal data from all three studies as being appropriate. Both rosyface and carmine shiner occur primarily in small to medium streams with fast current but also occur occasionally in rivers as large as the Ohio River.

Cherry et al. (1977) reported that the 7-day upper lethal for rosyface shiner acclimated to 30°C was 33°C. Kowalski et al. (1978) reported a CTM of 31.8°C for rosyface shiners acclimated to 15°C. The lower endpoint value reported by Kowalski et al. (1978) compared to that reported by Cherry et al. (1977) might be due to differences in how the endpoint was measured and particularly the relatively low acclimation temperature (15°C) used by Kowalski et al. (1978). Smale and Rabeni (1995) reported a CTM of 35.3°C for rosyface (carmine) shiners acclimated to 26°C. This CTM was second lowest of the 34 species tested, and the lowest of the 16 cyprinids tested. Collectively, the data show that rosyface shiner is among the most thermally sensitive cyprinids, especially among those that occur at least occasionally on larger waterbodies.

Bluntnose Minnow

Bluntnose minnow occupies a wide range of habitats from fairly small streams to large rivers, as well as nearshore areas of lakes and reservoirs. Overall, it is generally considered to be a tolerant species (Ohio EPA, 1987; Lyons, 1992). However, it is considered by some to be somewhat thermally sensitive (Yoder and Rankin, 2005; Yoder et al., 2006). Table 6-2 provides several estimates of the temperature tolerance of bluntnose minnow.

Table 6-2
Temperature tolerance of bluntnose minnow

Acclimation Temp. (°C)	Upper Lethal Temperature (°C)		Author(s)
	CTM	UILT	
25	34.8	33.3	Hart, 1947
25	-	34	Hart, 1952
30	-	32	Cherry et al., 1977
15	31.9	-	Kowalski et al., 1978
26	36.6	-	Smale and Rabeni, 1995
24	37.9	-	Mundahl, 1990

These data show that UILT values for bluntnose minnow acclimated to 25 to 30°C ranged from 32 to 34°C and CTM values ranged from 35 to 38°C for fish acclimated to 24 to 30°C. The lower CTM of 31.9°C is attributable to fish acclimated to 15°C, and thus not representative of the summer tolerance of bluntnose minnow. Collectively, these data indicate that bluntnose minnow is thermally tolerant.

Emerald Shiner

In contrast to rosyface shiner which only occasionally occurs in large rivers, and bluntnose minnow, which occurs in a wide range of habitats, emerald shiner is a large-water fish. It is common in large lakes including the Great Lakes and it is one of the most abundant fishes in the large rivers in the nation’s midsection such as the Ohio, Mississippi, and Missouri Rivers. Hart (1947) reported an UILT value of 30.7°C for emerald shiner acclimated to 25°C and a CTM value of 34.3°C. Hart (1952) subsequently reported an identical UILT for emerald shiner collected from Lake Erie and again acclimated at 25°C. Brungs and Jones (1977) reported UILT values ranging from 23 to 31°C depending on acclimation temperature. They incorrectly attribute these data to Carlander (1969), who in turn ascribed the data to Hart (1947) and Strawn (1958) when in fact all the data came from Hart (1947). Thus, there are considerably less tolerance data for emerald shiner than Brungs and Jones (1977) indicate. In a paper that was not reviewed, Matthews and Maness (1979, as cited by Beitinger et al., 2000) reported a CTM of 37.6°C for emerald shiner acclimated to 25°C, a value about 3°C higher than the CTM reported by Hart (1947) for emerald shiner acclimated to the same temperature. The most detailed evaluation of the thermal tolerance of emerald shiner was conducted by McCormick and Kleiner (1976) who studied the effects of temperature on both survival and growth. They reported that growth occurred at temperatures as high as 32.8°C with growth at 31°C comparable to growth at temperatures of 24-30°C. Emerald shiner were initially acclimated at 20°C, and then the water was heated at a rate of 1°C/day. This would yield what was earlier described as a chronic lethal maximum (CLM). Almost no fish died until the temperature reached 34.9°C and at 36.7°C all fish were dead within a week. They reported an UUILT of 35.2°C and opined that the lower ILT of 30.7°C reported by Hart (1947) was a result of his lower acclimation temperature (25°C). Given the number of fish tested and the carefully controlled conditions during testing, I believe the UUILT of 35.2°C reported by McCormick and Kleiner (1976) most closely approximates the true upper lethal limit for emerald shiner.

Etheostomatini (Darters)

As discussed earlier, the large-bodied members of the perch family—walleye, sauger, and yellow perch—are important recreational and commercial species but the diversity within the family comes from the darters (tribe Etheostomatini) which includes nearly 200 species (Page and Burr, 2011). As opposed to the larger members of the family, which are often considered coolwater species, most darters are warmwater species. Despite the number of darter species, thermal tolerance values have been established for less than 10 darter species. Furthermore, almost all *Etheostoma* darters and many *Percina* darters are restricted to small streams, not large rivers where power plants are located. Of the species tested, only four could reasonably be expected near power plants: greenside darter *(Etheostoma blennioides)*, rainbow darter (*E. caeruleum)*, Johnny darter *(E. nigrum)*, and logperch *(Percina caprodes)*. The three *Etheostoma* species occur primarily in medium size rivers like the Wabash River in Indiana or the Muskingum River in Ohio, whereas logperch occur in the largest rivers of the United States.

Rainbow Darter

Upper lethal data for rainbow darter are shown in Table 6-3.

Table 6-3
Upper lethal data for rainbow darter

Acclimation Temp. (°C)	CTM (°C)	Author
15	32.1	Kowalski et al., 1978
20	32.8-34.0 (depending on season)	Hlohowskyj and Wissing, 1985*
26	35.6	Smale and Rabeni, 1995

*as cited by Beitinger et al., 2000

Again, the effect of acclimation temperature is clear with the CTM estimate at an acclimation temperature of 26°C being 3.5°C higher than the CTM estimate of 32.1°C at an acclimation temperature of 15°C. If acclimated to 30°C, the CTM for rainbow darter would likely be 36 to 37°C.

Greenside Darter

When acclimated to 15°C, Kowalski et al. (1978) estimated a CTM of 32.2°C for greenside darter, which is nearly identical to the CTM of 32.1°C they estimated for rainbow darter. Hlohowskyj and Wissing (1985, as cited by Beitinger et al., 2000) reported CTMs of 32.2 to 34.5°C for this species depending on season when it was acclimated to 20°C. These seasonal estimates are very similar to those estimated for rainbow darter. Collectively, these data suggest that these two darters have similar thermal tolerances.

Johnny Darter

CTMs for johnny darter are as shown in Table 6-4.

Table 6-4
CTMs for johnny darter

Acclimation Temp (°C)	CTM (°C)	Authors
15	30.7-31.4 depending on season	Kowalski et al., 1978
15	30.5-30.9 depending on season	Ingersoll and Claussen, 1984*
20	~33	Lydy and Wissing, 1988*
20–30	34.0-37.4	Smith and Faush, 1997*
26	36.4	Smale and Rabeni, 1995

*paper not reviewed

The CTM estimates for johnny darter are consistent with those for the other two *Etheostoma* and again clearly show the effect of acclimation temperature.

Logperch

No studies were found that used standard testing protocols to establish upper lethal estimates for any *Percina*, which is the darter genus most common in large rivers. However, logperch data from Hubbs (1961) has been considered for thermal criteria development (Yoder and Rankin, 2005; Yoder et al., 2006). Hubbs (1961) indicated that he collected his test specimens *"within a 200-mile radius of Austin, Texas."* Due to taxonomic changes, the species he tested which was then called *Percina caprodes* would now be known either as Texas logperch *(Percina carbonaria)* or bigscale logperch *(P. macrolepida)*, not the much more widespread logperch *(P. caprodes)* that is common in many Midwestern rivers. Because the species tested is unknown, we will simply refer to it as logperch *(Percina* sp*)*. For reasons described elsewhere (EPRI, 2011), I do not believe data from the Hubbs (1961) study is suitable to establish upper endpoint values.

Rejection of the Hubbs data is supported by the fact ambient temperatures in the Ohio River often exceed 25°C, the value at which he reported poor larval survival, yet the river supports large numbers of logperch. Similarly, large numbers of logperch were collected from the Wabash River in July 2011 at temperatures of 30-32°C (unpublished EA data).

Ictaluridae (Catfishes)

The large commercially and recreationally important catfish and bullhead species are all thermally tolerant (Beitinger et al., 2000) so there is no need to discuss them further. Little data are available regarding the thermal tolerance of madtoms; however, based on their distribution being centered in the southeast, one can infer that, as a group, madtoms are not thermally sensitive. Only two studies have attempted to measure the tolerance of madtoms. Smale and Rabeni (1995) reported that the CTM for slender madtom *(Noturus exilis)* acclimated to 26°C was 36.5°C. It ranked almost exactly in the middle of the 34 species they tested. Yoder et al. (2006) reported a CTM of 29°C for stonecat (*Noturus flavus*) based on data taken from Reutter and Herdendorf (1975, 1976). Yoder et al. (2006) indicated incorrectly that this CTM is based on fish acclimated to 16°C. Actually, these stonecat were collected during the winter when the ambient temperature was 1.6°C not 16°C and they were immediately transferred to 12.8°C water, after which the CTM test immediately began. Thus, this CTM was for cold-acclimated fish and is certainly not appropriate for developing upper lethal tolerance values. Also, only two stonecat were tested; one had a CTM of 29°C and the other had a CTM of 26°C. For these reasons and others (see EPRI, 2011), the stonecat CTM of 29°C should not be used to develop thermal criteria.

Catostomidae (Suckers)

The sucker family has two groups; the *Ictiobinae* (carpsuckers and buffalos), which are thermally tolerant and need no further discussion, and the more speciose *Catostominae* (sometimes referred to as the "round-bodied" suckers) that has several species or groups that are considered by some to be among the most thermally sensitive warmwater fishes. Species or groups that are considered to be somewhat thermally sensitive are spotted sucker (*Minytrema melanops*), white sucker (*Catostomus commersonii*), northern hog sucker (*Hypentelium nigricans*), and redhorse (*Moxostoma* spp.). Each is discussed below.

Spotted Sucker

Although spotted sucker has only been tested once (Reutter and Herdendorf, 1975), it is a potentially important endpoint. It was included in a previous EPRI compilation of thermal data (Talmage and Opresko, 1981) and the same thermal endpoint was proposed for use during standards development for the Ohio River (Yoder et al., 2006) and in Illinois (Yoder and Rankin, 2005). The endpoint of greater than 31°C for spotted sucker listed by Reutter and Herdendorf (1975, 1976) has been referred to as a CTM by both Talmage and Opresko (1981) and Yoder and Rankin (2004, 2005). However, it is not a CTM. Reutter and Herdendorf (1975) tested only one spotted sucker that was collected on 2 July 1974 at an ambient temperature of 20.0°C, which was then subjected to a ΔT of 11.1°C. According to the remarks in Table 4 of their paper, Reutter and Herdendorf noted that this specimen was “normal” after the one-hour post-shock observation. For reasons that were not explained, these authors did not raise the temperature above 31.1°C and reported the CTM in Reutter and Herdendorf (1976) as greater than 31°C. The value of 31°C for spotted sucker should not be used for criterion development because it is not a CTM and only one fish was tested.

White Sucker

As shown in Table 6-5, white sucker has been tested by several investigations and appears to be one of the more thermally sensitive warmwater species.

Table 6-5
Temperature tolerance for white sucker

Acclimation Temperature (°C)	Upper Endpoint (°C)		Author(s)
	CTM	UILT	
20		29.3	Hart, 1947
25		29.3	Hart, 1947
25–26		31.3	Brett, 1944*
16	30-33		Seegert, 1973
26	34.9		Smale and Rabeni, 1995
15–21		30-32	McCormick et al., 1977

*paper not reviewed

Using standard ILT methods, Hart (1947) and Brett (1944) estimated the UILT for white sucker as 29.3°C and 31.3°C, respectively. McCormick et al (1977) reported that one to seven day UILT values ranged from 30 to 32°C for white sucker larvae acclimated to either 15 or 21°C. The lower CTM (30-33°C) reported by Seegert (1973) relative to the value reported by Smale and Rabeni (1995) is likely due to the lower acclimation temperature used by Seegert. Also, Seegert was monitoring the fish he was testing electronically so his endpoint detection was likely more sensitive than the visual methods that are typically used. Smale and Rabeni (1995) found that white sucker was the most thermally sensitive of the 34 warmwater species they tested. They did not test any other suckers, but did test 16 cyprinid, 6 sunfish, 4 darter, 3 catfish, and 3 topminnow species, plus brook silverside. Thus, we conclude that white sucker is indeed one of the most thermally sensitive warmwater species. This conclusion is supported by observations made by Seegert et al. (1979) who found that they could not hold small (5 to 9 g) white suckers for several weeks at a constant temperature of 30°C without significant mortality but were able to do so at 27°C.

Northern Hog Sucker

Kowalski et al. (1978) found that northern hog sucker *(Hypentilium nigricans)* had the lowest CTM (30.8°C) among 10 species acclimated to 15°C. The relatively low acclimation temperature used by Kowalski et al. (1978) suggests that the upper thermal tolerance of summer-acclimated northern hog suckers would be considerably higher than the CTM value they reported for fish acclimated to 15°C. This suggestion is supported by results from Cherry et al. (1977) who determined that the 7-day UILT was 33°C for northern hog suckers acclimated to 30°C, suggesting that the CTM for summer-acclimated northern hog suckers would be in the mid-30s.

Moxostoma (Redhorse)

The thermal tolerance of redhorse has long been an issue on Midwestern rivers. Unfortunately, little quantitative data are available to either support or refute the purported thermal sensitivity of this group. Neither the review by Talmage and Opresko (1981) nor the review that was conducted about 20 years later by Beitinger et al. (2000) listed any redhorse studies. However, two studies are now available that are relevant to this issue in response to questions from Ohio EPA regarding the thermal tolerance of golden redhorse *(Moxostoma erythrum)* and shorthead redhorse *(M. macrolepiditum)*.[1] American Electric Power sponsored studies to determine the upper thermal tolerance of these two species. Small to medium size (153 to 350 mm TL) specimens were field-collected and tested at the Conesville Power Plant. Tests were conducted to derive both UUILT and CTM values (Reash et al., 2000). UUILT values were based on the "slow-heating" method recommended by Hokanson and Koenst (1986). Reash et al. (2000) reported that the UUILT for shorthead redhorse was 33.3°C and the CTM for this species was 35.1°C for fish acclimated to 21°C. These authors reported a similar CTM of 35.4°C for shorthead redhorse acclimated to 20°C. Walsh et al. (1998) determined CTM values of 34.9 and 37.2°C for juvenile robust redhorse *(M. robustum)* acclimated to 20 and 30°C, respectively. Thus, CTMs of the three *Moxostoma* that have been tested range from 35 to 37°C. This range encompasses about three quarters of the range of CTM temperatures reported by Smale and Rabeni (1995) for 34 warmwater species suggesting that, on average, the thermal tolerance of redhorse is similar to many other warmwater species. The endpoints for redhorse are roughly comparable to those of northern hog sucker and above those reported for white sucker.

Collectively, the thermal literature indicates that the thermal tolerance of catostomids tested to date can be characterized as follows: Ictiobinae is more tolerant than redhorse, the tolerance of redhorse is about equal to that of northern hog sucker, and northern hog sucker and redhorse are more tolerant than white sucker.

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[1] This species has now become *M. breviceps*

Discussion

One of the objectives of this study was to review the quality of the data used to make decisions regarding thermal criteria. Overall, I found few problems with the data. The main exception was a paper by Reutter and Herdendorf (1975) that involved a combination type exposure period, used variable heating rates for the CTM portion of their tests, provided no acclimation for field-collected fish, and often tested only one or two individuals per species (see EPRI, 2011 for further details).

Observations Regarding Each of the Species Groups

Coldwater Species

The thermal tolerance of most salmonids is well established. Furthermore, it appears that most salmonids have very similar upper thermal endpoints; about 25°C when measured using the ILT methodology and 29-30°C using the CTM methodology (Table 6-1). Bull trout appear to be the most sensitive of the salmonids with endpoint estimates about 1°C lower than most other species (Selong et al., 2001).

Coolwater Species

I noted previously that the term coolwater species has not been rigorously defined but often has been used for the commercially and recreationally important members of the esocid and percid families, namely northern pike, muskellunge, walleye, sauger, and yellow perch. Recently, Lyons et al. (2009) attempted to define and characterize coolwater streams and their fish assemblages in Michigan and Wisconsin. Based on upper lethal values in the literature, they initially classified northern pike, walleye, and yellow perch as “transitional” species meaning they fit neither their definitions of warmwater nor coldwater species. However, based on their field data, both northern pike and yellow perch were both reclassified as warmwater species. They were not able to collect enough data to classify walleye, sauger, or muskellunge.

Based on my review of multiple papers, but especially those of Wrenn and Forsyth (1978), Hokanson and Koenst (1986), and Peterson (1993), I recommend that walleye and sauger be considered warmwater species. Too few data are available to assign muskellunge to a thermal tolerance guild with any confidence.

Thus, of the five species often assigned to the coolwater guild, four show greater affinities to the warmwater guild and too few data are available to assign muskellunge to any thermal guild. In any case, there is little support for placing the larger percids and esocids in an artificially constructed group (i.e., coolwater species)

Warmwater Species

My classification of smallmouth bass as a warmwater species is supported by Lyons et al. (2009) who classified it as such based on both laboratory and field data. Furthermore, they reported that it was more strongly associated with warmwater than its cousin, largemouth bass.

Earlier in this paper, I concluded that the purported thermal sensitivity of stonecat is erroneous. The results from Lyons et al. (2009) clearly show that stonecat is not thermally sensitive. They not only classified it as a warmwater species but reported that the only species more strongly associated with high July water temperatures than stonecat was common carp.

It was previously noted that of the cyprinids known to at least occasionally inhabit large streams, rosyface shiner was among the more thermally sensitive species. Based on field data, Lyon et al. (2009) assigned this species to their warmwater guild. A reasonable interpretation of both the laboratory and field results is that rosyface shiner is relatively thermally sensitive compared to most other cyprinids that occur in large waterbodies but that it is not particularly sensitive in an absolute sense.

Lyons et al. (2009) collected field data on three of the sucker species discussed in this paper, white sucker, northern hog sucker, and shorthead redhorse. Lyons et al. (2009) classified white sucker as warmwater transition and placed the other two species in the warmwater guild. This placement supports my conclusion that at least among the widely occurring sucker species, white sucker is the most thermally sensitive.

Factors to be Considered During Development of Thermal Criteria

Acclimation Temperature

Upper lethal estimates will increase with acclimation temperature until the UUILT is reached. The magnitude of the changes in endpoint estimates can be dramatic (Table 6-6). In each of these cases, the studies were done by the same group of researchers, so it is reasonable to assume that the differences in endpoints are the result of acclimation temperature. For the four warmwater species, CTM values varied by 7.5 to 11.8°C, depending on acclimation temperature and, except for channel catfish, the CTM changed by 10°C or more. The change in endpoint estimates, though still significant, appears to be less for coldwater species. The difference for slimy sculpin was 6.7°C, 3°C for sockeye salmon, and only 1.7°C for rainbow trout, *Oncorhynchus mykiss* (Table 6-6). Beitinger and Bennett (2000) also found that a salmonid (brook trout [*Salvelinus fontinalis*]) was the least affected by acclimation temperatures among the 21 species they considered. Thus, it is clear that testing warmwater species acclimated to temperatures well below their expected UUILT, will yield erroneously low estimates of the true thermal tolerance of such species and the greater the difference between the acclimation temperature and each species' UUILT, the greater the underestimate. Underestimation also occurs for coldwater species but the magnitude appears to be less than for warmwater species. Beitinger and Bennett (2000) established quantitative relationships between acclimation temperatures and temperature tolerance estimates that could be used by those developing thermal standards to adjust endpoint estimates derived at low acclimation temperatures.

Methods to Estimate the Thermal Endpoint

The two principal methods for estimating thermal tolerance (ILT and CTM) yield different endpoint estimates. The difference in these endpoints is not trivial. For salmonids, it appears to be about 5°C on average (Table 6-1). Differences for warmwater species seem to be similar, on average, but are more variable. Kilgour and McCauley (1986) indicate the difference is typically 2-6°C.

Historically, most endpoints were determined by the ILT method, which has largely been replaced by the CTM method because the latter method is quicker and requires fewer test fish.

As a result, any database that has endpoints for multiple species is likely to contain endpoints generated by both methods. Regardless of how the data are to be used for subsequent criteria development, these disparate estimates should be standardized, either all converted to CTMs or all to UILT estimates. Kilgour et al. (1985) and Kilgour and McCauley (1986) discuss the quantitative relationships between the methods. Although the method of standardization is subject to debate it seems that almost any attempt at standardization is preferable because ignoring the inherent differences is almost certain to lead to erroneous criteria.

Table 6-6
Effect of acclimation temperature on CTM estimates

Species	Acclimation Temperature (°C)	CTM (°C)	Author(s)
Bluegill	16	31.5	Murphy et al., 1976
	24	37.5	
	32	41.4	
Largemouth bass	8	29.2	Fields et al., 1987
	16	33.6	
	24	36.5	
	32	40.9	
Fathead minnow	5	28.6	Richards and Beitinger, 1995
	12	30.7	
	22	36.4	
	32	40.4	
Channel catfish	12	34.5	Cheetham et al., 1976
	16	34.2	
	20	35.5	
	24	37.5	
	28	39.2	
	32	41.0	
Slimy sculpin	5	22.7	Otto and O’Hara Rice, 1977
	10	24.8	
	15	26.3	
	20	29.4	
Rainbow trout	10	28.1	Currie et al., 1998
	15	29.1	
	20	29.8	
Sockeye salmon	5	22*	Brett, 1952
	10	23*	
	15	24*	
	20	25*	

*UILT values.

Other Factors

The two factors just discussed are by far the most important in selecting and standardizing data to be used as part of criteria development. However, there are other factors that should also be taken into account

Condition of the Test Fish

Anything that reduces fish health likely lowers their thermal tolerance. Factors that could reduce the fitness of the fish include poor water quality (e.g. high ammonia levels), disease, overcrowding, and inadequate nutrition. Diligent researchers would not knowingly test fish whose health was comprised but many of these factors are difficult to detect unless their influence is severe. Given that it is effectively impossible to make fish too fit, any resultant bias would be unidirectional, i.e., the result would always be lower, not higher, endpoint estimates.

Season

Although the endpoints for some species have been shown to vary seasonally when acclimated to the same temperature, the magnitude of the effect usually appears to be small (~1°C) (Kowalski et al., 1978; Ingersoll and Clausen, 1984; Hlohowskyj and Wissing, 1985) but can be as high as 2.6°C (Hart, 1952) so this does not appear to be a major concern.

Size or Life Stage

In general, juveniles are more thermally tolerant than adults of the same species but the difference again appears to be small (about 1-2°C, Baker and Heidinger, 1996). Rodnick et al. (2004) found no difference in CTM values between small (40 to 140 g) and large (400 to 1400 g) redband (rainbow) trout. However, few species have been tested to determine size/tolerance relationships and few of these involve adults of large species (e.g., salmon, most catostomids, and *Micropterus*).

CTM Endpoints

Multiple indicators have been used to determine CTM endpoints. The most common indicators are loss of equilibrium and onset of muscle spasms, but other indicators have been used. Again, the difference in endpoint values that are due to the indicator used appears to be on the order of about a degree (Peterson, 1993).

Sample Size

A CTM value can and has been reported on a single fish (Reutter and Herdendorf, 1975) and small numbers (<5) of fish are tested rather frequently. Such small sample sizes increase the chance of erroneous endpoints being reported.

Guidance and Recommendations

This section provides guidance regarding how to evaluate and standardize endpoint data to ensure that thermal criteria are derived appropriately. This guidance is consistent with recommendations by others designed to ensure that datasets undergo quality control checks before they are used to derive criteria or enforceable standards (EPA, 1985).

Acclimation Temperature

As noted previously, acute maximum endpoints vary directly with acclimation temperature. Therefore, criteria should be developed using endpoint data that were derived from tests conducted at seasonal norms or preferably somewhat warmer. In many cases, summer will be the season when compliance with temperature standards will be most difficult. Therefore, summer acclimation temperatures are suggested in Table 6-7.

Table 6-7
Summer acclimation temperatures

Thermal Tolerance Group	Suggested Acclimation Temperature (°C)
Coldwater	20
Coolwater	25-30
Warmwater	≥30

Upper lethal endpoints being considered for use in criterion development that were calculated using acclimation temperatures below these ranges should either be adjusted upward or removed from consideration if they cannot be adjusted. Ideally, any adjustments would be based on the slope of species-specific curves. These curves would show how much upper lethal temperatures change for each degree change in acclimation temperature. If the available data are inadequate to develop a species-specific curve, an adjustment could be made using the slope for other species of the appropriate family or by applying the mean slope of 0.41 (i.e., the endpoint changes 0.41°C for each degree that the acclimation temperature increases) calculated by Beitinger et al. (2000). If no adjustment is made, the endpoint derived will underestimate the true short-term upper lethal for that species by several degrees. It could also be argued that an adjustment should be made even when acclimation temperatures are within the recommended acclimation ranges because, by definition, the upper lethal temperature will continue to increase as acclimation temperature increases until the UUILT is reached. Although true, the relationship between acclimation and lethal temperatures is not linear as the UUILT is approached (Fry, 1947; 1967; Beitinger et al., 2000). Because any adjustment would likely be small for testing done within the recommended acclimation range, no adjustment may be necessary so long as acclimation temperatures are within or above the ranges listed above.

Test Method

For reasons discussed earlier, acute upper lethal endpoint estimates for a given species depend on the methodology used to derive those endpoints. Endpoints based on the CTM method tend to be 3-5°C higher than those based on the ILT method assuming acclimation temperatures are similar. Endpoints based on the “slow heating method” (usually about 1°C/day) are typically intermediate between the other two methods. Given the difference that 3 to 5°C can make in terms of compliance, standardization of endpoint estimates is appropriate. Given that the preponderance of acute estimates are now derived from CTM tests, the simplest approach would be to adjust ILT-based estimates into CTM estimates using methods described by Kilgour et al. (1985) and Kilgour and McCauley (1986). This approach would result in fewer values being adjusted, than the reverse (i.e., adjusting CTM values to their UILT equivalent). Given that databases for some species may be dominated by CTM values, another alternative would be to use only CTM estimates. Although the number of endpoints likely would be reduced for some species, few species would be eliminated. At a minimum, when compiling the database it should be acknowledged that test method does affect endpoint estimation and if no adjustment is made to the dataset, explain why adjustments were not made. Lastly, the adjustment process should be uniformly applied to all the species being considered for the database.

When Colorado was developing new thermal standards, they determined that standardization of acute thermal endpoints was necessary and that the UUILT was the most conservative endpoint and thus appropriate for their purposes. If UUILT values were not available for a particular species, they used UILT data generated at acclimation temperatures representative of "summertime conditions" in Colorado streams (Todd et al. 2008). When neither a UUILT nor an appropriate UILT was available for a species, the CTM estimate minus a conversion factor was used to approximate the UILT. Thus, Colorado converted all data to a common endpoint as we suggest, except they converted CTMs to UILTs, which is the reverse of what is suggested above. The direction one converts is largely a matter of personal preference and how the data will be used. The important point is to normalize or standardize the endpoints.

Minimum Number of Fish to be Tested

Although a CTM value can be generated with a single fish, test results based on a small number of test organisms should be rejected. I recommend that CTM values based on tests with less than six fish not be used for criteria development. Ideally six or more fish would be tested and tests would be run on more than one "batch" of fish because there likely will be differences in thermal sensitivity due to a fish's overall condition, as well as its size, spawning condition, and recent exposure to stressors including disease pathogens. If the fish tested were all purchased or collected at the same time and place, variance in the endpoint estimate likely would be minimized. Conversely, because a single batch shares a common history, the natural variation in the factors just mentioned will not be captured (i.e., the batch will not be representative), so the fewer fish and batches tested, the less likely that the full range of thermal sensitivity will be captured.

Other Considerations

Reconciling Multiple Endpoint Estimates for the Same Species

For some of the more commonly tested species there may be multiple upper acute estimates. In similar situations for other parameters, EPA (1985) recommends using the geometric mean of the estimates to derive the Species Mean Acute Value. This approach is reasonable where estimates for one species can differ by an order or more of magnitude. However, for temperature, most estimates will be within 5°C of one another so an arithmetic mean should suffice. It could also be argued that the highest reported value should be used because numerous factors (e.g., handling or confinement stress and disease) can result in endpoint values being erroneously low, whereas there are no factors that can inflate the true endpoint for a species. Therefore, the highest value is the one that does the best job of reducing or eliminating these factors.

Life Stage

For small species (e.g., minnows and darters) either adults or juveniles are tested. But for species reaching moderate to large sizes as adults, tests are usually done on juveniles or YOY. This is simply a matter of convenience because testing larger fish requires larger test tanks and better temperature control systems. Although data are scant, it is believed that YOY and juveniles are more temperature tolerant than adults of the same species. Based on the fact that few species have been tested across a variety of life stages, I currently do not recommend making adjustments to the database based on the life stage tested, however, this recommendation could change as more data become available.

Derivation Methodology

Probably because of regional differences, EPA has not established national temperature standards like those set forth in their criteria documents for metals, ammonia, and many other water quality parameters. Thus, there is not an established method for deriving temperature criteria. It is beyond the scope of this paper to discuss all the pros and cons of the different methods that have been used either at the state (Todd et al., 2008; Wenholz, 2004) or regional level (Yoder et al., 2006). However, methods like those developed to establish thermal standards for Colorado and Wisconsin that use data from a cross-section of studies will be less affected by incorrect or aberrant data than methods like those proposed for the Ohio River (Yoder and Emery, 2004; Yoder et al., 2006) or the Chicago Area Waterway System (Yoder and Rankin, 2005) that use the most thermally sensitive species to establish criteria.

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7

USE OF BENTHIC INVERTEBRATE THERMAL TRAITS TO EVALUATE STREAM USE CLASSIFICATIONS

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Abstract

Surface water quality criteria for aquatic life, including both standards and use classifications, are expected to protect a balanced aquatic life community which includes both fish and aquatic invertebrates. In Colorado, aquatic life use classifications (i.e., cold or warm water) and temperature standards have historically been based only on the fish community and species present or expected to be present. However, the State of Colorado revised their aquatic life use assessment policy in 2010 such that only aquatic invertebrate community data are considered during aquatic life use 303(d) attainment evaluations. This new policy is based on a macroinvertebrate multi-metric index (MMI) using an ecoregional approach (i.e., mountains, transition zone, plains and xeric). This ecoregional approach largely corresponds to cold and warm water streams, but in some transitional circumstances fails to adequately make that distinction. We present a case study demonstrating an instance where population data and species thermal preferences for aquatic invertebrates became a valuable tool for determining the appropriate stream use classification. This stream receives discharge water used for cooling and other uses by Tri-State Generation & Transmission Association, Inc. Using thermal preference data, we were able to demonstrate that the invertebrate communities at multiple sites upstream of the facility were dominated by warm eurythermal invertebrates, similar to sites downstream of the facility. The Colorado MMI showed that all sites were in attainment of the aquatic life use classification for this ecoregion. When the thermal preference data were placed in the context of statistically indistinguishable sites with respect to the invertebrate and fish assemblages, we were able to successfully reclassify the Segment 4 as warm water. This study showed that benthic invertebrate thermal preferences can and should be considered when designating and evaluating stream thermal use classification.

Introduction

In the State of Colorado, aquatic life use classifications for streams have been dichotomously divided into cold water or warm water streams, which have historically been based on the expected fish communities in those streams. The derivation and specific application of these standards in the San Miguel River, as well as the application of data in the context of the Clean Water Act (CWA) Section 316(a) are discussed in depth in Johnson et al. [1].

We believe it is appropriate to include thermal tolerance data from benthic invertebrates as well as fish in both assigning and evaluating the aquatic life use classifications of Cold Water or Warm Water. We present a case study conducted from 2005 to 2009 on the San Miguel River near Nucla, Colorado, in which benthic invertebrate thermal tolerances provided key evidence to support a change in stream use classification.

The San Miguel River

The San Miguel River has its headwaters near Telluride, Colorado, at an elevation of 9,100 ft and drains a watershed over 1,600 square miles at its confluence with the Dolores River at an elevation of 4,760 ft. It transitions from a high mountain stream with average summer temperatures of 10 to 15°C to a high desert stream with average summer temperatures of 15 to 20°C along its 162 km length [2]. Because of the drop in elevation and the transition of the stream from a montane environment to a high desert shrubland, the characteristics of the stream vary widely [3]. The hydrograph of the San Miguel River in the study area at the gage at Brooks Bridge near Nucla, Colorado (USGS gage #09174600) is characterized by late-spring/early-summer snowmelt-driven high flows of 500 to 1,000 cubic feet per second (cfs) and late summer low flows that are often less than 50 cfs.

Tri-State Generation and Transmission Association, Inc. (Tri-State) operates a coal-fired power plant, referred to as the “Nucla Station”, on the San Miguel River. The power plant is located in Segment 4 of the San Miguel River that the Colorado Water Quality Control Commission (CWQCC) had historically classified as Cold Water. On average, approximately 3 cfs of water is diverted from the river just upstream of the Nucla Station and, after use, approximately 1 cfs of conditioned effluent is returned to the San Miguel River with no evidence of thermal shock.

The San Miguel River in the vicinity of the Nucla Station is considered relatively healthy, but human influence has affected its aquatic and riparian ecology [3]. Agricultural users withdraw water from the river from many diversions. Approximately 13 km upstream of the Nucla Station, the Colorado Cooperative (CC) Ditch is the largest and withdraws as much as 145 cfs from the stream [4], reducing flows through the study reach of the river. These water withdrawals remove a much smaller proportion of the water from the stream during peak flows, but during summer low flows the majority of the water is diverted.

Regulatory History

The regulatory history of the San Miguel River pertinent to the study area is discussed in greater detail in Johnson et al. [1]. Briefly, the main stem of the San Miguel River is divided into five regulatory segments, and the study area is located in Segment 4 (Figure 7-1), originally classified as Aquatic Life Cold Class 1 under CWQCC Regulation No. 35. Study results in 2005 found that an approximately 20 km reach near the downstream end of Segment 4 supported a predominance of warm water species [4]. Evaluation of flow, temperature, and fish assemblage data suggested that this portion of the San Miguel River more resembled a warm water stream than a cold water stream, reflecting the transition to a warm water stream, as is the current classification of the adjacent downstream Segment 5.

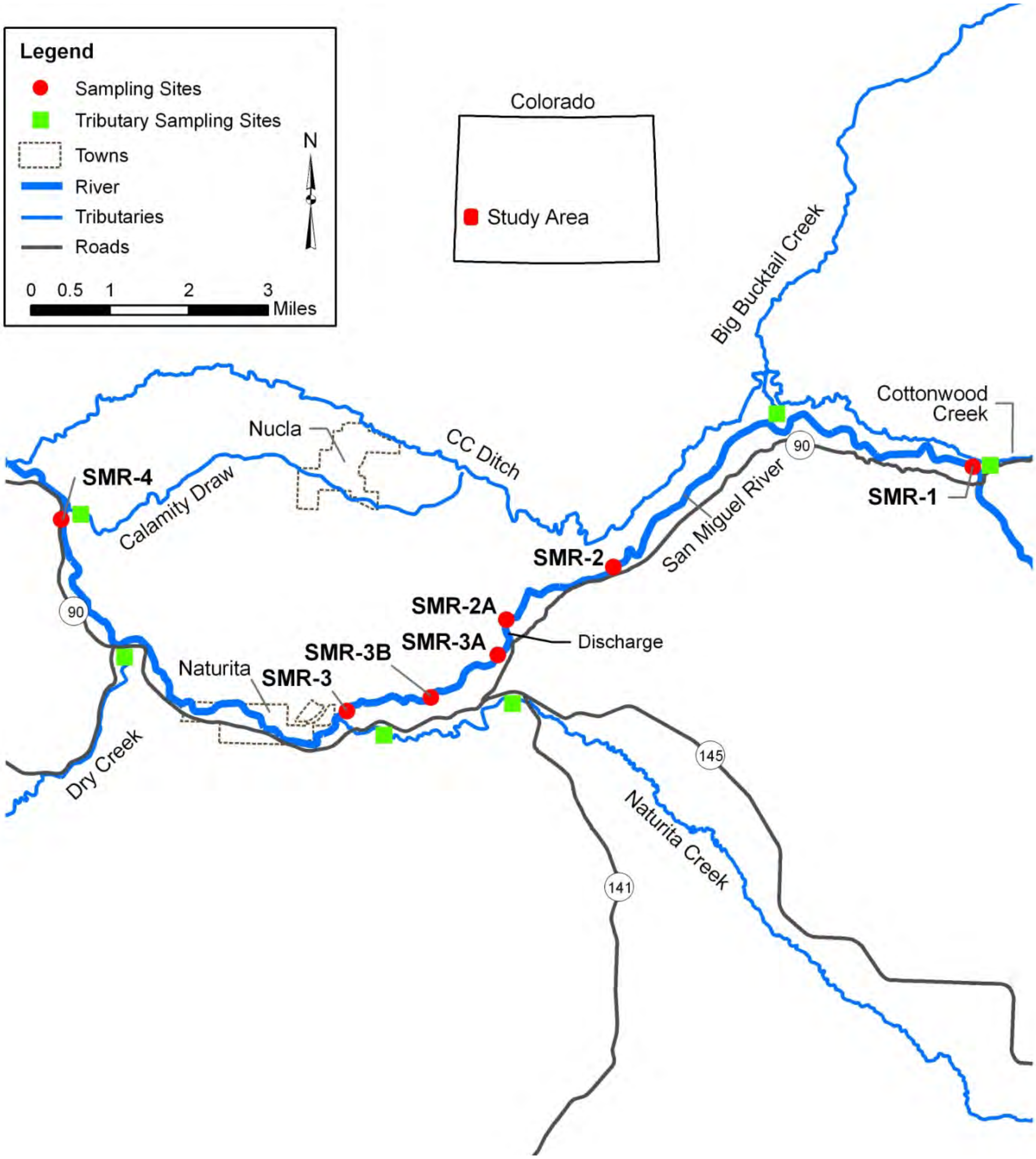

Figure 7-1
Sampling sites on the San Miguel River and selected tributaries near Nucla and Naturita, Colorado, 2005–2009

Segment 4 was divided into segments 4a and 4b during the 2007 CWQCC Regulation No. 35 hearings reflecting the influence of flow diversions on the stream. Segment 4a retained the original Segment 4 use classifications. Segment 4b begins at CC Ditch and ends downstream at the confluence with Naturita Creek. Segment 4b of the San Miguel River was classified as Aquatic Life Cold Class 2. The classification was appealed to the CWQCC for a change to Warm Water Aquatic Life Use classification because limited instream temperature data showed that there was no possibility of attaining the Aquatic Life Cold Class 2 temperature standards upstream or downstream of the power plant. The appeal was denied and there was no change in the classification or standards.

At a second hearing, CWQCC was presented with substantially more instream temperature data from upstream and downstream of the power plant (MWAT values up to 22°C and DM values up to 28°C) and new data on the fisheries for Segment 4b were presented, where warm water fish accounted for the majority of the species collected at every site and for 96 to 100% of the density of fish; cold water fishes are relatively rare or transient. The CWQCC adopted a site-specific temporary modification of the temperature standards subject to further studies that the Nucla station was not responsible for thermal stress to the San Miguel River. The temporary modification allowed a summer MWAT of 26.3°C (from June to September) which was to expire in 2011.

In a third hearing, data on the thermal structure of the benthic invertebrate communities were presented in addition to yet more instream temperature data and fisheries data. All of these data reinforced the inability of the San Miguel River to attain the cold water standard, although it might be able to attain the temporary temperature modification. Based on the new information, the CWQCC reclassified San Miguel River Segment 4b to Aquatic Life Warm Class 1 in 2010.

Benthic Macroinvertebrate Sample Collection and Analysis

Because the purpose of this paper is to discuss the role of benthic macroinvertebrate data in the aquatic life use classification of stream segments, we focus on the benthic macroinvertebrate data to the exclusion of water temperature data and fish population data. In 2005, macroinvertebrate density and taxa composition were estimated by collecting three samples in riffle habitat with a modified Hess sampler, with the three samples subsequently composited into a single sample [4]. This quantitative composite sample was supplemented by a separate, qualitative multi-habitat sweep sample at each site. In 2008 and 2009, ten replicate quantitative Hess samples were collected in riffle habitat at each site and kept separate [2]. A suite of metrics were calculated for analysis based on the benthic invertebrate samples. These metrics included general population composition metrics, pollution tolerance metrics, metrics required for calculation of the Colorado Macroinvertebrate Multimetric Index (MMI), and thermal preference metrics. Because the population composition and pollution tolerance metrics are frequently used as CWA §316(a) elements, they are analyzed in Johnson et al. (this volume) in regard to the San Miguel River.

Colorado Macroinvertebrate Multimetric Index

The Colorado MMI incorporates numerous individual metrics, based on state-wide sampling efforts by the CDPHE on “reference” and “stressed” sites [5]. The index is designed to differentiate between reference and stressed sites, and is organized by geographical site classes (Biotype Groups) delineated primarily by level IV ecoregions [6]. Because the study area is located in ecoregions 20b (Shale Deserts and Sedimentary Basins) and 20c (Semiarid Benchlands and Canyonlands), these sites are classified in Biotype Group 1, which is described conceptually as a “mid-elevation, semi-cold, low gradient, moist (Transitional)” ecosystem [5]. This bioassessment tool is currently used by CDPHE to determine if a stream segment is in “attainment” of the aquatic life use classifications or is “impaired.” However, this tool does not make the distinction whether a stream segment is appropriately classified with respect to its Cold or Warm Water classification or to the potential effects of temperature on the invertebrate assemblage. To adequately address this premise, the thermal tolerance information for the resident species or expected residents also needs to be evaluated [2].

Benthic macroinvertebrate population metrics used in the calculation of the Colorado MMI for Biotype Group 1 include the following metrics: Percent non-insect taxa, Ephemeroptera plus Plecoptera taxa richness, percent Chironomidae, percent sensitive Plains families, predator plus shredder taxa richness, and clinger taxa richness. The Ephemeroptera plus Plecoptera taxa richness and clinger taxa richness metrics are adjusted for elevation prior to scoring; we used an elevation of 1,640 m, which is the approximate elevation of the river at the Nucla Station, for all sites. The Sensitive Plains families are defined and listed in Jessup [5].

Even though collection methods differed between this study (ten replicate Hess samples in riffle habitat, for a total of 0.86 m^2) and those required for the Colorado MMI (1 square meter timed kick sample in riffle habitat), values for each metric at each site were scored [2] according to Colorado Department of Public Health and Environment (CDPHE) Policy 10-1, dated March 8, 2010. Sites in the Biotype Group 1 with a final MMI score less than 42 are classified as “impaired”, while sites with a final MMI score greater than or equal to 52 are classified as “attaining”. Sites with scores between those thresholds would require additional analysis, although this was not necessary because no sites fell between the thresholds (Figure 7-2). These data provided additional evidence that there was not water quality impairment within Segment 4b of the San Miguel River.

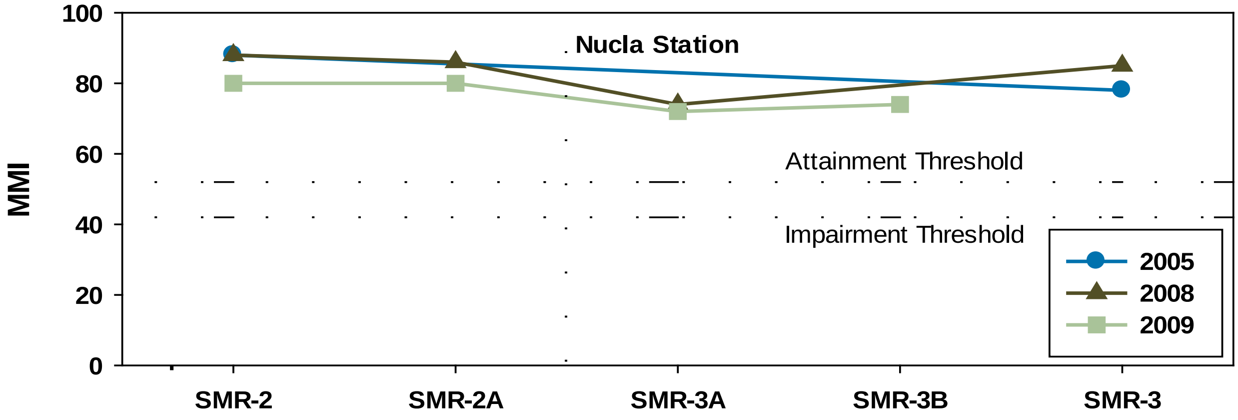

Figure 7-2
Colorado MMI scores at sites on the San Miguel River Segment 4b in the vicinity of the Nucla station

Thermal Preferences

An extensive list of qualitative thermal preferences compiled by Idaho Department of Environmental Quality (IDEQ) [7] was used for calculating thermal preference metrics for this study [2]. Possible categories included hypercold stenotherms, cold stenotherms, cool eurytherms, warm eurytherms, and hot eurytherms; IDEQ did not provide temperature cutoff values for these categories, and we interpret the categories as highly overlapping (Figure 7-3). When possible, a given taxon’s thermal preference category was extrapolated from that of the next higher taxonomic level (similar to the tolerance values); however, thermal preference data do not exist for many taxa (even at higher taxonomic levels), so some taxa were excluded *de* *facto* from the analysis. At the most, only 3.2% of organisms at a site were excluded due to unknown temperature tolerances.

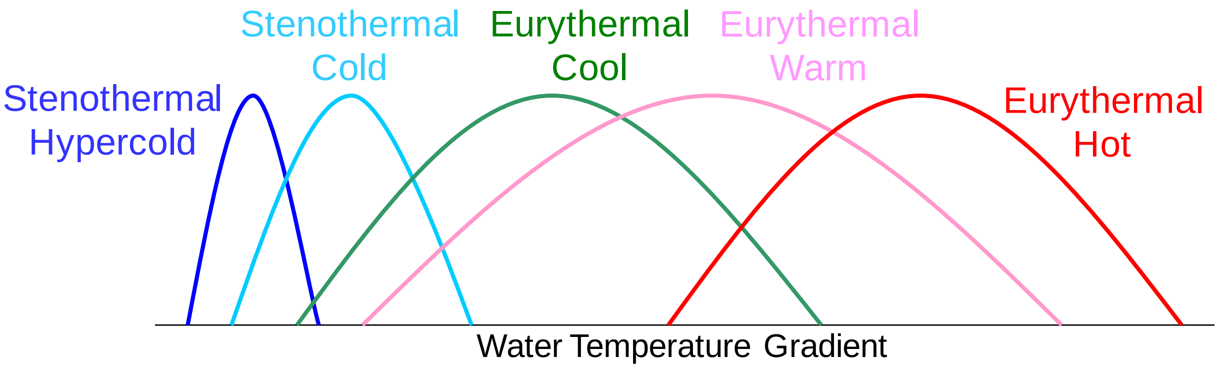

Figure 7-3
Conceptual diagram of thermal preference categories

A temperature preference for the genus *Hydropsyche* or the family Hydropsychidae, which comprised a large proportion of the invertebrates in the samples from all three years, was not assigned in the IDEQ document [8]. Although based on a consensus of literature statements (e.g., “lives in warm streams”) rather than actual stream measurements, temperature preference data can also be found in Vieira et al. [8]. Those data suggest that most species of *Hydropsyche* prefer warm water streams. Therefore we assigned a temperature tolerance of eurythermal warm to *Hydropsyche* [2].

Based on all of the benthic invertebrate community data collected in San Miguel River Segment 4b, there were no stenothermal hypercold taxa. Stenothermal cold taxa were represented only by the stonefly families Capniidae and Leuctridae, which were rare and found at only one site in 2009. There were 12 eurythermal cool taxa, including two taxa that were relatively abundant (the mayfly *Tricorythodes minutus* and the stonefly *Claassenia sabulosa*) and ten other taxa that were less common.

By far, the dominant group was the eurythermal warm taxa, with seven very abundant taxa (the mayfly *Baetis notos*, the caddisfly genera *Cheumatopsyche* and *Hydropsyche*, and the true fly genera *Cricotopus*, *Hemerodromia*, *Microtendipes*, and *Polypedilum*) and 41 additional taxa. Only one taxon, the dragonfly family Gomphidae, was classified as eurythermal hot. Additionally, on a density basis, individuals in the eurythermal warm taxa classification were overwhelmingly abundant in all three years (Figure 7-4).

The predominance of invertebrates with eurythermal warm preferences was consistent among all of the sites, not just those downstream of the Nucla Station. Eurythermal warm invertebrates accounted for over 82% of the density and at least 65% of the taxa at all sites in all three years. Additionally, severe declines in Shannon-Weaver diversity (values < 1.0) in a thermally-influenced stream have been reported [9], whereas diversity values in the San Miguel River were greater than 2.0 at sites SMR-2 and SMR-3 in 2005 and greater than 3.0 at all sites in 2008 and 2009. Regional influences did appear to affect the proportional distribution of the invertebrates across thermal preferences, because there were different patterns of thermal preference in each of the three years, yet the sites were remarkably consistent within each year [2].

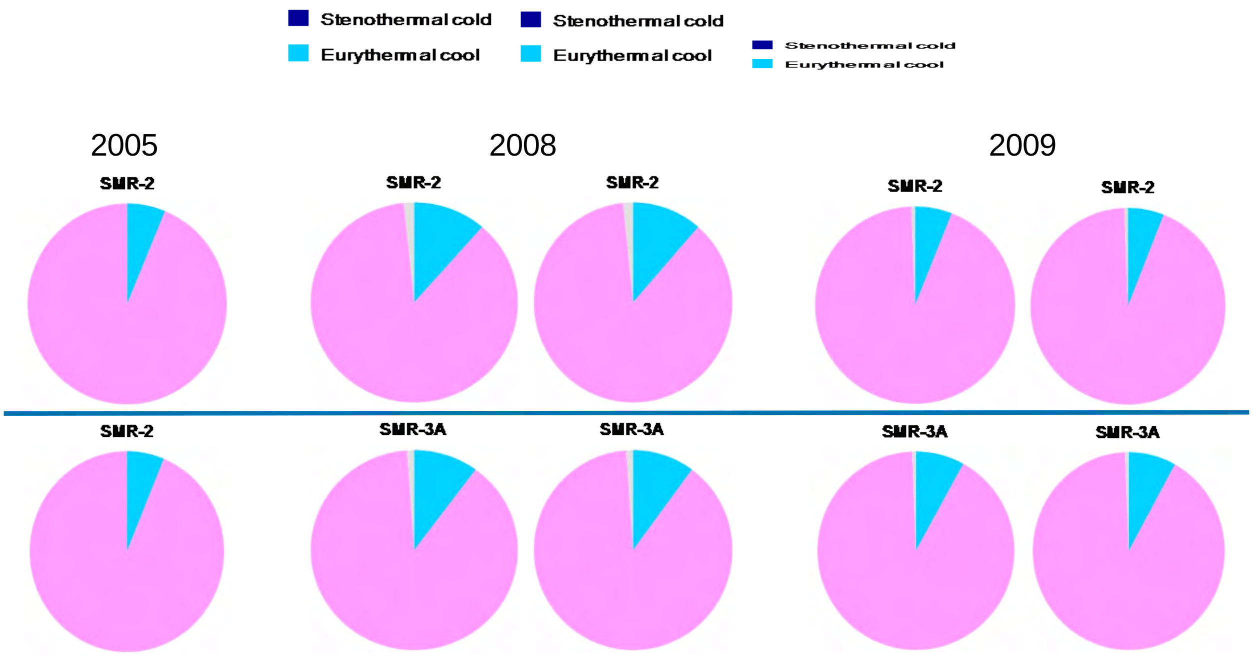

Figure 7-4
Proportional abundance of individuals with thermal tolerance classifications upstream and downstream of the Nucla station, designated by being above or below the blue line, within San Miguel River Segment 4b

Water diversions in 2009 reduced the San Miguel River to flows less than 10 cfs in the study area for several weeks in August and September, and discharges from the Nucla Station contributed approximately 2 cfs of water to the stream, or about 33% of the total flow. However, the difference in stream temperature at the thermograph site upstream of Nucla Station and the thermograph site 2,000 ft downstream of the Nucla Station discharge (i.e., immediately downstream of the regulatory mixing zone) was generally less than 2°C [1]. It is unlikely that discharges from the Nucla Station would negatively affect the benthic macroinvertebrate community of the San Miguel River due to thermal impacts, because the 2°C difference is likely far less than the range of temperatures tolerated by eurythermal warm invertebrate taxa. Therefore, we concluded that thermal changes due to the Nucla Station were not responsible for the limited changes in the composition of the benthic macroinvertebrate communities in the San Miguel River.

Habitat measurements in 2009 indicated that Site SMR-3A (corresponding to the 2000 ft downstream thermograph site) was 72% wider than the other sites and consisted primarily of shallow riffle habitat [1], which is generally the richest stream habitat type for benthic macroinvertebrates [10]. Habitat such as this can promote higher periphyton densities due to the shallower water and lack of canopy cover allowing greater rates of photosynthesis and better utilization of existing nutrient concentrations [11,12]. Higher algal densities, especially diatoms, could in turn promote larger invertebrate populations by providing abundant food resources [12], which may explain the significantly higher density at sites downstream of the Nucla station. Because of these facts, we concluded that habitat and flow modification appears to be the primary regional factors influencing the benthic macroinvertebrate communities [2].

Conclusions

Instream temperature data and fisheries composition data were useful in demonstrating that the San Miguel River Segment 4b was incapable of meeting the temperature standards for the Aquatic Life Cold Class 2 stream designation. While those data were helpful in garnering a temporary temperature standard modification, they were not considered to be sufficient evidence to warrant reclassification of the stream segment to a more appropriate warm water classification. A temporary modification of the temperature standards was allowed after two hearings, pending data that the Nucla Station was not affecting the stream. Fisheries data, benthic invertebrate pollution tolerance metrics, and the Colorado MMI demonstrated that water quality and the Nucla Station discharge, specifically, were not negatively impacting the stream communities [1].

There were some changes in the composition of the benthic invertebrate communities downstream of the Nucla Station. A critical analysis of the potential factors affecting the communities suggested that habitat availability for both invertebrates and periphyton was primarily responsible for the changes. Nutrient enrichment and thermal shock from the Nucla Station were demonstrated to not play a role in the changes in the benthic invertebrate communities [1].

The benthic macroinvertebrate assemblage throughout all the sites in Segment 4b was comprised predominantly by warm eurythermal taxa (i.e., more than 82% of the density and at least 65% of the number of taxa at all sites). While the temperature data and fisheries data demonstrated that the stream segment was incapable of meeting the Aquatic Life Cold Class 2 temperature standards, the addition of the benthic macroinvertebrate thermal tolerance data provided a key piece of evidence to support the reclassification of the San Miguel River Segment 4b from Aquatic Life Cold Class 2 to Aquatic Life Warm Class 1.

We recommend that invertebrate thermal preference data be considered when determining attainment of aquatic life use classifications. In Colorado, this would aid in determining whether many transitional streams from the colder mountainous ecoregions to the warmer plains – xeric ecoregions (MMI, Biotype Group 1) are correctly classified with respect to their Cold or Warm Water Aquatic Life Use classification.

Acknowledgments

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8

HEAT SHOCK PROTEINS: WHAT ARE THEY, AND DO THEY HAVE A ROLE IN ASSESSING THERMAL TOLERANCE?

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Abstract

Heat shock proteins (HSPs) are a suite of evolutionary conservative proteins of varying molecular weight produced across phylogenies. HSPs exist at latent “baseline” levels but induction accelerates under stress. Stressors that can induce the production of HSPs are several, including altered thermal regimes, hypoxia, exposure to toxic pollutants, and exposure to pathogens. Regarding exposure to thermal stress, the principal functions of induced HSPs are: (1) restore the original folding of polypeptides (proteins) that are altered, thus restoring function; (2) suppress the aggregation (agglutination) of proteins; and (3) delay or accelerate protein catabolism. The response of HSP induction to thermal stress in aquatic organisms has been investigated in the laboratory and, to a lesser extent, in the field. In recent years, the relationship between HSP induction and phenotypic expression (e.g., thermal tolerance) has been documented for some fish species. The finding that HSP expression is often linked to physiological, biochemical, and/or behavioral responses suggests the potential utility of HSPs as a biological indicator. One advantage of monitoring HSP expression in field settings is nonlethal handling techniques. Further research is needed to expand the faunal representation of HSP responses, and evaluate the sensitivity of induction as compared to other responses to thermal exposure at higher levels of biological organization.

Basic Biochemistry

HSPs, often called stress proteins and extrinsic chaperones, are a class of polypeptide molecules that are ubiquitous and cross across phylogenies (bacteria, plants, animals). HSPs are categorized by their molecular weight (in the range 16 – 100 kDa), with their nomenclature dictated by the molecular weight of the protein (e.g., the HSP90 family contains heat shock proteins having molecular weights ranging between 82 – 96 kDa). A key feature of HSPs is their evolutionary conservatism; even among diverse organisms, the amino acid sequence of HSPs is surprisingly similar. For example, the amino acid sequence similarity in the heat shock protein HSP70 among all eukaryotic organisms ranges between 60-80% [1]. HSPs were first discovered in fruit flies (*Drosophila* sp.) when chromosome “puffs” were observed after the flies were exposed to high temperatures [2].

There is a diverse variety of stress proteins, including some unrelated to HSPs. These molecules serve some kind of biochemical response (function) to stress, and the specificity of the response is variable. Some stress proteins are induced due to exposure to contaminants. Examples of these include metallothioneins and cytochrome P450 enzymes. These two particular stress proteins have been studied in a wide variety of exposure conditions, often in field settings where aquatic life is chronically exposed to pollutants [3, 4].

Mechanistic Function

For many HSPs, the precise function (biochemical pathways, induction stimuli) has yet to be delineated. What seems to be clear is that HSPs have functional roles for normal cellular function, and during periods of stress. For the well-studied HSP70 class, the development of thermal tolerance in animals has been documented by numerous researchers. In general, the induction of HSP70 molecules is correlated with increased thermal tolerance (depending, of course, on the regime of a sublethal exposure), and experimental manipulations that either block HSP70 accumulation or deliberately "over-express" their induction are directly related to thermal tolerance [1].

The principal function of HSPs is to modify a cellular response to heat stress. Since protein function is directly related to protein configuration, any disruption of the protein molecule (e.g., altered amino acid sequence, structural derangement) will cause aberrant function. Extreme heat stress in animals may lead to irreversible protein function loss resulting in the loss of homeostatic equilibrium (which may lead to mortality). HSPs – that are induced themselves by the heat stress – affect protein assembly and translocation, repair protein folding, prevent proteins from agglutinating, and delay or accelerate protein catabolism [5]. While the biochemical pathways of how HSPs affect cellular processes after heat stress are complicated (and insights to these processes have only recently been elucidated), the basic process of HSP function is summarized below (summarized from Figure 2 of Iwama et al. [5]):

- Before induction of a stress, heat shock factor molecules (HSF) are present in latent monomeric (unchained, not polymerized) form in the cell cytoplasm or nucleus.
- Following organism exposure to stress (e.g., elevated temperature), HSF molecules enter the nucleus and undergo trimerization (polymerization of three HSF molecules); the polymerized HSFs bind to amino acids on a HSP70 gene promoter site.
- Transcription of the bound amino acid sequences begins, resulting in the expression (translation) of HSP70 polypeptides, which are released to the cytoplasm.
- Cytosolic HSP70 proteins increase, which can be used to repair misfolded proteins or suppress agglutination of proteins (cellular damage). Once protein repair has taken place, the HSP70 proteins are released and these can either repair other deranged proteins or return to the nucleus.
- Once in the nucleus, HSP70 proteins bind to polymerized HSF molecules, causing the disassociation of the HSF molecules and release of monomeric HSF proteins into the nucleus or back into the cytosol.

The cellular function of HSPs (protein repair during heat stress) can be inactivated by any process that disrupts the gene transcription/translation cycle. The timing of HSP induction is variable (is highly dependent on the magnitude and duration of the heat stress), and can last between hours or days following the incipient thermal stress. Over-expression of HSPs has been documented in many cases. This is probably an adaptive evolutionary tactic, since ectothermic organisms – unable to escape the heat stressor through behavioral or physiological means – must use all cellular mechanisms to survive the present exposure conditions.

Heat Shock Protein Studies in Fish

Fish are ideal ectothermic organisms to study the function of heat shock proteins due to their relatively large size, well-known life history attributes, and (in some cases) the documentation of genome sequences. A review of HSP studies in aquatic organisms other than fish (freshwater and marine invertebrates) was summarized by Sanders [6]. Studies using fish involve three levels of organization: (1) fish cell lines; (2) primary cell cultures; and (3) whole fish, in laboratory or field settings [5]. In this section, a review of representative studies involving whole fish – in both laboratory and field settings – is provided.

Laboratory studies documenting the induction and expression of HSPs in fish exposed to manipulated thermal regimes involve several species, with some of these being mummichog [7], two gobiid species [8], four marine species [9], cutthroat trout [10], fathead minnow [11], and desert topminnows [12]. Most of these studies evaluated HSP induction using a rapid (acute) heating regime, which may not be representative of many *in situ* conditions where a point source of heat discharges to a water body. In contrast, Kikuchi et al. [13] exposed groups of goldfish to a constant temperature of both 10°C and 30°C, providing a five-week acclimation period. A novel 65kDa protein was isolated only in fish exposed to the 30°C water. The protein was chemically distinct from heat shock proteins in the HSP70 class.

In the vast majority of laboratory studies, the induction of specific HSPs cannot be definitely linked to some kind of phenotypic expression, such as increased thermal resistance or morphological changes. In a study using larval green sturgeon exposed to three different thermal regimes, the expression of specific HSPs was evaluated and compared to survival and development [14]. Newly hatched larvae were exposed to one of three temperature conditions: (1) constant control temperature of 17°C; (2) a short-term (3-day) exposure to an elevated temperature (26°C), followed by a return to the control temperature; and (3) constant exposure to 26°C up through yolk-sac absorption. Specific HSP70 proteins were assayed in both control and exposed fish. One-third of the fish exposed to the short-term elevated temperature developed deformed notochords. When these fish were returned to the lower control temperature, only 16.5% of the original 33% showed deformed notochords, suggesting a morphological recovery from the stress. In the fish that were returned to cooler water, the induction of HSPs continued for at least nine days. The percentage of deformed larvae, and the expression of two HSP70 proteins (HSP72 and HSP78), were highest in fish exposed to the most stressful thermal regime (continuous exposure to 26° C). Fish with irreversibly deformed notochords had significantly higher expression levels of HSP72 and HSP78, and lower HSP60 levels compared to normal larvae. Thus, the variation in phenotypic expression (normal or deformed notochord) was clearly linked to the over-expression, or under-expression, of certain HSP70 proteins.

There are many anecdotal observations made by biologists, in field studies where fish populations are exposed to limiting thermal regimes, suggesting that younger individuals of a species (juveniles) are more thermally tolerant than adults. Thermal tolerance studies with the fruit fly, *Drosophila*, demonstrated that heat-shock resistance decreases with age in these insects, which was associated with decreased expression of HSP70 proteins [15]. A biochemical mechanism of these observations in fish was lacking, until Fowler et al. [16] showed that the induction of HSP70 proteins in heart tissues of rainbow trout were significantly higher in fingerlings compared to adults when fish were exposed to a rapid heat stress (1 hr at 25°C). Juvenile fish also had a greater induction of constitutive (heat shock factor) proteins.

In a novel study, two subspecies of the common killifish (*Fundulus heteroclitus*) were collected from streams differing in latitude, and tested for thermal resistance [17]. Adult individuals of the northern subspecies (*F. heteroclitus macrolepidotus*) and the southern subspecies (*F. heteroclitus heteroclitus*) were collected from three stream sites each in lower and higher latitude regions. The critical thermal maxima (CTmax) and minima (CTmin);temperature at which 50% of test fish died following a slow heating or temperature lowering regime was determined, and tissue samples for analyzed for HSP70 profiles. Killifish collected from southern latitudes had significantly higher CTmax values compared to fish from northern latitudes; a temperature differential of about 1.5°C occurred within a wide range of acclimation temperatures. Both northern and southern fish showed significantly greater HSP70-2 levels compared to controls at a heat shock temperature of 33°C, however the magnitude of expression was higher in northern fish. Levels of HSP70-1 proteins during thermal trials, in contrast, did not differ between the two groups. Lastly, levels of the constitutive HSP70 protein were significantly elevated by heat shock in southern fish, but not in the northern fish. The variation in specific HSP expression between the southern and northern fish was closely linked to whole organism phenotypic expression (thermal tolerance).

Collectively, studies conducted to date have shown that, at minimum, the variability in thermal resistance in fresh and marine fish (especially between disjunct populations) is associated with the duration and magnitude of HSP expression. Advances in molecular assays and techniques will likely provide more insights into the role of HSPs in thermal acclimation and tolerance. It has been argued that the regulation and expression levels of HSPs are of major evolutionary and ecological importance, and that the expression of HSPs represent a balance of benefits (short-term resistance) and costs (cellular constituents taken away from growth and development) [18]. Clearly, HSPs have played an important role in the selection of taxa that can adapt and survive during conditions of climate change, which may be highly episodic but severe in terms of magnitude.

Heat Shock Factors as Biological Indicators (Biomarkers)

The use of HSPs as non-destructive biomarkers of thermal exposure and/or effect is appealing, however there are many factors – unrelated to temperature – that affect HSP expression [19]. The influence of confounding factors can be problematic when assessing HSP induction in field-collected aquatic life. As with most other biomarkers used for the assessment of stressor exposure, temporal and spatial variability of the assay endpoint (in both exposed and reference organisms) needs to be carefully evaluated before a conclusion can be made that a specific stressor caused a specific biological response.

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9

THE INFLUENCE OF COLD SHOCK AND REDUCED RATION ON THE IMPINGEMENT SUSCEPTIBILITY OF GIZZARD SHAD AND THREADFIN SHAD

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Abstract

Experiments were performed at Oak Ridge National Laboratory's Aquatic Ecology Lab from 2005 to 2008 to better understand the environmental and physiological conditions associated with the winter and early spring impingement of gizzard shad and threadfin shad at cooling water intake structures. In 2005, threadfin shad and gizzard shad were exposed to a constant rate of cold shock to determine the initial loss of equilibrium (Critical Thermal Minimum) temperature. This information was used in further experiments to determine the swimming endurance (at 15 cm/s) of gizzard shad and threadfin shad exposed to increasing levels of cold shock and reduced ration. Both species exhibited reduced swimming endurance at temperatures slightly above where loss of equilibrium occurs. We observed few differences in swimming endurance after three weeks of minimal ration for either species. Field observations suggested that the longest duration of reduced ration used, 21 days, was not sufficient to simulate the condition of shad in late winter. In 2008, the critical swimming speed (CSS) of both species was tested after cold shock to different target minimum temperatures. We found that gizzard shad CSS declined from 54 cm/s (1.8 ft/s) at the acclimation temperature of 11ºC to 28 cm/s at 5.5ºC. For threadfin shad, CSS declined from 55 cm/s at the acclimation temperature of 14ºC to 25 cm/s at 6ºC. Of particular interest is the wide range of endurance among fish within the same treatment groups which means that many fish were experimentally impinged more quickly and at a lower current velocity than the average would indicate.

Introduction

Environmental regulations in the U.S. (Clean Water Act Section 316(b)) require reduction in mortality of fish at water intakes. In the Southeast U.S., over 90% of fish impinged on intake screens of thermal power stations are threadfin shad *Dorosoma petenense* or gizzard shad *D. cepedianum*. The impingement of massive numbers of forage fish often impacts normal plant operations and could have community level effects.

Studies have shown peak impingement periods of these shad species often correspond to natural mortality in lakes and reservoirs in winter (Griffith and Tomljanovich, 1975; Loar et al. 1978;

Griffith, 1978; McLean et al,. 1980; 1982; Adams et al., 1985; White et al., 1986). For fish that are impinged, regulators have recognized the need to differentiate naturally moribund (dying) fish from otherwise healthy fish. No method currently exists to accomplish this. Therefore, research is needed to identify and quantify naturally moribund fish that enter the cooling water intake structure. Cold shock and nutritional status have been identified as two of the most important factors in natural mortality of shad and are likely contributors to a moribund condition that results in increased impingement.

Threadfin shad are abundant forage fish found in lakes and reservoirs of the Southeast. The species' natural range in Gulf Coast states has been expanded through stocking by fisheries agencies, which sought small, highly prolific prey species for game fish such as largemouth bass *Micropterus salmoides*. The populations occurring in the species' current northern range are subject to cold temperatures that can cause loss of equilibrium (CTMin) or death. Griffith (1978) found threadfin shad mortality to occur at temperatures as high as 9°C and 100% mortality by 4°C. Impingement of threadfin shad increases significantly when water temperatures drop below 7°C (McLean et al.; 1985). Gizzard shad are an abundant forage fish that occur throughout the eastern U.S. Gizzard shad account for a large percentage of impingement in the Great Lakes region where temperatures often reach the reported CTMin temperature for this species. Cox and Coutant (1976) showed the CTMin to be lower than 6.5°C and Neumann et al. (1977) reported this species can survive for less than 24 hours below 1°C. Heidinger (1983) suggested that mortality occurs in gizzard shad between 0 and 4°C.

Impingement likely increases when shad are subjected to temperatures that affect their physiological function and endurance. Increased susceptibility to impingement would occur at some point above the CTMin temperature for both species and is the preface to natural mortality probably induced by cold shock. Reduced ration has also been shown to affect the susceptibility to natural mortality in gizzard shad (Adams et al,.1985). Lipids are typically stored during periods of high food availability (summer and fall) and used during periods of low food availability or non-feeding periods (winter and early spring; Adams, 1999). The influence of reduced feeding at cold temperatures and duration of starvation on susceptibility to impingement has not been investigated. Bodola (1966) reported gizzard shad to discontinue feeding at 11°C. Both species are lethargic during cold periods, requiring the utilization of energy reserves, such as stored lipids, to maintain physiological homeostasis. The condition factor (K), an index that relates weight and length, reflects energy storage and metabolism due to starvation (Dutil et al., 2003).

Swimming endurance is an important behavioral measurement for relating physiological condition to impingement. Griffith and Tomljanovich (1975) used swimming endurance to determine the ability of cold-shocked threadfin shad to avoid impingement and found high impingement mortality below 8°C. Martinez et al. (2004) demonstrated that starved Atlantic cod *Gadus morhua* exhibited reduced swimming endurance compared to fed cod. However, the combined effects of ration and cold shock on swimming endurance have not been investigated.

The challenge for environmental managers and regulators is to determine whether fish impinged on intake screens would have died anyway because of natural environmental conditions. Natural conditions may not always lead to mortality but may result in increased susceptibility to impingement. The primary objectives of this study were to: (1) determine the CTMin and recovery temperatures, (2) identify the critical points where cold shock and/or reduced ration affect swimming endurance, and (3) determine the critical swimming speed (CSS).

Methods

Experiment 1-3

Gizzard and threadfin shad were collected by electrofishing from the Clinch River arm of Watts Bar Reservoir, Tennessee. Water temperatures ranged from 20-28°C. We transported live shad to the lab in 151-L barrels equipped with aerators and treated with 400 g of sodium chloride. Shad were then held at 24°C for 3 to 5 days in 889-L circular tanks with aeration and a constant 0.6 L/min flow through. Shad were acclimated to feeding on frozen brine shrimp and laboratory conditions during this period.

Experiment 1: CTMin and Recovery

Gradual Cold Shock - Gizzard shad were collected in March 2006 and threadfin shad in September 2006. Following the 3-5 day acclimation, groups of 22 gizzard shad (mean length = 143 mm, weight = 24 g) or 20 threadfin shad (mean length = 128 mm, weight = 17 g) were transferred to 530-L rectangular tanks receiving 0.25 L/min of flow. The test groups were then acclimated for one week at 15 ± 0.2°C prior to testing.

The test groups were subjected to a cold shock at 0.5°C/hr until their CTMin was reached. Portable refrigeration units paired with temperature controllers were used to regulate exposure temperatures within ± 0.2°C. The time and temperature at which CTMin occurred was recorded. Half of the fish were randomly assigned a holding period of 30 minutes in the cold shock tank after reaching their CTMin before being placed in the recovery tank. The other half of the test group was transferred immediately after CTMin was reached to the recovery tank. The recovery tank was the same dimension as the cold shock tank. It was filled to a depth of 7 inches to serve as a water bath and maintained at the same temperature as the cold shock tank. Within the tank were 12 square aquariums measuring 30.5 cm filled with water to a depth of seven inches. Each aquarium was equipped with a water supply and aerator. Individual fish were placed into an aquarium and water was dripped into the aquarium at ~25 mL/min. The initial aquarium temperature, recovery, time of recovery, aquarium temperature at recovery, weight, and length were recorded for each fish.

Instantaneous Cold Shock - Gizzard shad were collected in March 2006. Following the 3-5 day acclimation, a test group of 20 gizzard shad (mean length = 143 mm, weight = 24 g) was placed in a 530-L rectangular tank receiving 0.25 L/min of flow. The shad were acclimated for one week at 15 ± 0.2°C prior to testing. Portable refrigeration units paired with temperature controllers were used to regulate exposure temperatures within ± 0.2°C. Ten fish were then placed into a rectangular tank being maintained at 4°C and ten fish into another being maintained at 6°C. The tanks were maintained at these temperatures for the first 24 hours after which the tanks were allowed to warm at room temperature for the next 4 days. The time and temperature at which CTMin occurred and survival were recorded during the experiment.

Experiment 2: Effects of Cold Shock on Swimming Endurance

Fish for this experiment were collected from 11-August to 19-September 2005. The average size for gizzard shad for five collection dates during this time ranged from 143 to 162 mm and for threadfin shad for four collection dates from 128 to 134 mm. Following the 3-5 day acclimation, test fish were transferred to one of four 530-L rectangular tanks receiving 0.25 L/min of flow. Test groups of 34 gizzard shad (mean length = 153 mm, weight = 30 g) or 45 threadfin shad (mean length = 134 mm, weight = 17 g) were placed in each tank. The number of individuals in each test group exceeded the number required for testing to allow for mortality during acclimation. Portable refrigeration units paired with temperature controllers were used to regulate exposure temperatures within ± 0.2°C. Each of the four test groups were acclimated for 1 week at 15 ± 0.2°C prior to testing.

A preliminary experiment incorporating declining temperatures (0.5°C/hr from 15°C) was conducted to determine the mean CTMin for gizzard shad (1.7°C) and threadfin shad (5.6°C; Fost 2006). This information was used to select cold shock treatment temperatures for this study. Cold shock experimentation with gizzard shad was initiated with an acute cold shock (0.5°C/hr from 15°C) terminating at test temperatures of 4 or 5°C. We also tested gizzard shad that were held for 6 hours at 4°C (referred to henceforth as '4°C extended') or 6 hours at 5°C (5°C extended) after the decline to determine the effect of prolonged exposure at those temperatures. The 5°C test group was repeated 4 weeks after the initial tests with fish collected on 30 September and compared to the initial treatment. Cold shock experimentation with threadfin shad was initiated with an acute cold shock (0.5°C/hr from 15°C) terminating at test temperatures of 7.5° and 8.5°C. Threadfin shad were also held for 6 hours at 8.5°C (8.5°C extended) and 3 hr at 7.5°C (7.5°C extended) after the initial temperature decline. We repeated the 8.5°C extended test group 3 weeks after the initial test with fish collected on 30 September and compared to the initial treatment. Controls for both species were sampled at the acclimation temperature of 15°C. Fish were monitored for abnormal behavior or signs of distress during the cold exposure. Swimming endurance tests were used to assess the impact of cold shock treatment after the cold shock was completed.

For swimming endurance tests, 10 gizzard shad or threadfin shad were removed from their respective treatment tanks and placed five at a time into the corral area of the swimming endurance channel (Figure 9-1). The swim channel was maintained at the temperature that fish were exposed to within their treatment using portable refrigeration units. The flow (~0.15 m/s) in the test channel was produced by a ¾ horsepower centrifugal pump. Water was pumped from the corral zone and introduced to the upper end of the test channel through a series of increasing-diameter pipes and a 0.32 cm mesh screen which evened the flow distribution within the test zone. The endurance test channel was 10.8 cm wide by 122 cm long with water depth of 14.6 cm. The power to the pump was surged three to four times to allow the fish to orient upstream and gain swimming balance prior to initiating full flow velocity at initiation of each test. Individuals were observed for 1 hour to determine impingement at the rear screen for more than 15 s. Impinged fish were removed immediately, and swim duration (≤ 1 hr), total length (mm), and weight (g) were recorded and condition factor (K = (weight/length^3) * 1000) calculated.

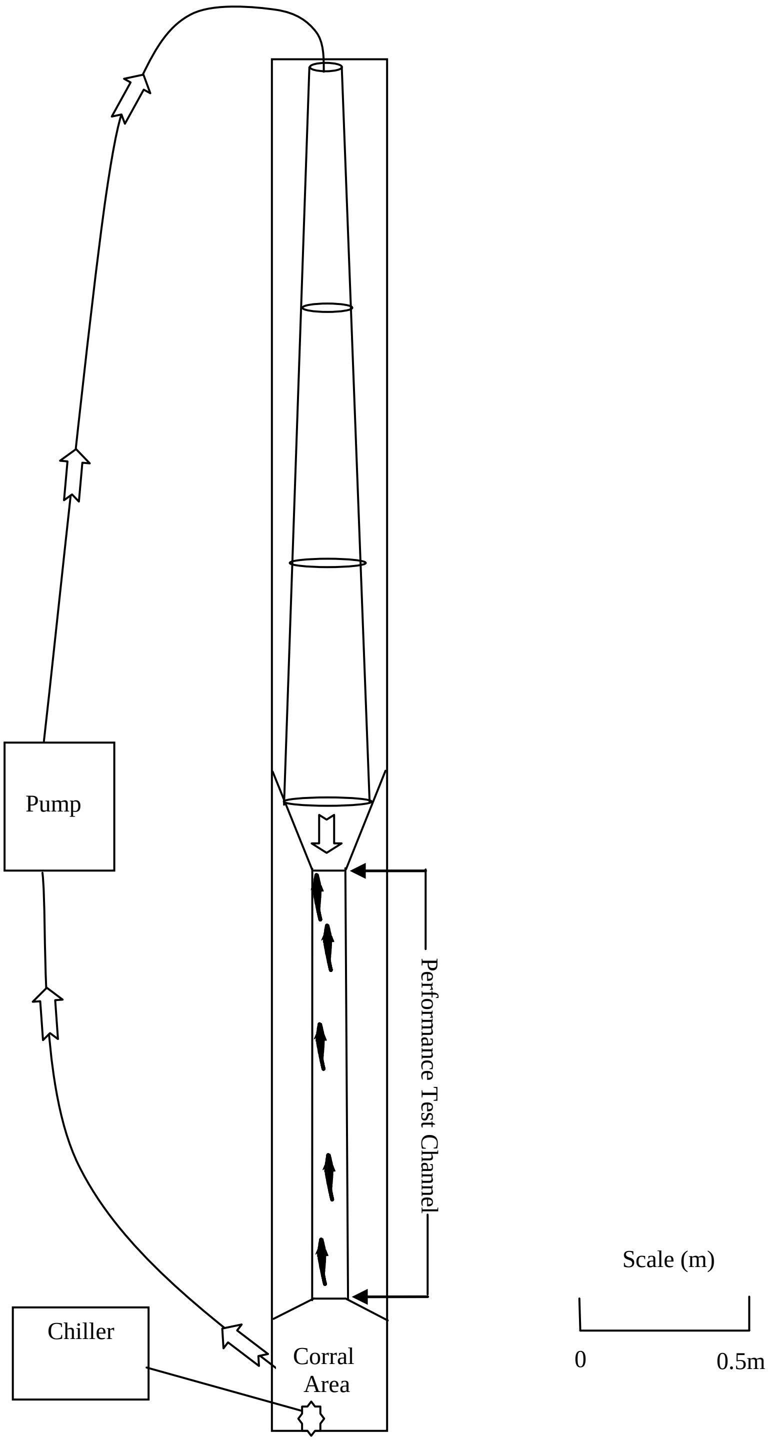

Figure 9-1
Schematic of the swim channel (top view). Fish were confined to the 10.8 cm wide by 122 cm long area during testing.

Experiment 3: Effects of Combined Cold Shock and Reduced Ration on Swimming Endurance

Fish for this experiment were collected from 13-September to 6-October 2005. The average size for gizzard shad for three collection dates during this time ranged from 143 to 159 mm and for threadfin shad for three collection dates from 133 to 140 mm. Test groups of gizzard and threadfin shad were fed a reduced ration of 0.5% of their mass in frozen brine shrimp per day for 14 and 21 days. Following these 14- and 21-day reduced ration periods, gizzard shad were cold shocked to a temperature of 5°C and threadfin shad to a temperature of 8.5°C at a rate of 0.5°C/hr from 15°C. The entire 21-day reduced ration group was repeated, beginning 24 hours after the initial replicate for each species and the results were compared. The control groups were fed 5% of their mass in frozen brine shrimp per day for 14 days and sampled at the holding temperature (15°C). The test groups were observed for changes in swimming activity during the reduced ration period. Swimming endurance tests were used to assess the impact of the reduced ration and cold shock treatments as described in Experiment 2. In March of 2006 we collected additional fish from the field to determine if the condition factor observed after 21 days of reduced ration in the laboratory was similar to that found in fish collected from the reservoir in late winter.

Experiment 4: Critical Swimming Speed

Threadfin shad and gizzard shad were collected in June 2008 by electrofishing from the Clinch River (upper Watts Bar Reservoir), Tennessee, between river kilometers 22 and 37. They were treated with approximately 3% NaCl solution to relieve handling stress during transport and returned to the laboratory within an hour of capture. Threadfin shad were acclimated for 7 days at 14.5°C and gizzard shad at 11°C in 1.3 m diameter fiberglass tanks prior to testing. Gizzard shad were acclimated at a cooler temperature than threadfin shad to match the difference in their respective CTMin temperatures.

Critical swimming speed (CSS) tests were conducted in an elongated circular fiberglass tank with a 0.3 m x 0.3 m cross-section and a linear distance of 12 m. The endurance test arena was a straight 3.4m section on one side of the tank. Fish were restricted to the test arena by 12 mm opening wire screen at each end. A 55-pound thrust Minn Kota trolling motor with a variable-speed controller generated a steady current through the test area. An acoustic Doppler velocimeter (ADV) connected to a laptop computer continuously measured water velocity in the test arena. Real-time output from the ADV was used to adjust water velocity during the tests. We conducted eight swimming trials with 15 threadfin shad each at five different temperatures from 6 to 14°C. Three of the temperatures were tested in replicate (6, 11, and 14°C). We conducted three swimming trials with 10 gizzard shad each at three different temperatures from 5.5 to 11°C. For each trial, 15 threadfin shad or 10 gizzard shad were removed from the holding tank and placed in the swim endurance tank at the respective acclimation temperature. Portable chillers cooled the test tank at approximately 2°C per hour to the target cold shock temperature prior to the introduction of any flow. Each trial was initiated at a modest flow of approximately 25 cm/s. Velocity was increased by approximately 5 cm/s every 5 minutes until all fish were impinged on the back screen (Figure 9-2). As fish tired and became impinged they were removed, measured (mm), and weighed (g). Impingement was defined as being against the screen for at least 15 seconds continuously. Time of impingement from the start of the experiment (i.e., when flow was turned on) was recorded for each fish and later used to determine the velocity at time of impingement from the recorded ADV output. Critical swimming speed was calculated for each fish as an indicator of swimming endurance. Since velocity exposure was in a step-wise fashion (Figure 9-2), critical swimming speed was calculated as:

$$U_{crit} = \text{Velocity at previous step} + (\text{Time at current step}/5\ \text{min}) \bullet (\text{size of velocity step}) \qquad (1)$$

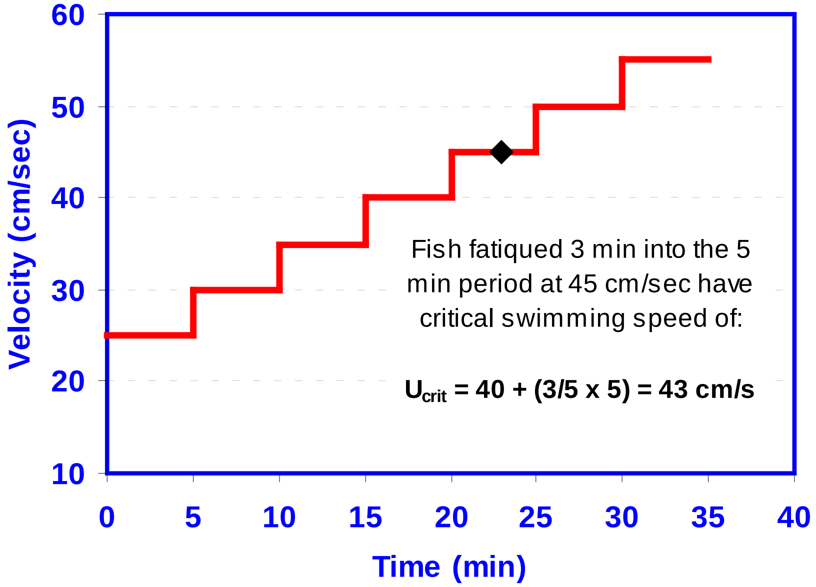

Figure 9-2
Target time course of velocities for the swimming endurance tests. The black diamond represents an example experimental endpoint and critical swimming speed calculation.

Statistical Tests

Statistical analyses on all swimming endurance data were performed using SAS, version 9.1, and SPSS, version 14. A value of $P<0.05$ was considered significant for all tests and simultaneous confidence was held at $P=0.05$ for all post hoc tests. Correlations between variables were investigated using Pearson correlation coefficients. Differences between controls, test groups, and replicates tests were analyzed with analysis of variance (ANOVA). The Shapiro-Wilk statistic was used to test the assumption of normally distributed errors. Non-normal data were log transformed (natural) for the dependent variable or ranked and used in the ANOVA. Homogeneity of variance between treatments was assessed with Levene's test. If significant differences in mean values were indicated by the ANOVA F test, paired means were evaluated using the least significant difference (LSD) test. Dunnett's mean separation test for unequal group variances was used when heterogeneous group variances exceeded a 3-fold difference between any treatment pair (van Belle, 2002). Some treatment groups were repeated to rule out possible tank or handling effects. The results from repeated groups were compared to the initial test group for differences. The term ‘repeated’ is used because the tests did not occur at the same time and therefore are not exact replicates.

Results

Experiment 1: CTMin and Recovery

Gradual Cold Shock

We observed signs of distress (abnormal response) in gizzard shad during the cold shock treatment. Activity levels decreased as temperatures approached 5°C and fish became totally lethargic by 4°C. There was little avoidance response to vibration in the water and netting at 4°C. The mean CTMin temperature for gizzard shad exposed to cold shock at a rate of 0.5°C/hr was 1.8°C with individual values ranging from 1.0°C to 2.7°C. All gizzard shad recovered to normal equilibrium when gradually warmed after reaching their CTMin. The mean recovery temperature was 2.6°C, 0.8°C above the mean CTMin.

Threadfin shad exhibited signs of distress during the cold shock treatment. Individuals began to swim out of sequence rather than in a school, often swimming into the side of the tank as if searching for warmer water. The activity level of these fish appeared to increase as temperatures decreased. There was little response to vibration and netting at 8.5°C. The mean CTMin temperature for threadfin shad exposed to cold shock at a rate of 0.5°C/hr was 5.0°C with individual values ranging from 4.6°C to 6.0°C. All threadfin shad recovered to normal equilibrium when gradually warmed after reaching their CTMin. The mean recovery temperature was 7.5°C, 2.5°C above the mean CTMin.

Instantaneous Cold Shock

Gizzard shad plunged into the 6°C water bath did not lose equilibrium or die during the 5 days of testing. The 10 fish placed into the 4°C water bath all experienced loss of equilibrium during the 5 days. Within the first 15 minutes of being transferred from the holding tank to the 4°C water bath, eight of ten had lost equilibrium. The remaining two fish experienced CTMin during the 24-48 hour time period. Two fish died on the third day of testing and one on the fourth day. The seven remaining fish recovered equilibrium and survived the 5 days of testing.

Experiment 2: Effects of Cold Shock on Swimming Endurance

We observed signs of distress (abnormal behavior) during the gizzard shad cold shock treatments. Activity levels decreased as temperatures approached 5°C and fish became totally lethargic (but upright) by 4°C. There was little startle response to vibration in the water and netting at 4°C. In swimming endurance tests, cold-shocked gizzard shad had significantly lower mean swimming time to impingement than the control (n=50, P=0.005; Figure 9-3). Mean swimming time was less in gizzard shad cold shocked to 4°C than to 5°C. Swimming endurance of gizzard shad in extended test groups was not different statistically from fish sampled immediately upon reaching the temperature, but the pattern of decreased endurance with increased exposure to cold was consistent with the overall trend. Mean condition factor was not different among test groups and there was no correlation between condition factor and mean swimming endurance for gizzard shad. The gizzard shad repeated treatment did not differ in swimming endurance compared to the initial group.

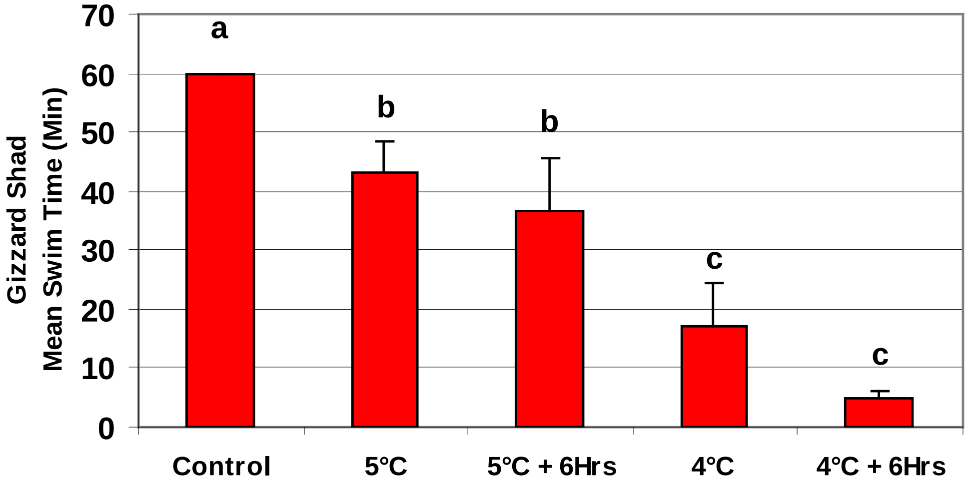

Figure 9-3
Mean (+1 SE) swimming time of gizzard shad exposed to cold shock treatment beginning at 15°C and declining at a rate of 0.5°C/hour to the test temperature. Treatments that are statistically different (P<0.05) have different letters.

We observed signs of distress in threadfin shad during the cold shock treatments at temperatures 2-3°C above the CTMin identified in Fost (2006). Individuals began to swim out of sequence rather than in a school, often swimming into the side of the tank. The activity level of these fish appeared to increase as temperatures decreased. There was little response to vibration and netting at 8.5°C and below. Cold shock decreased the swimming endurance of threadfin shad (n=50, p<0.01). As with gizzard shad, the results show a clear trend of decreasing swim endurance with increasing exposure to cold (Figure 9-4). Mean condition factor did not differ among test groups, and, like gizzard shad, there was no correlation between condition factor and mean swimming endurance for threadfin shad. The threadfin shad repeated treatment had a significantly longer mean swimming endurance compared to the initial group.

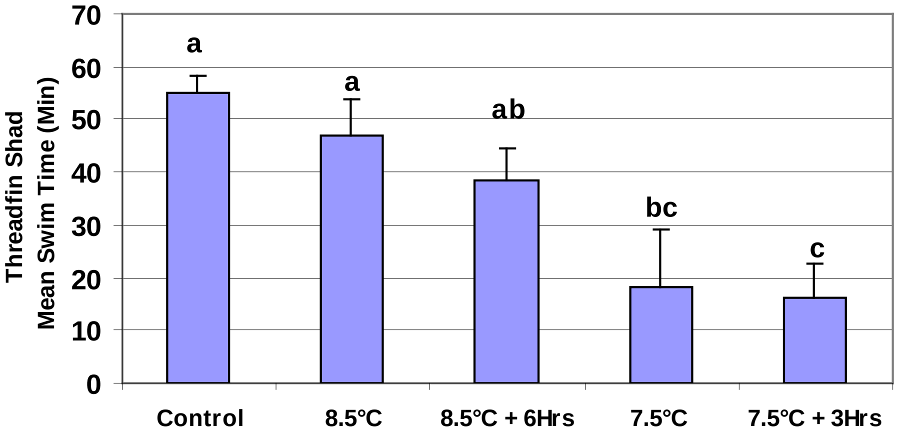

Figure 9-4
Mean (+1 SE) swimming time of threadfin shad exposed to cold shock treatment beginning

at 15°C and declining at a rate of 0.5°C/hour to the test temperature. Treatments that are statistically different (P<0.05) have different letters.

Experiment 3: Effects of Combined Cold Shock and Reduced Ration on Swimming Endurance

Gizzard shad generally remained active during the treatment periods (14 or 21 days) of reduced ration. Groups fed a reduced ration did not have significantly different mean swimming endurance after cold shock than fish fed a full ration (n=30, p=0.69; Figure 9-5). Mean swimming endurance was significantly lower in the repeated 21 day reduced ration group of gizzard shad compared to the initial 21 day reduced ration group. Mean condition factor was lower in the 21 day group than control. Gizzard shad collected in March 2006 had lower mean condition (K=7.4) than fall-collected fish held in the laboratory for 21 days of reduced ration (K=8.1).

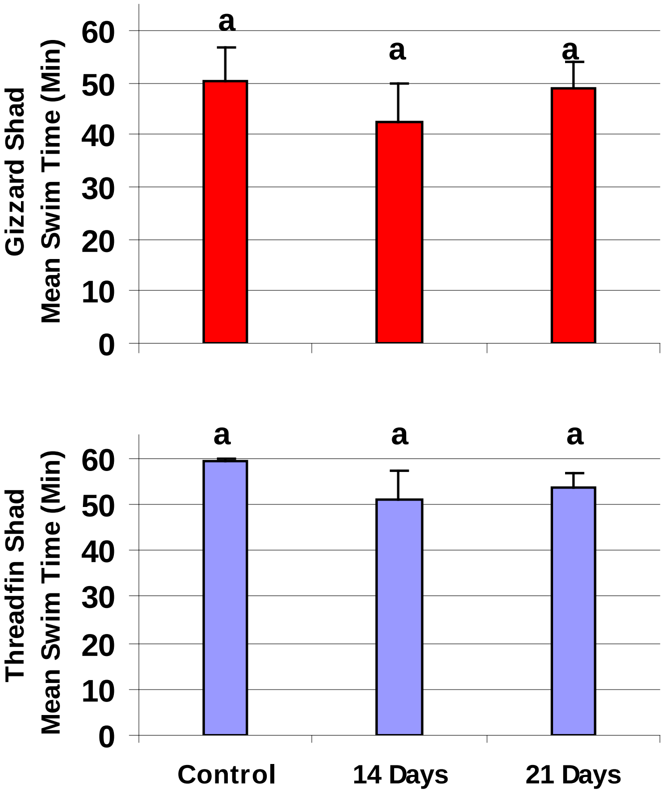

Figure 9-5
Mean (+1 SE) swimming time, plasma cortisol, and plasma chloride of gizzard and threadfin shad exposed to cold shock after one of three protocols: 14 days of full ration, 14 days of reduced ration, or 21 days of reduced ration. Treatments that are statistically different (P<0.05) have different letters.

Threadfin shad schooled and remained active during the reduced-ration test period. Groups fed a reduced ration did not have significantly different swimming endurance compared to controls (n=30, p= 0.61; Figure 9-5). Mean swimming endurance was not significantly lower in the repeated 21 day reduced ration group of gizzard shad compared to the initial 21 day reduced ration group. Condition factor was lower in the 21 day reduced-ration group than the 14 day group or control, which were not different. As with gizzard shad, threadfin shad collected in March 2006 had lower mean condition (K=6.7) than fall-collected fish after 21 days of reduced-ration (K=6.9).

Experiment 4: Critical Swimming Speed

Most test groups demonstrated a wide range of critical swimming speeds with the exception of the coldest test group for each species. At each temperature there was at least one fish that quit swimming within the first 7 minutes resulting in a critical swimming speed of less than 30 cm/s. All fish were examined closely for any signs of injury or illness at the end of each test and all were deemed normal. The threadfin shad group at 14.2°C included only 14 fish because one of the initial 15 was determined to be a different clupeid species at the end of the test.

As expected, endurance for both species declined with cold shock temperature (Figure 9-6 and Figure 9-7). Within the range of temperatures tested the relationship for both species appears to be linear. Plots of critical swimming speed versus length and condition factor suggest that size and condition have little effect on swimming endurance in threadfin shad.

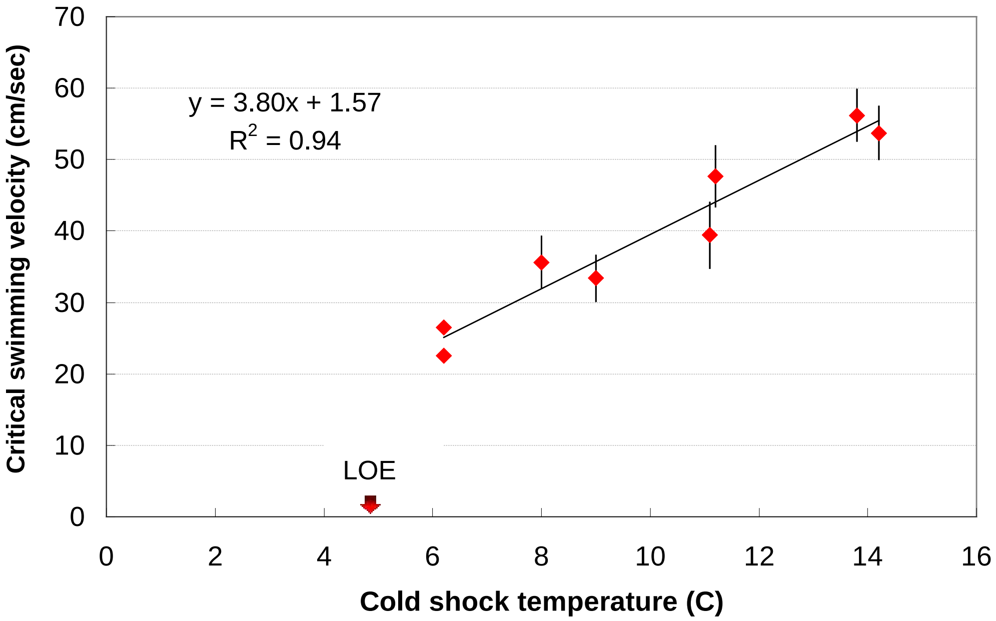

Figure 9-6
Mean (+/- 1 std err) critical swimming velocity for threadfin shad for five cold shock temperatures after being acclimated to 14.5°C. The loss of equilibrium (LOE) temperature of 5.6°C (indicated by arrow) was derived in an earlier study (Fost, 2006).

Discussion

The initial experiment yielded CTMin temperatures within the reported range of previous studies for both species. Signs of behavioral distress during cold shock prior to CTMin or death in threadfin shad have been reported by others. Threadfin shad exposed to acute temperature declines began showing signs of behavioral distress as much as 5°C prior to mortality and a lack of response to movement and vibration 6-7°C above lethal temperatures (Griffith, 1978). Moribund threadfin shad, exposed to 1-4°C temperature declines in 4 hours, swam individually rather than in schools prior to CTMin (Griffith and Tomljanovich, 1975). Studies reporting gizzard shad showing signs of distress or response prior to CTMin were not found.

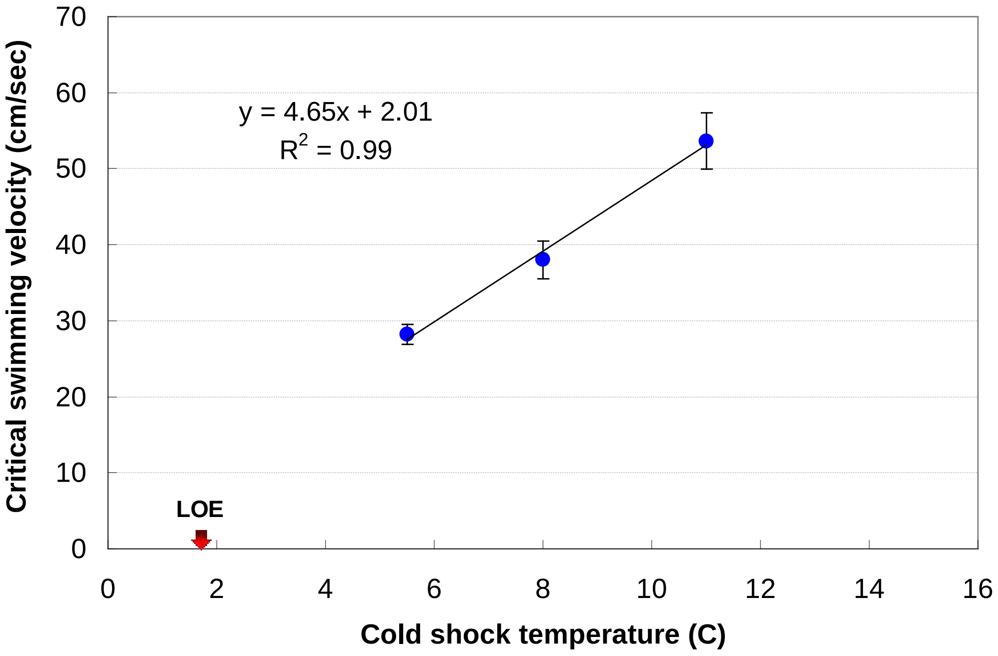

Figure 9-7
Mean (+/- 1 std err) critical swimming velocity for gizzard shad for three cold shock temperatures after being acclimated to 11°C. The loss of equilibrium (LOE) temperature of 1.7°C (indicated by arrow) was derived in an earlier study (Fost 2006).

We measured the response of gizzard and threadfin shad to cold shock alone and to a combination of starvation and cold shock to gain insight into various factors that may contribute to impingement of these species at cooling water intakes. Water temperatures of 5°C and below affected the swimming performance of gizzard shad when acclimated to 15°C, suggesting that susceptibility to impingement likely increases at these temperatures. For threadfin shad, we did not find a statistically significant decrease in performance at 8.5°C, but did see significant effects at 7.5°C. Similarly, a study by Griffith and Tomljanovich (1975) showed the ability of threadfin shad to resist impingement was severely impaired at temperatures below 8°C, but at higher temperatures resistance to impingement was slightly or not at all impaired. As expected, the temperature at which threadfin shad were affected was warmer than for gizzard shad making them more susceptible to cold-shock related impingement when the two occur in the same water body. For both species, extended exposure at cold temperatures seemed to further reduce swimming endurance. It is worth noting that most of the shad used in the control trials were able to sustain swimming for the maximum period of 60 minutes at a velocity of 0.15 m/s, which is the velocity often used as design criteria for cooling water intake screens.

The impingement of fish in late winter and early spring is often correlated with compromised nutritional status after several weeks or months of reduced food availability or low feeding activity (Adams et al., 1985). Previous studies on a variety of fish species indicated that swimming performance and condition factor decline as the duration of the starvation increased. Martinez et al. (2004) demonstrated that starved Atlantic cod Gadus morhua had reduced swimming performance compared to fed cod. Adams et al. (1985) reported lower condition factor levels in stressed gizzard shad compared to unstressed shad. In our study, gizzard and threadfin shad showed little response in swimming performance after 14 and 21 days of reduced ration followed by cold shock. The treatments did result in a lowering of the condition factor as would be expected. Either reduced ration had no effect on the stress response or the period of starvation was not long enough to cause an observed affect. Since these species typically experience periods of low food availability in winter, possible adaptation to periods of reduced feeding could explain the lack of a clear response in the lab to reduced ration.

To better understand the implications of reduced ration under natural conditions, we collected gizzard and threadfin shad from the Clinch River in March 2006 after a winter period when feeding was greatly reduced. These fish had significantly lower condition factors, (7.4 for gizzard and 6.7 for threadfin shad) than those we had collected during the summer and held for 21 days under reduced ration (8.1 for gizzard and 6.9 for threadfin shad). Therefore, even though the reduced ration period of 21 days in the laboratory resulted in poorer condition compared to controls, condition of fish in the lab did not quite approximate that of shad collected from the reservoir in late winter. If the condition of fish in the lab had been similar to that of shad collected in the field in late winter, the expected declines in indicators of nutritional status and swimming performance may have occurred in those fish subjected to cold shock treatment.

The results of the CSS study indicate that threadfin shad and gizzard shad swimming endurance is greatly reduced under cold shock conditions especially at and below 6°C. Testing did not differentiate if the effect is a function of the shock temperature or the amount of change in temperature from the acclimation temperature to the shock temperature. We expect it is a combination of both. Within the range tested, it appears that neither length nor condition factor have much effect on endurance.

Cold temperatures result in a natural reduction of gizzard shad and threadfin shad swimming endurance. Reduced swimming endurance leads to an increased susceptibility to impingement at CWIS. Our results have direct relevance to typical CWIS design and operational criteria which often restrict intake velocity to 15 cm/s (0.5 ft/s). Based on the results shown in Figure 9-6 and Figure 9-7 it appears that a 15 cm/s requirement is protective of both threadfin and gizzard shad even under cold shock conditions. During periods of the year when cold shock is improbable, the 15 cm/s requirement is perhaps overprotective given that the critical swimming speed of both species exceeds 50 cm/s.

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10

BIOENERGETICS-BASED FISH HABITAT SUITABILITY ALONG THERMAL GRADIENTS

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Abstract

The influence of consistent water temperature on fish growth has been well studied for many species. However, anthropogenic forces, including thermal discharge from power plants, create complex environments where thermal conditions and habitat suitability can change dramatically over fine temporal and spatial scales. The objective of this study was to index habitat quality by quantifying fish bioenergetics growth rate potential (GRP) along thermal gradients emanating from power plant discharges. We measured thermal differences by using stationary thermistors placed at intervals upstream and downstream of two power plants on the Ohio River. Environments adjacent to both power plants were divided into spatially-explicit cells in which GRP for smallmouth bass (*Micropterus dolomieu*) and walleye (*Sander vitreus*) was calculated using species-specific bioenergetics models. These GRP indices quantified relative habitat quality for juveniles and adults of both species, demonstrating how thermal discharges can contribute to fine-scale spatial changes in fish habitat suitability.

Introduction

Power plant thermal discharges offer a unique and oftentimes complex environment for fish. Thermal discharges into rivers generally cause dramatic temperature gradients, characterized by cooler waters upstream, a sharp temperature increase at the discharge point, and a gradual reduction in temperature downstream from the discharge point. Previous studies have investigated how individual fish move along discharge gradients [6, 12, 19], or how species abundances compare between affected and unaffected locations [9, 17]. Although such studies have demonstrated that species respond differently to temperature gradients, these studies are oftentimes only representative of discrete sampling events, are limited in their ability to conclusively link observed movement or distribution patterns to observed temperatures, or lack the ability to predict responses based on various temperature discharge scenarios. Therefore, it would be useful for plant operators and fisheries managers to be able to quantify thermal habitat quality for fish along discharge temperature gradients and compare these patterns through time.

Bioenergetics analysis constitutes a potentially useful approach for quantifying thermal habitat quality. Bioenergetics models depict species-specific energy budgets, balancing energy inputs via food consumption with growth, respiratory expenditures, and waste processes [11]. Species-specific bioenergetics models have been developed in controlled laboratory experiments where physiological functions including consumption, respiration, and waste processes are measured in response to various temperatures. These experiments are usually conducted on a range of fish sizes to incorporate allometric effects on physiological rates. Furthermore, different models have been developed for juveniles and adults within a species to account for ontogenetic effects on thermal responses and physiological rates.

Bioenergetics approaches have been used to compare habitat quality between locations for a variety of ecosystems and species. Under such applications, spatially- and temporally-specific temperatures and potential prey consumptions are the primary inputs of bioenergetics models and are integrated to quantify growth rate potential (GRP), an index of habitat quality [5]. In some previous applications, (1) salmonid habitat quality in the Great Lakes has been evaluated based on observed prey abundances and water temperatures [14]; (2) striped bass (*Morone saxatilis*) GRP has been calculated for spatially-explicit habitat cells, both vertically and horizontally, in Chesapeake Bay to determine the most beneficial regions for growth [4]; and (3) the effects of hypolimnetic hypoxia on habitat quality of various species in central Lake Erie have been quantified [2]. Moreover, the GRP approach has been extended to evaluate habitat quality in a diversity of aquatic environments, including stream and river systems [3, 16].

Since bioenergetics models rely heavily on temperature inputs, they are appropriate for quantifying and comparing fish habitat quality along power plant thermal discharges. The direct effects of heated effluent can be further explored if all variables in the model remain constant with only temperature inputs changing through space and time. We used this approach to quantify habitat quality for smallmouth bass (*Micropterus dolomieu*) and walleye (*Sander vitreus*), species with different thermal preferences, near two power plant thermal discharges. Our analyses include over 1 year of temperature observations from multiple locations in order to better understand how inter-seasonal habitat quality is enhanced or reduced by heated discharge.

Methods

Fish habitat quality was quantified near two power plants on the Ohio River (Figure 10-1). Tanner’s Creek Plant is located in the Markland Pool at river mile 494 near Lawrenceburg, Indiana. Cane Run Plant is located at river mile 616.6 in the Cannelton Pool near Louisville, Kentucky. Both are coal-fired plants using once-through cooling water systems. Heated water at both plants is discharged directly into the Ohio River.

Water temperature was measured using temperature data loggers (HOBO Pro v2, Onset Computer Corporation, Cape Cod, Massachusetts) programmed to record temperatures every thirty minutes. Each logger was anchored to the sediment and suspended in the water column with a subsurface buoy. All temperature loggers were deployed nearshore at depths between approximately 1.5 m and 2.0 m. Fifteen loggers were deployed on both sides of the Ohio River, near each power plant spanning distances approximately 1 km upstream to 1.6 km downstream from the thermal discharges (Figure 10-1). Five loggers were deployed at each plant in late April 2010 with the remaining loggers deployed in July 2010. For this study, temperature data from the initial deployment date to the end of June 2011 were included in the analyses. Furthermore, employees from both power plants provided plant discharge temperature data for these dates.

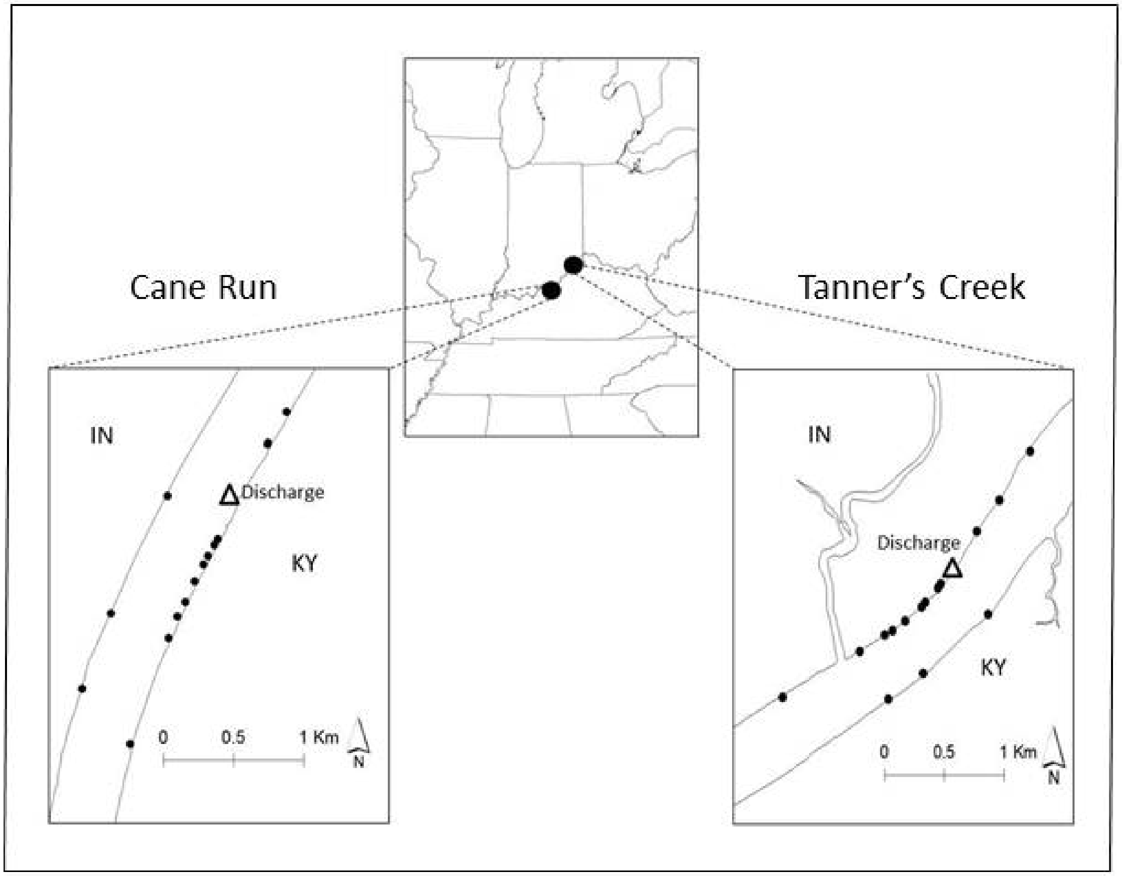

Figure 10-1
Location of temperature loggers (black points) near the thermal discharge from two power plants on the Ohio River

Analyses to quantify fish habitat quality were limited to a one-dimensional spatial comparison. Therefore, only temperature data from loggers on the same shore as the plant discharge were included in GRP calculations, giving an upstream-to-downstream spatial comparison. Mean daily temperature was first calculated for each logger and then values between loggers were interpolated at 10 m increments.

Daily fish GRP was calculated for each 10-m cell, using species-specific bioenergetics models. These GRP calculations were based on models described by Whitledge et al. [20] for adult and juvenile smallmouth bass and models from Kitchell et al. [11] and Madon and Culver [13] for adult and juvenile walleye, respectively. Growth rate potentials for adults of both species were modeled for 300 g individuals whereas juvenile weights were set at 50 g for both species. Prey energy density for adult and juvenile smallmouth bass and walleye remained constant at 3,853 J g^{-1} to represent consumption of forage fish [20]. All parameters, including activity level, prey consumption, and the weight of the modeled fish, remained constant within the analysis.

The influence of temperature on habitat quality was further explored by varying prey consumption between GRP analyses. For each species and life stage, GRP was separately calculated assuming a temperature- and mass-specific maximum consumption rate and then assuming constrained prey consumption (40% of maximum). The impact of this reduction in consumption was evaluated by calculating the proportion of days (from 22-April 2010 to 29-June 2011) with positive GRP for several locations along the thermal gradient.

Results

We were able to retrieve and download data from most temperature loggers at both plants until November 2010. However, flooding in March 2011 reduced the number of loggers we could locate in the spring. We were able to obtain overwinter temperature data for locations dispersed along the thermal discharge at the Tanner's Creek Plant. In contrast, our overwinter data for Cane Run is limited to an area between the thermal discharge and 500 m downstream.

Mean daily temperatures near the thermal discharge were generally higher at the Cane Run Plant than at the Tanner's Creek Plant (Figure 10-2). Mean daily temperature differences between upstream locations and the discharge were generally between 5°C and 7°C throughout the year at both plants. Maximum summer discharge temperatures reached 44°C at Cane Run and 37°C at Tanner's Creek in 2010. During most seasons, temperatures generally remained elevated within 400 m of the discharge, while temperatures 1,600 m downstream of the plants were similar to those upstream of the discharges. However, during winter, temperatures consistently remained elevated at our farthest downstream temperature logger at the Tanner's Creek Plant. The mean winter temperature (December through February) 500 m upstream from the Tanner's Creek discharge was 2.8°C whereas it was 7.3°C and 4.9°C 100 m and 1,600 m from the discharge, respectively.

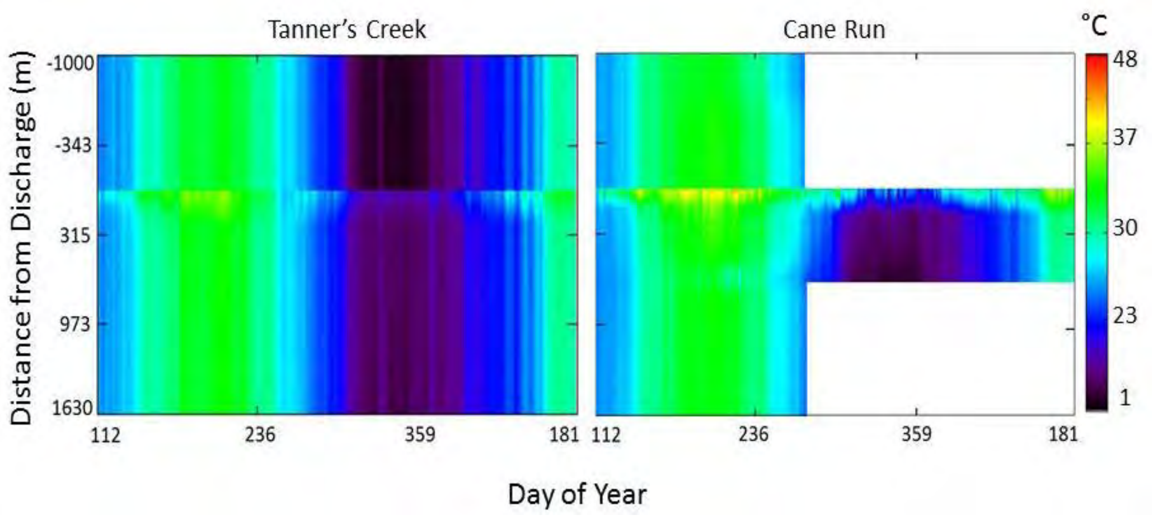

Figure 10-2
Mean daily water temperature near Tanner's Creek and Cane Run power plants on the Ohio River. Distances with negative values are upstream from the discharge and positive values are downstream.

Thermal habitat quality for adult and juvenile smallmouth bass feeding at maximum consumption levels was high throughout most locations and months adjacent to both power plants (Figure 10-3). Ambient habitat quality was greatest during spring and fall for both adults and juveniles as ambient river temperatures approached approximately 25°C. However, habitats within 300 m from the discharge were of relatively low quality during these periods. This area of poor habitat became more severe and extended farther downstream during the warmer summer months. Conversely, from December to March the discharge plumes exhibited the highest habitat quality for both adult and juvenile smallmouth bass. In particular, areas within 200 m downstream from the discharges were consistently better smallmouth bass habitat compared to upstream. Growth rate potential was especially high during the winter near the Cane Run discharge, although we lack the upstream temperatures to make a direct comparison of habitat quality.

Walleye habitat quality, under maximum prey consumption, showed similar spatial and temporal trends as those of smallmouth bass (Figure 10-4). Habitat quality was maximized for most locations during the spring and fall, with a reduction in GRP during the winter. Contrary to smallmouth bass, areas within approximately 300 m of the discharges showed prolonged reductions in habitat quality. Beginning in June, the discharge at Tanner’s Creek became particularly poor habitat for adult and juvenile walleye. The higher discharge temperatures at Cane Run resulted in low habitat quality for all walleye during most of the year, with the exception of October through March. As with smallmouth bass, walleye habitat quality near the thermal discharge was enhanced during the winter.

Since we were unable to obtain overwinter temperature data at Cane Run, we only evaluated the impact of reduced prey consumption at the Tanner’s Creek Plant. Under maximum prey consumption, the proportion of days with beneficial habitat (positive GRP) for smallmouth bass was highest for habitats nearest the discharge (Figure 10-4). Lowering prey consumption to 40% of maximum consumption reduced the proportion of days with positive GRP at all locations, and led the discharge to be the habitat with the lowest cumulative habitat quality for adult and juvenile smallmouth bass. Overall, the discharge provided the lowest proportion of days with beneficial habitat for adult walleye regardless of consumption levels. This was also the case for juvenile walleye under maximum consumption, however reducing prey energy intake to 40% resulted in poor habitat for all locations throughout the study period (i.e., at this constrained consumption rate, juvenile walleye GRP was never positive). Although lower ration resulted in diminished proportion of days with beneficial habitat, the proportion of days with positive GRP 100 m downstream from the discharge are nearly identical to those of upstream locations for both species.

Discussion

The areas of the Ohio River surrounding the Tanner’s Creek and Cane Run Plants offered spatially and temporally variable habitat quality for smallmouth bass and walleye. For both species, locations upstream and far downstream from the discharges exhibited similar GRP throughout the study period. In contrast, habitat quality of locations within approximately 400 m downstream of the discharges was impacted by altered thermal conditions.

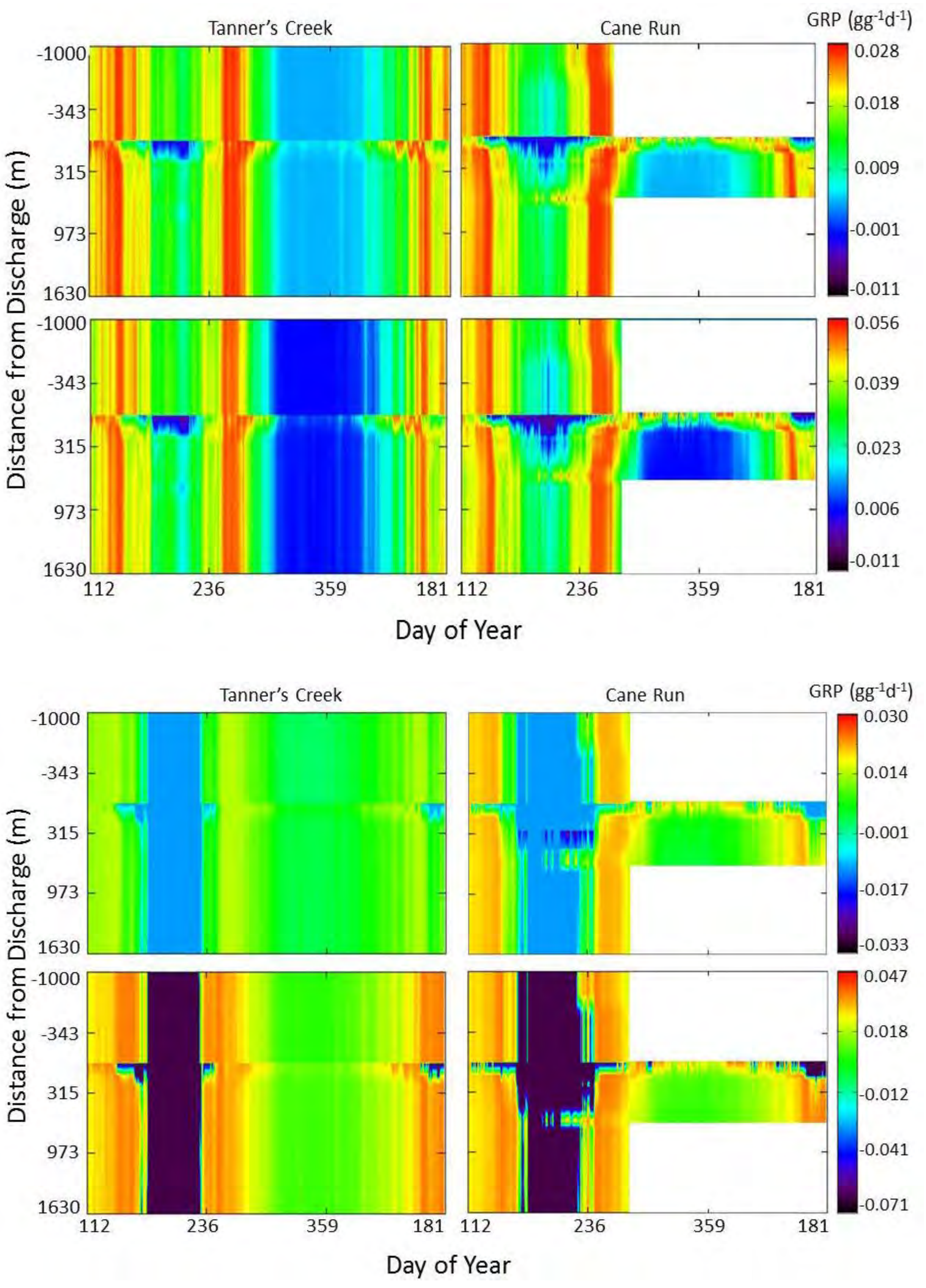

Figure 10-3
Growth Rate Potential (GRP) assuming maximum prey consumption for adult (top) and juvenile (bottom) smallmouth bass adjacent to the Tanner’s Creek and Cane Run power plants. Distances with negative values are upstream from the discharge and positive values are downstream.

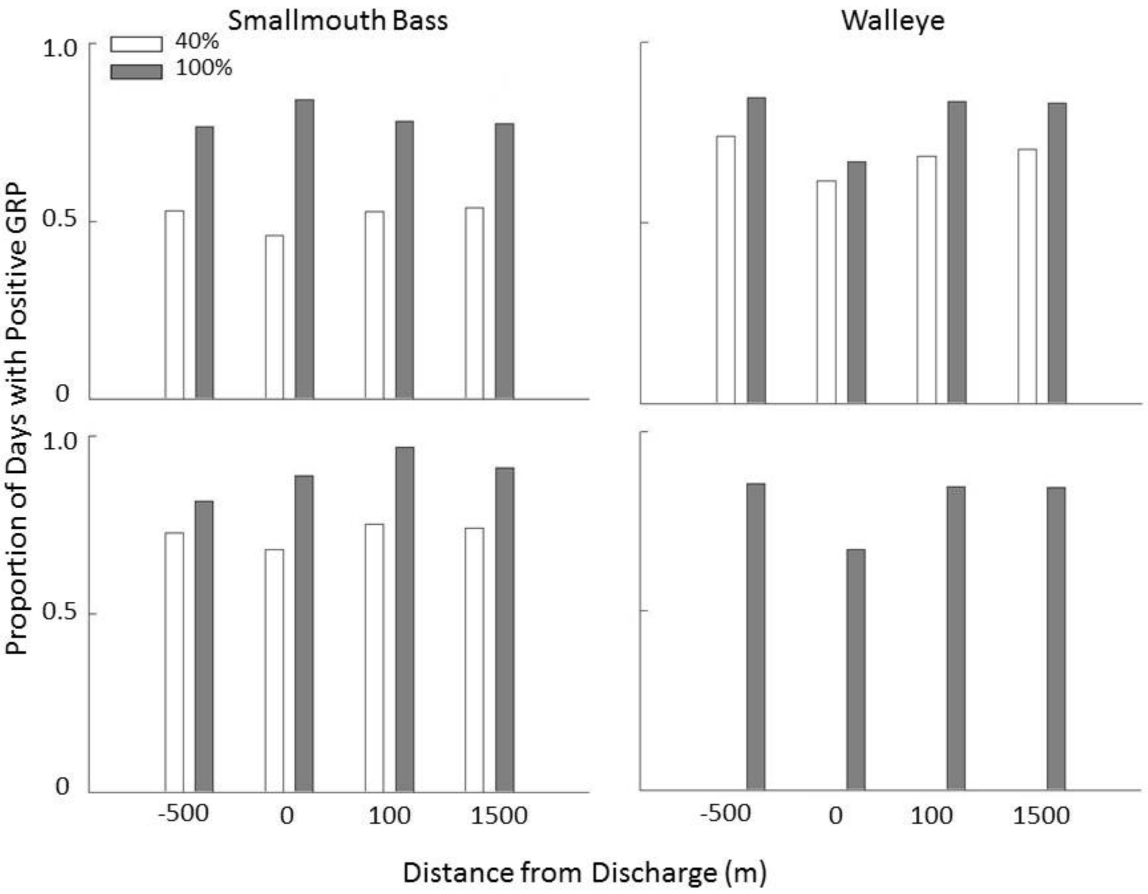

Figure 10-4
Proportion of days with positive growth rate potential (GRP; $gg^{-1}d^{-1}$) for adult (top) and juvenile (bottom) smallmouth bass and walleye under maximum (100%) and reduced (40%) prey consumption. Locations with negative distances were upstream from the thermal discharge (0 m) and positive distances were downstream.

Habitat quality of locations near the thermal discharges was most negatively impacted by heated effluent during summer months. Summer discharge temperatures for both plants were high compared to the thermal tolerances for smallmouth bass. Optimum temperatures for prey consumption in adults and juveniles occurs at 22°C and decreases as temperatures increase up to 37°C, at which point consumption ceases and respiration is maximized [20]. Mean daily discharge temperatures at Tanner's Creek consistently approached 37°C throughout July and August and exceeded this temperature at Cane Run until the end of September. Such high metabolic demand coupled with lower, or no, prey consumption results in a net energy loss in the model. Since the discharge temperatures at Cane Run exceeded 37°C for a longer duration, habitat quality near the discharge area was poor from late spring until early fall. Again, during the summer these areas of reduced habitat quality for smallmouth bass only extended downstream to approximately 400 m or less from the discharges.

Walleye habitat quality showed similar trends as smallmouth bass. However, during the summer, temperatures at all locations, including upstream of the thermal discharges, were of poor quality for walleye, as indicated by negative GRPs. The maximum mean daily temperature upstream from both plants during the summer was 31°C whereas the maximum temperature walleye can tolerate in the bioenergetics models we used is 32°C [11, 13]. Annual fish surveys on the Ohio River repeatedly capture walleye near the Tanner's Creek Plant [17], indicating that walleye in these areas must either survive on energy reserves or find more suitable habitat with cooler temperatures during the summer.

Contrary to summer months, winter habitat quality for both species was greatest near the thermal discharge. Cold temperatures reduced GRP to near zero values at most upstream habitats but the discharge offered positive GRP for both species and life stages. Smallmouth bass and walleye remaining in the discharge throughout the winter could potentially benefit by having an increased growing season. Telemetry studies have demonstrated that several fish species do take advantage of the increased winter habitat quality near power plant discharges. Cooke et al. [7] tracked smallmouth bass along a power plant discharge and found fish remaining in the discharge canal near the warmest waters throughout the winter. Yellow perch have similar thermal requirements as walleye and have also been shown to seek heated waters during winter months [18]. This increased winter habitat quality predicted from the bioenergetics models near the discharges remained high for both species until mid-May.

The amount and duration of beneficial thermal habitat near power plant discharges are largely dependent on prey consumption. Reducing prey consumption to 40% of maximum resulted in the discharge having the lowest proportion of days with beneficial habitat out of all locations for both species. Reducing prey intake to 40% represents a limited prey resource, which may be more reflective of natural conditions and has thus been used in other bioenergetics analyses [1, 15]. Habitat quality near the discharges declines with lowered prey consumption because the energy demand for metabolism at higher temperatures can become greater than the potential energy gained through prey consumption [11]. This is also why juvenile walleye GRP was negative for all locations under reduced prey consumption.

We documented seasonal differences in the potential effects of thermal discharges on habitat quality which may or may not be indicative of habitat quality at other thermal discharges. These indices of habitat quality were highly dependent on temperature measures near two power plants over approximately one year. Water flow, river stage, weather patterns, air temperature, and effluent discharge temperature, among other variables, all influence the size and severity of discharge plumes. As a result, the spatial and temporal patterns we document for thermal conditions and habitat quality may vary among years and across different power plant discharges.

Furthermore, although we calculated GRP as an index of habitat quality, these values will not represent the actual growth rates near these discharges. For a fish to actually exhibit the growth rates from our GRP calculations, a fish would have to remain at that specific location and consume the specified type and amount of prey for an entire day. Conversely, many fish are highly mobile and swim across multiple locations, especially within thermal discharges [10, 19]. Fish moving between locations likely encounter fluctuating temperatures along the thermal discharge gradient, which have been shown to increase growth in largemouth bass [8]. Similarly, we used mean daily temperatures as the input for the GRP calculations which conceal any sub-daily temperature fluctuations from the thermal discharge. Bioenergetics models may not accurately predict growth under such short-term temperature fluctuations. Moreover, the ability of fish to move between multiple habitats during a day may collectively provide fish with a higher habitat quality than estimated from static GRP measures. Despite these potential drawbacks, using bioenergetics models to quantify habitat quality is a useful tool in understanding the potential positive and negative impacts of thermal discharges to fish.

Acknowledgments

Funding for this study was provided by the Ohio River Ecological Research Program (ORERP) and the Electric Power Research Institute (EPRI). We also thank Louisville Gas and Electric (LG&E), American Power Electric (AEP), Sharon McFarland, Tony Osborne, and Doug Dixon. Carolyn Foley, Christian Perry, Alison Coulter, and Emily Grimm provided field assistance.

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11

FORECASTING INLET COOLING WATER TEMPERATURES AS PART OF A DECISION SUPPORT SYSTEM TO MAXIMIZE ELECTRICAL POWER PRODUCTION

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Abstract

Within recent years, a number of thermoelectric power plants, both in the United States and around the world, have had to curtail electrical power generation during heat wave episodes that are often coincident with drought conditions. One major reason for the power generation curtailment has been to maintain compliance with thermal discharge criteria developed to protect aquatic life from adverse thermal effects.

It would be beneficial to power companies and their customers if periods of power curtailment could be anticipated before they occur, so that power plant operators could estimate the maximum amount of power that could be generated without violating thermal discharge criteria. It is the purpose of this report to identify decision support systems (DSS) for power generation management.

One option for developing such a DSS has been examined in this paper. This option for the DSS is a short-term (e.g., a few days to a few weeks) forecasting tool, so that forecasted information such as weather, upstream water temperatures, and flow rates would be required. Information provided by satellites may also be needed.

Experts from NASA, NOAA, and other organizations were contacted during the course of this research to solicit their experience with similar types of DSS systems, and they were asked to comment on the feasibility of developing a power generation DSS. Nearly all contacts who responded were not aware of the existence of any such power generation DSS. However interest in partnering in the development of such a DSS was shown by several contacts.

Introduction

Within recent years, a number of thermoelectric power plants, both in the United States and around the world, have had to curtail electrical power generation during heat wave episodes that are often coincident with drought conditions. One major reason for the power generation curtailment has been to maintain compliance with thermal discharge criteria developed to protect aquatic life from adverse thermal effects.

It would be beneficial to power companies and their customers if periods of power curtailment could be anticipated before they occur, so that power plant operators could estimate the maximum amount of power that could be generated without violating thermal discharge criteria. If this estimate of power production is less than the anticipated power generation needs, the power plant could operate as usual. If not, the power plant could be operated to minimize potential impacts.

Figure 11-1 illustrates these concepts. A thermoelectric power plant adjacent to a river is using an open-cycle cooling system, and heated effluent is discharged back into the river. A weather forecast calls for a warming trend to continue at least until the next week, and water temperatures at the power plant intake are projected to increase over the next 24 hours. If the power plant continues to operate tomorrow as it did yesterday, it is likely that thermal discharge criteria could be violated. To prevent possible exceedances, power generation would need to be curtailed.

To minimize power demand deficits it would be worthwhile to estimate the "optimum" power that could be generated without violating standards. If the demand for power exceeds this amount then the "lost" power would be minimized.

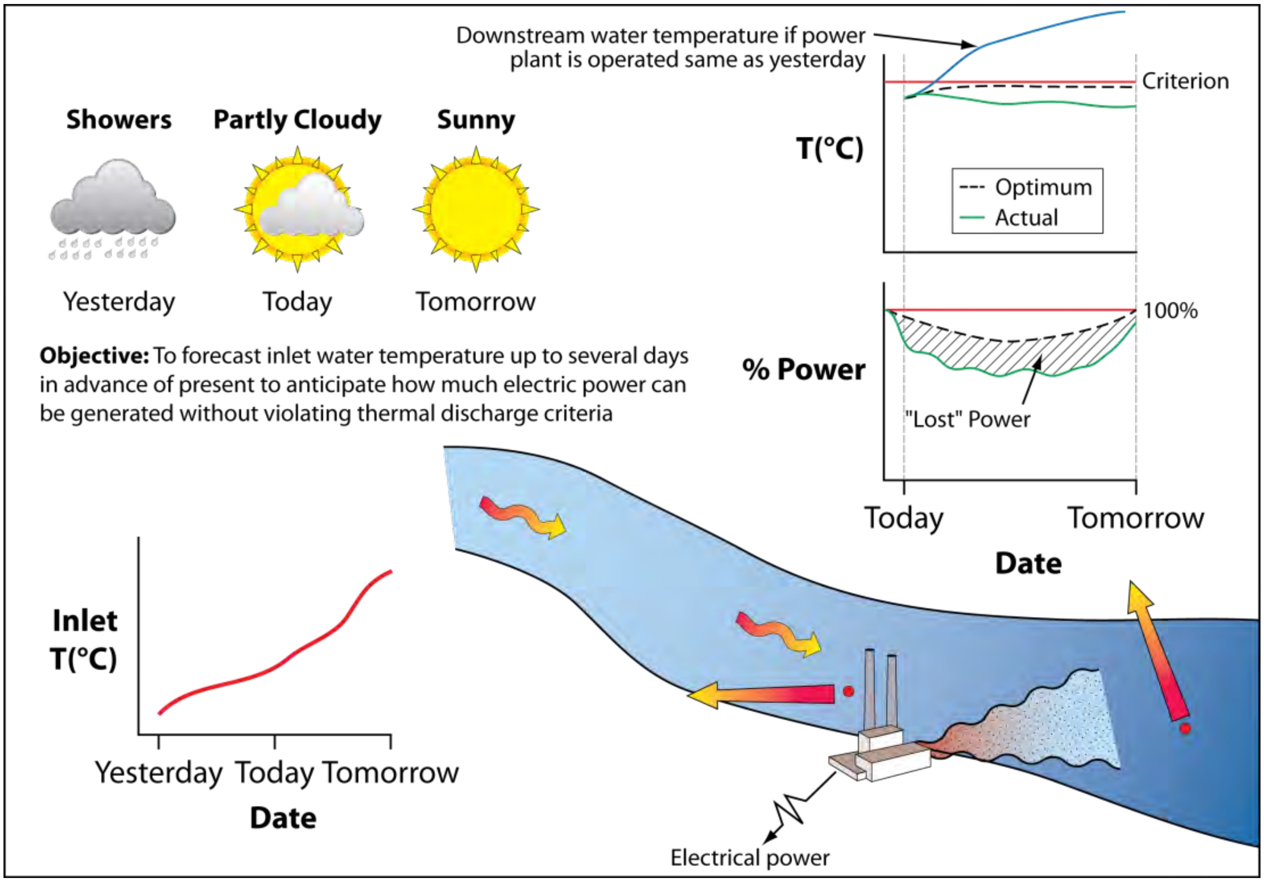


Figure 11-1
Conceptualization of forecasting to maximize electrical power generation

Purpose of this Paper

The purpose of this paper is to present the results of an exploratory research project that examines the plausibility of developing a decision support system (DSS) for electrical power generation during periods of extreme heat waves and concurrent drought. The tasks that have been completed and that are documented in this paper are as follows:

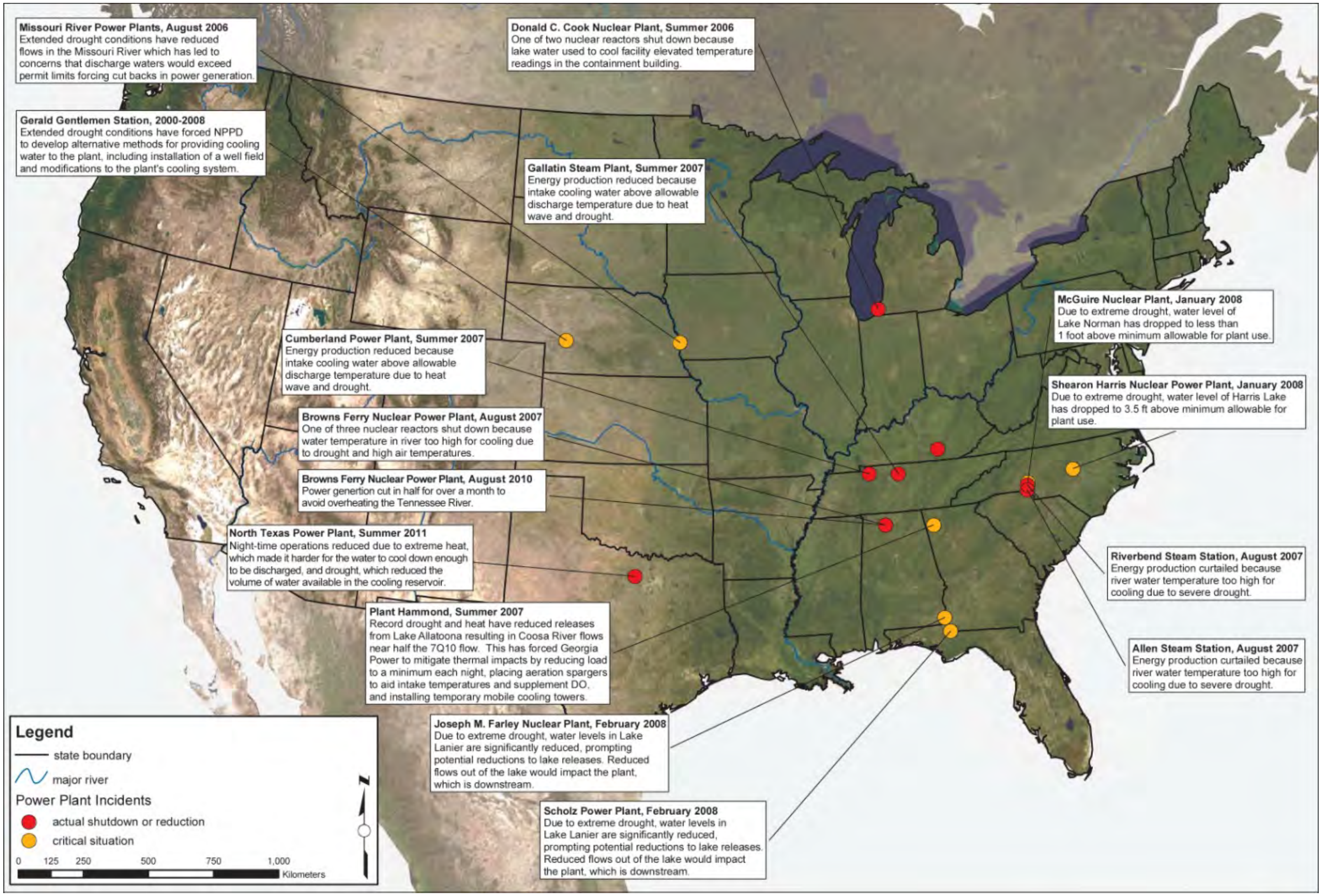
- Power plants that have curtailed electrical power generation in the past few years have been identified, and summaries of the circumstances have been provided.
- One option for developing a DSS has been examined. This option for the DSS is a short-term (e.g., a few days to a few weeks) forecasting tool, so that forecasted information such as weather, upstream water temperatures, and flow rates would be required. Satellite data may also be needed for short-term forecasting. Contacts with experts from NASA, NOAA, and others, who can provide a perspective on the feasibility of developing the envisioned DSS, have been made.
- A test DSS code to illustrate issues related to a full-scale DSS has been developed. Realistic synthetic data series are used so that the code can be tested under alternative conditions.
- Conclusions of the work and suggestions for further investigations are provided.

Examples of Power Plants That Have Faced Power Generation Curtailment Issues over the Past Few Years

Figure 11-2 identifies a number of power plants in the United States that have had to curtail power generation or have experienced critical conditions that, if conditions continued to worsen, could lead to reduction in power generation. The critical conditions are typically associated with heat-waves and droughts. The examples shown are recent. Most conditions shown occur in 2007 or 2008, and are associated with drought in the Southeast.

Figure 11-3 shows the cooling system type, on a nation-wide basis, for a large subset of power plants. The power plants previously shown in Figure 11-2 are identified by yellow arrows and employ once-through cooling systems. The large number of once-through, or open cycle, cooling systems indicates that the issue of power generation curtailment could become a more wide-spread issue should heat waves become more persistent and severe.

At least several of the power plants in the United States have taken actions to respond to the critical conditions they have recently faced. At the McGuire Nuclear Plant, water levels at the intake on Lake Norman in North Carolina had dropped significantly during the 2007 drought and were within one foot of the minimum level allowable. Since that time the intake elevation has been lowered three feet to provide additional buffer for drought situations. Plant Hammond in Georgia has taken multiple measures to help comply with thermal and dissolved oxygen standards. The measures include: nighttime load reductions, additional cooling towers, and dissolved oxygen aerators.



Missouri River Power Plants, August 2006
Extended drought conditions have reduced flows in the Missouri River which has led to concerns that discharge waters would exceed permit limits forcing cut backs in power generation.

Gerald Gentlemen Station, 2000-2008
Extended drought conditions have forced NPPD to develop alternative methods for providing cooling water to the plant, including installation of a well field and modifications to the plant's cooling system.

Donald C. Cook Nuclear Plant, Summer 2006
One of two nuclear reactors shut down because lake water used to cool facility elevated temperature readings in the containment building.

Gallatin Steam Plant, Summer 2007
Energy production reduced because intake cooling water above allowable discharge temperature due to heat wave and drought.

Cumberland Power Plant, Summer 2007
Energy production reduced because intake cooling water above allowable discharge temperature due to heat wave and drought.

Browns Ferry Nuclear Power Plant, August 2007
One of three nuclear reactors shut down because water temperature in river too high for cooling due to drought and high air temperatures.

Browns Ferry Nuclear Power Plant, August 2010
Power genertion cut in half for over a month to avoid overheating the Tennessee River.

North Texas Power Plant, Summer 2011
Night-time operations reduced due to extreme heat, which made it harder for the water to cool down enough to be discharged, and drought, which reduced the volume of water available in the cooling reservoir.

Plant Hammond, Summer 2007
Record drought and heat have reduced releases from Lake Allatoona resulting in Coosa River flows near half the 7Q10 flow. This has forced Georgia Power to mitigate thermal impacts by reducing load to a minimum each night, placing aeration spargers to aid intake temperatures and supplement DO, and installing temporary mobile cooling towers.

Joseph M. Farley Nuclear Plant, February 2008
Due to extreme drought, water levels in Lake Lanier are significantly reduced, prompting potential reductions to lake releases. Reduced flows out of the lake would impact the plant, which is downstream.

Scholz Power Plant, February 2008
Due to extreme drought, water levels in Lake Lanier are significantly reduced, prompting potential reductions to lake releases. Reduced flows out of the lake would impact the plant, which is downstream.

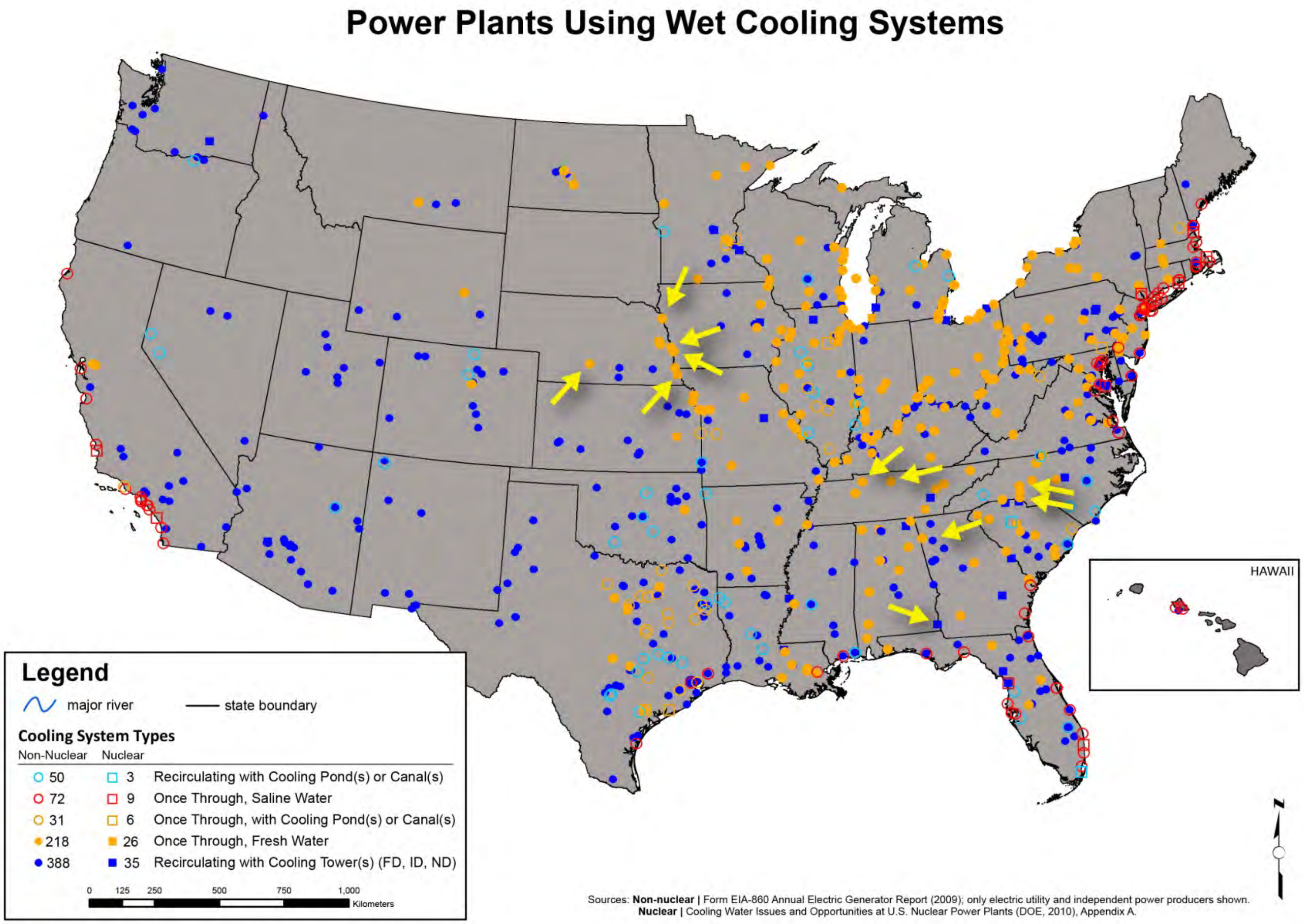
McGuire Nuclear Plant, January 2008
Due to extreme drought, water level of Lake Norman has dropped to less than 1 foot above minimum allowable for plant use.

Shearon Harris Nuclear Power Plant, January 2008
Due to extreme drought, water level of Harris Lake has dropped to 3.5 ft above minimum allowable for plant use.

Riverbend Steam Station, August 2007
Energy production curtailed because river water temperature too high for cooling due to severe drought.

Allen Steam Station, August 2007
Energy production curtailed because river water temperature too high for cooling due to severe drought.

Figure 11-2
Power plants identified that have experienced power generation curtailment or have faced critical conditions that could lead to curtailment. The examples shown focus on occurrences mostly 2007–2008.



Sources: **Non-nuclear** | Form EIA-860 Annual Electric Generator Report (2009); only electric utility and independent power producers shown.
Nuclear | Cooling Water Issues and Opportunities at U.S. Nuclear Power Plants (DOE, 2010), Appendix A.

Figure 11-3
Cooling system type for coal fired power plants and nuclear power plants [1, 2]. (Yellow arrows point to those power plants previously shown in Figure 11-2 and all plants with known cooling systems that are open cycle).

Alternative Approaches to DSS System Development

The first approach to DSS development that is examined in this report has been previously described (see Figure 11-1). To summarize, the projected forecast time period may range from a few hours from the present to a week or two into the future. Forecasts require the assimilation of weather and satellite data over the forecast period into algorithms (either statistical or mechanistic) that are intended to forecast inlet temperatures at a specified future time. For example, a ten-day forecast made on 3-August 2009 at 2 pm is intended to generate an estimate of inlet temperatures 10 days later (13-August 2009 at 2 pm). These ten-day forecasts must be made continuously (say hourly), and not just once, in order to maintain the desired forecast period. This approach to forecasting and data assimilation (data assimilation refers to the use of remotely sensed data and weather models to help make water temperature forecasts) has been developed and used by NASA and NOAA (although for purposes other than inlet temperature forecasting).

Several European countries have shown an interest in developing a DSS for water temperature forecasting, and they approach the problem quite differently. This second approach does not forecast inlet water temperatures tied to specific dates, but rather assesses whether historical weather and related data that have been collected in the winter and spring before the summer of interest can be used with any degree of confidence to assess likelihood of summer heat wave and drought conditions [3, 4, 5, 6].

A third approach, which is not truly forecasting, should also be mentioned because of its practicality. For this approach, only historical data are used, and are processed to establish statistics for the frequency and duration of historical heat waves and droughts. Long-term records are needed to do these analyses, and the results can be directly used for planning without the need for forecasting.

During this project numerous people who work for NASA, NOAA, and other organizations were contacted with the intent of asking them about the feasibility of developing a DSS for water temperature inlet forecasting. Contacts were also made in related fields (such as flood forecasting) as well. Approximately 30 contacts were made in total, and initial contacts focused on NASA.

NASA's Short-term Prediction Research and Transition Center (SPoRT) is located in Huntsville, AL and has relevance to this project. The primary focus of SPoRT is to support forecast improvements for the National Weather Service for a time scale of 0 to 24 hours. The spatial scale is regional (e.g., the Southeast). The forecasting techniques make use of a geostationary orbiting satellite that can provide continuous observing capability to monitor short-lived weather phenomena. Research underway at SPoRT is focused on improving forecasts using remotely sensed data collected from satellites.

A number of offices within NOAA's National Weather Service's (NWS) River Forecast Center (RFC) were also contacted. None of the personnel contacted were aware of water temperature forecasting activities by the NWS-RFC. Several people expressed interest in this topic, and indicated that the NWS-RFC might someday become involved in this area.

In addition to NASA offices, NOAA's NWS-RFC might in the future provide useful information related to inlet temperature forecasting. There are several reasons for this. One, while at present the NWS-RFC focuses on flood forecasting, it might be possible to transition to low flow forecasting as well. Two, there are 12 RFCs in the continental United States, and 122 weather forecast offices. Within each RFC, flow rate gages exist where flood forecasts are made. This distributed network would be useful in making localized inlet temperature forecasts. Figure 11-4(a) provides an illustration of the network used by the Southeast RFC. All of the RFCs in the United States are shown in the upper right corner. Figure 11-4(b) shows the distribution of weather forecast offices.

Table 11-1 shows a number of on-board instrument packages used by NASA and other organizations for Earth science applications. The intent here is to focus on the revisit period or repeatability (how frequently the same “patch” of earth is monitored), and the spatial resolution of that monitoring. For the forecasting applications envisioned for this project, continuous coverage at high resolution may be needed. Notice that such coverage does not yet appear to be available in present satellites. Also included in the table are several references to commercial satellites. At present, resolution of imagery is at the meter scale.

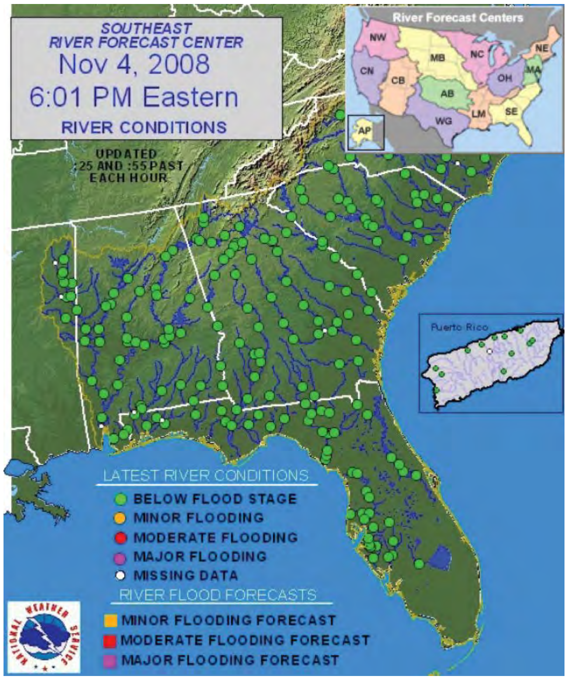
Of particular relevance to this project are the GOES satellites that orbit above the earth’s surface at the same speed as the earth rotates, so that each satellite remains over the same location on earth. This feature enables the continuous assimilation of real-time data into regional weather forecasting models, a necessary feature for the inlet temperature DSS.

While sea surface temperatures (SSTs) and their measurements by satellite are not of direct concern to this work (inland water temperatures and their measurement by satellite are however) it is worthwhile to briefly review the limitations of satellites to estimate SSTs. Since the 1980s satellites have been increasingly utilized to measure SST and have provided an enormous advance in understanding the spatial and temporal variations in SST. Satellite measurements of SST are far more consistent and, in some cases, more accurate than in situ temperature measurements. The satellite measurement is made by sensing the ocean radiation in two or more wave lengths in the infrared part of the electromagnetic spectrum or other parts of the spectrum which can then empirically be related to SST.

The satellite measured SST provides both a synoptic view of the ocean and a high frequency of repeat views, allowing the examination of basin-wide upper ocean dynamics not possible with ships or buoys. For example, a ship traveling at 10 knots (20 km/h) would require 10 years to cover the same area a satellite covers in two minutes.

However, there are several difficulties with satellite based SST measurements. First, using infrared remote sensing methodology, the radiation emanates from the top "skin" of the ocean, approximately the top 0.01 mm or less, and may not represent the bulk temperature of the upper meter of the water column. Second, the satellite cannot look through clouds, creating a "fair weather bias" in the long term trends of SST. Nonetheless, these difficulties are small compared to the benefits in understanding gained from satellite SST estimates.

(a) Southeast River Forecast Center (RFC) network



(b) NWS's 122 weather forecast offices [7]

Sources: NWS and MapArt.

Figure 11-4
NWS Southeast River Forecast Center and National Weather Service Forecast offices

Table 11-1
Examples of satellites and on-board instruments for earth science applications

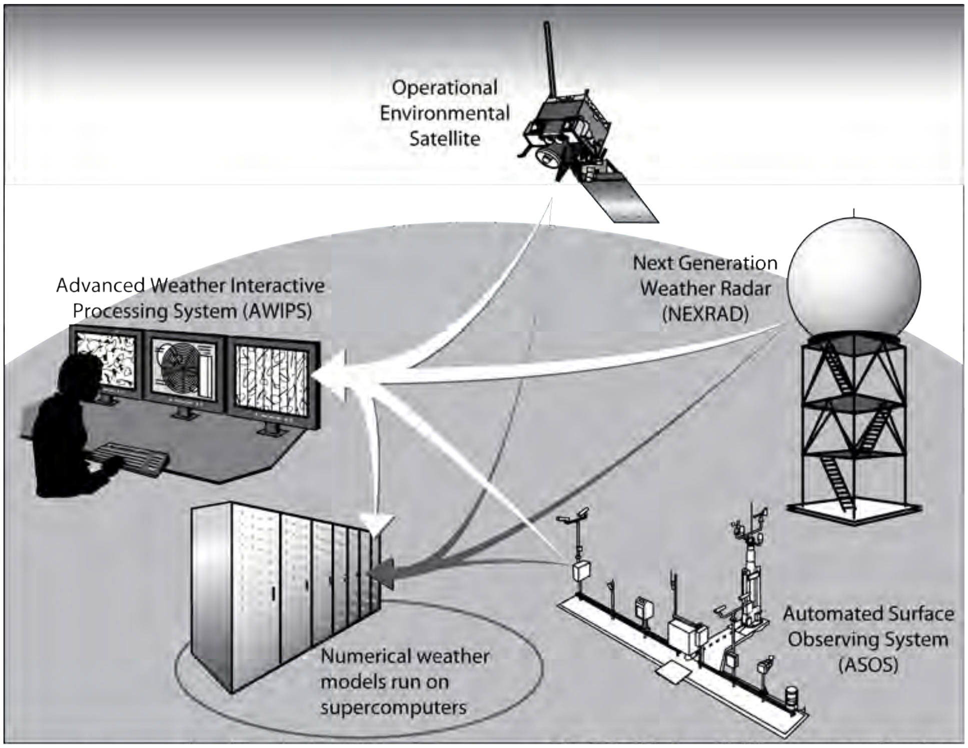
Name[1]	Measurements	Revisit Period	Spatial Resolution
MODIS launched on Terra and Aqua in 1999 and 2002 (http://modis.gsfc.nasa.gov/about)	General land, ocean, atmosphere; visible to infrared range	1 day	One to two km (SST) 500 m (snow cover)
ASTER (1999 and 2002) launched on Terra and Aqua (http://asterweb.jpl.nasa.gov)	Local scale studies, visible to infrared range; land surface temperature maps	16 days	15 to 90 m
AMSR-E launched on Aqua in 2002 (http://wwwghcc.msfc.nasa.gov/AMSR/)	Limited coverage of USA. Measures sea surface temperature and soil moisture.	1 day	5 to 50 km
GOES (http://goes.gsfc.nasa.gov/text/goesfaq.html)	Geosynchronous satellite; Provides information for short-term weather forecasting and severe storm information	Continuous over parts of USA (orbits at 1 cycle per day)	100's km
GRACE (2002) twin satellites (http://www.csr.utexas.edu/grace/)	Gravitational anomalies: terrestrial water storage	One to two days	400 km
LandSAT services launched in 1972 to 1999 (http://landsat.gsfc.nasa.gov/about/)	Moderate resolution images of Earth's landscape have been archived to provide large spatial coverage and long time frame of images,	16 days	60 m or higher
Geoeye (http://launch.geoeye.com/LaunchSite/)	High resolution images of earth-surface features(0.5 m)	Every 3 days or less	0.4 m
Digital Globe (http://www.digitalglobe.com/)	Also a commercial enterprise that provides sub-meter imagery from multiple satellites.	Similar to above	0.6 m-2.0 m
AVHRR on polar orbiting satellites (http://coastwatch.cheasapeakebay.noaa.gov/cw_avhrr.html)	Sea surface temperature (±0.5°C), surface vegetation, snow cover, and other features	6 hours	1.1 km
TRMM (http://trmm.gsfc.nasa.gov)	Soil moisture and rainfall distribution for use in forecasting flash floods	16 times/day	2-5 km

[1] Moderate Resolution Imaging Spectroradiometer (MODIS)
Advanced Spaceborne Thermal Emission and Reflection (ASTER)
Advanced Microwave Scanning Radiometer (AMSR-E)
Geostationary Operational Environmental Satellite (GOES)
Advanced Very High Resolution Radiometer (AVHRR)
Tropical Rainfall Measuring Mission (TRMM)

Systems and Technology to Support Forecast Generation

Figure 11-5 shows an overview of the key systems and technologies that support generation of short-term forecasts, as depicted by the General Accounting Office (GAO) [4]. Such a system, with appropriate satellites, surface observing systems, processing systems, and weather models are all used together to generate these forecasts. Even with this advanced level of technology, there presently exist significant issues associated with developing an inlet water temperature DSS that include:

1. **Real time requirements to generate each forecast.** Each forecast should be generated at a high frequency and may continue over 2-4 months. Suppose a one-week forecast is needed from mid-June to mid-October, designed to capture a critical high-temperature low-flow condition. To maintain the one-week forecast, forecasts have to be issued at a high frequency (say hourly), or the one-week forecast throughout the critical period would not be maintained. This means that 24x30x4=2880 forecasts would be issued. It may not be possible for the DSS to issue such a high frequency of forecasts, given the amount of information processing required. However, a lower frequency (e.g., every 3 hours) may be acceptable.
2. **Instrumentation requirements.** The technology and instrumentation needed to implement a DSS could be extensive. The costs associated with developing and maintaining a heavily instrumented DSS system would need to be estimated before committing to this expense.
3. **Reliability.** System reliability needs to be high to issue the 2880 forecasts estimated previously. Should the information generation system fail in some component (such as satellite-generated data), either the forecasts would cease, or a simpler back-up system could operate (less accurately) temporarily.
4. **Accuracy.** Ultimately, the DSS system needs to accurately forecast inlet temperatures for it to be of value. The question becomes “How accurate?” Since the goal of the DSS is to forecast optimal power generation without violating permit conditions, the DSS needs to make very accurate predictions. Otherwise, a safety factor could be incorporated into the analysis. If the safety factor is too large, the purpose of the DSS would be defeated. Later in this section, an example illustrates that depending on the inaccuracies of the data assimilated into the forecasting system, forecasts can be either very accurate or very inaccurate.
5. **Nature of Permit Conditions.** The nature of the permit conditions themselves need to be considered. In several of the examples shown later, three different permit conditions were assumed to require simultaneous compliance. Other types of conditions, such as allowing no more than a specified number of exceedances over a time frame such as a week, could require even more computational effort and lead to non-unique solutions.
6. **Multi-dimensional Water Temperature Profiles.** Large power plants that use open-cycle cooling systems likely discharge into large rivers and may generate three-dimensional temperature profiles. This further complicates inlet water temperature predictions. Recirculation of effluent in the receiving water is an additional complicating issue. Satellites provide information to predict surface water temperatures, so the degree that important vertical and lateral temperatures gradients exist, these need to be simulated.



Source: GAO.

Figure 11-5
Overview of key systems and technologies supporting NWS forecasts [8]

7. **Alternative Simpler DSS Frameworks.** It might be appropriate to examine and test alternative simpler DSSs to prove the concept before attempting to implement a comprehensive DSS based on the approach shown in Figure 11-5. Several examples using simplified algorithms are shown later in this report.
8. **Limitations of Satellite Coverage and Resolution.** At present it does not appear that satellite coverage, resolution, and repeatability (revisit time) of data generation are sufficient to support the development of the inlet temperature DSS. To provide a continuous forecast (say over several months) a continuous stream of high resolution data near a frequency of one hour would be needed.

Test Code Applications to Illustrate Concepts of Short-term Forecasting

In order to illustrate the concept of water temperature inlet forecasting and to help clarify what such a DSS might be able to do, several test codes were developed. The codes consist of both a river temperature model, and statistical techniques. Since the ultimate goal of the DSS is to maximize electric power production without violating thermal permits, additional test code was developed to illustrate how power generation might be impacted by heat-wave events, by drought-like flow conditions, or by climate variability. The test codes were developed for two reasons. Reason one was out of necessity: no such codes appropriate for this analysis were found. Reason two was that by developing a test code, what the code does is completely understood, and better insights can be provided into the process of forecasting.

An overview of the components of the DSS test code is shown in Figure 11-6. The DSS code consists of three major components:

- **Data generation module.** Meteorological data from weather prediction models are synthetically created to illustrate how the DSS would respond to continuously changing weather conditions. The predictions are assimilated into the forecasting model.
- **Uncertainty Analysis Module focusing on spin-up period.** The concept of a spin-up period was conceived and implemented. A spin-up period is defined as a period of time generally several months before the time when forecasting begins. Since forecasting is expected to be implemented during the hot, dry months of the year (say July through September), the spin-up period could be the spring (say March through June). It is assumed that data are continuously collected during this period of time (including inlet water temperatures) that can be analyzed prior to the forecast period and eventually help to make better forecasts, and to estimate the magnitude of predicted uncertainties.
- **Forecast Model.** The part of the test code that actually makes the inlet temperature forecasts is called the forecast model. While the model theoretically can make forecasts far into the future, such forecasts eventually become dominated by uncertainties, and are of no use.

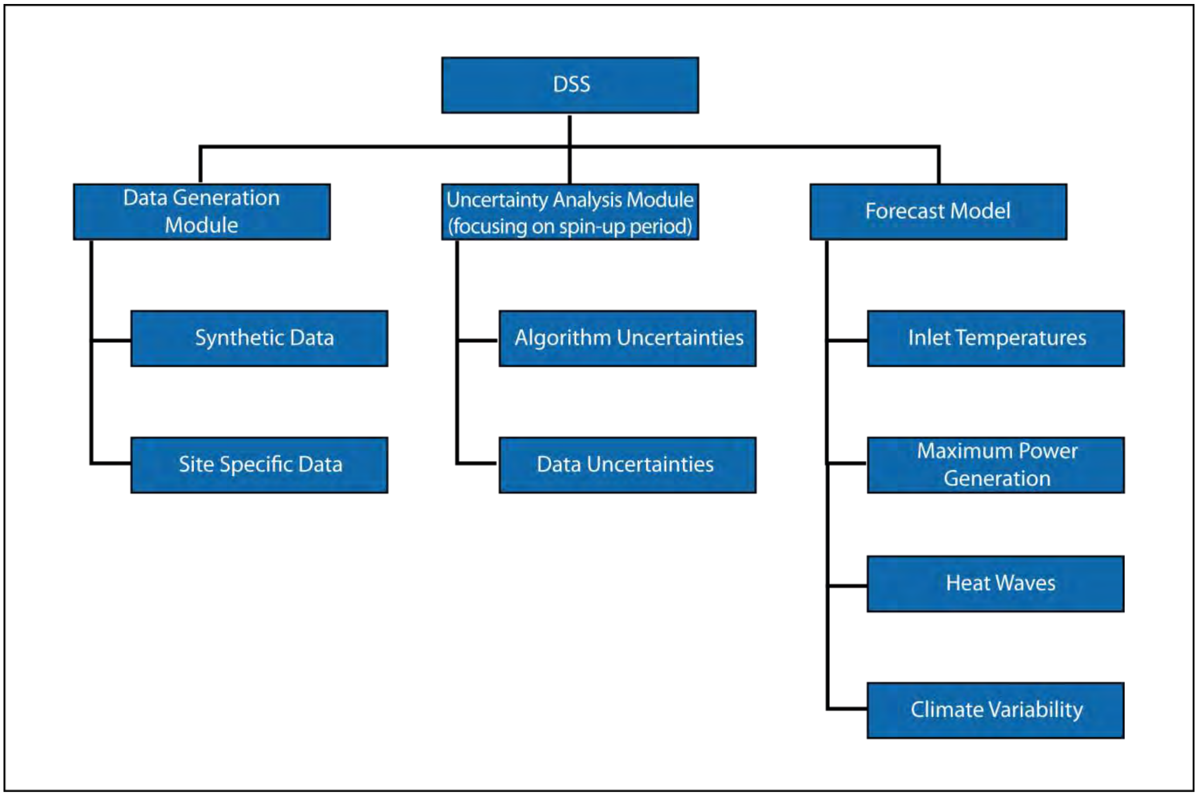


Figure 11-6
Components of the DSS test code

Examples follow that illustrate the concept of short-term forecasts using the test codes. The six examples are summarized in Table 11-2. However, only three (#1, #3, and #5) are shown in detail. Since the ultimate purpose of these forecasts is to determine how much electrical power could be generated without violating thermal standards, several of the examples address this issue. The synthetically generated air temperature and other input variables are allowed to vary by time of day and season of the year, which is a realistic pattern over much of the United States.

Table 11-2
Six forecasting examples

Example #	Focus of Example	Description
1	Concepts of a basic forecast.	This example illustrates an eight-hour forecast made continuously for a one-week period, and shows how data assimilation can improve the quality of the forecast. It further illustrates how electrical power generation is affected by the forecasts.
2	Impacts on forecast of assimilating data with unknown errors.	This example illustrates that some error in the assimilated data can be tolerated, but if these errors become large enough the forecast is no longer useful.
3	Impacts of passage of heat wave conditions on electrical power generation.	The impacts of heat waves on limiting power generation are evaluated.
4	Impacts of climate variability on electrical power generation.	The meteorological forcing used in previous examples is changed on a seasonal basis to illustrate impacts on electrical power generation.
5	Use of regression analysis in forecasting.	As an alternative technique to those illustrated in examples #1 through #4, a regression approach was used.
6	How a linear water temperature profile in time can influence forecast accuracy.	For water temperature profiles that do not change abruptly or oscillate significantly on a daily basis, forecasts can be more accurate.

Example #1: A Basic Forecast

Prior to presenting this example, it is worthwhile to review the concepts of forecasting as used here. Forecasts are made with specific target time periods in mind. Suppose a continuous forecast is needed for a one-week period. Then a week's worth of continuous forecasts is needed. If the forecast interval is one hour, 24x7=168 forecasts are needed.

Because we have developed test codes and do not have access to site-specific data sets, we developed synthetic data which is based on weather forecasting models that supply the estimates of future air temperature, etc. Using the synthetic data sets we can incorporate uncertainties or errors into the data to account for the limited precision of instruments, or simply remove some of the data from the synthetic record to simulate missing data.

Example #1 illustrates the basics of a forecast. First, synthetic meteorological data are generated over a period of interest, in this case from the spring of 2009 to the fall of 2009. An example air temperature profile used is shown in Figure 11-7. The forecast period begins June 1, 2009 and continues until the end of September 2009 (yellow panel in Figure 11-7(a). Prior to June 1, 2009, the three month period is called the spin up period. By the time forecasts begin (June 1), the spin up data are historical and can be used to help make forecasts more accurate. The air temperature data during the forecasting period are assumed to be generated from short-term weather forecast models. It is this data that is input (assimilated) into the forecasting tools.

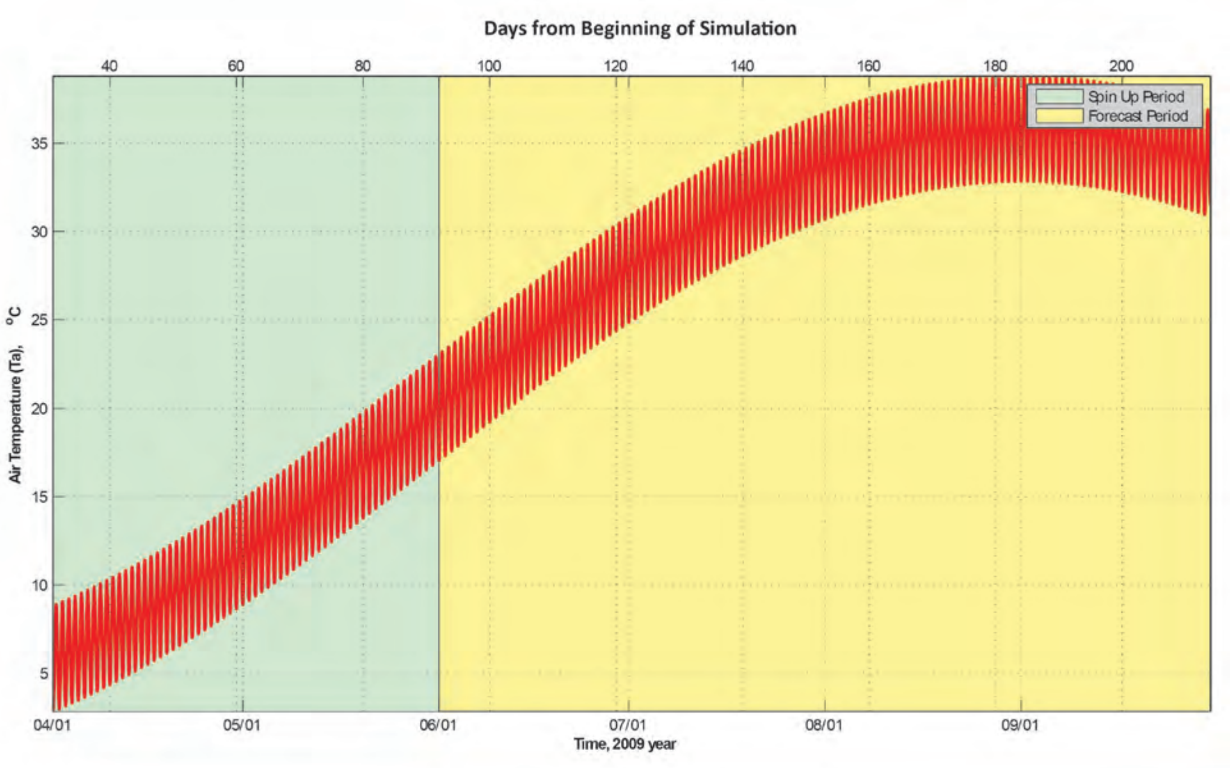


Figure 11-7
Air temperature profile used for forecast in Example #1

Only two days of the nearly 4 months forecast is shown in Figure 11-8. The forecasts are continuous, and are eight hours into the future. The forecast is typically made each hour over the four-month forecast period. The blue bar denotes present time during the summer of 2009.

To the right of the blue line is the future, and two types of forecasts are shown. First are the "exact" forecasts where the future weather data (such as air temperature) are perfectly assimilated into, or used by, the predictive inlet temperature algorithm (given by blue diamonds). Second are forecasts made without using any assimilated or "future" data (which could occur if the transmission of forecasted data was disrupted). To the left of the present date the forecasted data are again shown (they are in the past) along with the historical record of inlet data (it is assumed that the inlet is instrumented). The perfectly assimilated data compare very well with historical inlet temperatures, as they should. On the other hand, it can be seen that the forecasts not using the assimilated data are generally very poor. They are up to 4°C different from the actual inlet temperatures. One of the reasons for this large discrepancy is that the observed temperatures are rapidly fluctuating so that conditions change dramatically over the forecast time interval, and good input data are needed to make accurate forecasts.

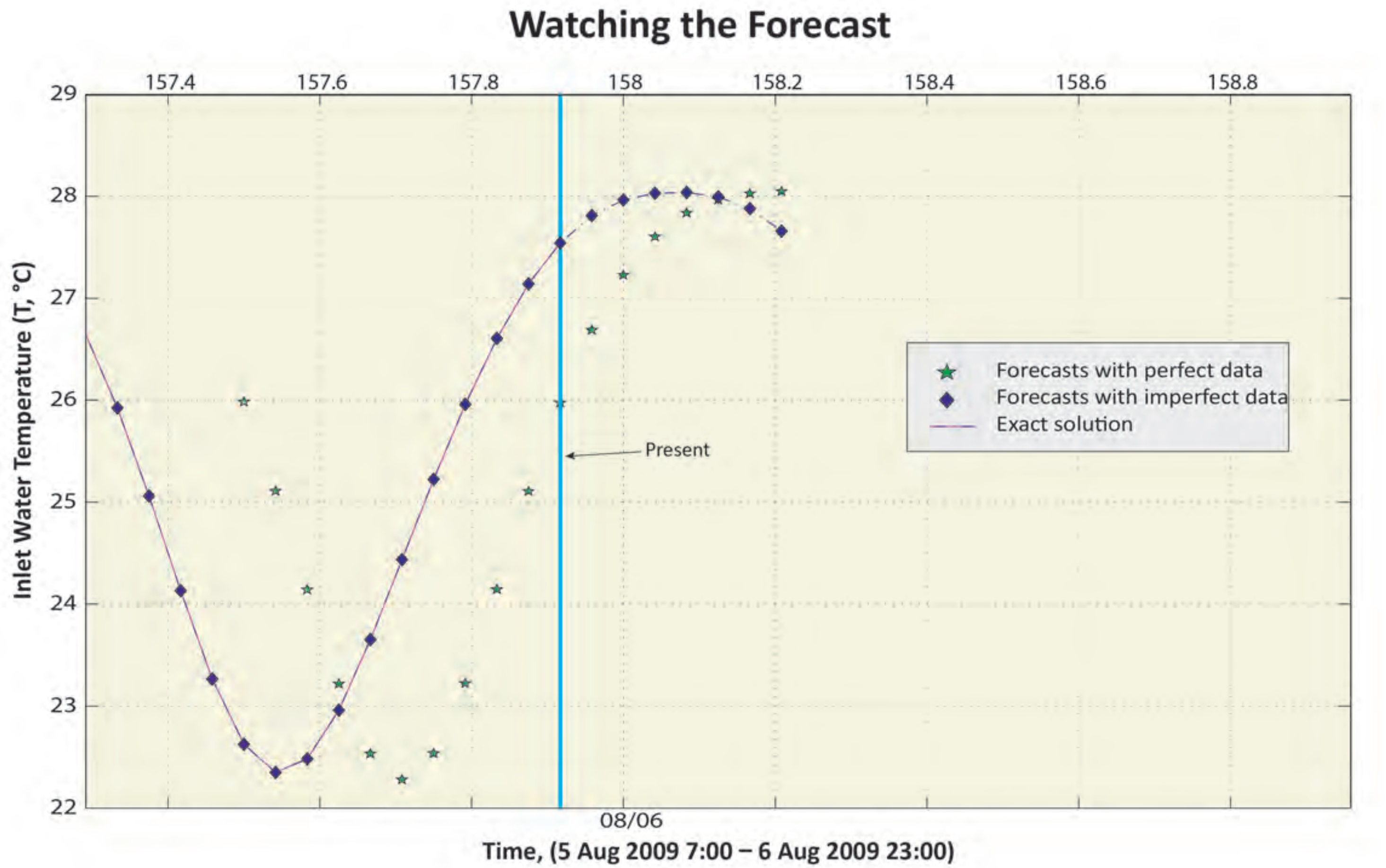


Figure 11-8
Inlet temperature forecasting over two days: Example #1
(The forecasts are eight-hour forecasts that are made every hour over the two day period shown. The blue bar denotes the present time, and this bar moves from left to right across the plot to denote the passage of time. The blue diamonds denote forecasts with perfect assimilation of the data from the forecast period and green stars denote forecasts with no data assimilation at all).

As mentioned previously, the forecasts are eight-hour forecasts, and they are made hourly. This is why the blue diamonds and green stars are spaced at hourly intervals. Looking to the right of the present day line, the eight-hour forecasts can be seen as the blue and green symbols. This example illustrates the process of forecasting, and shows that by accurately assimilating the input data, forecasts can be accurate.

Example #2: Forecasted Power Reduction to Reduce Thermal Standard Violations

First, the power generation limitation analyses are shown. Figure 11-9 shows a period of time of approximately 20 days. It is assumed that three water temperature criteria need to be simultaneously satisfied:

- Maximum water temperatures in the mixing zone that can exist (denoted by TMAX and it is 35°C)
- The maximum water temperature difference that can exist (denoted by ΔTMAX, which is the difference in the water temperature in the mixing zone and the inlet water temperature (10°C in this example))
- The maximum discharge temperature before mixing which is 45°C in this case.

Based on a specific set of meteorological data and river conditions, the forecasted river water temperatures and how those temperatures compare with the thermal standards are shown. The predicted temperatures in the first two panels (column 1) do not exceed the thermal criteria (the thermal criterion is denoted by the dashed blue line). Because neither the first nor second criteria are exceeded, neither of those criteria limit the power that can be generated, as can be seen from the first two panels in the second column. However, the third criterion is exceeded, and in order to prevent permit exceedances, the power generated has to be curtailed as shown by the panel 3 plot in the second column. The oscillating green line is the maximum power that could be generated during this time period. Note that if only 350 MWe of power are needed, all criteria are satisfied and the power plant can operate without constraints. However, for maximum power production without violating criteria, the oscillating red curve should not be exceeded.

Figure 11-10 shows the maximum power generation, (first column, first panel) that can be generated without violating any criteria. For this example the maximum power generation is the same as shown previously in Figure 11-9, second column, third panel because only the discharge temperature is limiting. More generally, the maximum allowable power generation would be set based on limitations from up to all three criteria. The remaining three panels in Figure 11-10 show how the water temperatures would compare to the criteria. Note that all criteria, including the discharge temperatures, are met. Specifically, the discharge temperature would range between 44°C to 45°C, where formerly they ranged from 44°C to nearly 50°C.

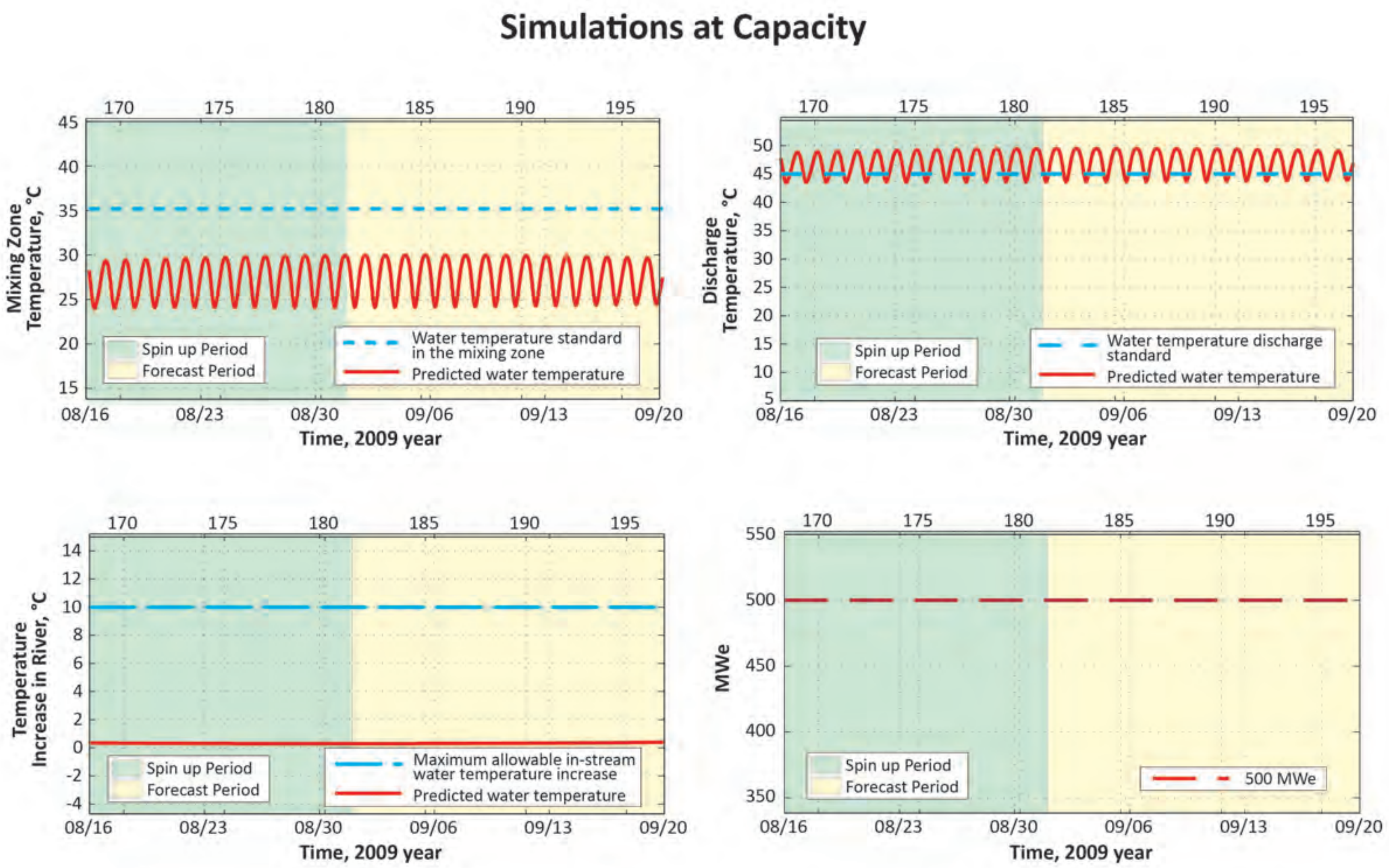


Figure 11-9
Water temperature criteria vs. forecasted temperatures, and maximum power that can be generated not to violate criteria. (The dashed blue line in the first column of figures denotes thermal standards: maximum allowable water temperature, maximum allowable temperature increase in the river, and maximum discharge temperatures. In the second column, the maximum allowable amount of electricity generated over the period is shown. Maximum allowable refers to the amount of electricity that can be produced without violating the thermal standards. The power plant capacity is 500 MWe in this example.)

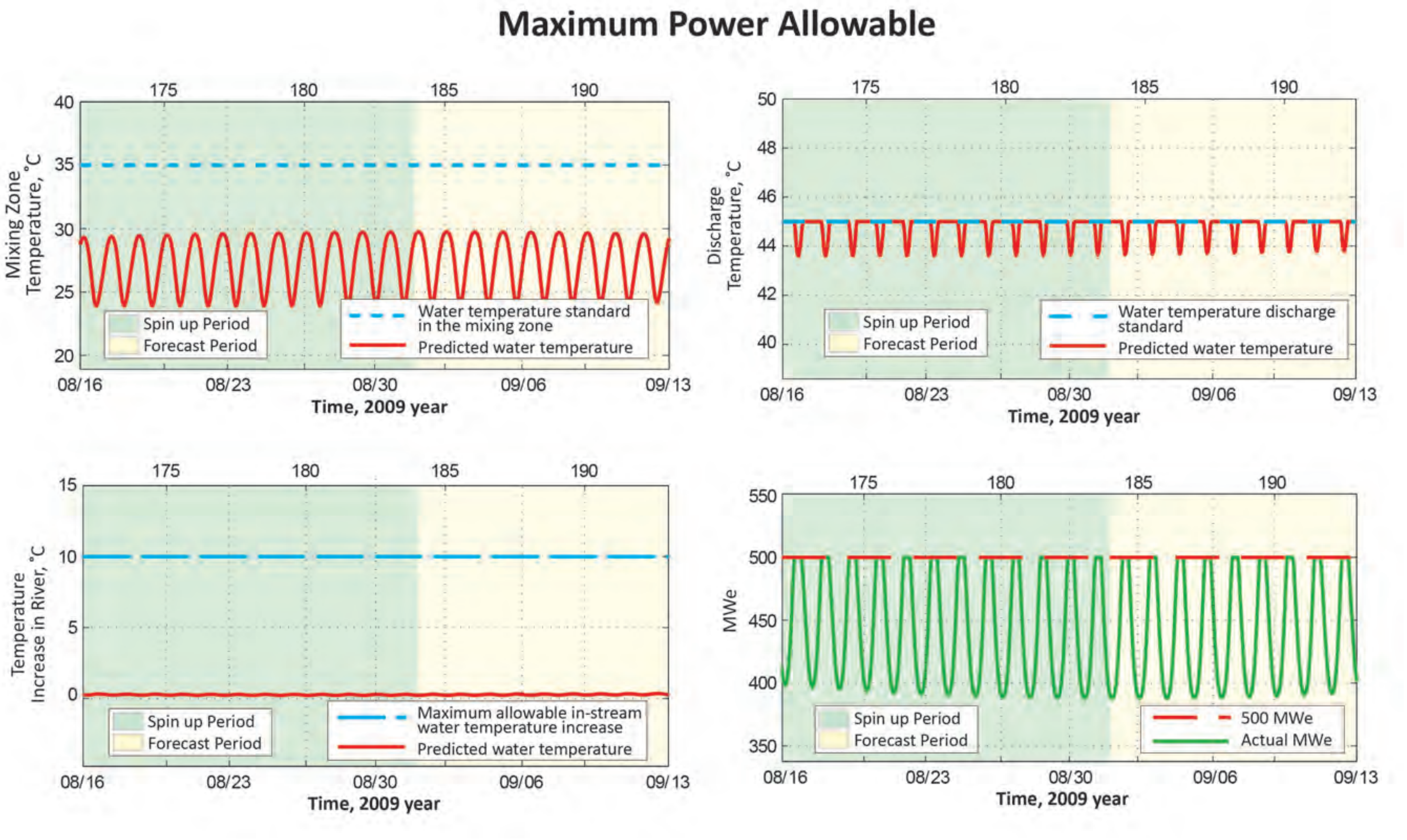


Figure 11-10
Maximum permissible power to maintain compliance with all criteria. The dashed blue lines are the thermal standards.

Example #3: The Impacts of Passage of Heat Wave Conditions

In this example, the effects of warm frontal systems are evaluated. Warm fronts, as used here, are periods of time (perhaps a few days to a week) when air temperatures are significantly higher than normal. As a result water temperatures tend to increase, and power production may need to be curtailed to prevent exceedances of thermal standards. In Figure 11-11(a), five fronts pass between the period examined (March through September 2009). Air temperatures increase by 3°C to 5°C during the passage of four of the fronts, and decreases during the passage of the fifth front. The responses to the fronts are shown in Figure 11-11(b), in terms of optimal electrical power production such that thermal standards are not exceeded. The most important conclusion from this plot is that if warm fronts occur during the middle of the summer when air temperatures are typically high anyway, the water temperature increases can cause the plant to be shut down or else violate standards. As seen in Figure 11-11(b), power production would go to zero for a few days in August. Without the heat wave, power production could be as high as 400 MWe during that time.

Example #4: Use of Regression Analysis to Train Forecasts during Spin Up Period

In this example, data from the spin up period were used to “train” a statistical algorithm (linear regression) that would then be used to make forecasts during the subsequent forecast period. Figure 11-12 shows the situation that is simulated. In this case it is assumed that data have been continuously collected during the spin up period at the three locations shown. A regression analysis was used to generate a least-squares error estimate of the inlet temperatures, during the spin up period. Figure 11-13 illustrates the forecasts. As seen in Figure 11-13 (a) the forecasts become progressively worse over time following the end of the training period (spin up). This is not unexpected, as the spin up period training becomes less relevant as time passes.

This deterioration in forecasting accuracy can be remedied as follows. As the forecasting period unfolds, inlet temperature should be re-calculated using the spin up period in Figure 11-13 (b). The trained inlet temperature can also be continuously updated with the most recent data in order to keep forecasts as accurate as possible.

Summary and Conclusions

This paper has examined the feasibility of developing a decision support system (DSS) that would help power plant operators anticipate upcoming periods of heat waves and droughts. The DSS is for short term forecasts, and is intended to provide power plant operators with estimates of reductions in electrical power generation needed to comply with thermal standards. Forecasts would be made over a period of time into the future (say 5 days). The forecasts would be made continuously (say hourly) in order that the 5-day forecast be continuously updated. For example, suppose 5-day forecasts were to be made over the three warmest summer months: July, August, and September (92 days). The number of hourly five-day forecasts would be 92x24=2,208. Based on the contacts made and literature reviewed during this project, it does not appear that a DSS of the typed described above exists. Further, it does not appear forecasting is being done for any water quality variable based on information from NOAA. A test DSS code was developed specifically for this project in order to illustrate the basic concepts of the DSS. Six examples were developed using the test code. The examples include forecasting of inlet water temperature and predicting how power plant electrical energy generation might be impacted to maintain compliance with thermal criteria. Those criteria were used in the examples to illustrate how they would simultaneously be satisfied.

Experts from NASA, NOAA, and other organizations were contacted during the course of this research to solicit their experience with similar types of DSS systems, and to comment on the feasibility of developing a DSS. Nearly all contacts who responded were not aware of any such support systems. Generally it does not appear that the current generation of satellites has the combination of high spatial resolution and temporal frequency of data retrieval needed for the envisioned DSS system. In spite of this, a number of the contacts expressed the opinion that such an idea had merit, and could be pertinent to the work they do.

During the course of this research, it was found that both statistical and mechanistic techniques are being used for various forecasting applications (but not for the type of DSS envisioned here) by experts at NASA and other organizations. Statistical techniques appear to be more widely used for seasonal forecasts, where winter-spring conditions are correlated with forecasted summer conditions. Mechanistic techniques appear to be widely used by NASA in many of their short-term forecasting applications.

The following suggestions or recommendations have emerged from this work:

- During the course of this research, it was found that several power plants did take action to reduce potential impacts associated with critical low-flow, heat-wave situations. For example, at one power plant, the water inlet was lowered by a meter in the intake reservoir. Identification and examination of options for mitigating adverse impacts at power plants across the country would be a worthwhile undertaking.
- A number of researchers were enthusiastic about the idea of developing a DSS for inlet water temperature. Those researchers might be willing to collaborate with EPRI on future research efforts of this type. Of particular relevance would be research associated with the NWS, the River Forecasting Center (RFC), NASA, NOAA, European Researchers, and possibly NCAR. If it were possible for the RFCs to forecast low flow conditions, then a nation-wide infrastructure would exist that could be used to plan for drought conditions, which are often associated with heat-waves. The many local NWS weather forecasting centers would provide a nation-wide basis for local forecasts. A workshop is suggested where those who have shown an interest in this topic are brought together to exchange information, and to identify next steps.
- A number of power plants around the United States, including those that have experienced power curtailment issues, might have over the years accumulated long-term operational and monitoring data sets. Such data sets, along with climatic and weather data available from organizations such as NOAA, could be used to examine issues such as the historical frequency and severity of heat-wave and drought conditions. This information could be useful for long-term planning to address these critical discharge situations.

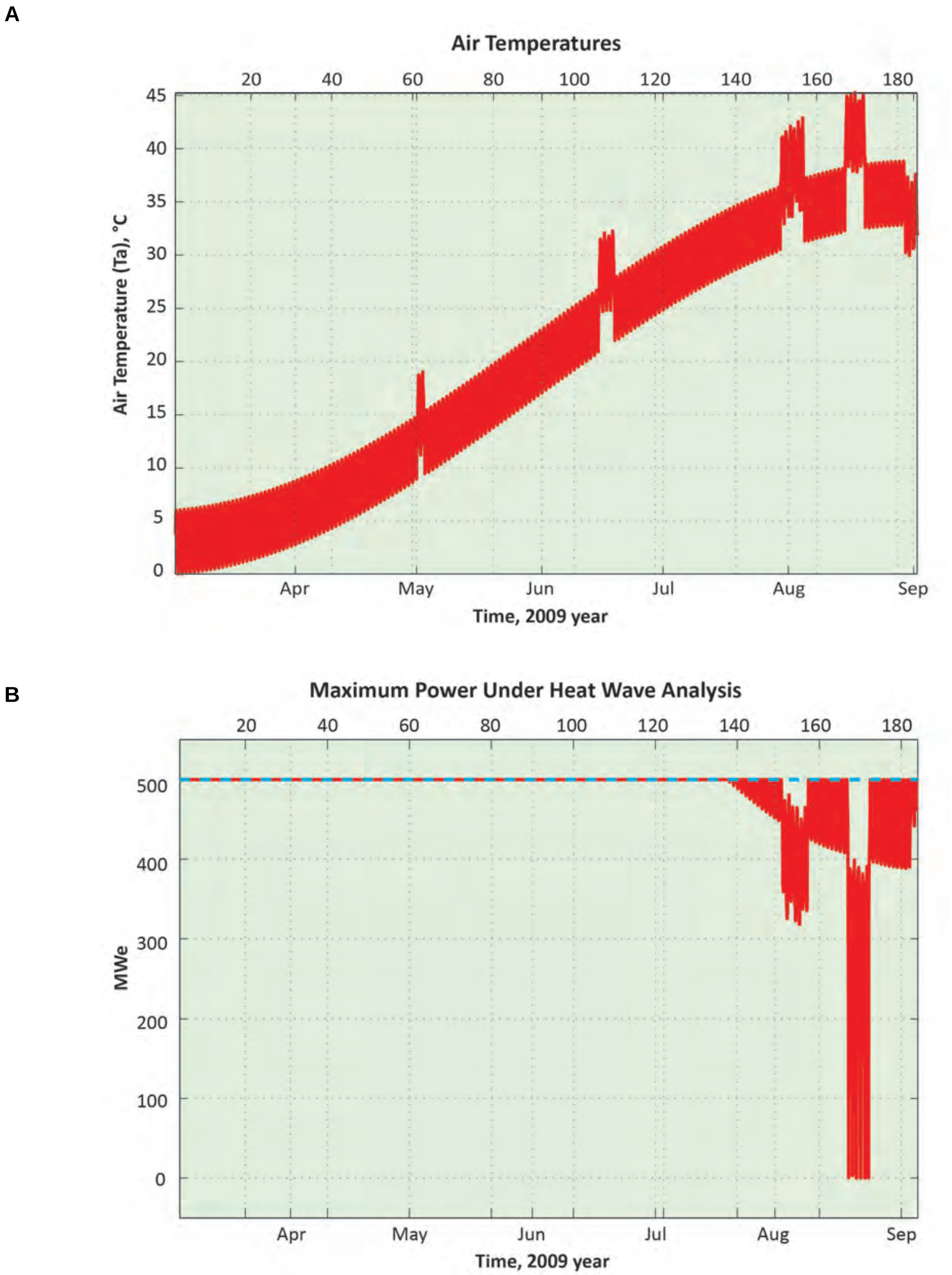


Figure 11-11
Seasonal predictions of impacts of heat waves on electrical power generation: Example #3. The dashed blue lines denote the thermal standards.

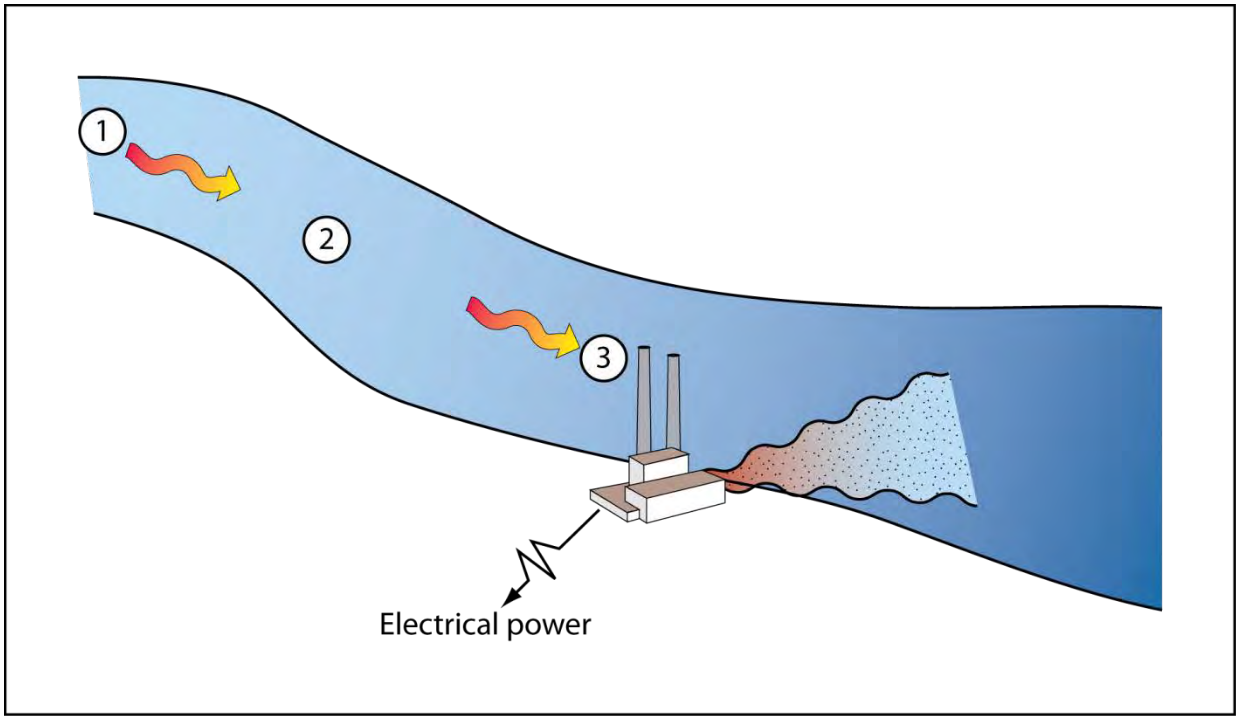
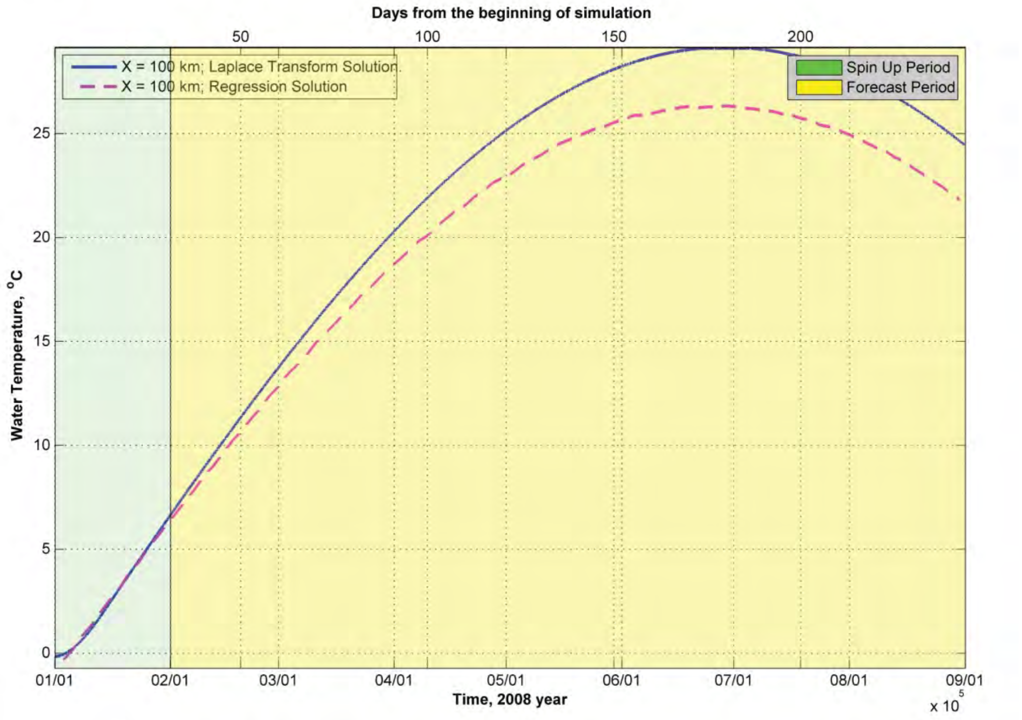


Figure 11-12
Forecasting inlet temperatures based on training the inlet temperature algorithm during the spin up period, and continuous updates into forecast period

- The concept of using satellite data to help develop a DSS that might lead to forecasts of up to two weeks was not one that researchers seem to have thought about at this point in time. Seasonal forecasting methods (where winter-spring conditions are used to forecast summer conditions) are, however, now available. It is suggested that the capabilities and limitations of using such systems be investigated in some detail. Some questions to be answered during such an investigation would include:
    - Is spatial resolution fine enough to be applicable to the current problem?
    - Are forecasts accurate enough to be usable? For example, would they be useful for long-term planning purposes?
    - Are electrical utilities now using a seasonal approach for forecasting? Who are they and what are the applications?
- The data requirements and instrumentation needs for each of the two approaches should be identified in order to evaluate the feasibility of each approach. Also, trade-offs should be examined (for example, projected accuracy of each approach versus capital and operating costs for each system). As some of the examples have shown, even with relatively small errors in assimilated data, forecasts can deteriorate dramatically due to the multiple uncertainties examined. Since the ultimate goal of these forecasts is to assist power plant operators to operate power plants at near optimal conditions without violating thermal standards, it is important that predictions be accurate (else the thermal standards might still be violated).

(a) Regression model trained on one month of data (green area)



(b) Regression model trained on three months of data (green area)

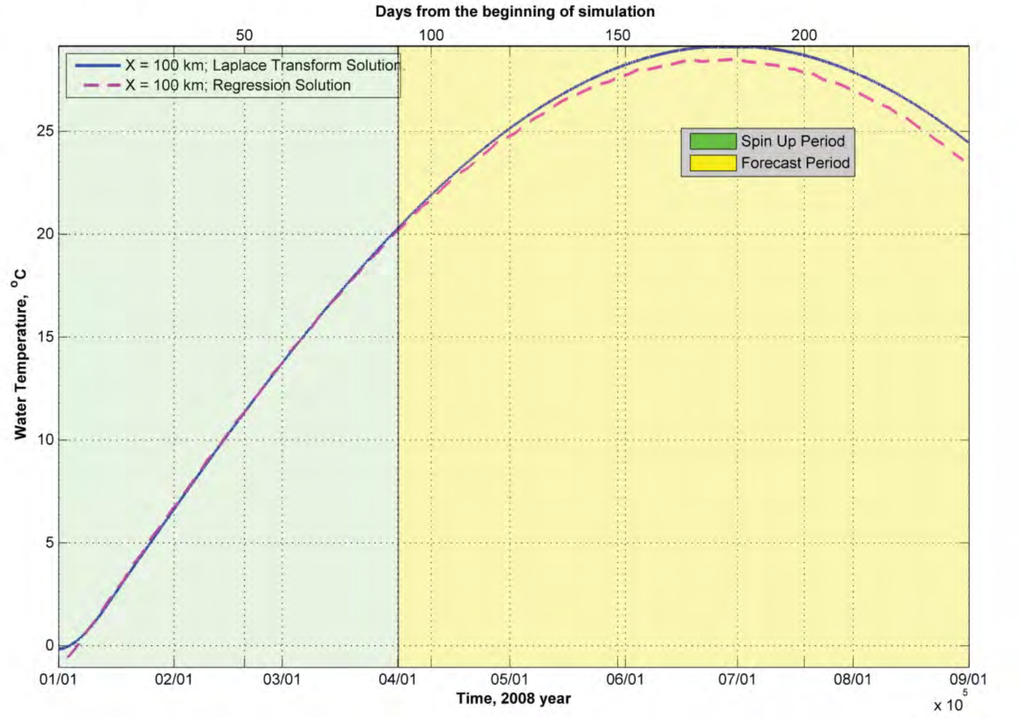


Figure 11-13
Use of Laplace transform solution and regression analysis to make forecasts: Example #4

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12

EVALUATION OF REASONABLE POTENTIAL TO EXCEED WISCONSIN'S NEW TEMPERATURE CRITERIA USING CORMIX MODELING

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Abstract

After many years of development, the Wisconsin Department of Natural Resources (WDNR) finalized new water quality standards for temperature in May 2009. Subsequently, Alliant Energy initiated an evaluation of the new rules by determining the potential for compliance by the Nelson Dewey Generating Station (NED). Monthly water-quality based effluent limits for temperature were calculated using the methodology, default sub-lethal and acute criteria, and prescribed ambient water temperatures in the new rules. Discharge temperatures from the NED were found to comply with all monthly acute limits, but exceeded the sub-lethal limits in several summer months. The new rules, however, provide for using a site-specific mixing zone study to demonstrate compliance with the mixing zone size limits, which are 50 percent of the width and 25 percent of the cross-sectional area of the receiving stream. The hydrodynamic model CORMIX was used to estimate the boundaries of the mixing zone at the regulatory low flow for each month. Assuming the lateral and vertical distribution of heat in the plume was Gaussian and the shape of the plume cross-section was half an ellipse, and using trigonometry and polynomial regression, the longitudinal results from CORMIX were extrapolated into plume widths and cross-sectional areas. The maximum predicted mixing zone width was 46.7 percent of the width of the river, just under the 50 percent limit. The maximum cross-sectional area, however, was only 2.6 percent and well below the 25 percent limit. The results indicated that sub-lethal and acute temperature limits were not required for the cooling water discharge from the NED.

Introduction

After many years of development, the WDNR finalized new water quality standards for temperature (NR 102 subch. II and NR 106 subch. V) at the May 26 and 27, 2009 meeting of the Wisconsin Natural Resources Board. The new standards have the potential to impact the operation of facilities that discharge waste heat into waterbodies in Wisconsin. Facilities most likely to be impacted are steam-electric generating stations. To assess the potential impacts of the new standards on the NED, Wisconsin Power and Light Company, a subsidiary of Alliant Energy and the owner and operator of NED, contracted with Burns & McDonnell Engineering

Company, Inc. to evaluate the thermal component of the wastewater discharge from NED based on the new Wisconsin water quality standards for temperature.

The NED is located on the northeast bank (left descending) of the Mississippi River at River Mile 608 in Pool 11 and began operations in 1959. This 200-MW facility uses once-through cooling with the Mississippi River as the source and receiver of cooling system circulating water. The NED has three circulating water pumps available to service the cooling requirements of Units 1 and 2. Two pumps are rated at 25,000 gallons per minute (gpm) and serve Unit 1. The third pump is rated at 50,000 gpm and serves Unit 2. Unit 1 has two service water pumps rated at 6,000 and 4,000 gpm, respectively. Unit 2 has a single 6,000-gpm service water pump. The total design intake rate is 116,000 gpm or 167 million gallons per day (MGD) or 258 cubic feet per second (cfs). Because the NED uses once-through cooling, the maximum design discharge rate is the same as the intake rate.

Compliance by the NED with the new standards was assessed using two methods: (1) the water-quality based effluent limitation (WQBEL) method in NR 106.55(6), and (2) discharge plume modeling, as allowed under NR 106.58, with the new Wisconsin temperature standards and existing mixing zone dimension limitations as the criteria.

Default Water Quality-Based Effluent Limitations

WQBEL for temperature based on the new Wisconsin thermal discharge rules were calculated for NED using the formulas (NR 106.55(6)(b)), water quality criteria (NR 102.25 and 102.26), and procedures provided by WDNR. These procedures included two scenarios. The first scenario used ambient receiving waterbody temperatures estimated by WDNR and corresponding sub-lethal and acute temperature criteria (NR 102.25)). The second scenario used site-specific ambient receiving waterbody temperatures and procedures for determining sub-lethal and acute criteria based on the site-specific ambient temperatures (NR 102.26)). Temperature limits for NED were calculated under both scenarios. Specific inputs for WDNR's methodology included the "Receiving Water Flow Rate" for the Mississippi River at Cassville, Wisconsin, and the "Design Discharge Rate" for the NED. For comparison to the calculated discharge limits and evaluation of "Reasonable Potential to Exceed", the mean, maximum weekly average, and maximum discharge temperatures from NED were calculated for each mouth.

The default Receiving Water Flow Rate used was ¼ of the 7-day average low flow with a recurrence interval of ten years (7Q10) (NR 106.53(1)(a)). The 7Q10 for the Mississippi River at Cassville, Wisconsin, was 10,400 cfs as provided by the WDNR. The default Receiving Water Flow Rate, therefore, was 2,600 cfs.

Water pump operations and intake and discharge rates at the NED vary systematically over an annual cycle (Figure 12-1, Table 12-1). Based on daily observations of intake rates from 2002 through 2007, separate monthly design discharge rates were calculated for winter (January, February, and March) and the rest of the year of 122.40 and 167.04 MGD, respectively.

Monthly geometric mean discharge temperatures for 2002 through 2007 ranged from 64.7°F in January to 104.7°F in July (Table 12-2). The maximum 7-day average discharge temperatures for each month were 12.1 to 21.1°F greater than the monthly means. The maximum observed discharge temperature was 122°F (Table 12-2). Based on NED cooling water intake temperatures for 2002 through 2007, monthly geometric mean river temperatures ranged from 34.2°F in

January and February to 80.7°F in July (Table 12-2). These site-specific ambient temperatures were up to 4°F higher than WDNR's default ambient temperatures (Table 12-2).

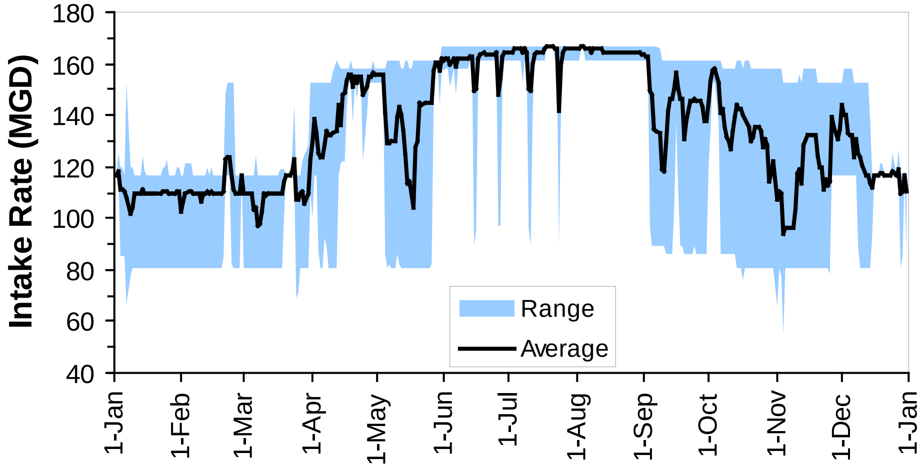


Figure 12-1
Average and range of daily intake rates for the NED, 2002-2007

Table 12-1
Cooling service water pump operating scenarios at various intake water temperatures for the NED

Circulating Water Pumps in Operation	Circulating Water Intake Rate (MGD)	Intake Water Temperature (°F)	Service Water Pumps in Operation	Service Water Pumping Rate (MGD)	Total Intake (MGD)	Application
2	72	<55	1A or 2	8.64	80.64	
2	72	≥55 and <70	1A or 2 + 1B	14.40	86.40	
2	72	≥70	1A + 2	17.28	89.28	
1A or 1B + 2	108	<50	1A or 2	8.64	116.64	
1A or 1B + 2	108	≥50	1A or 2 + 1B	14.40	122.40	Max for Jan, Feb, Mar
1A and 1B + 2	144	<56	1A or 2	8.64	152.64	
1A and 1B + 2	144	≥56 and <60	1A or 2 + 1B	14.40	158.40	
1A and 1B + 2	144	≥60 and <78	1A + 2	17.28	161.28	
1A and 1B + 2	144	≥78	1A + 1B + 2	23.04	167.04	Max for rest of year

Table 12-2
Monthly discharge and ambient temperatures (°F) for the NED

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Discharge												
Geometric mean	64.7	64.8	68.7	78.5	86.9	97.3	104.7	103.8	96.0	79.9	70.5	66.5
Maximum daily	93	85	90	104	110	114	121	122	120	112	101	88
Maximum 7-day	79.9	79.9	81.7	99.1	102.3	109.4	118.3	119.0	113.9	101.0	85.9	78.6
Ambient												
Site-specific	34.2	34.2	38.5	53.0	63.7	74.6	80.7	78.9	70.9	56.5	44.0	35.4
WNDR default	32	33	36	47	60	72	76	76	67	54	40	33

For each month, sub-lethal and acute discharge limits were calculated using the methods specified at NR 106.55(6)(b). The monthly maximum 7-day average effluent temperatures for NED exceeded the default chronic temperature criteria in June, July, and August (Table 12-3, Figure 12-2). Exceedance of a chronic criterion means the facility meets WDNR's test for Reasonable Potential to Exceed a Sub-Lethal Effluent Limitation (NR 106.56(3)). Monthly maximum daily effluent temperatures did not exceed the acute temperature criteria (Table 12-3). As such, NED does not have a reasonable potential to exceed an acute effluent limit (NR 106.56(2)).

Similar calculations were made based on site-specific ambient temperatures and criteria developed according to NR 102.26. In this case, monthly maximum 7-day average temperatures exceeded the sub-lethal criteria for June through September (Table 12-4). The acute criteria were not exceeded.

The WQBEL methodology uses a weighted average mixing equation that is a crude approximation of a discharge plume. The only part of the equation that relates to the limitations on mixing zones is the use of one-quarter of the receiving stream low flow, which is equivalent to the one-quarter of the receiving stream cross-sectional area allowed for mixing zones. Otherwise, the WQBEL does not consider the dynamics of discharge plumes, cannot be used to evaluate mixing zone width and cross-sectional area, and could produce overly conservative discharge limits.

CORMIX Modeling

The Cornell Mixing Zone Expert System (CORMIX), Version 5.0.2.0 was used to estimate the size of the mixing zone generated by the thermal discharge from NED as allowed under NR 106.58. This computer simulation program was developed for the U.S. Environmental Protection Agency (EPA) to analyze and predict the distribution of pollutants from discharges into diverse types of water bodies. The model emphasizes predicting the geometry and dilution characteristics of pollutant plumes for assessing regulatory compliance [1]. The configuration of the NED discharge structure corresponds with CORMIX module 3 for shoreline, surface outfalls.

Table 12-3
Calculation of water quality-based effluent limits for the NED using default ambient temperatures and criteria

WQBEL = [((WQC - Tb)(Qs + (1 - f)Qe)) / Qe] + Tb
7Q10 = 10,400 **f = 1.0** **Qe = 189.4 cfs for Jan, Feb, Mar**
Qs = 2,600 cfs **Qe = 258.5 cfs for rest of year**

		Water Quality Criteria (°F)				Discharge Limits (°F)		Discharge Temperatures (°F)	
Month	Background temperature (°F)	Sub-Lethal	Acute	Qs (cfs)	Qe (cfs)	Sub-Lethal	Acute	Maximum 7-Day Average	Maximum Effluent
Jan	32	49	75	2,600	189.4	262.3	619.3	79.9	93.0
Feb	33	50	76	2,600	189.4	270.7	627.6	79.9	85.0
Mar	36	52	76	2,600	189.4	250.5	580.0	81.7	90.0
Apr	47	55	79	2,600	258.5	129.5	370.9	99.1	104.0
May	60	65	82	2,600	258.5	107.5	278.6	102.3	110.0
Jun	72	75	85	2,600	258.5	102.1	202.7	109.4	114.0
Jul	76	80	86	2,600	258.5	114.4	174.7	118.3	121.0
Aug	76	79	86	2,600	258.5	110.5	180.9	119.0	122.0
Sep	67	73	84	2,600	258.5	126.6	237.3	113.9	120.0
Oct	54	61	81	2,600	258.5	124.0	325.2	101.0	112.0
Nov	40	50	77	2,600	258.5	141.8	413.4	85.9	101.0
Dec	33	49	76	2,600	258.5	192.4	464.0	78.6	88.0
								🟥	= exceeds limit

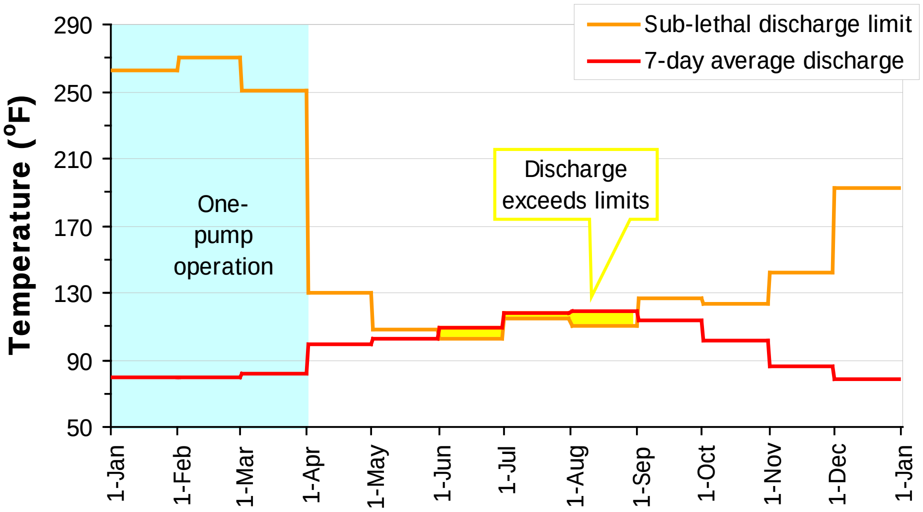


Figure 12-2
Monthly 7-day average discharge temperatures and estimated sub-lethal discharge limits for the NED

Model Development and Calibration

River cross-section information was derived from bathymetric data collected on 12-September 2005 (Figure 12-3) when flow in the river was 23,711 cfs, the water surface elevation was 603.49 feet (as measured at the Stoneman Generating Station), and the ambient water temperature was 80.4°F. (Note: the ambient temperature on this date was 13.3°F higher than the WDNR default ambient temperature for September.) Temperature measurements were also made in the river on that day to map the thermal plume from NED.

A transect across the river was selected that was considered representative of the location of the discharge plume (Figure 12-3). At this location, the river had a maximum depth of 9.1 m (30 ft), a width of 450 m (1476 ft), an average depth of 5.53 m (18.14 ft), and a cross-sectional area of 2488 m^2 (26,780 ft^2) on the date the bathymetric data were collected. For the CORMIX model, which assumes a rectangular receiving stream cross-section, the river depth was set to 6.1 m (20 feet) to be representative of average depth on the side of the river where the discharge plume was located (Figure 12-4). The width of river was set to 408 m (1339 ft) to maintain cross-sectional area and average water velocity.

Conditions as they existed on 12-September 2005, including the discharge rate and temperature from NED, were entered into CORMIX. The resulting plume centerline temperature profile was then compared to that obtained from the field measurements. The predicted and observed centerline temperatures were a good match (Figure 12-5) indicating the model was suitably calibrated. The modeled temperatures were somewhat higher than observed in the region from approximately 50 to 300 meters downstream of the discharge point. This discrepancy can occur because the field measurements do not always detect the highest temperatures in the plume, especially in areas where the plume is of intermediate width and the horizontal temperature gradient is relatively high.

Table 12-4
Calculation of water quality-based effluent limits for the NED using site-specific ambient temperatures and criteria

Month	Background temperature (°F)	Water Quality Criteria (°F)		Qs (cfs)	Qe (cfs)	Discharge Limits (°F)		Discharge Temperatures (°F)	
		Sub-Lethal	Acute			Sub-Lethal	Acute	Maximum 7-Day Average	Maximum Effluent
Jan	34	49	76	2,600	189.4	238.2	607.9	79.9	93.0
Feb	34	52	76	2,600	189.4	280.0	608.5	79.9	85.0
Mar	39	55	77	2,600	189.4	266.0	566.7	81.7	90.0
Apr	53	61	80	2,600	258.5	132.1	324.3	99.1	104.0
May	64	69	84	2,600	258.5	117.9	268.0	102.3	110.0
Jun	75	77	86	2,600	258.5	102.0	189.2	109.4	114.0
Jul	81	83	88	2,600	258.5	98.8	153.7	118.3	121.0
Aug	79	82	87	2,600	258.5	110.8	160.8	119.0	122.0
Sep	71	75	85	2,600	258.5	108.7	212.4	113.9	120.0
Oct	56	62	81	2,600	258.5	115.1	304.2	101.0	112.0
Nov	44	50	78	2,600	258.5	105.4	385.2	85.9	101.0
Dec	35	49	76	2,600	258.5	176.4	444.2	78.6	88.0
								🟥	= exceeds limit

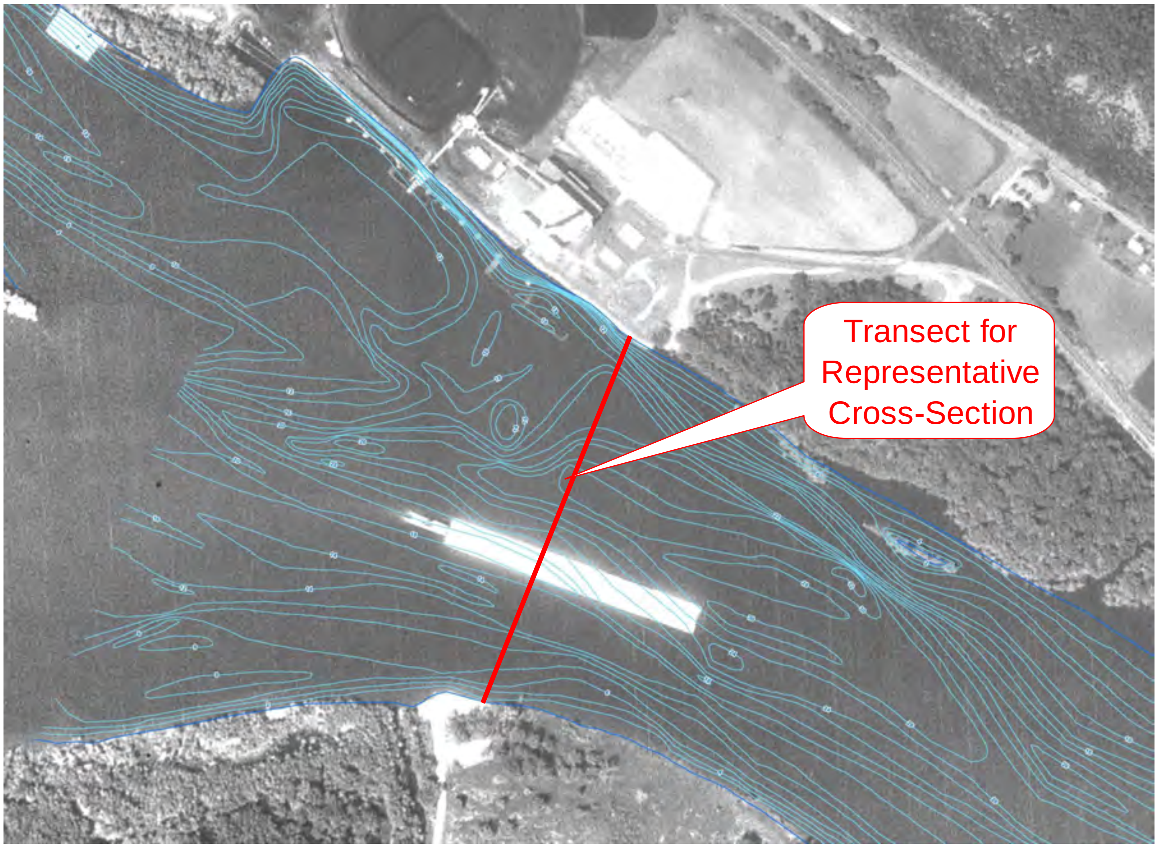


Figure 12-3
Bathymetric Map of the Mississippi River at NED on 12-September 2005

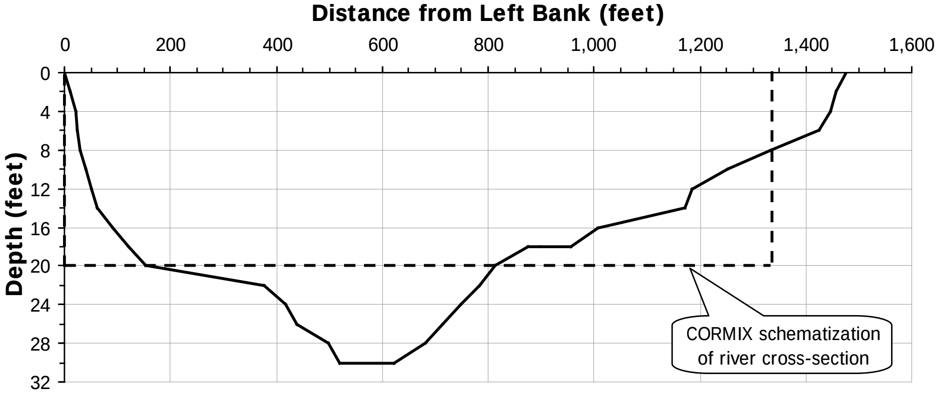


Figure 12-4
Cross-section of the Mississippi River at NED on 12 September 2005

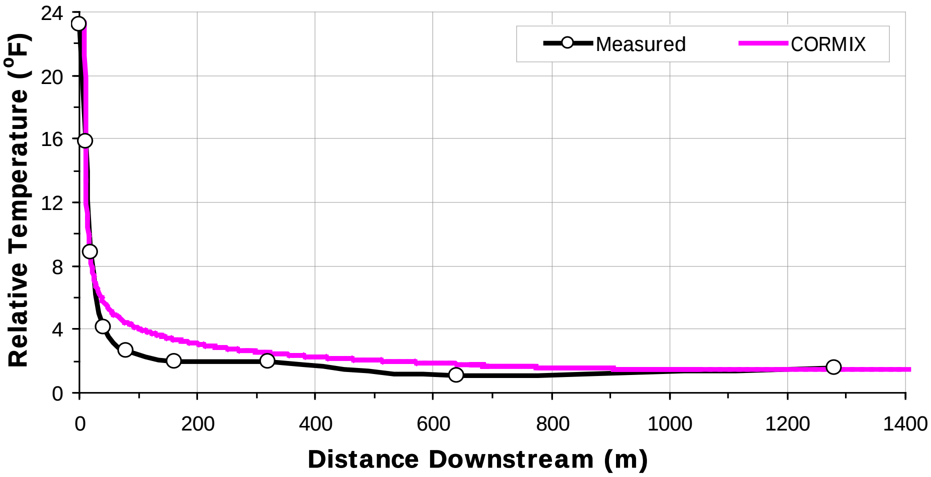


Figure 12-5
Observed and modeled discharge plume centerline temperatures for NED on 12 September 2005

Compliance Evaluation

The model was run for each month using WDNR's default ambient river temperatures and sub-lethal water quality criteria. Discharge flows from NED were same as those used in the WQBEL calculations and discharge temperatures were the monthly maximum weekly averages, which were appropriate discharge temperatures for comparison to the sub-lethal criteria. The WDNR rules state that a discharge plume should not exceed one-half the width or one-quarter of the cross-sectional area of the receiving stream. The discharge was considered compliant if the mixing zone was within one of these limits.

Reducing the modeled river flow to the 7Q10 necessitated a reduction in the modeled river elevation. The elevation of the Mississippi River at Cassville, Wisconsin, is partially controlled by Lock and Dam 11 at Dubuque, Iowa. At 7Q10, the elevation of Pool 11 was assumed flat with an elevation equal to the spillway crest at Lock and Dam 11 of 603.00 feet above sea level. The river cross-section was adjusted to the lower elevation (Figure 12-6) and had a cross-sectional area of 2421 m^2 (26,058 ft^2). The new depth for CORMIX modeling was set to 5.94 m (19.5 ft) with a corresponding width of 407 m (1336 ft). The change in river elevation also necessitated a change in the depth of the modeled discharge structure because the 7Q10 river elevation was below the top of the discharge pipe.

The primary outputs from CORMIX were a set of coordinates for the plume centerline in three dimensions, and corresponding pollutant concentrations, dilution factor, and half-width statistics that define the horizontal and vertical distribution of the pollutant around the centerline. For all months, the thermal mixing zones fell within the near field of the discharge plume. The near field is where active mixing takes place because of the turbulence and entrainment generated by the velocity difference between the discharge jet and the receiving stream. In the near field, the pollutant concentrations away from the plume centerline were characterized by a Gaussian distribution. The horizontal distance perpendicular from the plume centerline to a specific pollutant concentration (d), therefore, was calculated as:

$$d = BH\sqrt{-\ln\left(C_D / C_C\right)} \tag{1}$$

where BH is the Gaussian half-width, C_D is the pollutant concentration at distance d, and C_C is the centerline concentration [1]. Calculating this distance using the water quality standard as C_D provided distances to the edge of the mixing zone. The location of the mixing zone boundary was then approximated from d and the centerline location by using trigonometry as illustrated in Figure 12-7. Mixing zone boundaries were calculated for each modeled point along a plume's centerline. The farthest distance from the nearshore to the mixing zone boundary point was considered the mixing zone width.

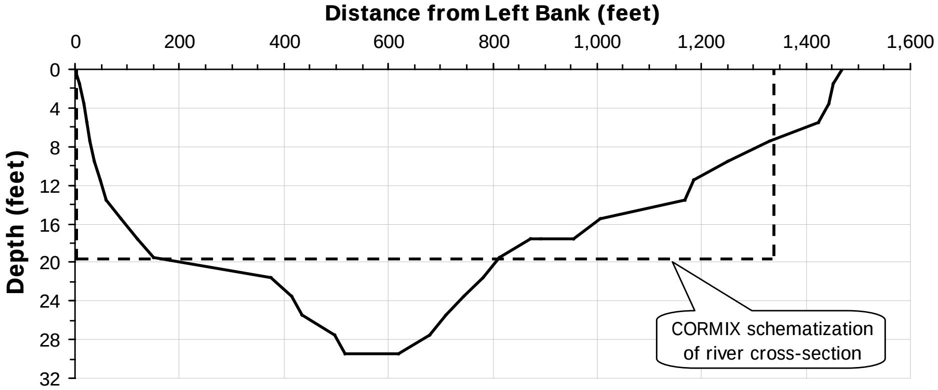


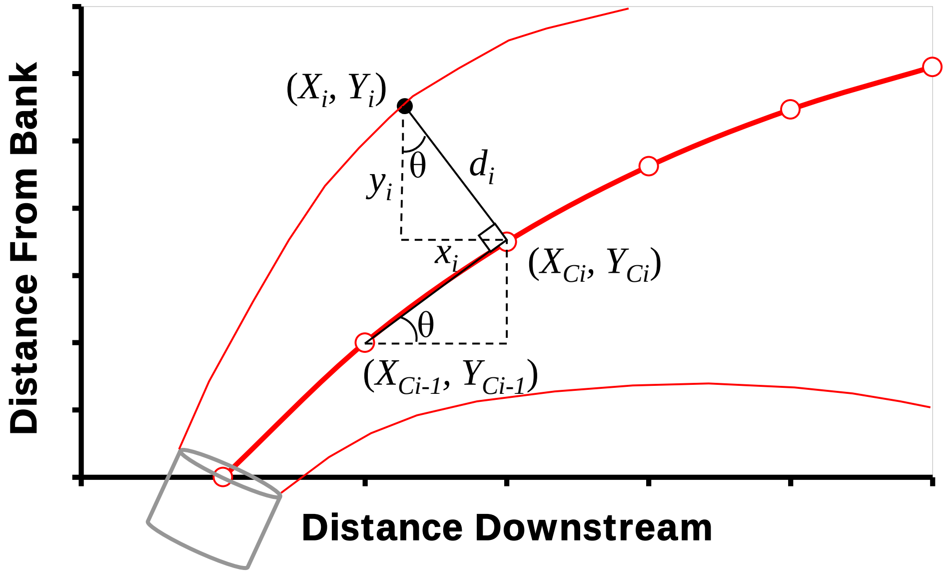
Figure 12-6
Cross-section of the Mississippi River at NED at 7Q10

At the 7Q10, the mixing zones extended out into the river at approximately the same angle as the discharge pipe with only modest downstream bending (Figure 12-8). At less than 20 m long and 20 m wide, the mixing zones for December, January, February, and March were relatively small. Mixing zone sizes increased as ambient water temperatures increased and the differences between the ambient temperatures and the water quality criteria decreased. None of the mixing zones, however, exceeded the one-half-width limit (Figure 12-8).

The purpose of the width and cross-sectional area limits is to assure an adequate zone of passage for migrating or otherwise translocating aquatic biota (particularly fish). An exceedance of the width limitation by the NED temperature mixing zones, however, would not necessarily mean the cross-sectional area limitation would have been exceeded because the warm water discharge from NED and other once-through cooled power plants is less dense than the receiving waterbody and the discharge plume floats. As a result, such discharges are confined to a region of the receiving waterbody near the surface.

Mixing zone cross-sectional areas perpendicular to the shoreline of the river were estimated along the centerlines of the mixing zones. Because the discharge plumes from NED were buoyant, the cross-section of each mixing zone was assumed shaped like half an ellipse (Figure 12-9). For this analysis, the main axis of the half-ellipse is assumed oriented perpendicular to the shoreline to be comparable to how the cross-sectional area of the receiving stream is estimated, and to reflect the fact that for non-bank attached plumes the area of the plume that exceeds water quality standards is not contiguous with the shoreline over the entire length of the mixing zone.

To find the width of an ellipse, the coordinates describing the nearshore and far shore horizontal boundaries of the mixing zone were fitted with polynomial regression equations. These equations were used to estimate the distances from the nearshore to the edges of the mixing zone on both sides of the plume centerline for each downstream point on the plume centerline (Figure 12-10). These distances provided an estimate of the plume width ($r_f + r_n$ in Figure 12-9).



$$X_i = X_{c(i)} \pm d_i\{sin[arctan((Y_{c(i)}-Y_{c(i-1)})/(X_{c(i)} - X_{c(i-1)}))]\}$$

$$Y_i = Y_{c(i)} \pm d_i\{cos[arctan((Y_{c(i)}-Y_{c(i-1)})/(X_{c(i)} - X_{c(i-1)}))]\}$$

Figure 12-7
Estimating the location of the mixing zone boundary

Plume thickness (Z in Figure 12-9) was estimated using the preceding distance equation where *BH* was replaced with *BV*, the vertical Gaussian half-width. The area of the mixing zone cross-section (A) was calculated using the formula for half the area of an ellipse assuming the ellipse was not necessarily laterally symmetrical:

$$A = [\pi Z(r_f + r_n)/2]/2 \qquad (2)$$

Half-ellipse areas were then calculated for each modeled downstream point in each mixing zone and the maximum area along the plume centerline was considered the cross-sectional area of the mixing zone.

Cross-sectional areas of the monthly, sub-lethal mixing zones for the NED ranged from 7.1 m^2 in January to 88.8 m^2 in June (Figure 12-11). All of these cross-sectional areas were well below the 25 percent of receiving stream cross-sectional area allowed by the Wisconsin water quality standards (Figure 12-11).

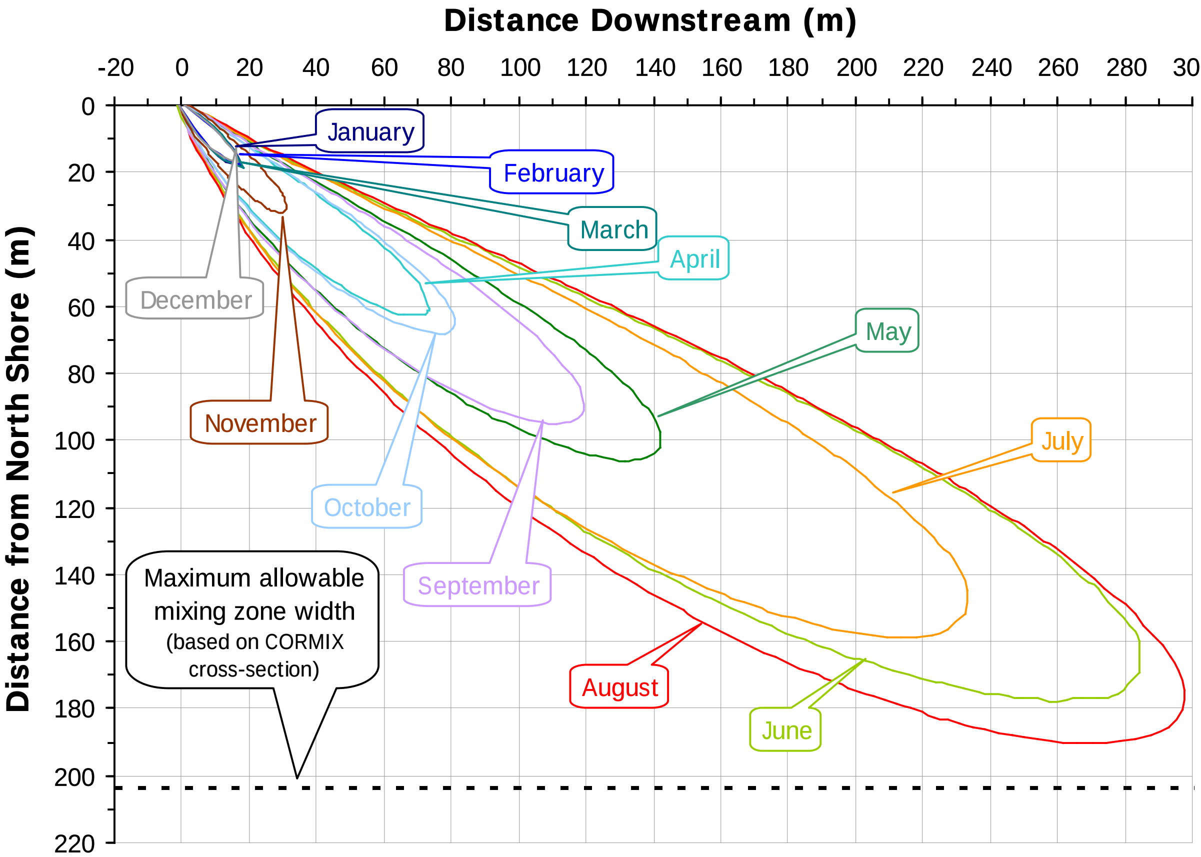


Figure 12-8
Monthly sub-lethal thermal mixing zones predicted by CORMIX for NED

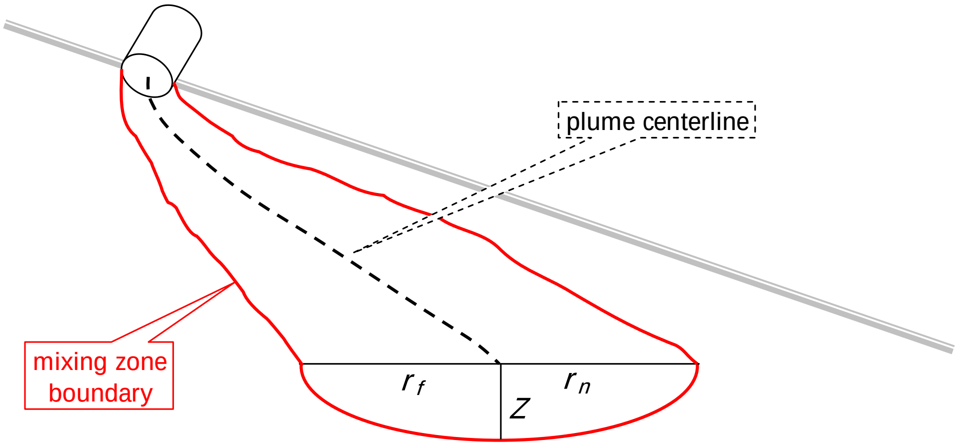


Figure 12-9
Schematic of mixing zone cross-sectional area

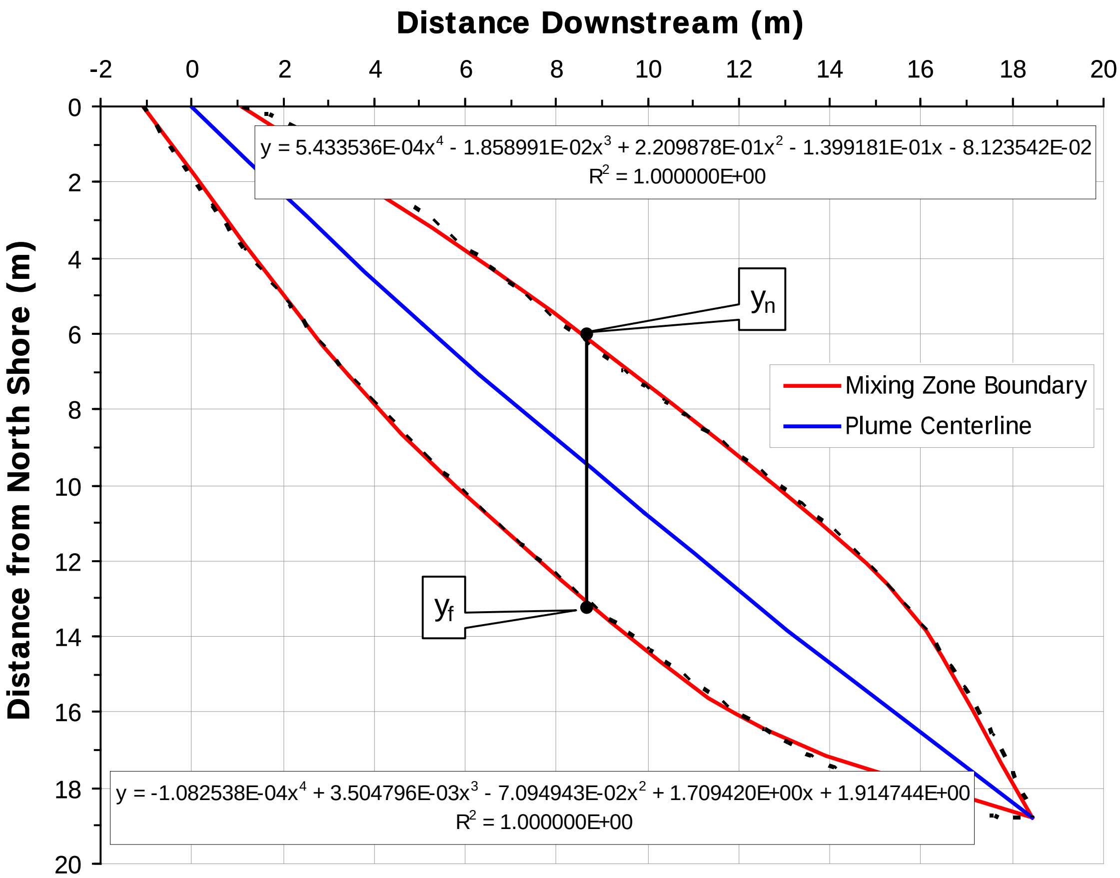


Figure 12-10
Schematic of the calculation of mixing zone width for estimating mixing zone cross-sectional area

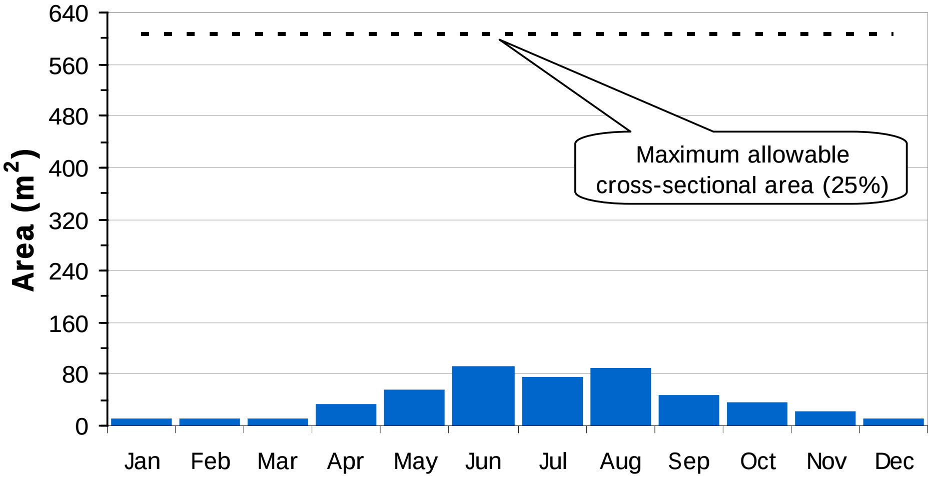


Figure 12-11
Monthly mixing zone cross-sectional area for the thermal discharge from NED

Revised Water Quality-Based Effluent Limitation and Limit Request

The default WQBEL analysis indicated the thermal discharge from NED had a potential to exceed the temperature criteria in June, July, and August assuming 25 percent of the receiving stream's 7Q10 was used for the mixing zone. The 25 percent of flow is meant to represent the 25 percent of the cross-sectional area that can be occupied by the mixing zone so that an acceptable zone of passage is provided. The CORMIX modeling, however, determined that the monthly mixing zones ranged from only 0.29 to 3.66 percent of the river's cross-sectional area. Because the modeling demonstrated the existence of an adequate zone of passage, as allowed under NR 106.53(1)(c), no need exists to restrict the receiving stream flow (Q_s) for purposes of estimating WQBELs for NED. The proposed modified Q_s is the maximum allowable, which is 100 percent of the 7Q10 (NR 106.53(1)(d)) or 10,400 cfs. At this river flow, the minimum monthly WQBEL would be 192.3 ºF in June (Table 12-5).

At the default Q_s (2,600 cfs), the Q_s:Q_e ratios for NED are 13.7 for one-pump operation and 10.1 for two-pump operation. Based on those ratios, effluents limits established for NED would be the lesser of 120 ºF or the sub-lethal WQBEL because the Mississippi River is designated as Warm Water and the ratios are less than 20 and greater than 2 (NR 106.55(6)(a), Table 1). At the modified Q_s (10,400 cfs), the Q_s:Q_e ratios are 54.9 and 40.2 for one-pump and two-pump operations, respectively, and the only applicable effluent temperature limit is the 120ºF limit for the protection of human health (NR 106.55(6)(a), Table 1).

Given the WQBELs and flow ratios based on the modified Q_s, a years-round limit of 120ºF is a potential limit for NED. Within the 7-year (2539-day) period of record of daily discharge temperatures analyzed for NED, the 120ºF limit was exceeded on only 2 days and only by a maximum of 2ºF. Based on the results of the August CORMIX modeling, the centerline plume temperature for a 122ºF discharge would cool to 120ºF approximately 2.6 m downstream of the discharge. Because the discharge structure is located on NED property, the only way for the public to be exposed to potentially scalding hot water is by falling out of a boat in the area immediately downstream of the mouth of the discharge. No institutional memory exists at NED of such an occurrence in the past and such an occurrence in the future is considered highly unlikely. In accordance with NR 106.56 (8), therefore, the establishment of a 120ºF limit is NOT required for NED.

References

1. Doneker, R.L. and G.H. Jirka. 2007. CORMIX User's Manual. U.S. Environmental Protection Agency. Washington, D.C.

Table 12-5
Calculation of water quality-based effluent limits for the NED using the modified receiving water flow rate

7Q10 = 10,400 cfs **f = 1.0** **Qe = 189.4 cfs for Jan, Feb, Mar**
Qs = 10,400 cfs **Qe = 258.5 cfs for the rest of the year**

Month	Background temperature (°F)	Water Quality Criteria (°F)		Qs (cfs)	Qe (cfs)	Discharge Limits (°F)		Discharge Temperatures (°F)	
		Sub-Lethal	Acute			Sub-Lethal	Acute	Maximum 7-Day Average	Maximum Effluent
Jan	32	49	75	10,400	189.4	952.7	2380.4	79.9	93.0
Feb	33	50	76	10,400	189.4	984.7	2412.4	79.9	85.0
Mar	36	52	76	10,400	189.4	892.8	2210.8	81.7	90.0
Apr	47	55	79	10,400	258.5	377.7	1343.5	99.1	104.0
May	60	65	82	10,400	258.5	249.2	933.3	102.3	110.0
Jun	72	75	85	10,400	258.5	192.3	594.7	109.4	114.0
Jul	76	80	86	10,400	258.5	228.8	470.3	118.3	121.0
Aug	76	79	86	10,400	258.5	215.4	497.1	119.0	122.0
Sep	67	73	84	10,400	258.5	305.2	747.8	113.9	120.0
Oct	54	61	81	10,400	258.5	333.7	1138.5	101.0	112.0
Nov	40	50	77	10,400	258.5	447.7	1534.1	85.9	101.0
Dec	33	49	76	10,400	258.5	670.0	1756.4	78.6	88.0

13

PLAN FOR STUDIES TO SUPPORT RETAINING SECTION 316(A) VARIANCES AT POWER PLANTS IN KENTUCKY

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Abstract

A consortium of Kentucky Utilities has developed a non-binding, statewide plan for Section 316(a) variance renewal studies (the Plan). The purpose of the Plan is to facilitate the preparation of site-specific study plans by providing procedures that have been reviewed and approved by the Kentucky Department of Water (KDOW). The Plan is designed to accommodate the variety of power plants in the state, take advantage of existing data and established sampling protocols and indices of biological integrity, and minimize site-specific plan preparation and data collection efforts. Procedures are given for characterizing the thermal discharge plume and the potentially affect biological community. A decision tree, based on the existence of applicable data, is provided to determine the specific activities that should be conducted at a given facility. Biological characterization is limited to the fish, mussel, and wildlife communities and is designed to determine if the receiving waterbody in the area of the thermal discharge supports a "balanced, indigenous community". The Plan specifies fish sampling in summer and fall using boat-mounted electrofishing in areas inside and outside of the Primary Study Area (PSA, 2ºC above ambient temperature contour). Facilities on the Ohio River can use the sampling and analytical protocols of the Modified Ohio River Fish Index. Existing fisheries data from the Ohio River Ecological Research Program can be used if compatible with the PSA. A generic fish community evaluation protocol is provided of facilities not on the Ohio River. The KDOW is particularly concerned about potential impacts on freshwater mussel communities and the Plan provides several evaluation methods, ranging from literature review only to a semi-quantitative survey to accommodate the range of site-specific likelihood for the presence of significant mussel communities. On-site sampling of the mussel community is specified for summer. The U.S. Environmental Protection Agency (EPA), Region IV, is particularly concerned about potential impacts on wildlife. The Plan specifies summer and fall visual and auditory inventories of wildlife on the receiving water and the adjacent riparian area for the same reaches of shoreline subject to electrofishing.

Introduction

Among pollutants, heat is unique in that the background concentration tends to vary naturally, substantially, and cyclically. Additional heat has the potential to be harmful to aquatic organisms, particularly when ambient temperatures are high, but can also be beneficial when ambient temperatures are low. As a result, water quality criteria for temperature in the United States are expressed as the difference from ambient or as multiple values corresponding to different times of year. Section 316(a) of the Clean Water Act (CWA), 33 U.S.C. § 1326(a)1, allows the EPA and delegated state agencies to authorize alternate thermal limits (ATLs) in National Pollutant Discharge Elimination System (NPDES) permits for facilities that demonstrate that the statutory criteria are more stringent than necessary to assure the protection and propagation of balanced and indigenous populations or communities of aquatic organisms in and on the receiving waterbody. Federal regulations (40 CFR Part 125 Subpart H) and state regulations, in turn, describe the general criteria for the granting of ATLs.

Section 316(a) variances (i.e., ATLs) must be reevaluated and reissued on a five-year cycle with each discharge permit renewal. In a 2007 quality review of permits, the EPA, which administers the CWA and the included NPDES, found that documentation supporting the continuation of Section 316(a) variances was lacking [1]. The EPA contends that hydrological cycles, long-term flows, and ambient water temperatures have changed in the past several decades since many of the Section 316(a) variances were issued and, therefore, directed delegated states to increase attention on thermal discharge limits. In Kentucky, the issuance of NPDES discharge permits is the responsibility of the KDOW, which has responded to the EPA directive by requiring dischargers with temperature limits to update the historical data. Kentucky is in EPA's Region IV.

An applicant for a Section 316(a) variance has the burden of demonstrating through predictive or empirical means that a balanced, indigenous community (BIC) of fish, shellfish, and wildlife is or will be maintained and protected. Existing dischargers may base this demonstration upon the absence of prior appreciable harm in lieu of predictive studies. The purpose of this document is to facilitate preparing site-specific study plans for the demonstration that BIC is still being maintained by providing to the owners of Kentucky generating facilities with Section 316(a) variances guidance that has been reviewed and approved by KDOW. Individual facilities, however, may develop their own plans that are based on other approaches.

The following plan is applicable to existing facilities in Kentucky that have been operating more or less continuously for many years. As such, any impacts on the aquatic community by a thermal discharge are assumed fully manifest relative to the aquatic community outside of the influence of the thermal discharge (i.e., control sites).

A central consideration in the design of this plan was consistency with the EPA's draft 1977 Interagency 316(a) Technical Guidance Manual and Guide for Thermal Effects Sections of Nuclear Facilities Environmental Impact Statements [2], which has been indicated to be KDOW's and EPA Region IV's guide to Section 316(a) variance studies. In particular, the specification of the Primary Study Area (PSA) as the portion of the thermal plume bounded by the 2ºC above ambient surface isotherm [2, page 78] was central to the basic designs of the studies in this plan.

This plan is the product of a cooperative effort between utilities in Kentucky and is based on Kentucky water quality regulations, KDOW practices, recent utility consultation with EPA Region 4 regarding Section 316(a) variance studies in other EPA Region 4 states, and comments by KDOW on the initial draft of this study plan.

Regulatory Background

Kentucky Administrative Regulations (KAR) state that "Temperature shall not exceed thirty-one and seven-tenths (31.7) degrees Celsius (eighty nine (89) degrees Fahrenheit)" (401 KAR 10:031, Section 4(1)(d)). The regulations also provide guidelines for temperature criteria that vary by time of year (Table 13-1). Compliance with temperature criteria may be determined at the edge of an allowable regulatory mixing zone, or upon successful demonstration that less stringent ATLs are justified pursuant to Section 316(a) of the CWA.

Table 13-1
Kentucky guidelines for surface water temperature (401 KAR 10:031, Section 4(1)(d)(2)(b))

Month/Date	Period Average		Instantaneous	
	(°F)	(°C)	(°F)	(°C)
January 1-31	45	7.2	50	10.0
February 1-29	45	7.2	50	10.0
March 1-15	51	10.6	56	13.3
March 16-31	54	12.2	59	15.0
April 1-15	58	14.4	64	17.8
April 16-30	64	17.8	69	20.6
May 1-15	68	20.0	73	22.8
May 16-31	75	23.9	80	26.7
June 1-15	80	26.7	85	29.4
June 16-30	83	28.3	87	30.6
July 1-31	84	28.9	89	31.7
August 1-31	84	28.9	89	31.7
September 1-15	84	28.9	87	30.6
September 16-30	82	27.8	86	30.0
October 1-15	77	25.0	82	27.8
October 16-31	72	22.2	77	25.0
November 1-30	67	19.4	72	22.2
December 1-31	52	11.1	57	13.9

In rivers and streams, mixing zones are limited in size in any direction from the point of discharge to one-third the width of the receiving waterbody[1] (401 KAR 10:029, Section 4(1)(c)). Mixing zones in lakes or reservoirs are limited to one-tenth the width of the receiving waterbody at the point of discharge (401 KAR 10:029, Section 4(1)(d)). Discharge limits for temperature are primarily for the protection of aquatic life. For receiving waters that are rivers or streams, limits are derived using the 7-day average low flow with a recurrence interval of 10 years (7Q10) (401 KAR 10:031, Section 3(3)(a)).

Study Plan

The approach to reevaluating thermal variances at power plants in Kentucky consists of two basic components:

1. Characterization of the thermal discharge plume
2. Characterization of the biological community

Discharge plume mapping is used to define the boundary of the PSA, identify zone of passage, and, if needed, provide a basis for calibrating a discharge plume model. The biological studies are used to support a variance from the temperature criteria by determining if a BIC is supported in the receiving waterbody. The selection of components to include in a Section 316(a) study will depend on facility-specific circumstances as outlined in Figure 13-1.

Discharge Plume Characterization

In-situ Measurements

Surface to bottom temperature profiles will be made along transects across the plume. In rivers and streams, one transect will be located as close to the discharge point as safely possible. Subsequent downstream transects will be concentrated in the presumed near field of the plume where the change in plume temperature is most rapid. The distance between transects in the remainder of the PSA can increase with distance downstream or away from the discharge point. One transect should be located at the regulatory maximum length of the mixing zone if demonstration of compliance with mixing zone spatial limitations is intended. The farthest downstream transect must be outside of the PSA. A transect upstream of the discharge in the vicinity of the cooling water intake will be included for determining the ambient temperature. The specific locations of temperature measurements will be determined in consultation with the KDOW [2].

Temperature profile measurement points along a transect will begin at or near the shoreline from which the discharge originates and continue across the plume until the ambient background temperature or the far shore is reached. The number of measurement points on a transect will generally be proportional to the width of the plume and the magnitude of the temperature change across the transect. The distances between transects and measurement points will depend on the size of the discharge plume and will be site-specific.

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[1] This regulation goes on to state “or one-half of the cross-sectional area.” This latter restriction is no longer used by KDOW to assess compliance or set discharge limits and may have been included in the regulations has an exception for a specific facility [3].

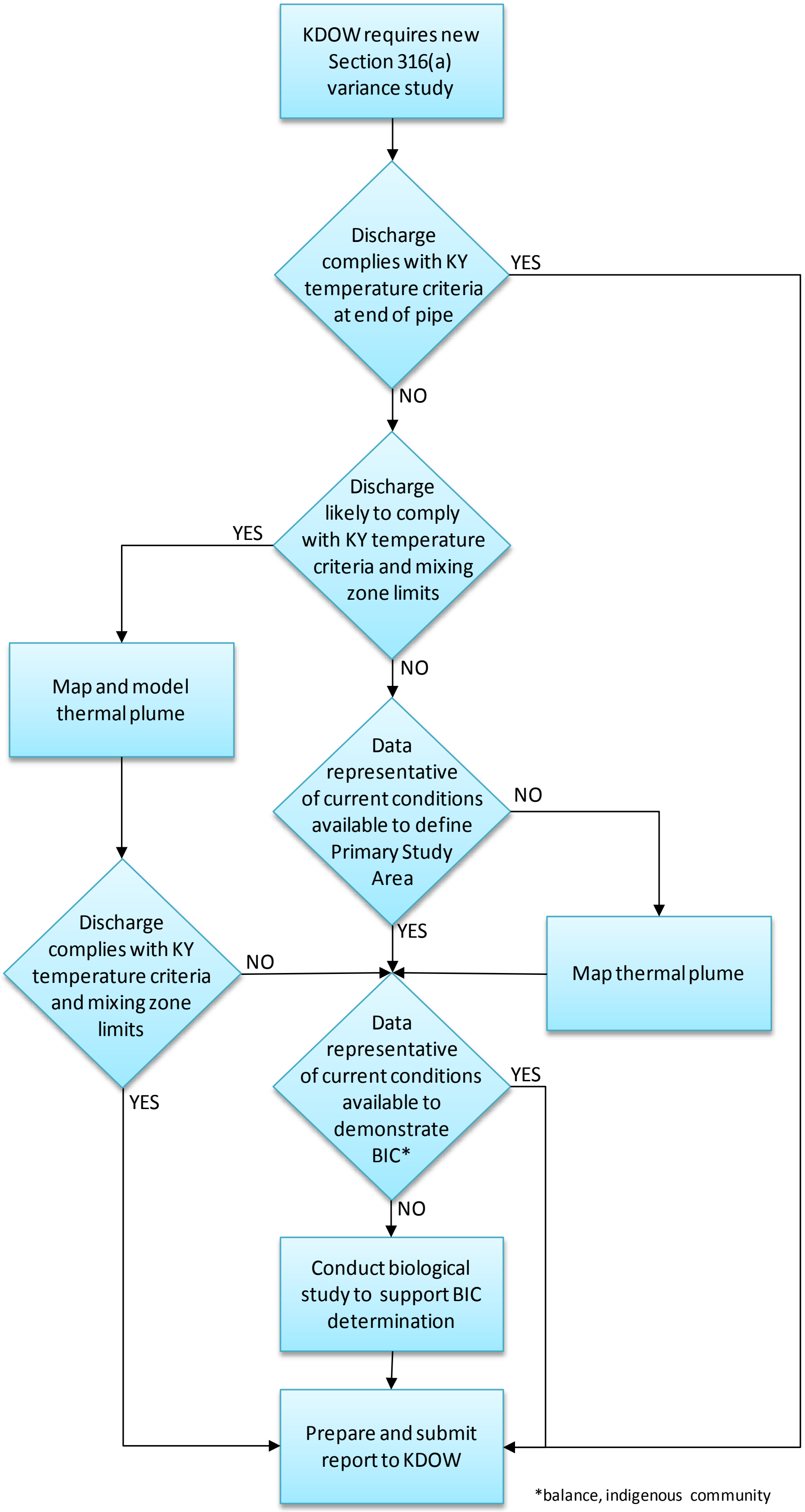

Figure 13-1
Decision flow chart for the selection of Section 316(a) study components

Each temperature profile measurement point and transect origin on the nearshore will be located using a sub-meter accurate global positioning system (GPS).[2] Plume mapping should be scheduled for when the power plant is operating at peak load and, for rivers, when flow is relatively low. The temperature measurement instrument will be calibrated to a thermometer whose calibration is traceable to the National Institute of Standards and Technology. Measurement of dissolved oxygen, pH, and conductivity may be made concurrently with temperature if these parameters could interact with the temperature plume. For example, dissolved oxygen data may be useful in evaluating zone of passage around a thermal plume in a thermally stratified lake, and conductivity can be expected to co-vary with temperature in discharges from cooling towers.

Additional data will be collected on the ambient conditions that affect the plume at the time the plume is mapped. If the receiving waterbody is a river or stream, flow at the time of plume mapping can typically be obtained from one or more nearby stream gaging stations operated by the U.S. Geological Survey (USGS) or the U.S. Army Corps of Engineers (Corps). Interpolation between two gaging stations may be required to estimate flow at the power plant site and will be based on the watershed areas at the gages and the site. Watershed area at the site will be interpolated based on the relationship between watershed area and river mile at the surrounding gaging stations. Discharge rate from the power plant will be obtained from the facility. If the discharge temperature from the power plant was not measured directly in the field as part of the plume mapping, this information, along with the intake temperature data, will be obtained from the power plant. Because multiple instruments will likely have been used to measure the ambient river, intake, and discharge temperatures, steps will be taken to calibrate the measurements from the various instruments to a common standard.

The plume map will be created by plotting the location of each temperature profile measurement point on a base map and labeling each point with the profile’s maximum temperature. Because the measurement points will typically be unevenly spaced, manual interpolation will usually be the most satisfactory method to plot temperature contours. The temperature contours can be hand digitized into a geographic information system (GIS) to prepare a presentation version of the plume map (*e.g.*, Figure 13-2). Plotting temperature versus depth and distance from shore for individual transects and interpolating temperature isolines will yield plume cross-sections, which can be used to demonstrate the existence of a zone of passage under or around the plume. Plotting the maximum temperature on each transect versus the distance downstream produces a plume centerline temperature curve to which a plume model can be calibrated.

Plume Modeling

Discharge plume modeling may be used if needed to estimate the extent of the PSA or characterize the discharge plume for ambient and facility operating conditions other than those under which the in-situ temperature measurements were made. Such modeling will likely be required by the KDOW for facilities seeking to demonstrate compliance with Kentucky’s mixing zone size limits (401 KAR 10:029, Section 4(1)). The KDOW uses the plume model CORMIX to establish mixing zones and discharge limits for temperature [4]. CORMIX, originally known as the Cornell Mixing Zone Expert System, is a hydrodynamic computer simulation program

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[2] Sub-meter accuracy can be achieved using real-time or post-processing differential correction.

developed for the EPA to analyze and predict the distribution of pollutants from discharges into diverse types of water bodies. The model emphasizes predicting the geometry and dilution characteristics of pollutant plumes for assessing regulatory compliance [5].

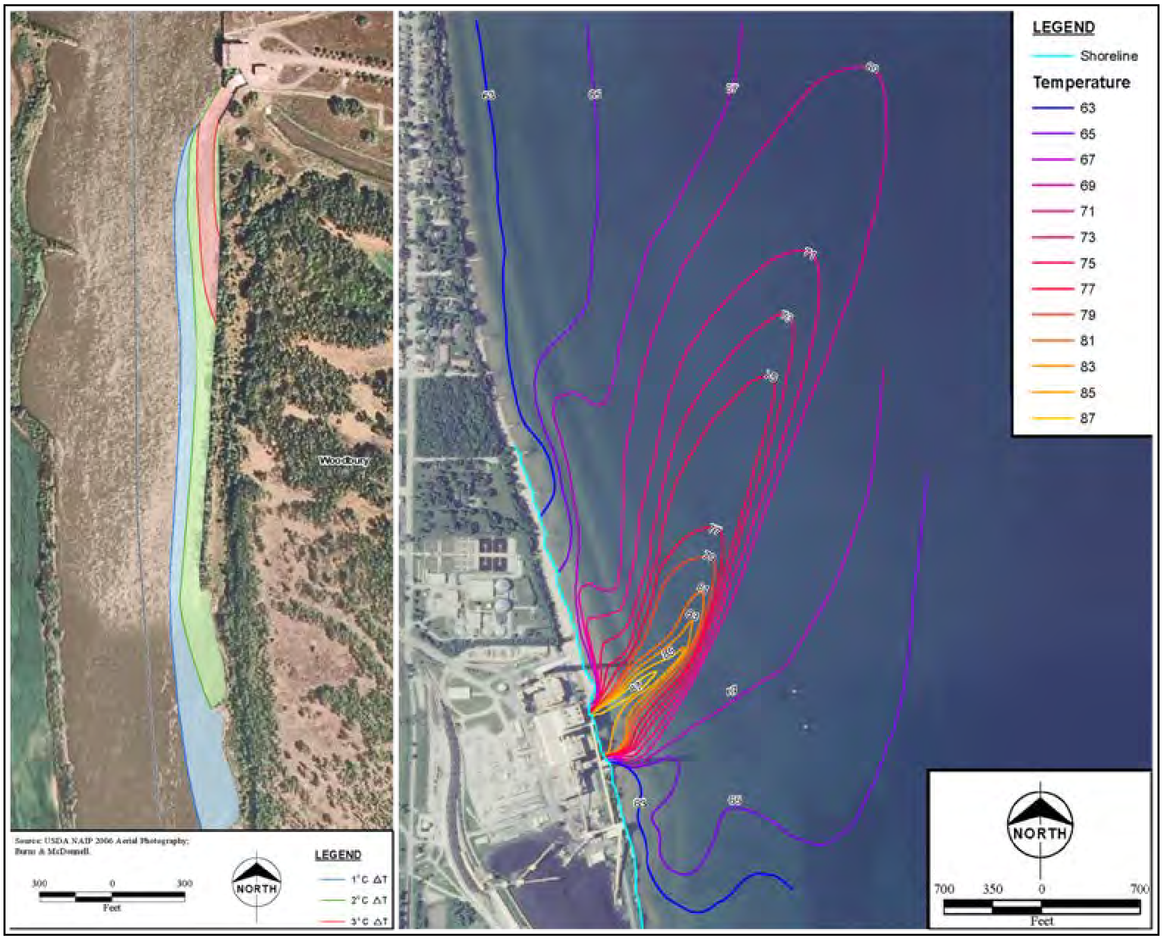

Figure 13-2
Examples of thermal plume maps for discharges into a river (left) and a lake (right)

CORMIX requires input data on the ambient (receiving waterbody) conditions, effluent characteristics, and outfall structure dimensions and location. A bathymetric map may have to be prepared to determine some of the input data.

CORMIX is particularly applicable to modeling discharges into flowing waterbodies. The model, however, can have difficulty resolving discharge plumes in low-flow receiving waterbodies such as lakes. In these cases, finite element models (e.g., AQUASEA, MIKE21) or computational fluid dynamics models (e.g., ANSYS, FLOW-3D) may produce more useful results.

Biological Community Characterization

Unless opting to demonstrate compliance with temperature criteria within the allowable mixing zone, facilities will need to conduct a Section 316(a) demonstration study to assess the biological condition of the receiving waterbody with respect to the thermal discharge. For an existing facility that has been operating under Section 316(a) ATL, the goal of the biological study is to demonstrate that the receiving waterbody continues to supports a balanced, indigenous aquatic community. A balanced community is characterized by:

- Diversity
- Sustainability through seasonal cycles
- Presence of necessary food chain species
- Non-dominance of pollutant tolerant species

An indigenous community is made up of species that are native to the receiving waterbody and non-native species that have historically been present, that would be expected to occur in the community in the absence of the thermal discharge, and that are now an integral component of the ecosystem.

The following study plan is designed to assess the above characteristic of the fish community by systematic sampling in the PSA. Essentially identical sampling will also occur in a nearby area of the receiving waterbody that is similar in habitat but unaffected by the thermal discharge (reference area) to provide a basis of comparison for assessing the degree to which the balanced and indigenous characteristics are being met in the potentially thermally impacted communities. Implicit in this comparison is the assumption that the fish community in the thermally unaffected area of the receiving waterbody can be deemed balanced and indigenous. In the event that the control area does not demonstrate BIC, the comparison between the PSA and the control area and a demonstration of the “absence of prior appreciable harm” (40 CFR 125.73(c)) will provide evidence that the desired ATL would assure a BIC in the absence of the environmental impact affecting the control area.

Power plants in Kentucky considered most likely to require a Section 316(a) biological study are those that use once-through cooling for some or all generating units or are relatively large facilities that discharge cooling tower blowdown into small waterbodies. Eighteen such power plants were identified (Table 13-2). Of these facilities, nine discharge cooling water into the Ohio River, five into the Green River, two into the Kentucky River, and one into the Cumberland River. Only one facility discharges into a reservoir (Herrington Lake). The facilities in Table 13-2 typically have shoreline surface discharges, which are expected to produce buoyant thermal discharge plumes that align closely to the shoreline and generally diminish in thickness with distance from the discharge point. As such, the thermal plumes are expected to have the greatest potential to impact nearshore communities as opposed to open water communities.

The typical freshwater aquatic ecosystem includes phytoplankton, periphyton, aquatic macrophytes, zooplankton, ichthyoplankton (eggs and larvae of fish), shellfish (mollusks and crustaceans), other benthic macroinvertebrates, fish, and wildlife (amphibian, reptiles, birds, and mammals) communities. Rivers are generally considered “low potential impact areas” for the phytoplankton, periphyton, macrophytes (not the base of the food chain), zooplankton, and ichthyoplankton (only transient exposure in a small portion of the receiving water) [2]. Given that the purpose of the biological study is to verify that an existing Section 316(a) variance is still valid, assessing the current condition of the communities that have a low potential to be impacted was not considered necessary.

Table 13-2
Power plants in Kentucky that might require a Section 316(a) biological study

Utility	Power Plant	Receiving Waterbody
Duke Energy	East Bend Generating Station	Ohio River
East Kentucky Power Cooperative	Dale Generating Station	Kentucky River
	HL Spurlock Generating Station	Ohio River
	JS Cooper Power Station	Cumberland River
Henderson City Utilities Commission	Henderson One Generating Station	Ohio River
Kentucky Utilities	EW Brown Generating Station	Herrington Lake
	Ghent Generating Station	Ohio River
	Green River Generating Station	Green River
	Tyrone Generating Station	Kentucky River
Louisville Gas and Electric	Cane Run Generating Station	Ohio River
	Mill Creek Generating Station	Ohio River
Owensboro Municipal Utilities	Elmer Smith Generating Station	Ohio River
Tennessee Valley Authority	Paradise Fossil Plant	Green River
	Shawnee Fossil Plant	Ohio River
Big Rivers Electric Corporation	Coleman Generating Station	Ohio River
	DB Wilson Generating Station	Green River
	Green Generating Station	Green River
	Henderson Two Generating Station	Green River

The reassessment of the maintenance of a BIC will be based on the study of the fish, shellfish, and wildlife communities. Fish communities can consist of species that represent a wide range of trophic levels and pollution tolerance and are frequently the basis of biotic integrity indices. The shellfish community (benthic macroinvertebrates) will be assessed by sampling mussels because the native species are generally considered sensitive to perturbation and many are listed as endangered, threatened, or as species of concern. Benthic macroinvertebrates (e.g., aquatic insects) are also used to assess biotic integrity, but are not specified for Kentucky Section 316(a) studies because fish sampling provides more immediate results, the public has a better appreciation for fish communities, and similar conclusions about the state of the aquatic community can be drawn from fish or benthic macroinvertebrate sampling. Visual surveys will be used to assess potential impacts on wildlife on and around the thermal discharge.

Fish Community Characterization

The following provides two main approaches to assess the fish community: one for the nine facilities on the Ohio River that can use the modified Ohio River Fish Index (mORFIn), and another more generic approach for facilities on other waterbodies.

Ohio River Facilities

Multi-metric bioassessments based on fish communities are useful in evaluating thermal discharge effects in Kentucky. The original ORFIn was developed by the Ohio River Valley Sanitation Commission (ORSANCO) to assess the condition of fish assemblages along the Ohio River [6]. The index contains a variety of metrics (Table 13-3) that are assigned a score based on the results of standardized fish sampling. Summation of individual metric scores provides a total score that equates to a measure of biotic integrity.[3] Recently, the calculation of the metric scores has been modified from discrete to continuous and new thresholds have been established for qualitative ratings of biological conditions.

Table 13-3
Community metrics in the Ohio River Fish Index

Number of native species
Number of sucker species
Number of centrarchid species
Number of great-river species
Number of intolerant species
Percent tolerant individuals
Percent simple lithophilic individuals
Percent detritivorous individuals
Percent insectivorous individuals
Percent piscivorous individuals
Number of DELT* anomalies
Catch per unit effort
Percent non-native individuals

* Deformities, eroded fins and barbels, lesions, and tumors

For the scoring to be relevant, the fish sampling must be conducted in the same manner used to develop the indices. For facilities using the *m*ORFIn, the fish community will be sampled by nighttime, boat electrofishing. Two or more 500 m sections of shoreline, at least one within the

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[3] Biotic integrity is defined as “The ability of an aquatic ecosystem to support and maintain a balanced, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of natural habitats within a region.” [7] and is considered synonymous with BIC.

PSA and at least one reference site upstream or on the opposite side of the river from the thermal discharge, will be electrofished. If the PSA is less than 500 m long, the generic approach described below for facilities not located on the Ohio River will be used.

The sampling site(s) within the PSA will be matched for similarity of habitat to the site(s) in the reference area to the extent feasible. Each site will be electrofished for a minimum of 25 minutes (1,500 seconds) of shock time. A GPS will be used to record the electrofishing tracks. Fish sampling will be conducted at the height of summer (mid-July to mid-August) to assess conditions at the time of maximum thermal stress, and in autumn (mid-October to mid-November) to provide an indication of the cumulative effects of seasonal stressors including overwintering, spawning, and exposure to the thermal discharge. Sampling can also be conducted in winter and spring if desired to confirm the seasonal consistency of results and/or to characterize potential benefits of the heated discharge in winter. Each sampling event will use the same electrofishing equipment, number of crew, and, if possible, the same boat pilot.

All fish collected greater than 20 mm standard length (tip of snout to base of caudal fin) will be identified to species and enumerated; and the presence of deformities, eroded fins and/or barbels lesions, and tumors will be noted. Calculating the *m*ORFIn does not require measurement of length and mass. Representative specimens of species that cannot be positively identified in the field will be preserved in four percent formaldehyde for detailed taxonomic examination in a laboratory. For each study, at least one specimen of each species collected will be retained and preserved to create a voucher collection. Those personnel collecting the fish will include a biologist trained and experienced in fish identification, and will have a scientific collector’s permit from the Kentucky Department of Fish and Wildlife.

An integral part of the *m*ORFIn methodology is substrate habitat characterization using a copper pole. The standard operating procedure for this characterization is available from ORSANCO.

The species collected will be assigned to guilds for great river species (yes/no), pollution tolerance (tolerant/intolerant), trophic category (insectivore/detritivore/piscivore), spawning habitat (simple lithophilic/other), and native (yes/no) based on Table A.1 in Emery et al. [6]. Metric values, scores, and condition rating will be calculated for each sampling area at each sampling date using the spreadsheet mORFIn generator.xlsx.[4] Condition ratings of good or better for the PSA will be considered a demonstration that the fish community is balanced and indigenous despite the thermal discharge and no further analysis of the fish data will be required. If the PSA rating is fair or worse, then the condition rating for the reference area will be calculated and compared to the PSA rating. A reference area rating equal to or worse than the PSA rating will indicate that factors other than the thermal discharge are adversely impacting the fish community, but that no appreciable harm is caused by the thermal discharge.

Facilities on Other Waterbodies

The primary differences between the *m*ORFIn-based and generic approaches are that the sampling sites are not a prescribed length, the community metrics are not aggregated into a single score.

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[4] mORFIn generator.xlsx is available from Ryan Argo at ORSANCO.

A minimum of two sampling sites should be established within the PSA. One site will be immediately downstream of the allowable mixing zone. Another site will be immediately within the 2ºC above ambient isotherm. Additional site(s) may be located within the PSA if sufficient shoreline is available. An unsampled buffer zone of at least 50 m will be established between adjacent sampling sites [8]. An equal number of sampling sites will also be established nearby the PSA in areas unaffected by the thermal discharge. The sampling sites in the unaffected area will be matched by physical habitat to the sampling sites in the PSA to avoid confounding the affects that temperature and habitat can have on community metrics. The exact locations and lengths of sampling sites will depend on the size of the PSA, and will be facility-specific.

The fish community will be sampled by nighttime, boat electrofishing as described in Flotemersch et al. [7]. Each site will be electrofished for at least 20 minutes (1200 seconds) as quantified by the duration the shock generator is energized. For sampling sites where the length of appropriate shoreline is limited, multiple electrofishing passes may be necessary to meet the minimum sampling time requirement. Any additional passes must sample the entire sampling site. If multiple passes are used at one site, then all sites will be sampled with the same number of passes. A GPS will be used to record the electrofishing tracks. Fish sampling will be conducted at the height of summer (mid-July to mid-August) to assess conditions at the time a maximum thermal stress and in autumn (mid-October to mid-November) to provide an indication of the cumulative effects of seasonal stressors including overwintering, spawning, and greatest potential exposure to the thermal discharge. Sampling can also be conducted in winter and spring if desired to confirm the seasonal consistency of results and/or to characterize potential benefits of the heated discharge in winter. Each sampling event will use the same electrofishing equipment, number of crew, and, if possible, the same boat pilot.

All collected fish will be identified to species in the field and enumerated; and up to 100 specimens per species will be measured for length and mass. Representative specimens of species that cannot be positively identified in the field will be preserved in four percent formaldehyde for detailed examination in a laboratory. For each study, at least one specimen of each species collected will be retained and preserved to create a voucher collection. Those collecting fish will include a fisheries biologist trained and experienced in fish identification and will have a scientific collector's permit from the Kentucky Department of Fish and Wildlife.

Various aspects of each sampling site relative to fish habitat will be documented to demonstrate that the PSA and non-PSA control sites are similar. Qualitative observations with photo backup (where applicable) will be made of stream bend (*i.e.*, inside, outside, straight), bottom slope, bank overhang, bank vegetation, in-water structure, and substrate composition. Multiple qualitative determinations of substrate composition (*e.g.*, bedrock, boulder, cobble, gravel, sand, fines, silt, detritus, and combinations thereof) will be made at each site from grab samples, core samples, or metal pipe probe.

Flotemersch et al. [7] identified 37 community metrics that have been used in large-river, fish-based indices of biotic integrity. The following fish community metrics are specified for Kentucky Section 316(a) studies because they are commonly used, relevant to warm-water rivers and reservoirs, and address the qualities of a BIC:

Catch per Unit Effort will be calculated in two forms: as total number of individuals and total biomass collected per unit of time the shock generator is energized.

Species Richness will be calculated as the total number of species collected.

Diversity (H') will be calculated as:

$$H' = \sum_{i=1}^{S}\left(p_i ln(p_i)\right) - [(S-1)/2N] \qquad (1)$$

where S is the species richness, p_i is the relative abundance of each species and N is the total number of specimens collected per site.

Percent by Trophic Classification will be used to evaluate the "presence of necessary food chain species." Each species collected will be assigned to a trophic group (Table 13-4). Sources of trophic classifications will include, but are not limited to, Barbour et al. [9, Appendix C], Etnier and Starnes [10], Pflieger [11], and Burr and Warren [12]. Percent composition of the community for each trophic group classifications will then be calculated based on the number of specimens collected and on biomass.

Table 13-4
Fish trophic classifications

Classification	Primarily Eats	Examples
Herbivore	macrophytes and periphyton	grass carp, central stoneroller
Planktivore	phytoplankton and zooplankton	gizzard shad, paddlefish, bigmouth buffalo
Invertivore	macroinvertebrates	most sunfish, darters, shiners, and minnows
Omnivore	wide variety of living and dead plant and animal matter	common carp, bullheads, channel catfish
Piscivore	fish	bass, flathead catfish

Percent by Pollution Tolerance Classification will be used to evaluate "non-dominance of pollutant tolerant species." The collected species will be classified as tolerant, intolerant, intermediate based on Barbour et al. [9, Appendix C] and Emery et al. [6, Table A.1], and percent composition of each tolerance class will be determined based on the number of specimens collected and on biomass.

Percent Indigenous Species will be used to quantify the "indigenous" portion of BIC. Each species collected will be classified as indigenous or non-indigenous. Indigenous species include native and non-native species that have historically been present and are now integrated into the aquatic ecosystem (*e.g.*, common carp). Non-indigenous species are recently introduced non-native species that can usually be classified as invasive (*e.g.*, silver carp, bighead carp).

A variety of statistical methods can be used to test the above metrics for differences between the PSA and reference area (e.g., *t*-test, paired *t*-test, Mann-Whitney *U*-test, Wilcoxon test). Data used in parametric statistical tests will be appropriately transformed to correct for non-normal distributions and heterogeneous variances [13]. Finding one or more statistically significant differences or a substantial number of adverse but not statistically significant differences within the PSA could indicate one or more aspects of a BIC is not being supported and could result in additional targeted studies to be developed in conjunction with KDOW. The use of statistical tests, however, comes with the following caveat: because the number of data points for each community parameter will be as few as 4 (2 in the PSA and 2 control sites), hypothesis testing may have little power to distinguish significant differences. In this case, a weight-of-evidence approach, such as consistent indications of impacts (or lack thereof) in the PSA sites relative to the control sites over numerous community metrics, may be more appropriate methods to draw a conclusion.

Additional Data Collection

For both BIC determination approaches, additional data will be collected to characterize the sampling sites. Surface water temperature will be measured at the beginning and end of each electrofishing pass. If the thermal discharge consists of blowdown from cooling towers, conductivity will also be measured. Other water quality parameters that are anticipated to vary in relation to the discharge plume and impact the fish community (*e.g.*, pH, dissolved oxygen) will also be measured. Shortly after sampling is completed, river flow (if applicable), power plant discharge rate, and discharge temperature will be obtained for the duration of the sampling event.

Mussel Sampling

The KDOW has indicated special interest in native freshwater mussels as indicators of potential impacts from thermal discharges. The KDOW has stated, “A survey should be performed upstream and downstream of thermal discharges that could harbor mussel beds; the intensity of the survey will be judged on a case by case basis.”[5] Based on this guidance, three approaches are provided:

1. Demonstrate in the study plan that a mussel survey is not necessary because the area of the thermal discharge is not expected to harbor mussel beds.
2. Demonstrate in the study plan that mussels are a minor constituent of the aquatic community and conduct a qualitative survey upstream and downstream of the thermal discharge.
3. Acknowledge that the area of the thermal discharge could harbor mussel beds and conduct a semi-quantitative survey.

No Survey

The demonstration of no need to conduct a mussel survey will be based on a literature review of all available mussel studies conducted by natural resource agencies, academic institutions, and industry relevant to the study area. Included in this review will be U.S. Fish and Wildlife Service and Kentucky Department of Fish and Wildlife records for threatened, endangered, candidate and special concern mussel species and associated habitats that might be present in the study area. The results of this review will be included in the Study Plan.

Qualitative Study

The demonstration of a need to conduct only a qualitative mussel survey will be based on a literature review like that described above. The type of qualitative survey will depend on the accessibility of the shoreline. For easily accessible and open shoreline, a qualified malacologist

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[5] Kentucky Department of Water. January 2011. “Comments on UIE Generic Study Plan for 316(a) Variance”.

will walk the same portions of shoreline in the PSA and reference area that where electrofished identifying and counting shells on the shoreline or shells that are visible in the water.

For study areas with gravel or finer substrates and shorelines not amenable to walking, a brail will be towed over the same portions of the PSA and reference area that were electrofished. A brail is a pole or board with a cluster of several ropes and chains attached. Beaded hooks are at the end of each chain. The brail is pulled parallel to the current in a downstream direction. As the brail is pulled along the bottom of the river, mussels clamp down on the beaded ends of the brail hooks and can be brought to the surface [14]. Collected mussels will be identified to species and enumerated by a qualified malacologist.

For either method, community parameters, such as species richness, catch per unit shoreline length, and the presence or absence of species of concern, will be used to make a best professional judgments of the relative quality and comparability of the mussel communities in the PSA and the reference area. Because mussels are long-lived and generally sedentary, qualitative mussel sampling will be conducted only in summer.

Semi-Quantitative Survey

If significant populations of mussels are suspected to be present in the study area, the PSA and reference areas will be semi-quantitatively sampled. The sampling areas for mussels will be the same areas electrofished. A minimum of 10 transects, each starting at the water's edge and extending perpendicular to the shoreline across the sampling area, will be established in each area. The transects will be evenly spaced and encompass the entire length of the sampling area (Figure 13-3). The locations of the end points of each transect will be determined using GPS. Sampling will be limited to water depths less than or equal to 15 meters.

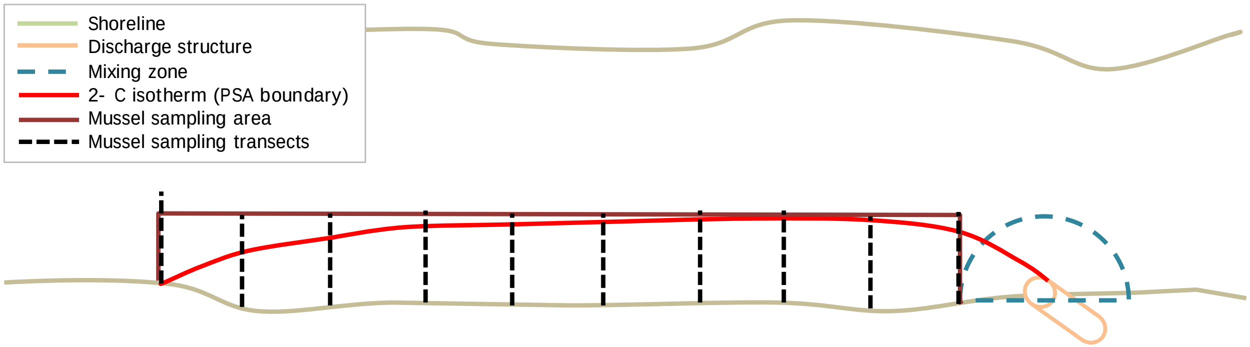

Figure 13-3
Schematic of mussel sampling area and transects in a hypothetical PSA

Mussels will be collected by certified scuba or surface supplied air diver. All freshwater mussels encountered visually or tactually within one meter (an arm's length) of the transect line and within each 10 meter section of transect will be collected. Water depth, substrate composition (Wentworth scale), bottom water temperature, and other basic water quality parameters that could influence mussel distribution will be recorded at 10-meter intervals along the transects. Live mussels will be identified, counted, measured (length in millimeters), and aged (external annuli count). The sex and reproductive condition of sexually dimorphic species will also be noted. Shells of freshly dead individuals (with or without soft parts, lustrous nacre, and periostracum intact, dead less than one year) will be identified and counted. Species collected as relic shells will be scored as either weathered dead (nacre dull or chalky, periostracum often heavily worn, dead one year to many years) or subfossil (shell margin heavily worn or fragmented, periostracum mostly or completely gone, dead many years to many decades) and noted as present for each transect. Dead shells of representative species will be retained as voucher specimens. All live specimens will be returned to the water. Because mussels are long-lived and generally sedentary, semi-quantitative mussel sampling will be conducted only in summer. Miller and Payne [15], in a study at the William H. Zimmer Power Station on the Ohio River at Cincinnati, demonstrated that the semi-quantitative method describe above produced similar estimates of community composition, species richness, diversity, and evenness as the more labor intensive quadrate method.

For each site, the following mussel community metrics will be calculated for the indigenous species:

- Catch per unit effort
- Rarefaction species richness
- Percent composition by species
- Percent indigenous
- Diversity (*H'*) (if sufficient sample size)
- Average age
- Percent juveniles
- Percent gravid or charging (for those species for which these conditions can be determined)
- Percent freshly dead
- Age range

Results from the PSA area will be compared to the control area to assess the impact of the thermal discharge.

Wildlife Community Assessment

> Most sites in the United States will be considered ones of low potential impact for other vertebrate wildlife simply because the projected thermal plume will not impact large or unique populations of wildlife. The main exceptions will be sites in cold areas (such as the North Central United States) which would be predicted to attract geese and ducks, and encourage them to stay through the winter. Other exceptions to sites classified as low potential impact would be those few sites where the discharge might affect important (or threatened and endangered wildlife such as manatees [2].

Although the location of the power plants in Kentucky indicates the sites are of low potential impact, EPA Region IV has indicated a wildlife community assessment must be performed as part of any Section 316(a) demonstration study. The purpose of the assessment is to determine if a BIC of wildlife (non-fish vertebrates: amphibians, reptiles, birds, and mammals) exists in, on, and around the PSA.

Inventories of wildlife will be conducted along the same stretches of shoreline that were electrofished. Each area will be surveyed by slowly traversing the length by boat or by foot and recording observations of wildlife. The width of each area surveyed will include the river from the shoreline to the approximate width of the PSA and from the shoreline landward to the minimum of the limit of visibility or approximately 30 m (100 ft). Information recorded will include identification to the lowest practical taxon of individuals that are observed visually and/or audibly, and a direct count of individuals observed. Birds and bats seen flying through the survey areas will not be counted unless they are observed to be actively foraging in the airspace above the survey area. Sampling will be conducted during the day in summer and again in the fall concurrent with aquatic community sampling.

All observed specimens will categorized by trophic group (e.g., herbivore, omnivore, carnivore) based on existing life history accounts. Abundance will be standardized by length of shoreline surveyed. Community metrics will be calculated for each area, such as:

- Percent composition by vertebrate class
- Percent composition by trophic group
- Percent composition by native species
- Species diversity
- Abundance by class or other groupings

Comparisons between the PSA and the reference area metrics will be used to assess the BIC status of the PSA.

Reporting

A study report will be prepared providing a description of the study design, study area, environmental setting, data collection methods, facility operational data, thermal plume mapping results, water quality monitoring data, and biological and wildlife community information. Raw data and associated field collection parameters will be appended to the report.

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14

A LOW COST METHOD OF EVALUATING THERMAL DISCHARGE COMPLIANCE USING DETAILED FIELD MEASUREMENTS AND MASS-BALANCE SCALING

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Abstract

Many power generating and other industrial facilities with thermal discharges are periodically required to demonstrate compliance with thermal effluent standards per Section 316(a) of the Clean Water Act, often as a condition of permit issuance or renewal. Normandeau Associates, Inc. has developed an alternative to the typical assessment of thermal discharge impacts (i.e. with complex mechanistic modeling) by using a combination of highly detailed field measurements and simple mass-balance theory to assess compliance under specific operating and environmental conditions. Our method involves deploying a string of proprietary rapid response micro-thermistors linked to sub-meter accuracy Global Positioning System (GPS) receivers on a boat to perform highly detailed, real-time temperature surveys in receiving waters. We then extrapolate our empirical observations to specific discharge and receiving water temperatures to evaluate compliance at targeted levels. This methodology was approved for the assessment of thermal discharges from two steam electric plants located in New York State by the New York Department of Environmental Conservation. We present the development and utilization of this methodology as well as a case study from one of the aforementioned generating plants in New York to demonstrate the application of this methodology in a thermal verification study.

Introduction

Normandeau Associates, Inc. (Normandeau) has a long history of performing environmental studies in support of permit renewal and regulatory compliance at power generating stations. Of particular concern are the impacts of thermal discharges to receiving waters and meeting the thermal standards of Section 316(a) of the Clean Water Act as well as any state level criteria for thermal discharges and/or permit limitations. Measuring thermal plumes in receiving waters and using measured data to parameterize hydrothermal and other environmental models remains a challenge, particularly within the confines of a limited budget and highly variable environmental conditions and plant operations.

Our client needs have required us to create field studies to determine thermal plume characteristics and ecological impacts in a variety of receiving water environments including river, estuary, marine, and freshwater lakes to assess compliance with regulations and permit requirements. Typically, our study sites have been steam electric power generating stations withdrawing non-contact cooling water for plant operations and discharging the heated wastewater back to the environment per a National Pollutant Discharge Elimination System (NPDES) or state equivalent permit. A condition of the permit is often a verification study showing compliance with all applicable regulations and permit specific variances. Examples of measurable parameters include maximum temperature rise, mixing zone conformance, changes in temperature with depth, and cross sectional area requirements. In response to these needs, we have developed methods of obtaining in situ measurements of receiving water temperatures through the use of mobile surveys and continuous deployment temperature monitoring equipment to simultaneously measure water temperatures at multiple depths and across a large range of scales (study areas cover 10s of acres to 1,000s of acres). Through the use of mobile surveys and deployed instrumentation, we have successfully performed thermal discharge verification studies in New Hampshire, Vermont, New York, and Michigan with approval of our methodology by each state's regulators.

In our most recent studies, at two steam electric stations in New York, we had been tasked with evaluating hypothetical scenarios of plant operating conditions and environmental conditions which were within permitted ranges but not directly measured during the field studies. The permits allowed plant discharge temperatures higher than would likely be measured outside of a prolonged extreme weather event and/or peak electrical demand and therefore would be logistically difficult to target in a given field season. This necessitated the use of a model simulation, however the cost and scope of creating a full hydrothermal model simulation was unjustified. As a cost effective alternative, we proposed using temperature survey data as the basis for a simplified model simulation based on the elemental laws of mass balance and treating the discharge of heated wastewater as a simple mixing problem. For the stations of interest these assumptions were justified due to an ideal combination of receiving water environment and plant operations. The receiving water bodies at both stations were tidal estuaries with very strong currents that reversed with each phase in the tide cycle. Therefore the greatest concern with respect to maximum thermal impacts was during slack tide conditions when the current stopped running and the thermal discharge plume would have the fewest mechanisms for dissipation (i.e. by the removal of the additional mixing and advection of heat provided by the tidal currents). This also meant that the period of interest was very short (slack currents lasted 15 – 30 minutes at these sites) and therefore we were able to evaluate an individual event rather than simulating conditions over time to assess a "worst case" scenario. Additionally, the subject stations operated with fixed rate circulating pumps such that the thermal discharges occurred at a constant flow rate, and therefore in slack current conditions the distribution of the discharge plume would ideally be very similar from one event to another.

Our assumption was that over the short period of time of a slack current event, nearly all cooling of the thermal plumes from our subject stations was the result of dilution, and mechanical mixing with the receiving waters and other heat transfers such as evaporation, advection, and conduction could be discounted (For an overview of thermal effluent processes and modeling see Dunn et al. [1], Lee et al. [2], and Miller and Brighouse [3]). Therefore, if we could delineate the entirety of a thermal plume through direct precise measurements of water temperature, and background water temperatures were reasonably homogeneous, then we would have an estimate of dilution coefficients in the receiving waters within the timeframe of interest (e.g. slack tide). Using the empirically derived dilution patterns we could then scale the results to show the temperature patterns that would result with the same dilution factors but different operating and environmental conditions, e.g. combinations of high ambient and discharge temperatures at the upper permit limits. We recognize these assumptions neglect the buoyancy effects in changing the outfall temperatures relative to ambient temperatures, however, incorporating a buoyancy factor was beyond the scope of this study and determined to be unnecessary for the level of confidence the clients and regulators were seeking. The New York State Department of Environmental Conservation approved this methodology to assess thermal discharge conditions and compliance with thermal standards at both the stations of interest.

We anticipate that this methodology is applicable to other environments where effluent discharge rates are steady state and heated wastewater is sufficiently warmer than background temperatures to facilitate plume delineation. We believe this method presents a robust estimate of thermal plume temperature patterns at specific targeted operating conditions and in many cases should be sufficient for verification study criteria.

Methods

The foundation of our thermal plume characterization studies was a mobile temperature survey which was conducted by boat in a receiving water within the vicinity of a station outfall. Temperature data were collected by an array of instruments deployed at multiple depths from a survey boat. Normandeau has developed a proprietary rapid response micro-thermistor for these surveys which facilitated highly accurate temperature measurements at a high sampling rate. The thermistor contained a thin (<1mm) low-mass sensor combined with a rapid step response constant and a polling rate of 1 second which allowed for accurate characterization of rapid changes in temperature. The array of thermistors was deployed at multiple depths (e.g. every 1 meter from the surface to near the bottom or to a maximum of seven meters) from a vertical boom fixed to a survey boat. The boom could be raised and lowered to account for changes in channel depth. In situations where the channel bottom featured large boulders or other shallow areas that could snag and break a fixed boom while underway we deployed the array of thermistors from a weighted trawling line.

During a survey, temperature measurements were synchronized with GPS measurements and recorded by an onboard data logger. GPS data was provided by a Trimble R8 GNSS Receiver which was mounted adjacent to the boom or trawling line hosting the thermistor array. Real-time GPS differential corrections were provided by a Wide Area Augmentation System (WAAS) and allowed for sub-meter accuracy of horizontal measurements. GPS data was logged at a one second interval, synchronized with the thermistor data. Real time temperature and position data could be seen while underway to aid with the survey navigation.

Mobile temperature surveys were conducted when receiving water and thermal discharge conditions were expected to be within a particular range, such as high ambient temperature and large operating temperature rise (ΔT, difference in intake and outfall temperatures due to plant operations) to evaluate thermal plume characteristics as close to permit limits as possible. Surveys were also conducted during conditions with the greatest thermal impact including slack tides in estuaries or low flow in non-tidal rivers. A typical survey navigation route would pass by the station outfall as close to the shore as was safe, then make multiple subsequent passes though the receiving waters parallel to the river bank at increasing distance to delineate the full extent of the discharge plume (Figure 14-1). Boat speeds were generally kept constant and on the order of 1-2 m/s. If the thermistor array was deployed from a fixed boom, adjustments were made to the depth of the boom as water depth changed. Likewise, depth adjustments were made if the instrument array was deployed from a weighted trawling line with the added consideration of slightly adjusting boat speed to maintain the lines angle of deflection. It was important to maintain a constant relative speed (constant throttle setting) when using a trawling cable setup as this generally kept the angle of deflection from the rigging at a consistent position.

Figure 14-1
Planned temperature survey route in the vicinity of a station outfall. Yellow line shows planned navigation route.

Temperature and GPS data were post-processed after a survey and corrections were applied as necessary for changes in the depth of the instruments due to raising or lowering the boom or trawling line or due to changes in speed which affected the angle of deflection in a trawling line. A GPS offset was applied to account for the difference in position of the GPS antenna versus the instrument array. A simple fixed-distance offset was used for thermistors attached to a vertical boom, while thermistors attached to a trawling line required a trigonometric correction to account for the angle of deflection in both the vertical and horizontal axes. For simplicity we assumed the trawling line maintained a nearly linear profile in the water. First we determined the mean direction of travel based on the 6 data points prior to a given data point (to account for the trailing effects of the line dragging through the water) then we applied an offset based on the trailing distance of a thermistor both vertically from the angle of deflection and horizontally from the mean direction of travel for each thermistor. Temperature data from the surveys were also corrected for each thermistor based on laboratory calibrations in a constant temperature bath with a thermometer traceable to the National Institute for Standards and Technology.

Survey data were eliminated from the final dataset in instances of closely overlapping tracks, with the earlier track being kept and the later track, which typically briefly overlapped as a result of veering off course, discarded. This was consistent with our following the plume from the discharge point out into open water and was necessary due to the creation of artificially high temperature gradients from conflicting temperature values at points in very close proximity (but measured at different times) which could significantly skew any subsequent data interpolations. We also elected to remove any data taken at a sharp turn during the survey (e.g. when the boat was reversing direction, or when the thermistor array was being raised or lowered) due to the uncertainty of instrument depth at those times. These measures ensured that the final datasets were as accurate as possible.

In order to estimate the full spatial extent of a thermal plume and to make any assessment of conformance with thermal standards, it was necessary to interpolate our measured temperatures onto a gridded data field, typically 1 ft^2. We performed the interpolation in Matlab®, on a 2D grid clipped to the survey boundaries using the natural neighbor method of interpolation (Sibson [4]). All spatial calculations and figures were then based on the interpolated data grids. We performed all calculations requiring a vertical axis from the 2D layers by extending the interpolated cell values vertically to fill a given layers depth interval.

The primary limitation in using empirical data for a thermal verification study was the likelihood that ambient temperatures and plant operations would not be at the exact levels targeted for the study. To address this inevitable limitation, we used common mass balance theory to extrapolate our empirical results to various water temperature and ΔT scenarios. This simple mass balance scaling exercise was based on the following assumptions:

- In a thermal plume, on a short timescale (~ 1 hr) changes in temperature result overwhelmingly from dilution in cooler receiving waters while other processes (such as evaporative cooling, advection from the study site, conduction to the channel bed, etc) can be effectively discounted
- The dilution coefficient at any point in the receiving water will remain essentially constant across a range of discharge and ambient temperatures so long as the outfall discharge rate and receiving water flow rates remain constant (true for fixed cooling pump rates and slack current conditions) and plant operating ΔT is within a reasonably confined range
- Based on the principles of mass balance, predicted temperatures in the receiving waters can be determined as a function of the dilution coefficient at a given point, the discharge temperature at the outfall, and ambient water temperature

Based on the above assumptions, we estimated the dilution coefficients at each point within a thermal plume data field, i.e. each interpolated grid point as discussed previously. At any point in a thermal plume, dilution was determined as:

$$D = (T - T_{d1}) / (T_{a1} - T) \tag{1}$$

Where D was the dilution that the discharge plume received at any particular location, unitless; T was the interpolated temperature at a particular location within a discharge plume, °F; T_{d1} was the average measured temperature of a station discharge over the survey time period, °F; T_{a1} was the average measured ambient water temperature at the time of a survey, °F.

Using the empirically derived patterns of receiving water dilution, the temperature at any point in a thermal plume could then be predicted for other combinations of discharge temperature and ambient temperature:

$$T_p = ((T_{a2} * D) + T_{d2}) / (D + 1) \qquad (2)$$

Where T_p was the predicted temperature at a point in a discharge plume, °F; T_{a2} was the average ambient temperature for a given scenario, °F; T_{d2} was the average station discharge temperature for a given scenario, °F.

One issue we encountered in our thermal surveys was the entrainment of heated wastewater back to a stations inlet, with measured station inlet temperatures consistently higher than ambient water temperatures. We assumed this was a simple mixing problem and determined that for our predicted temperature scenarios the entrainment of heated wastewater should remain constant and affect inlet temperatures proportionally to the difference in ambient water temperatures and discharge temperatures as:

$$(T_{i1} – T_{a1}) / (T_{d1} – T_{a1}) = (T_{i2} – T_{a2}) / (T_{d2} – T_{a2}) \qquad (3)$$

Where T_{i1} was the average measured inlet temperature for a station at the time of a survey and T_{i2} was the predicted average inlet temperature for a station for a given scenario. We used equation 3 to predict inlet temperatures for all ambient temperature/discharge temperature scenarios.

The above exercise produced gridded data fields as discussed previously and all estimates of maximum temperature, areas of exceedance, and other thermal plume indicators were derived from the gridded data fields. Note that any size grid can be produced as is convenient for a particular scenario, but it must be initialized with interpolation of the original quality controlled dataset.

Case Study

To demonstrate the application of the methodology outlined above, we present the results from one thermal verification study for a gas powered steam electric cogenerating station in New York. The station was rated at 600+ MW and supplied the local 69kV system in addition to producing more than 5 million lbs per hour of steam to the local steam distribution system. The station withdrew once-through cooling water from the adjacent tidal estuary for plant operations, primarily condenser cooling and cable cooling. Discharge of heated wastewater back to the tidal estuary was permitted by the State Pollution Discharge Elimination System (SPDES) as issued by the New York State Department of Environmental Conservation (NYSDEC) and in accordance with the Clean Water Act. The SPDES permit was recently renewed and NYSDEC required a study to assess conformance with thermal standards under variable operating conditions and under the maximum permitted discharge temperature for the station. State regulations [6NYCRR §704.2(b)(5)] required that:

i. The water temperature at the surface of an estuary shall not be raised to more than 90°F at any point.

ii. At least 50% of the cross sectional area and/or volume of the flow of the estuary including a minimum of one-third of the surface as measured from water edge to water edge at any stage of tide, shall not be raised to more than 4°F over the temperature that existed before the addition of heat of artificial origin or a maximum of 83°F, whichever is less.

iii. From July through September, if the water temperature at the surface of an estuary before the addition of heat of artificial origin is more than 83°F, an increase in temperature not to exceed 1.5°F at any point of the estuarine passageway as delineated above, may be permitted.

The Station's SPDES permit specifically granted a variance from 704.2(b)(5)(i) within a 0.1 acre (4,360 sq. ft.) mixing zone for assimilation of the thermal discharge. Therefore the objective of the study was to assess conformance with the above standards, as well as the mixing zone variance, under different operating conditions including a maximum permitted discharge temperature of 98°F. To address these requirements we performed a total of four thermal surveys in the summers of 2009 and 2010, with two consecutive or nearly consecutive surveys taking place at flood slack tide and ebb slack tide each year. The 2010 surveys took place during higher ambient water temperatures and greater station production than the 2009 surveys and were therefore more representative of conditions at the upper end of permitted station operations. In addition, our field sampling design during the 2010 surveys allowed us to better delineate the thermal discharge plume than the 2009 surveys. Consequently, we elected to base the predicted plume conditions on the 2010 survey data and we present the results only from the 2010 surveys. At the time of our study the plant was operating at a typically high output for summer demand (90+ percentile based on operating history) and ambient water temperatures were warm (76°F).

Figure 14-2 and Figure 14-3 show water temperatures by depth for the flood and ebb surveys, respectively. At the time of the surveys all of the applicable thermal standards were easily met as the maximum discharge temperature was well below 90°F and the area of influence of the thermal plume was well below the area criteria in 704.2(b)(5)(ii), above. We saw similar results during the 2009 surveys, therefore our study adequately demonstrated conformance with thermal standards under variable operating conditions at relatively high summer ambient temperatures.

Using the temperature projection method outlined previously, we evaluated multiple ambient temperature/discharge temperature scenarios at maximum operating conditions. The SPDES permit allowed the station to operate with a maximum ΔT of 18°F or a discharge temperature of 98°F, whichever was less. To evaluate the thermal plume impacts at maximum operating conditions, we ran our temperature scaling exercise at increments of 1°F ambient water temperature up to the highest allowable ambient temperature at which the station could operate with both the flood and ebb survey datasets. In all of the scenarios, the areal impact of the thermal plume was well below the area criteria in 704.2(b)(5)(ii) and 704.2(b)(5)(iii) as we demonstrated no measurable temperature rise beyond a few hundred feet laterally of the outfall (total channel width was ~2700 ft.), while lateral spreading upstream or downstream of the outfall was sufficiently diluted to be well below either the 4°F or 1.5°F temperature rise standards depending on ambient temperature. Figure 14-4 shows the worst case scenario evaluated with respect to 704.2(b)(5)(iii) with an ambient water temperature of 83°F and the maximum permitted discharge temperature of 98°F and demonstrates temperature rise at the surface was within the thermal standards.

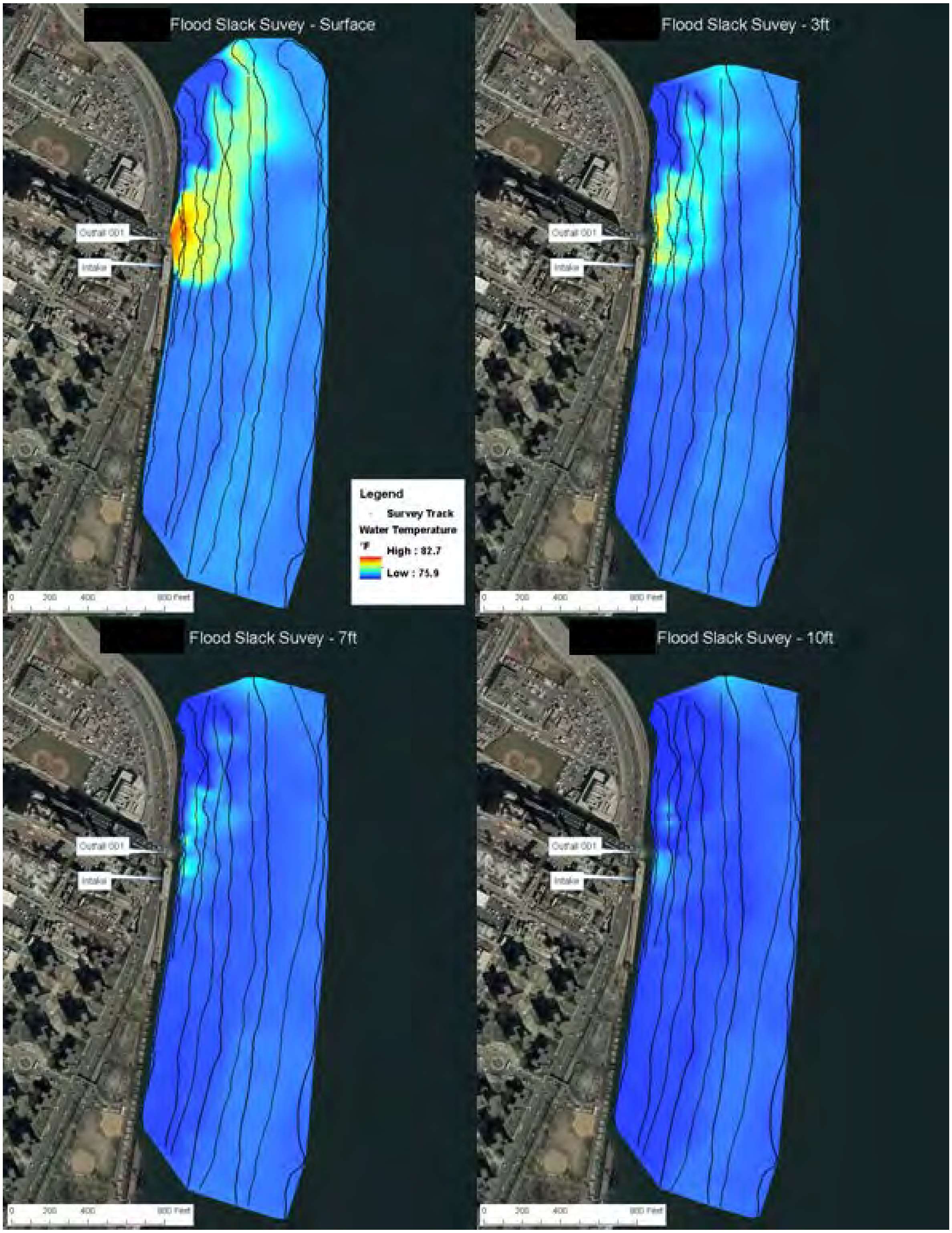

Figure 14-2
Water temperatures by depth in vicinity of station outfall – flood survey

Figure 14-2 (continued)
Water temperatures by depth in vicinity of station outfall – flood survey

The primary concern was potential exceedance of the station's mixing zone variance at maximum operating conditions. In Table 14-1 we show that at ambient water temperatures of 66°F and above the station could exceed its mixing zone variance with surface temperatures above 90°F in an area larger than the permitted 0.1 acres. Similar results were seen for both the ebb and flood datasets although the flood dataset had a slightly greater impact and is shown in Table 14-1 as well as Figure 14-5. We demonstrate that at maximum discharge temperatures as the ambient temperature rises, the area in excess of 90°F would also rise, although the total thermal impact would lessen due to maximum discharge temperature being capped at a 98°F, thus lowering the operating ΔT.

Our analysis adequately demonstrated this station would meet the thermal standards of 6NYCRR §704.2(b)(5)(ii) and (iii) under variable operating conditions and at maximum operating conditions. However, we also showed that the station would likely exceed its permitted mixing zone variance for 6NYCRR §704.2(b)(5)(i) by raising the surface water temperature greater than 90°F in an area larger than 0.1 acres at maximum permitted discharge temperatures. NYSDEC approved of our study plan and accepted this work for the purpose of assessing compliance with all applicable thermal standards and permit variances. As a result of our study findings NYSDEC and the station were reviewing the SPDES permit issued and determining whether it would be necessary to revise the mixing zone area stated in the permit.

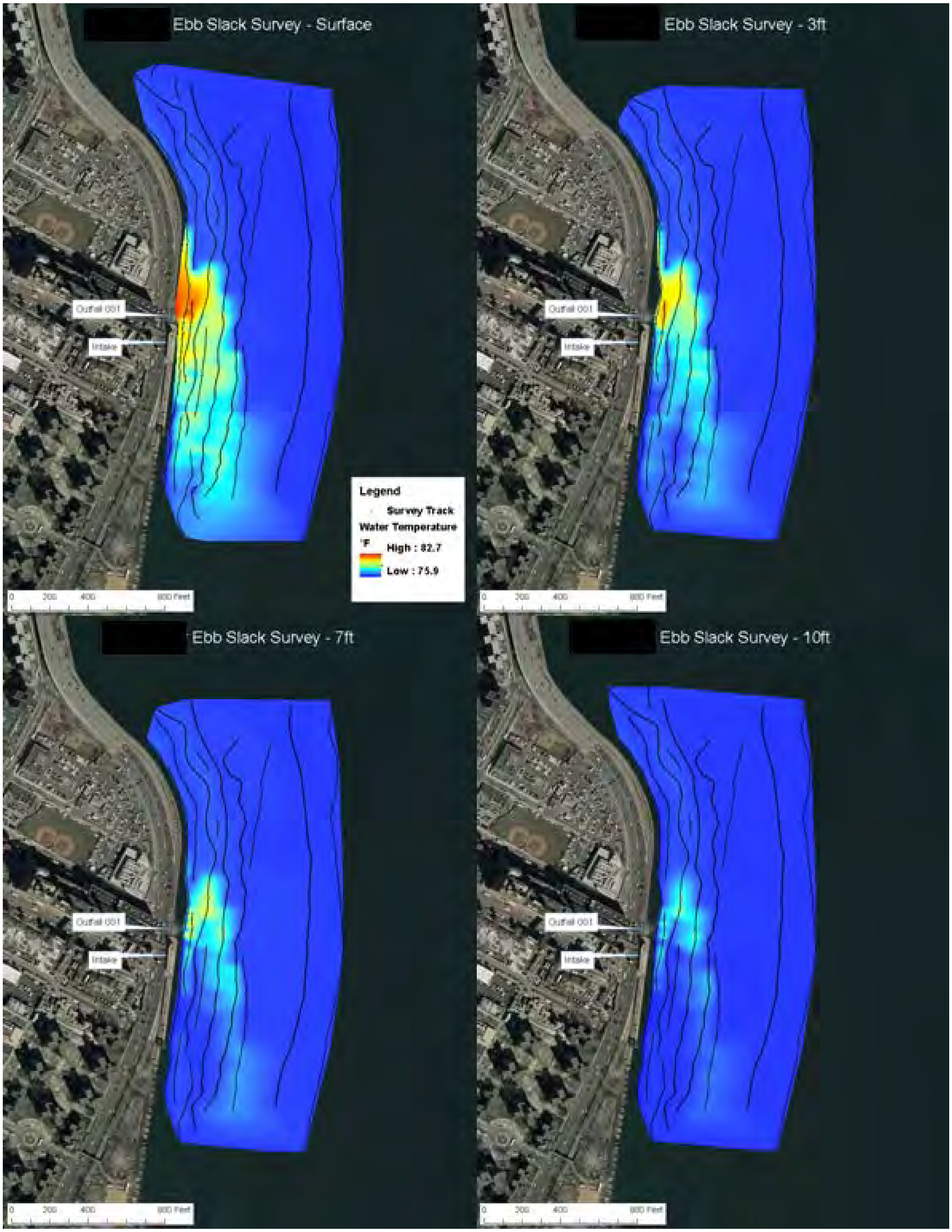

Figure 14-3
Water temperatures by depth in vicinity of station outfall – ebb survey

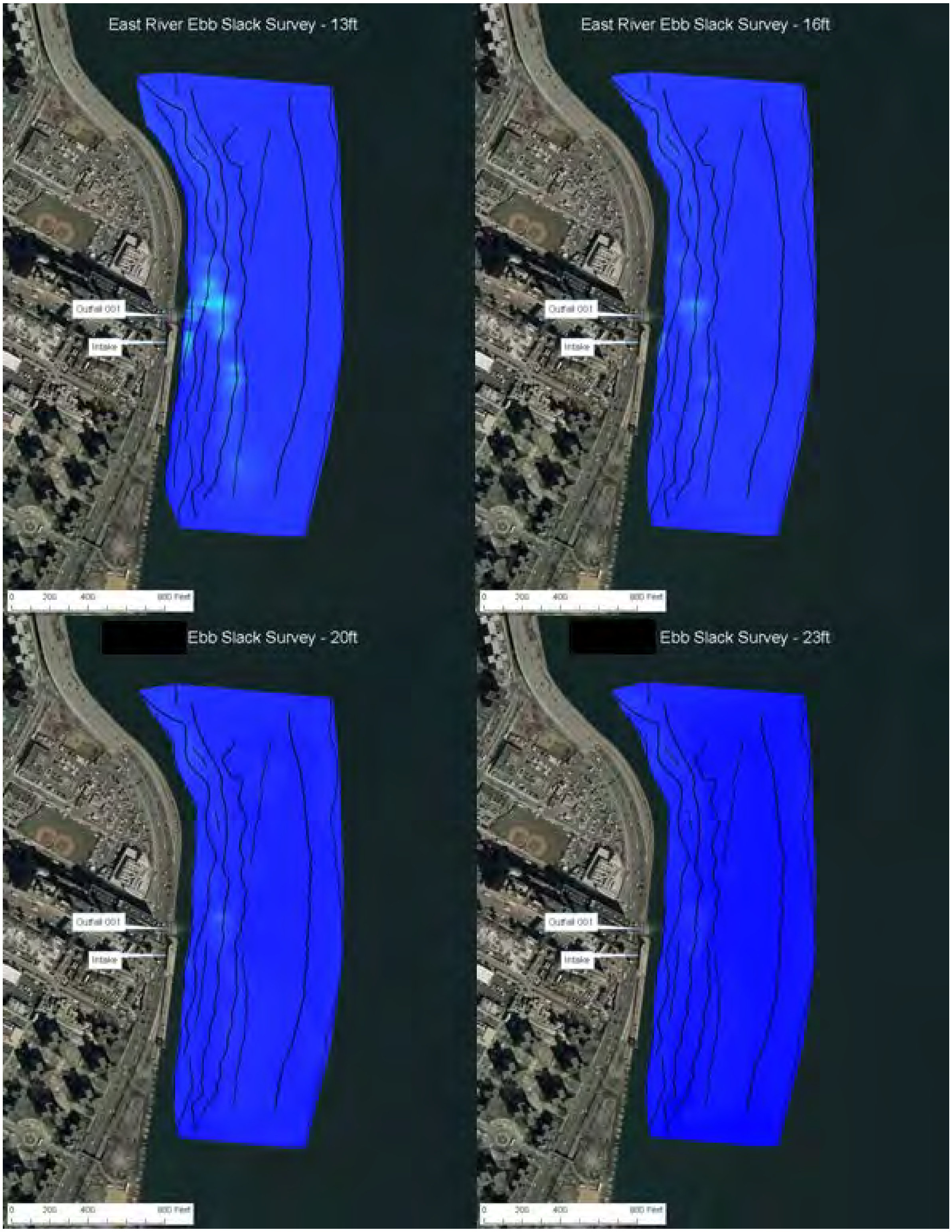

Figure 14-3 (continued)
Water temperatures by depth in vicinity of station outfall – ebb survey

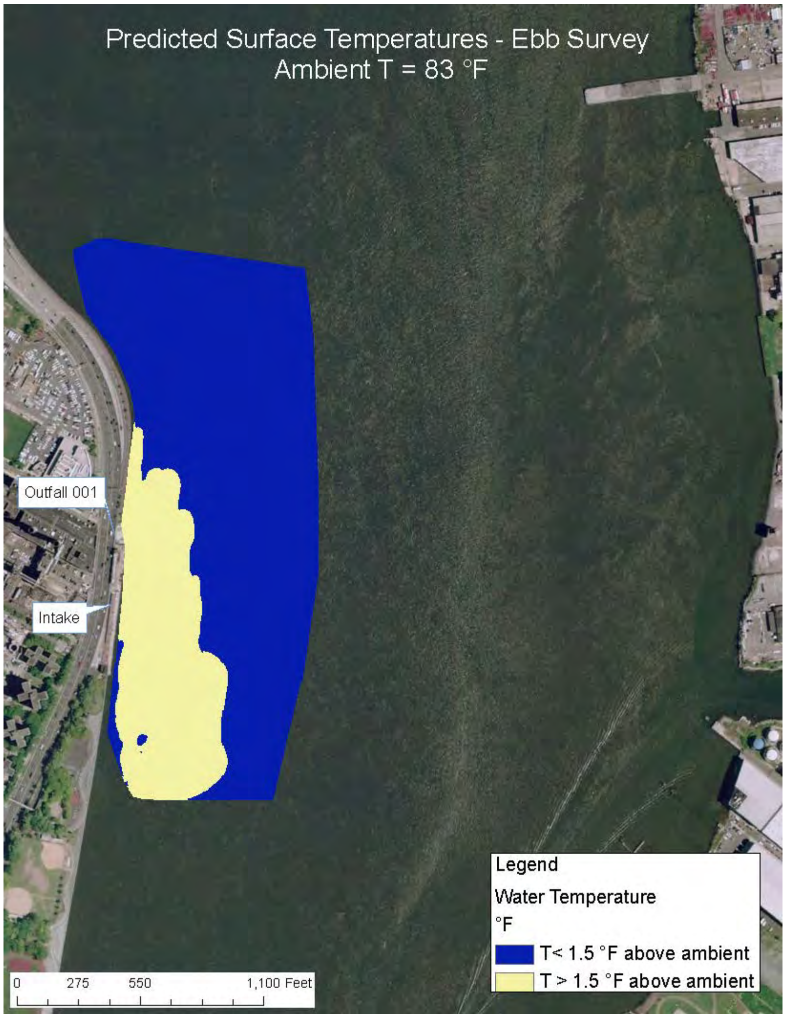

Figure 14-4
Predicted surface temperatures at ebb slack tide in vicinity of station outfall with ambient temperature of 83°F and maximum discharge temperature

Table 14-1
Maximum operating conditions summary at flood slack tide. Cells highlighted in gray indicate an exceedance of permitted mixing zone area (0.1 Acres).

Predicted Temperatures at Flood Slack Tide						
Ambient Water Temperature (°F)	Discharge Rate (GPM)	Inlet Temperature (°F)	Maximum Permitted Delta T (°F)	Maximum Permitted Discharge Temp (°F)	Area in Excess of 90°F Under Maximum Permitted Operating Conditions (Acres)	Largest Allowable Delta T to Comply with 0.1 Acre Mixing Zone (°F)
61	256400	72.0	18.0	90.0	0.00	18.0
62	256400	73.0	18.0	91.0	0.00	18.0
63	256400	74.0	18.0	92.0	0.01	18.0
64	256400	75.0	18.0	93.0	0.04	18.0
65	256400	76.0	18.0	94.0	0.09	18.0
66	256400	77.0	18.0	95.0	0.14	17.4
67	256400	78.0	18.0	96.0	0.21	16.6
68	256400	79.0	18.0	97.0	0.29	15.9
69	256400	80.0	18.0	98.0	0.37	15.2
70	256400	80.6	17.4	98.0	0.39	14.5
71	256400	81.2	16.8	98.0	0.42	13.8
72	256400	81.9	16.1	98.0	0.45	13.0
73	256400	82.5	15.5	98.0	0.48	12.3
74	256400	83.1	14.9	98.0	0.53	11.6
75	256400	83.7	14.3	98.0	0.58	10.9
76	256400	84.4	13.6	98.0	0.64	10.1
77	256400	85.0	13.0	98.0	0.71	9.4
78	256400	85.6	12.4	98.0	0.80	8.7
79	256400	86.2	11.8	98.0	0.91	7.9
80	256400	86.8	11.2	98.0	1.05	7.3
81	256400	87.5	10.5	98.0	1.27	6.5
82	256400	88.1	9.9	98.0	1.60	5.8
83	256400	88.7	9.3	98.0	2.09	5.1
84	256400	89.3	8.7	98.0	2.98	4.3
85	256400	89.9	8.1	98.0	4.41	3.6
86	256400	90.6	7.4	98.0	5.95	2.9
87	256400	91.2	6.8	98.0	7.28	2.2
88	256400	91.8	6.2	98.0	8.70	1.4
89	256400	92.4	5.6	98.0	10.87	0.7

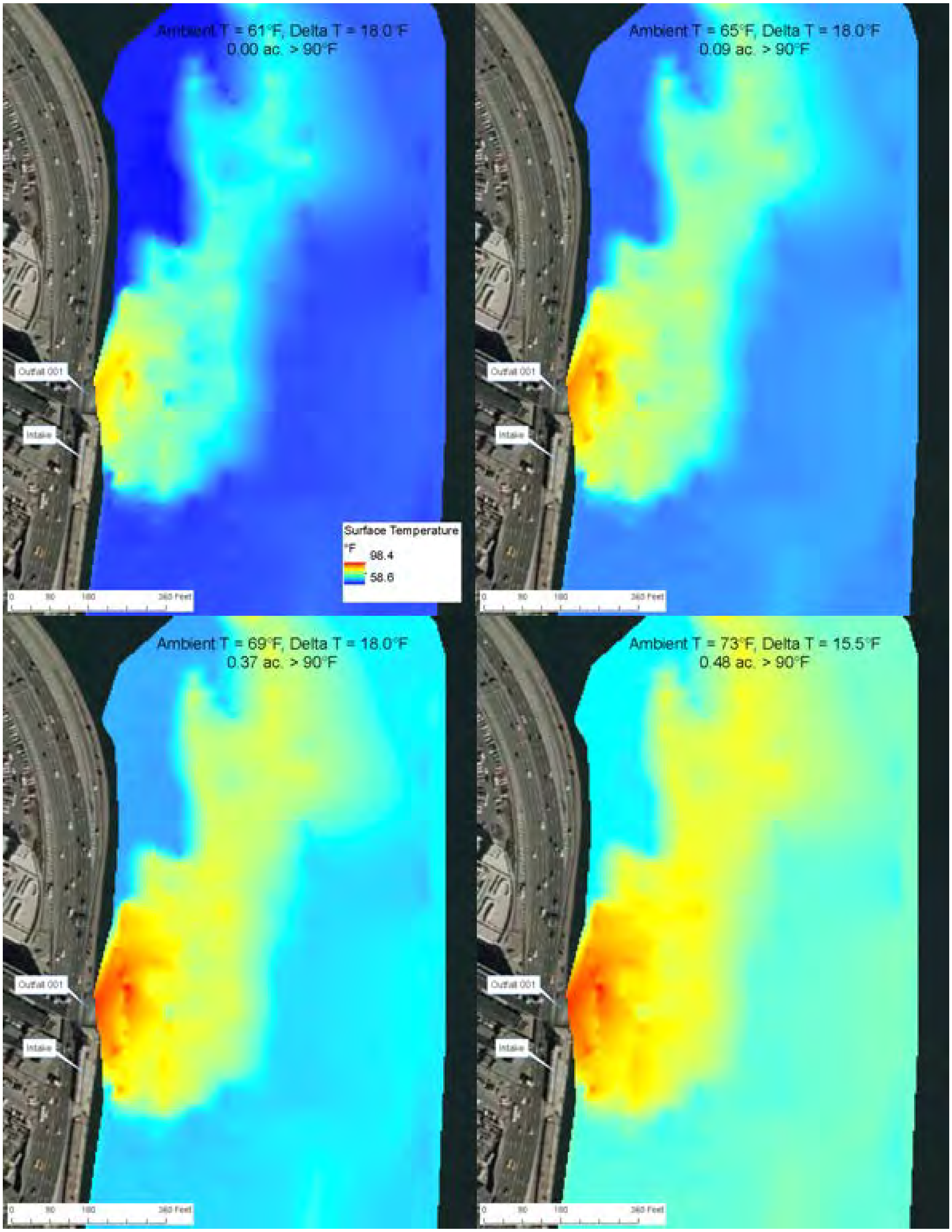

Figure 14-5
Predicted surface water temperatures in vicinity of Station outfall – flood conditions. Panels show increasing ambient temperature and maximum permitted discharge temperature for given conditions.

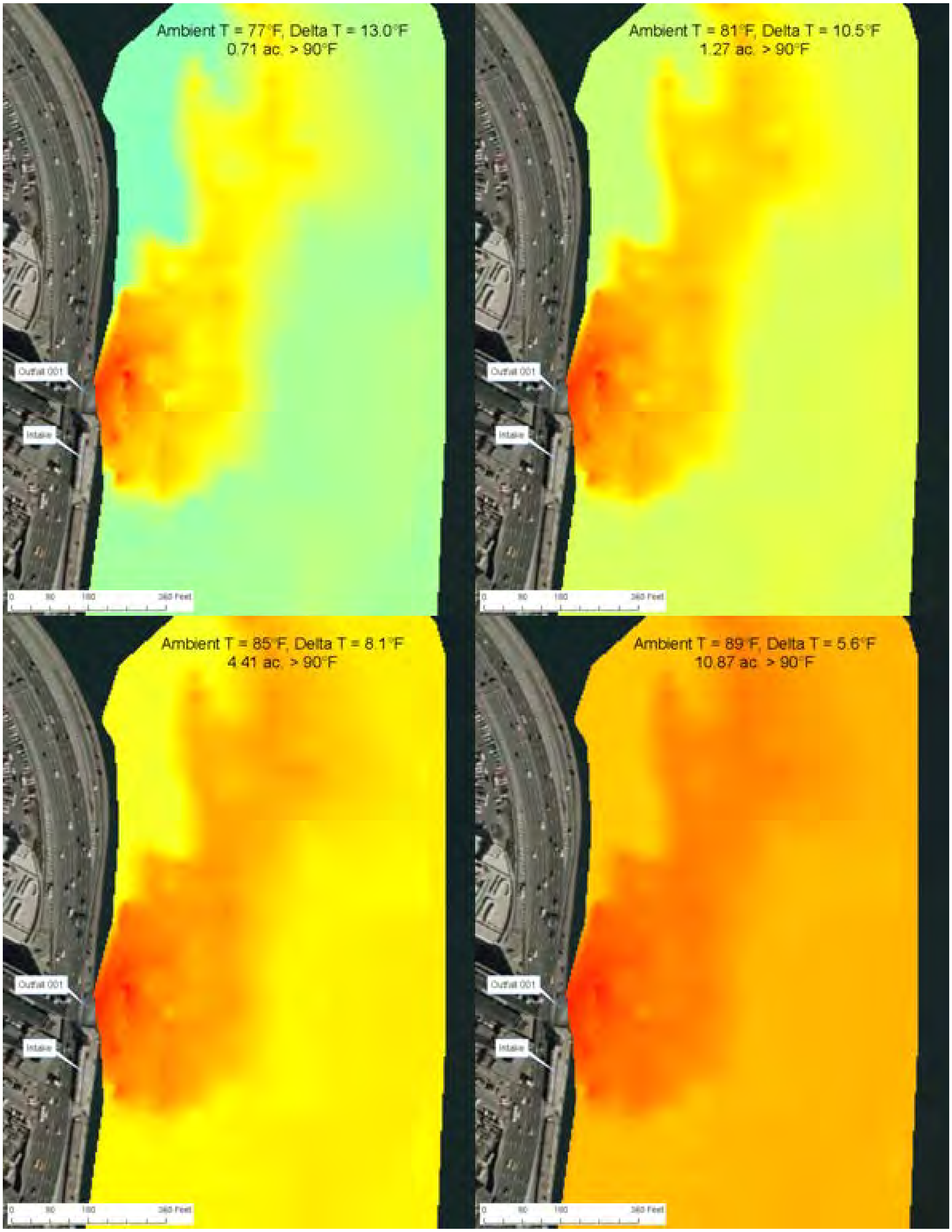

Figure 14-5 (continued)
Predicted surface water temperatures in vicinity of Station outfall – flood conditions. Panels show increasing ambient temperature and maximum permitted discharge temperature for given conditions

Conclusions

Normandeau was recently tasked with performing thermal verification studies at two steam electric power plants in New York which included an assessment of thermal impacts under variable operating conditions and at maximum plant output. A formal hydrodynamic modeling exercise was unjustified for either of these studies due to the cost constraints and the required level of confidence in simulation results as agreed upon by the clients and regulators. In response, we performed multiple real-time mobile temperature surveys at the study sites using proprietary temperature sensing technology to delineate the three dimensional extent of each thermal effluent plume. We then used our empirical results and common mass balance theory to scale up our results to simulate specific plant discharge and ambient receiving water temperatures. The foundation of these scaling exercises was based on conventional heat dispersion principles and conservatively assumed that the only process of significance was dilution of the plume in cooler receiving waters. Therefore, our simulations very likely represent the upper range of potential thermal impacts for a given set of conditions and offer a “worst case” scenario. Our methodology was approved by the New York State Department of Environmental Conservation for both thermal verification studies and was used to effectively demonstrate conformance with thermal standards, as well as a potentially inadequate mixing zone variance in one stations permit.

We believe this methodology offers a lower cost alternative to complex hydrodynamic modeling and can provide acceptable assessments of thermal discharge impacts for event-based or steady state scenarios. Our surveying methods have been used in multiple receiving water environments: estuaries, rivers, lakes, etc. therefore these techniques can applied to a diverse range of thermal discharge generators and settings. Our methodology has already been approved by regulators in New York, and should be considered among other options for clients and regulators when assessing thermal effluent impacts.

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RECENT EXPERIENCE WITH THERMAL COMPLIANCE AT THE TVA BROWNS FERRY NUCLEAR PLANT

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Abstract

The Browns Ferry Nuclear Plant, located in northeastern Alabama, is the largest steam electric power plant owned by the Tennessee Valley Authority (TVA). The plant includes three units, each containing a boiling water reactor licensed to operate at 3458 MWt. Condenser circulating water for the plant is obtained from Wheeler Reservoir, an impoundment on the Tennessee River. When the river temperature approaches a regulatory limit, cooling towers are used to reduce the amount of waste heat dissipated in the reservoir. During the summer of 2010, extreme meteorology in the southeast created conditions wherein a National Pollutant Discharge Elimination System (NPDES) limit for the maximum allowable river temperature was regularly threatened. Despite these extreme conditions, the plant was able to successfully operate through the summer without any hydrothermal-related forced outages. The experience, however, did require significant unit derates and brought to focus a weakness of the plant in terms of its ability to serve as a source of reliable generation under severe weather conditions. Provided herein is a summary of the basic hydrothermal features of the Browns Ferry Nuclear Plant (BFN). The river temperature limits and the process used to monitor compliance with these limits are discussed. With this background, an account is provided of the operating experience for the summer of 2010. Studies for upgrading the capacity of the plant cooling system have examined several alternatives for adding new cooling towers and refurbishing or replacing existing cooling towers. A brief summary of the selected upgrade alternative is given. Additional work to obtain regulatory relief for large-scale, cooling events in Wheeler Reservoir also is briefly discussed.

Basic Hydrothermal Features

The location of BFN is shown in Figure 15-1. The plant is situated on the northern shore of Wheeler Reservoir about 55.0 miles downstream of Guntersville Dam (GUH) and 19.1 miles upstream of Wheeler Dam (WEH). In the vicinity of the plant, Wheeler Reservoir is characterized by a main channel that is about 30 feet deep and 2000 feet wide, with adjacent shallow overbanks that have a total width of about 5000 feet. The river flow at BFN is regulated by releases from the upstream and downstream dams. Flows from these dams are scheduled to meet the multipurpose objectives of the TVA river system. In the summer this can lead to daily average flows as low as about 13,000 cfs during the months of June and July. In August and early September, the reservoir operating policy usually provides daily average flows of at least 25,000 cfs. To optimize the generation assets at GUH and WEH, hourly releases following daily peaks in power demand are desired. In the summer, this typically leads to high river flow in the late afternoon and early evening, and low river flow in the late evening and early morning. This peaking pattern can create sloshing in Wheeler Reservoir with the hourly flow at BFN varying within the course of a day between over 50,000 cfs in the downstream direction and over 10,000 cfs in the upstream direction.

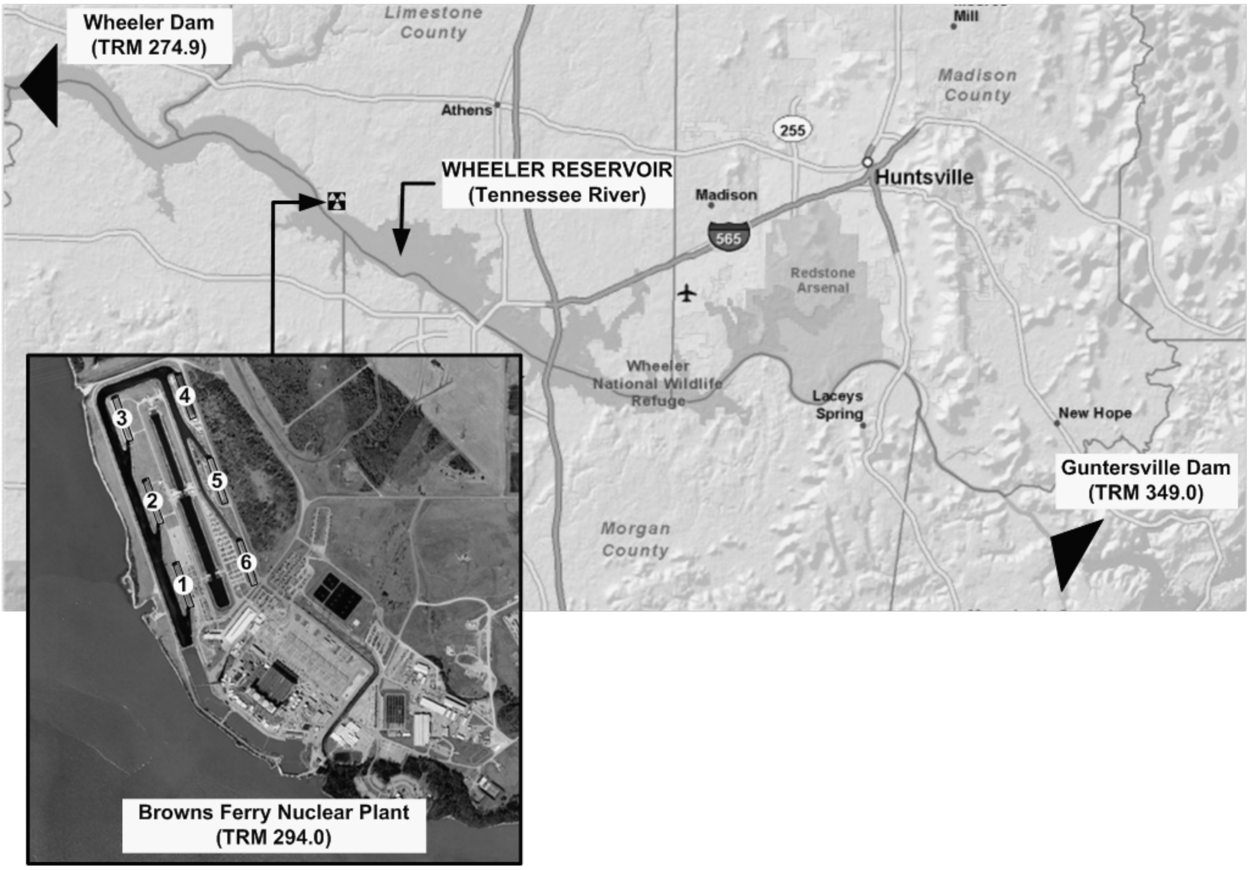

Figure 15-1
Location of Browns Ferry Nuclear Plant on Wheeler Reservoir

The BFN ambient water temperature in Wheeler Reservoir varies continuously in response to ever changing meteorology and hydrology. The hourly water temperature ranges between an average of about 43°F in the winter and an average of about 85°F in the summer. For low river flow, the impact of meteorology on reservoir water temperature is more extreme. In the summer, the reservoir water column upstream of the plant is often characterized by diurnal stratification, wherein the surface is warmed by solar heating during the day, but then cools and becomes mixed with the bottom water at night. In the summer, daytime stratification can yield a peak difference in temperature between the surface and bottom layers of the reservoir as high as 6°F. Other spatial variations in temperature occur between the main channel and overbank portions of the reservoir. In general, water in the overbanks is more responsive to changing meteorology, and in the summer is usually between 1°F and 2°F warmer than water in the main channel of the reservoir.

The condenser circulating water (CCW) for BFN is withdrawn from Wheeler Reservoir by an intake pumping station containing three pumps per unit. With all three pumps in operation, the flow per unit is about 670,000 gpm. The corresponding condenser duty is about 7.8×10^9 Btu/hr. The CCW system is configured to provide dissipation of the plant waste heat in any of four possible modes of operation–open, helper, closed, and mixed (e.g., a combination of open and helper). Performance limitations of certain components of the cooling system currently do not allow operation in any configuration that includes any units in closed mode. For each unit, the CCW pumps deliver the flow to an intake tunnel that supplies the water to the condenser. At the exit of the condenser, and in open mode operation, the flow enters a discharge tunnel that carries the CCW effluent to a submerged multiport diffuser located on the bottom of the main channel of Wheeler Reservoir. The approximate location of the diffuser for each unit is shown in Figure 15-2. The Unit 1 diffuser is in the center of the main channel, Unit 2 on the far-shore side of the main channel, and Unit 3 on the near-shore side of the main channel. The outlet ports for the diffusers are located in the upper, downstream quadrant of the conduits. This location releases the thermal effluent in the wake of the diffuser conduits, to promote mixing. The port spacing provides about thirteen, 2-inch diameter holes per foot of diffuser conduit, yielding a total of about 7800 holes per diffuser. The diffusers are only about 1600 feet downstream of a skimmer wall/gate structure for the intake pumping station.

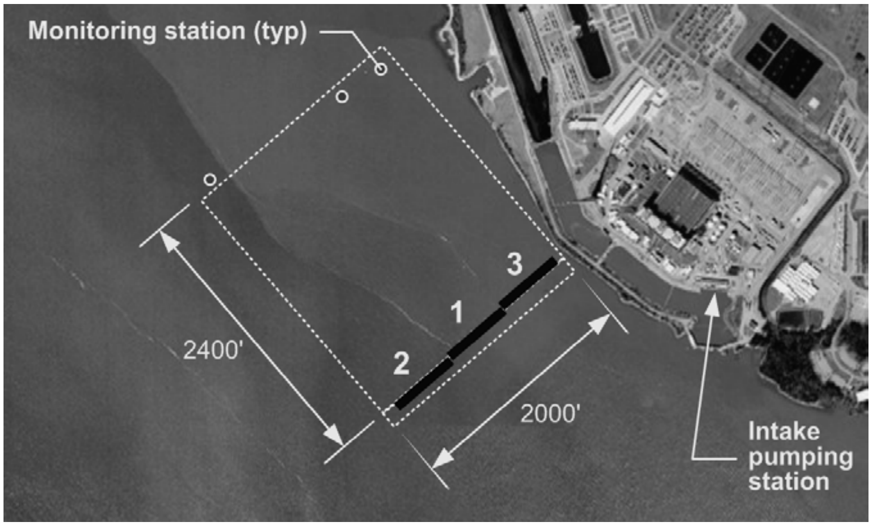

Figure 15-2
BFN submerged diffusers and mixing zone

For a unit in helper mode, the CCW effluent from the condenser is diverted through a siphon to a hot water channel centrally located in a cooling tower "arena" (see Figure 15-1 insert). This is accomplished by adjusting gates in the discharge tunnel of the unit and operating vacuum pumps. The arena includes six, rectangular crossflow mechanical draft cooling towers, each with 16 cells. A pumping station is provided in the hot water channel to supply the flow for each cooling tower. The discharge from each tower flows into a cold water channel that extends around the tower arena. The cold water channel returns the treated effluent to a gate structure that delivers the flow back to the discharge tunnels leading to the submerged diffusers in the river.

The design flow for each cooling tower is 275,000 gpm. When required, the number of cooling towers placed in service is selected to balance the flow from units operating in helper mode. The cooling towers with the highest capability are placed in service first. In general, it takes about 2½ cooling towers to balance the flow of one unit operating in helper mode with three CCW pumps.

In this manner, the capacity of the original cooling towers is insufficient to treat all of the CCW flow from all three units operating concurrently in helper mode, each with three CCW pumps. Such would require about 7½ of the 16 cell cooling towers. As such, if it is necessary to operate all three units in helper mode, the original design of the cooling towers calls for the CCW flow for each unit to be reduced from three CCW pumps to two CCW pumps. Depending on the condition of other components of the cooling system (e.g., condensers), reducing the number of CCW pumps in this manner can require the power level of a unit to be lowered as much as 50 percent. This process, however, allows treatment of all of the CCW flow by the six cooling towers, avoiding the need to shut down a unit. Since the original design, TVA has uprated the BFN units to operate at 105% of the original license thermal power (OLTP), and in the years ahead is planning to uprate the units to 120% OLTP. In the uprate studies, TVA decided not to provide additional cooling beyond the original number of towers–that is, six.

River Temperature Limitations

The NPDES instream water temperature limits for BFN are summarized in Table 15-1. The limits apply along the boundaries of a mixing zone spanning 2000 feet across the main channel of the reservoir and extending downstream 2400 feet (Figure 15-2). The limitation that regularly requires summertime helper mode operation of units at the plant is the 24-hour average downstream limit of 90°F. In recognition of extreme natural heating that can occur in Wheeler Reservoir, the permit also specifies that for situations where the 24-hour average ambient river temperature upstream of the plant exceeds 90°F, the 24-hour average downstream temperature can also exceed 90°F, as long as the 24-hour downstream temperature does not exceed the 24-hour average ambient temperature. That is, in such cases, the impact of the plant on the river must be negligible at the compliance depth. The limits in Table 15-1 are higher than Alabama standards for the Tennessee River, which are 86°F for the maximum instream temperature and 5°F for the maximum instream temperature rise. The higher limits were obtained in the mid 1980's by a §316(a) variance.

Table 15-1
BFN NPDES river temperature limitations

Parameter	Limit
24-hr Avg Downstream Temperature	90°F
1-hr Avg Downstream Temperature	93°F
24-hr Avg Temperature Rise	10°F

The instream water temperature for the diffusers is measured by three temperature stations located at the downstream end of the mixing zone, one for each BFN unit/diffuser. The stations, shown in Figure 15-2, are positioned to provide an average measurement representative of the flow-weighted average temperature across the downstream end of the mixing zone. The larger gap between the center and the far-shore stations is required to accommodate river navigation. A single station is used to measure the ambient river temperature upstream of the plant. The station, not shown in Figure 15-2, is located about 3.8 miles upstream of the diffusers. All of the instream temperature limits in Table 15-1 are applied at a depth of 5 feet. Sensor readings from the temperature stations are collected via telemetry every 15 minutes, and the compliance parameters are determined by computing average values based on the most recent 15-minute measurements. In this manner, BFN hydrothermal compliance is enforced based on continuous rolling averages (verses midnight-to-midnight/daily averages). The discussion herein will focus on operating BFN for the river temperature limit of 90°F, which in terms of recent experience, has emerged as a significant summertime challenge for TVA.

Monitoring and Operating for Thermal Compliance

The current values and trends of the temperature parameters given in Table 15-1 are displayed continuously in the BFN control room, and at other key operation centers throughout TVA. Hydrothermal models are run regularly to provide predictions of the water temperature at the plant. Predictions are provided for both short-term expectations (e.g., up to ten days), and long-term expectations (e.g., up to ninety days). The short-term model is based on the dominant processes for reservoir heat and mass transfer in the immediate vicinity of the plant. The long-term model is based on the same processes, but due to the larger time-scale, must include all of Wheeler Reservoir and many of the main stem reservoirs upstream of Wheeler. In general, the models rely on measurements of water temperature and flow at a number of key locations, and forecasts for the expected meteorology, river operation, and thermal plant operation. For the short-term model, forecasts for river operation and thermal plant operation are provided by the TVA operating organizations responsible for these assets. Forecasts for the short-term meteorology are obtained from a weather contractor. These forecasts in themselves can entail the use of a host of other modeling tools; for example, the use of hydrologic and flow routing models to determine expected river flows. Long-term forecasts rely on analog years of hydrology and meteorology, selected based on long-term expectations of the regional precipitation and air temperature provided by the National Weather Service.

Examples of short-term and long-term model predictions are given in Figure 15-3 and Figure 15-4, respectively. The short-term example shows the last five days of historical data along with the first two days of the forecast period. Beyond the period of the short-term forecast, the long-term forecast is given as a temperature range based on simulations with four separate analog years. In its present form, the only value of the long-term forecast is in providing an estimate as to whether the river temperature in the next month or so is likely to reside near the upper, middle, or lower portion of the historical temperature band. In contrast, the short-term forecast provides significant value in helping TVA optimize the combined operation of BFN and the river over the upcoming days.

In general, helper mode operation with cooling towers at BFN is initiated to keep the 24-hr average downstream temperature from exceeding 89°F–that is, 1°F below the NPDES limit. As the ambient river temperature increases, the desired sequence for placing units in helper mode is: Unit 3 first, followed by Unit 1, and then Unit 2. This sequence is based on a pattern of mixing of the diffuser effluent in the river that tends to produce warmer water in the near-shore portion of the mixing zone and cooler water in the far-shore portion of the mixing zone (see Figure 15-1). If the plant is operating with three CCW pumps per unit, which usually is the case, it is not possible to place the third unit in full helper mode (due to the flow capacity of the cooling towers).

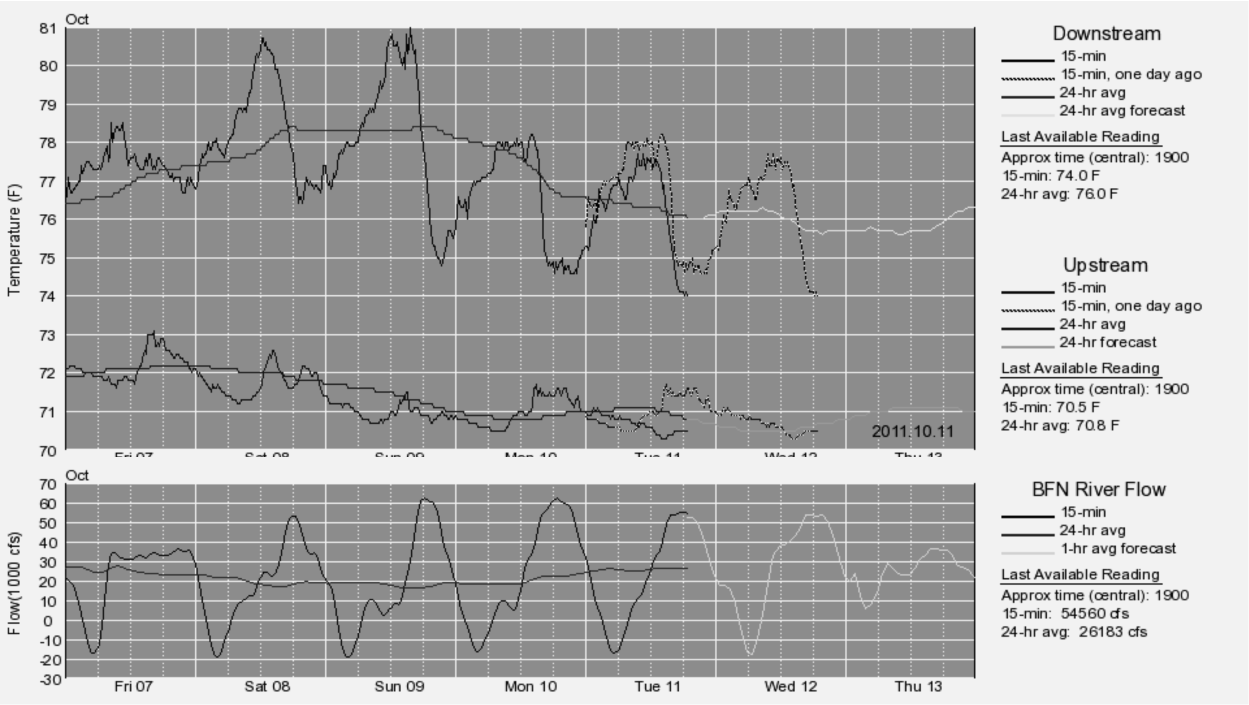

Figure 15-3
Example short-term water temperature forecast

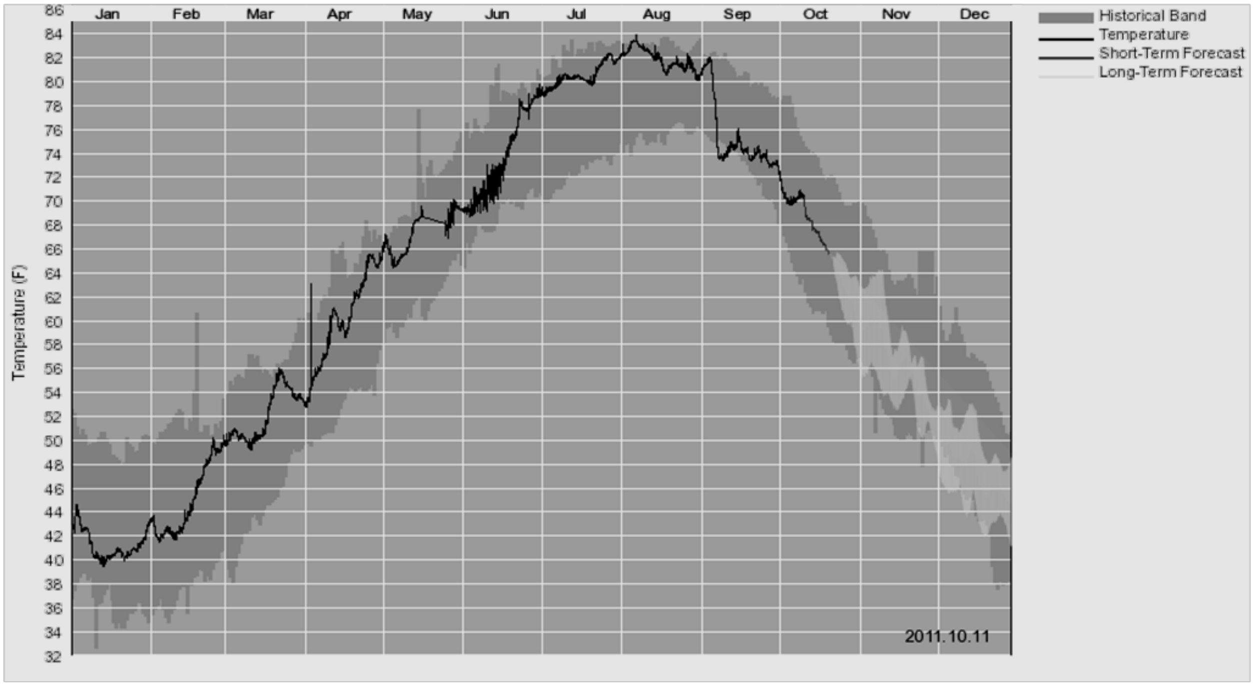

Figure 15-4
Example long-term water temperature forecast

Reservoir sloshing created by hydro peaking is known to increase the water temperature in river impoundments, and at BFN it also promotes recirculation of the diffuser effluent at the plant intake. If the plant is operating with as many units as possible in helper mode, and the downstream temperature continues climb, hydro generation at GUH and WEH is shifted to steady operation around-the-clock. This sometimes is implemented even sooner if the river flow is low (below about 20,000 cfs), or if weather forecasts suggest an extended period of above normal meteorology. Steady operation of Wheeler Reservoir tends to confine solar heating to the surface portion of the water column and reduces the mixing of warm water in the overbanks with cooler water in the main channel of the reservoir. This helps to preserve cooler water in the bottom of the main channel where the BFN pump intakes and discharge diffusers are located.

In periods of low summertime river flow, early onset cooling tower operation (i.e., before the downstream reaches 89°F) has been used to allow the river flow to be reduced even further for the purpose of building higher pool levels in Wheeler and upstream reservoirs. At BFN, higher pool levels provide additional depth for mixing of the diffuser effluent, and the extra water in the reservoirs can be used to temporarily increase river flow and provide additional dilution of waste heat during extreme temperature excursions.

Beyond these strategies, if the downstream temperature reaches about 89.5°F and is forecast to continue to climb, unit derates are implemented. The required amount of derate is determined based on hydrothermal model simulations. If the plant is operating with three CCW pumps per unit so that one unit yet resides in open mode, which is usually the case on the “rising limb” of a thermal event, derates are initiated first on the open mode unit. That is, the unit discharging the warmest water to the river. If generation on the open mode unit is reduced to minimum load (usually around 50% power) and the river temperature continues to climb, derates are implemented on units operating in helper mode. The river impact of derating units operating in helper mode is far less dramatic than that of a unit operating in open mode. This is because of the action of the cooling towers, which tend to reject heat to the atmosphere in a manner to produce a somewhat common discharge/approach temperature, no matter what the temperature of water entering the tower.

In general, in terms of the recovery of BFN generation following a hydrothermal event, it is best for the plant to operate with three CCW pumps per unit. However, if measured and modeled trends in Wheeler Reservoir suggest a hydrothermal event of magnitude and duration that requires temperature reductions beyond that which can be obtained with all the units operating at minimum load, the plant is shifted to a configuration with two CCW pumps per unit. As previously discussed, this allows treatment of all of the CCW flow by the six cooling towers, and if all the cooling equipment is in good working condition, usually provides for operation of the plant in manner that keeps the 24-hour average downstream temperature at or below the 24-hour average upstream temperature. This action allows the plant to continue to operate with ambient river temperatures in excess of 90°F, as long as the hourly average downstream temperature does not exceed the NPDES limit of 93°F (see Table 15-1).

Experience of Summer 2010

Overall summer conditions for TVA hydrothermal compliance is classified based on the air temperature and natural river flow in Chattanooga, which is centrally located in the Tennessee River watershed. The natural flow is the discharge that theoretically would exist in the Tennessee

River in the absence of any water control projects, and is a measure of the overall rainfall/runoff in the eastern half of the watershed. Shown in Figure 15-5 is a scatter plot showing for the past 64 years in Chattanooga, the deviation in the average June-July-August air temperature from the historical mean June-July-August air temperature, and the deviation in the average June-July-August natural river flow from the historical mean June-July-August natural flow at Chickamauga Dam. Chickamauga Dam is located on the Tennessee River in Chattanooga. The plot can be divided into four quadrants–Warm and Wet, Warm and Dry, Cool and Wet, and Cool and Dry. Since rainfall/runoff is produced by meteorology, the data displays a trend from the Cool-Wet quadrant to the Warm-Dry quadrant. That is, in general, wetter conditions occur with cooler meteorology and dryer conditions occur with warmer meteorology. Overall, the data suggests that roughly 40% of the time, summer hydrothermal conditions for the Tennessee Valley can be expected to be warm and dry. The data for the last ten summers are shown explicitly in Figure 15-5, six of which have fallen in the warm-dry quadrant. The warmest summer for the period of record is 2010, which included an average summertime air temperature almost 5°F warmer, and an average natural river flow about 30% below the historical mean values for these parameters.

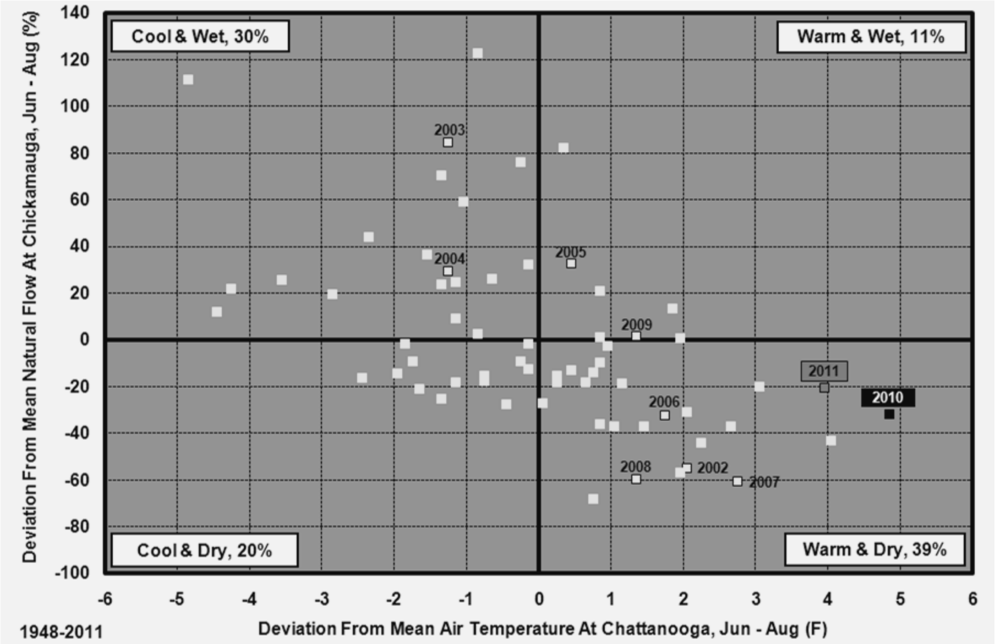

Figure 15-5
Historical summer hydrothermal conditions

With the extreme meteorology and low flow conditions, the observed water temperature in Wheeler Reservoir for the summer of 2010, in similar fashion, was the highest ever observed for the period of record. At the compliance depth of 5 feet, the rolling 24-hour average ambient temperature exceeded 90°F in three separate events for a total duration of about 13.25 days. The maximum observed water temperature was 91.6°F. Within the period of record, the only other time the 24-hour average ambient temperature exceeded 90°F was for an event lasting about 4.5 hours in 1993, where the temperature reached 90.2°F.

The more interesting aspects of the events of 2010 can be described with the data shown in Figure 15-6. Provided are the 24-hour average river compliance temperatures upstream and downstream of BFN, the computed river flow past the plant (hourly), and the power level for each of the three units. The river temperatures are given in the manner provided in the monthly discharge monitoring reports–daily maximum values rounded to the nearest degree Fahrenheit. In early July the river flow was only about 15,000 cfs, significantly below the amount needed to effectively assimilate waste heat in a direction downstream of the plant. All three units were running between 90% and 100% power with no hydrothermal-related derates, each with three CCW pumps per unit and with two units in helper mode. By this time, peaking operations had already been suspended for Wheeler Reservoir (i.e., the river flow was near steady). In the second week of July, with the ambient river temperature reaching about 88°F, a hydrothermal derate was initiated on Unit 1 to keep the downstream river temperature below 89.5°F. At that time, Unit 1 was the sole unit operating in open mode. In the following days, compliance was maintained by appropriate manipulations of the power level of Unit 1.

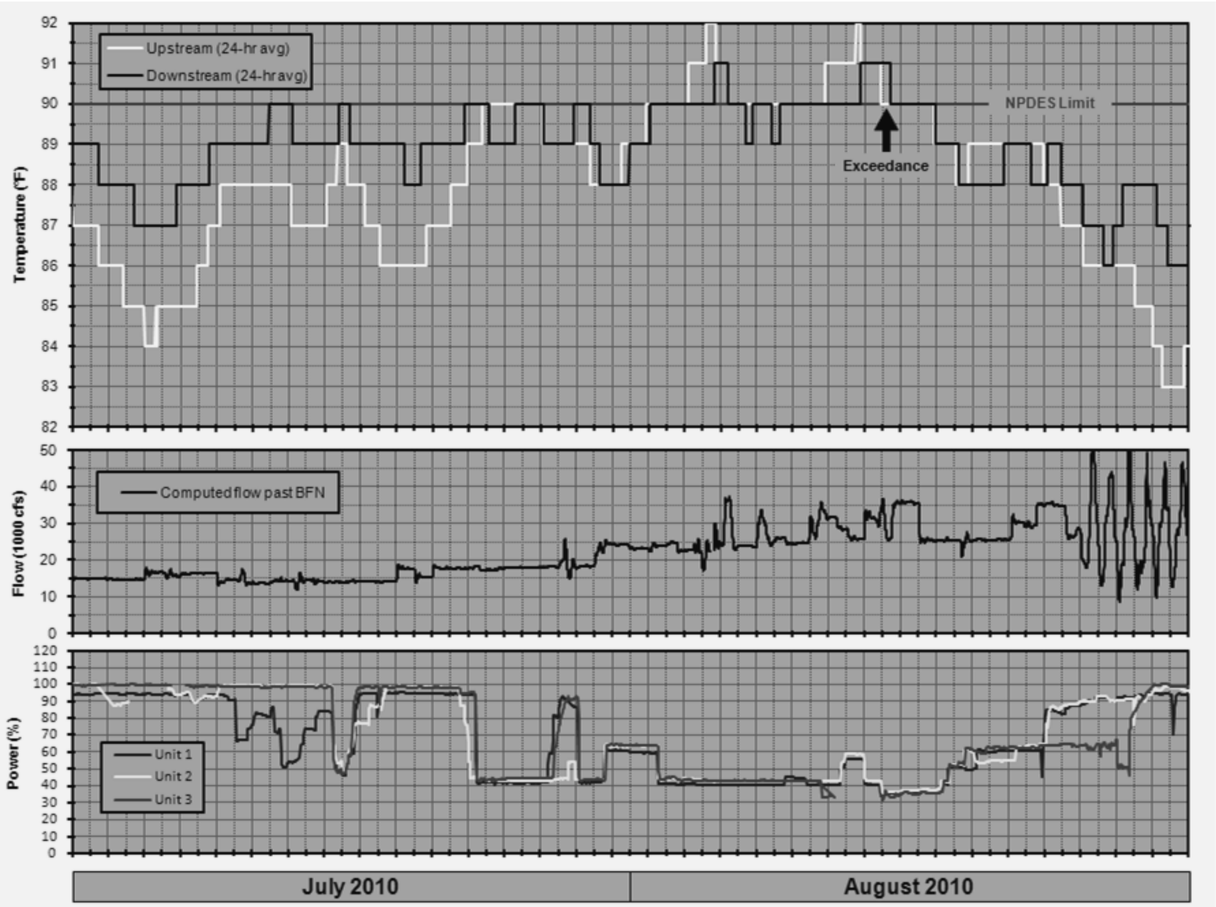

Figure 15-6
BFN hydrothermal compliance for July and August 2010

In the early part of the third week of July, the prevailing meteorology pushed the upstream temperature to 89°F, resulting in a downstream temperature that threatened the 90°F limit. To prevent exceeding the limit, the plant was switched to a mode operation including two CCW pumps per unit with all three units running in helper mode. In this process, plant generation was curtailed to a near minimum power level. About one day later, a cool front reduced the ambient river temperature to about 86°F, allowing all three units to be restored to near 100% power with three CCW pumps per unit. However, warm meteorology returned about one week later, forcing the plant to once again curtail generation to a near minimum power level, with all three units operating in helper mode with two CCW pumps per unit.

Apart from a brief opportunity to increase the power of the units to near 90% in the last week of July, the plant was forced to operate at significantly reduced power levels (with two CCW pumps per unit and with all three units in helper mode) until the summertime meteorology began to recede in the latter part of August. With this cooling, the BFN units were restored to near full power and hydro peaking was resumed at Wheeler Dam and Guntersville Dam. Other items of note in the 2010 experience of Figure 15-6 include the following:

- Under the TVA reservoir operating policy, additional flow is provided in the Tennessee River as the summer unfolds. In August, the minimum river flow is at least 25,000 cfs. Higher river flow provides greater dilution of the BFN waste heat and helps to reduce recirculation of the diffuser effluent at the plant intake. However, when the ambient river temperature resides at levels at or near the regulatory limit, the impact of higher river flow can be marginal. At such temperatures, higher flow increases mixing of warm surface water with cooler bottom water, and also entrains warm water from the overbanks into the main channel of the reservoir. Together, these processes can diminish the benefit of greater dilution.
- In addition to an overall higher river flow, Figure 15-6 shows short-term events (in August) wherein the flow was pulsed to levels as high as 35,000 cfs. The flow in these events comes from water in storage above the minimum pool levels in the Wheeler and Guntersville Reservoirs. These pulses are strategically provided to alter adverse trends in the river temperature that if left unattended would likely lead to an NPDES exceedance, or other drastic action (e.g., shutdown of a unit). Extra pulses have been successfully used to flush the local buildup of heat in the reservoir from an adverse thermal wedge created by the effluent plume, or adverse shoreline recirculation created by the action of the bottom diffusers. The amount of water for extra pulses, of course, is limited by the volume of water in storage above minimum reservoir pool levels.
- In the first half of August, the 24-hour average upstream ambient river temperature resided rather consistently at a level above 90°F. As previously described, in these periods, the NPDES permit requires the 24-hour average downstream river temperature to remain at or below the upstream temperature. Operating the river in a near steady fashion helps this to be accomplished. Limiting solar heating to the surface portion of the water column tends to keep the upstream compliance temperature high, and protecting cooler water in the bottom portion helps to curb temperatures in the diffuser mixing zone.
- Despite the “control” offered by operating the river in a near steady fashion with strategic pulsing, and operating BFN in a mode yielding minimal thermal impact on the river, one event yet occurred in August that resulted in an NPDES exceedance. In the event, a sizeable cold front moving through the southeast caused rapid, large-scale cooling of Wheeler Reservoir. The reservoir became fully mixed, eliminating the benefits of stratification. Despite the fact that the influence of BFN was minimal, the temperature in the mixing zone cooled more slowly than the upstream ambient temperature, resulting in a situation where the downstream temperature was not contained at a level at or below the upstream temperature, as is required when the ambient temperature is above 90°F.

> The actual difference between the rolling 24-hour average upstream and downstream temperatures was only 0.3°F, but in the rounding process it was reported as a temperature difference of 1.0°F (the upstream temperature rounded down to 90°F, whereas the downstream temperature rounded up to 91°F). The event exposed a regulatory impasse in the context that for large-scale atmospheric cooling events, the natural characteristics of the reservoir can perhaps make it unduly difficult to maintain compliance with the NPDES requirements for an ambient temperature above 90°F. This is strengthened by the fact that in large-scale cooling events, the reservoir is in the process of moving to a condition of reduced thermal stress for aquatic habitat. That is, by the current requirements, BFN is perhaps overly exposed to regulatory penalty at a time when reservoir conditions are actually improving.

Upgrade of Plant Cooling System

Apart from the NPDES exceedance, the experience of the summer of 2010 demonstrated, in general, the veracity of the design for the original cooling towers. That is, the process of "enduring" extreme hydrothermal events by reducing the flow through the plant (i.e., two CCW pumps per unit) to provide operation of all units in full helper mode. Throughout the extreme heat of the summer of 2010, no BFN units had to be shut down for hydrothermal reasons. However, the magnitude and duration of the events of 2010 were far beyond expectations of the original design. Purchases of replacement power for BFN hydrothermal derates and for the loss of local hydro peaking cost TVA between $50 million and $60 million in 2010. It brought to focus the weakness of the plant for serving as a source of reliable generation in the presence of severe summer meteorology. Under these conditions, TVA decided to increase the capacity of the BFN cooling system.

Over the past few years, a variety of alternatives have been examined for adding cooling capacity at BFN. These have included various forms and combinations of mechanical draft and natural draft cooling towers. Of these, the final alternative selected as a result of the events of 2010 is illustrated in Figure 15-7. The key feature of the alternative is a new 28 cell mechanical draft, crossflow cooling tower (Tower 7). The tower is to be supplied by a new pumping station located on the existing hot water channel, with the discharge entering the existing cold water channel downstream of Tower 4. The new tower is designed to cool 410,000 gpm of condenser flow from a hot water temperature of 118.5°F to a cold water temperature of 90°F, with a local wet bulb temperature of 82°F. The selected alternative also calls for replacing Towers 1, 2, 5, and 6 with new 19 cell mechanical draft cooling towers. These four cooling towers are original to the startup of the plant in the 1970's. The original structures for Tower 3 and Tower 4 were destroyed by fire years ago, and have since been replaced by new 16 cell towers of higher capability. The proposed new replacements for Towers 1, 2, 5, and 6 are to be designed to cool 275,000 gpm of condenser flow from a hot water temperature of 118.5°F to a cold water temperature of 90°F with a local wet bulb temperature of 82°F. The selected alternative also includes enhancements for the cooling tower power supply and transformer redundancy.

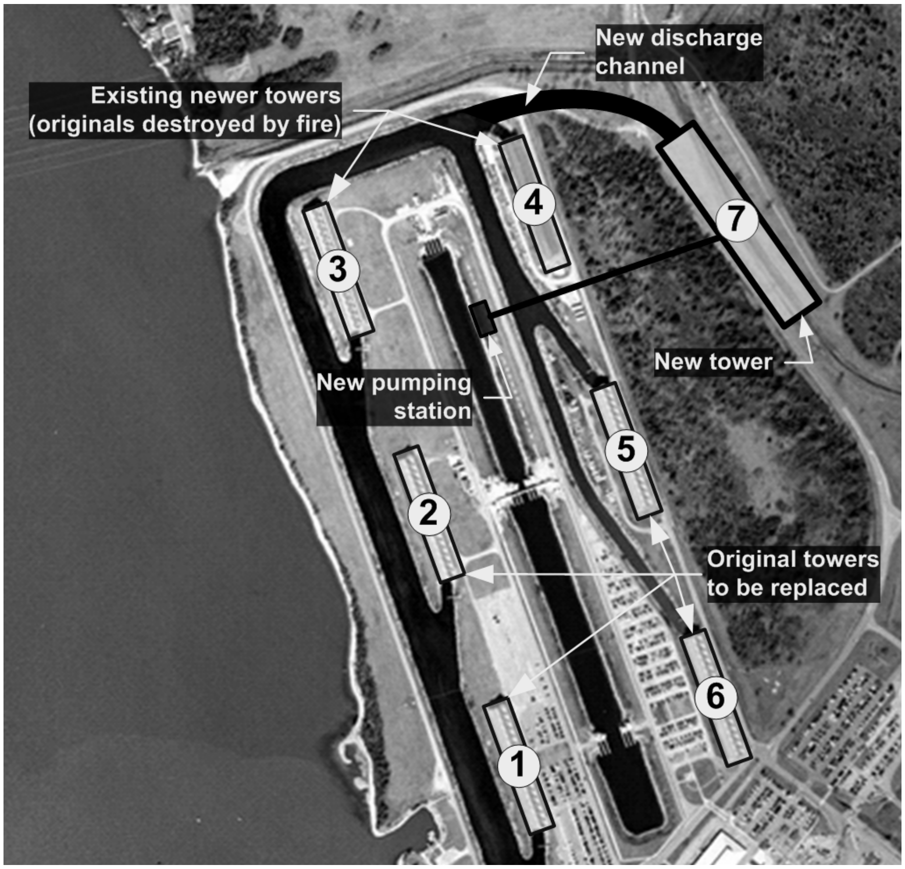

Figure 15-7
Selected alternative for upgrade of BFN cooling system

Implementation of the cooling system upgrade is to be accomplished in phases. The first phase includes the addition of Tower 7, the second phase the replacement of Towers 1 and 5, the third phase the replacement of Towers 2 and 6, and the last phase the enhancements for the power supply and transformer redundancy. For those phases that include new tower construction, shown in Table 15-2 are results of model simulations for the expected reduction in hydrothermal derates for the case including a repeat of 2010. The addition of Tower 7 alone will allow treatment of all of the plant condenser flow with all of the units operating with three CCW pumps. At the current power level of the plant, this is expected to reduce derates for a 2010-type event by about 70%. It is for this reason, and because much of the work can be performed with minimal impact on the operation of the existing towers, that the construction of Tower 7 was selected for the first phase of the implementation plan. Because of the additional waste heat, the expected reduction in derates is diminished to about 50% if the plant were operating at extended power uprate (EPU–120% OLTP). With Tower 7 and replacements for Towers 1, 2, 5 and 6, derates for a 2010-type event are expected to be minimal, for both the current power level and at 120% OLTP. This performance, of course, assumes all the condensers, cooling towers, and other related equipment are in good working condition.

Table 15-2
Hydrothermal model results for BFN cooling system upgrade alternative

Phase	BFN Power Level	Approx Reduction in Derate for 2010
New Tower 7	105% OLTP (current)	71%
New Tower 7 + Replace Towers 1 & 5	105% OLTP (current)	98%
New Tower 7 + Replace Towers 1 & 5 + Replace Towers 2 & 6	105% OLTP (current)	100%
New Tower 7	120% OLTP (EPU)	48%
New Tower 7 + Replace Towers 1 & 5	120% OLTP (EPU)	96%
New Tower 7 + Replace Towers 1 & 5 + Replace Towers 2 & 6	120% OLTP (EPU)	100%

In November 2010, approval was obtained to complete the first phase of the upgrade. That is, to add Tower 7. Provided in Figure 15-8 and Figure 15-9 are images of the construction as it appeared in September 2011. Figure 15-8 shows the new 28 cell cooling tower and Figure 15-9 shows the new pumping station. In Figure 15-9, the new cooling tower is visible in the background, with the existing Tower 4 in the left-hand side of the image.

Closing Comments

The original construction schedule for Tower 7 included a completion target for the summer of 2011. Unexpected delays, however, prevented this from occurring. Unfortunately, hydrothermal conditions for the summer of 2011 again were extreme, although not as extreme as those of the summer of 2010 (see Figure 15-5). Hydrothermal derates were needed, and for a period of about three days, BFN again was required to operate the plant with all three units near a minimum load (in helper mode with two CCW pumps per unit). In this event, the prevailing meteorology pushed the reported 24-hour average upstream ambient river temperature to 90°F. The plant was successful in maintaining compliance with the river temperature requirements without any NPDES exceedances; however, the cost to TVA for hydrothermal derates was yet about $6 million. Tower 7 will be operational for the summer of 2012.

Figure 15-8
BFN new Cooling Tower 7 (under construction)

Figure 15-9
BFN new pumping station for Cooling Tower 7 (under construction)

It is important to note that since the startup of BFN, especially in the recent years of warm, dry meteorology, biological monitoring has shown that the NPDES instream river temperature limits (i.e., Table 15-1) and procedures for operating the plant to comply with these limits have been protective of a balanced, indigenous population of aquatic wildlife in Wheeler Reservoir. Field scores have consistently shown aquatic communities to be in good health. At the same time, biological data also suggests that there is limited margin for increasing the temperature limits beyond the current values.

The cooling system upgrade summarized in Figure 15-7 will help TVA resolve most, but not all, BFN thermal compliance issues. Even with the upgrade, large-scale atmospheric cooling events of the type responsible for the NPDES exceedance in the summer of 2010 can still push the plant into deep derate situations. For this reason, TVA is negotiating with permitting authorities about the possibility of obtaining regulatory relief for these types of events. As currently proposed, opportunities for relief would be identified by events when the ambient reservoir temperature is cooling at a rate of at least 0.5°F per day.

Although the short-term hydrothermal forecasting model significantly helps TVA in making operational decisions, the model still could benefit from improvements in predicting the impact of important processes in the river. Among these are the transient behavior of river stratification, the exchange of water between the main channel and overbank portions of Wheeler Reservoir, the low flow dynamics of the intake withdrawal zone and discharge mixing zone (leading to recirculation at the plant intake), and variations caused by wind. The uncertainty of these processes often leads to unexpected “spikes” in river temperature that require unanticipated, short-term changes in operating plans. These can be costly when such requires the purchase of power in spot-markets. For this reason, TVA is investigating options for increasing the accuracy of the short-term hydrothermal forecasting model. To a lesser extent, the same also is true of the long-term forecasting model. Prior to the summer of 2010, the long-term model did not suggest the occurrence of record breaking excursions in river temperature. Obviously, a higher level of confidence of such events would provide benefits in negotiating power supply contracts, and in scheduling long lead-time activities for operation and maintenance.

Beyond building Tower 7, implementation of the remaining phases of the cooling system upgrade for BFN is uncertain at this time. In general though, the plan is proactive in that it was developed in light of an evolving regulatory climate that may require more cooling tower operation in the future, perhaps even closed mode. Examples include pending requirements for impingement and entrainment of aquatic wildlife at the plant intake (§316(b)), and the ever present uncertainty surrounding the potential impacts of global climate change. To this end, the cooling towers for the upgrade plan are designed not only to treat all of the plant flow (with three CCW pumps), but to deliver the water in all but perhaps the most extreme situations, at a temperature not exceeding 90°F. Undoubtedly, throughout the remaining life of the plant, maintaining thermal compliance at BFN will always be a challenge for TVA.

16

MONITORING AND MODELING THE THERMAL PLUME FROM THE INDIAN POINT ENERGY CENTER IN THE HUDSON RIVER

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Abstract

The Indian Point Energy Center (IPEC) is a 2-unit nuclear-fueled electrical generating facility located 68 km north of New York City on the Hudson River using a once-through cooling system. As part of its license and permit renewals the plant owner, Entergy, needed a monitoring and modeling (tri-axial) study to assess the thermal distribution in the River from the facility and its compliance with regulations. Two major field studies were conducted in 2009 and 2010; both designed to acquire detailed information on the thermal structure in the River in the area of the IPEC discharge. Hundreds of thermistors were deployed for multiple months along with several bottom-mounted Acoustic Doppler Current Profilers (ADCPs). This extensive data set captured the longitudinal and vertical time varying thermal and current structure along approximately 49 km of the River, an extent which spanned both upstream and downstream of IPEC. A three-dimensional, general curvilinear coordinate, baroclinic hydrothermal model was then applied to the River. The model was successfully calibrated to the 2009 field data set and verified against the 2010 field data set. Furthermore, to address regulatory concerns, a time period of extreme, but actual, environmental conditions was identified from the historical record that resulted in the highest ambient temperatures in the River. Model runs were performed and results post processed to show IPEC compliance with New York State thermal criteria governing the allowable extent of the thermal plume.

Introduction

IPEC consists of two operating nuclear power plants, referred to as Units 2 and 3, respectively owned by Entergy Nuclear Indian Point 2, LLC and Entergy Nuclear Indian Point 3, LLC (Entergy). IPEC is located along the eastern side of the Hudson River (River), approximately 68 km upstream of the Battery (located at the southern tip of Manhattan and defined as the mouth of the River) in the village of Buchanan, New York. IPEC uses a once-through cooling water system that discharges a maximum of 9.46 Mm^3/day heated water to the River, through a common discharge canal, subject to and with the benefit of a New York State Department of Environmental Conservation- (NYSDEC) issued State Pollutant Discharge Elimination System (SPDES) permit which a maximum discharge temperature of 43.3°C (110°F). In addition the permit requires a head differential (ΔL) between the discharge structure and the River of 0.53 m to promote dilution of the discharge in an inferred mixing zone.

Issues

Two outstanding thermally-related regulatory issues needed to be addressed at both the state and federal level. First, IPEC needed a Water Quality Certification from NYSDEC as part of the nuclear operating license renewal from the Nuclear Regulatory Commission. Secondly, the NYSDEC SPDES permit was up for renewal. For both the Certification and Permit renewal, NYSDEC required IPEC compliance with thermal water quality standards. To show compliance NYSDEC required that a tri-axial thermal study (a three dimensional monitoring and modeling effort) be performed.

This paper describes the multi-year monitoring and modeling effort conducted for IPEC. More details of the project can be found in [1, 2].

Description of Study Area

The Hudson River is approximately 510 km long and originates at Lake Henderson in the Adirondack Mountains from which it flows south toward the Atlantic Ocean via New York Harbor. The lower half of the River is a drowned-river tidal estuary approximately 247 km long (from the Battery north to Troy) with widths up to 5.2 km and depths to 66 m. Due to its connection to the Atlantic Ocean via New York Harbor, the River at Indian Point is subject to periodic intrusions of ocean salinity, ranging up to 9 psu but typically averaging 1.8 psu [3]. Ambient temperature typically varies from 0°C in January to 27°C in July with lower maxima downstream toward ocean. Tide varies between a progressive wave at the Battery with a mean range of 1.38 m to a standing wave at Troy of 1.43 m while the mean range at IPEC drops to 0.85 m. Freshwater flow at Troy averages 370 m^3/s and ranges from 25 to 4,300 m^3/s.

Field Program

A multiyear (2009 and 2010), multidimensional field program was designed by ASA and executed by Normandeau to document the extent of the thermal plume from the IPEC during the periods of deployment, provide suitable data sets for model calibration and validation, and to assess IPEC compliance with thermal water quality standards.

2009 Field Program

The 2009 field survey consisted of long term (8-September to 3-November), high resolution, fixed temperature and current measurements consisting of the following components: 50 strings of six thermistors located in the River from 9.0 km south to 6.4 km north of IPEC and two ADCP stations, one near IPEC and one near Stony Point (approximately 3 km south of IPEC). In addition, meteorological and river observations from public sources were acquired during this time period as was IPEC operating data. A review and analysis of the data acquired during this field program is described in [1].

2010 Field Program

The 2010 field survey, shown in Figure 16-1, consisted of long term (5-July to 10-September), high resolution, fixed temperature, salinity and current measurements consisting of the following components: 66 strings of up to six thermistors (417 total) located in river from 33.6 km south to 15.0 km north of IPEC and three ADCP / CTD stations near IPEC, Stony Point (3 km south of

IPEC) and Bear Mountain Bridge (5 km north of IPEC). The thermistor moorings had to be located outside the main shipping channel to prevent instrument loss and so we typically placed on either side of the channel shown in Figure 16-1. In addition, meteorological and river observations from public sources were acquired during this time period as was IPEC operating data.

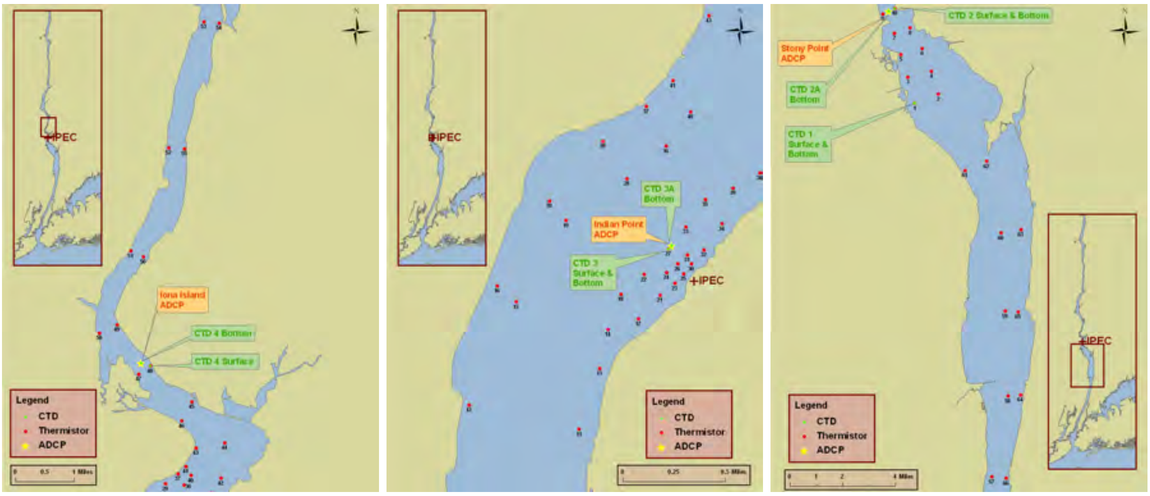

Figure 16-1
Extent of the 2010 field program in the Hudson River (left panel: northern portion, center panel: central portion, right panel: southern portion)

To give an overall sense of the variation of temperature, the data were aggregated into minimum and maximum for each 1-hr interval, as shown in Figure 16-2. There was a general heating effect from early to mid-July, then a plateauing through the last week of July and finally a decrease in temperature that persisted to the beginning of September, as seen in both the surface minimum and maximum temperature time series. The hottest temperature always appeared at the surface; therefore the maximum surface thermistor temperature was identical to the maximum of all thermistors. The relatively large oscillations shown most clearly in the maximum temperature were caused by the tides with a 12.42 hour period transporting the discharge plume to the thermistor station at the IPEC discharge. A more thorough review and analysis of the data acquired during this field program is described in [2].

Hydrothermal Model

Model Description

The hydrothermal computer model used to predict the velocity and temperature structure of the Hudson River, and IPEC's potential thermal influence, is part of a PC-based modeling system, known as Water Quality Mapping and Analysis Program (WQMAP) [4]. WQMAP consists of a family of computer models, one of which is a hydrodynamic (hydrothermal) model known as BFHYDRO. A three dimensional, general curvilinear coordinate, boundary-fitted computer model [5, 6] BFHYDRO was used to predict elevations, velocities, salinities and temperatures in the Hudson River. The boundary-fitted model matches the model coordinates with the shoreline boundaries of the water body, accurately representing the study area. This system also allows the user to adjust the model grid resolution as desired. This approach is consistent with the variable geometry of shoreline features of the River. The embedded surface heat balance submodel includes all of the primary heat transfer mechanisms for environmental interaction, including evaporative and sensible heat exchange with the air just above the water surface, long wave radiation exchange between the water surface and the sky, and net short wave solar radiation between the loss due to reflection and the gain due to absorption at the water surface. Details of this surface heat transfer submodel are found in [1].

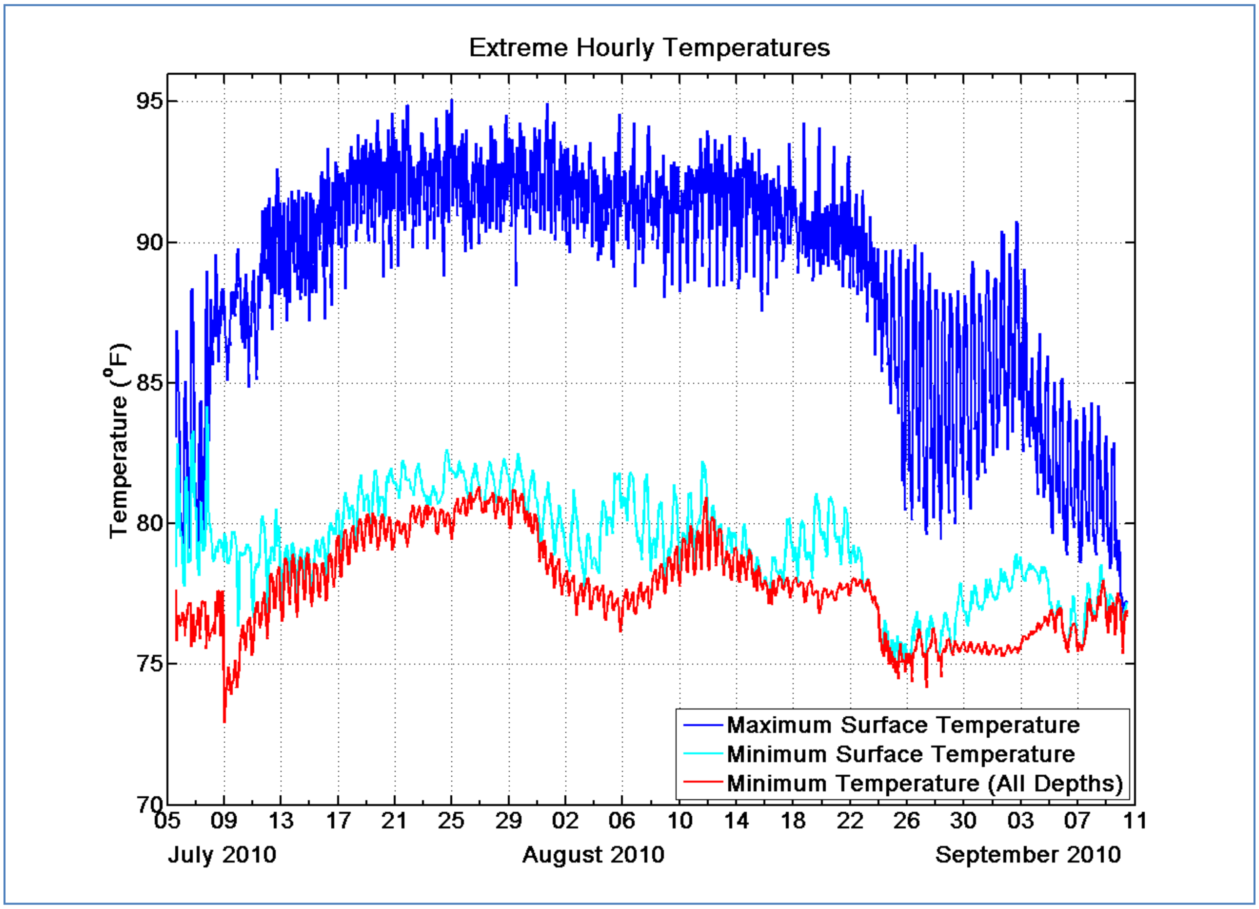

Figure 16-2
Maximum and minimum temperatures of all surface IPEC thermistors and the minimum temperature for all thermistors during the summer 2010 survey period

There are various options for specification of vertical eddy viscosity (Av, for momentum) and vertical eddy diffusivity (Dv, for constituent mass [temperature and salinity]). The more complex formulation adds the dependence on mixing length and turbulent energy and was chosen for use here to better simulate vertical momentum shear and thermal stratification. Details on turbulence closure formulations can be found in [1].

Application to the Hudson River

The model application to the Hudson River requires defining the spatial extent and resolution of the model grid and creating boundary forcing files. Figure 16-3 shows the model grid for this application. The full grid covers a 210 km span of the River from Hastings on Hudson, approximately 32 km north of the Battery, to the dam upstream at Troy, with 4,719 water grid cells in each of 11 layers for a total of 51,909 grid cells. The grid resolution ranges in size with larger cells located furthest from the plant up to 1,800 m in length while the grid is finer (50 m x 50 m) in the area near the IPEC discharge to better resolve the circulation and thermal structure there.

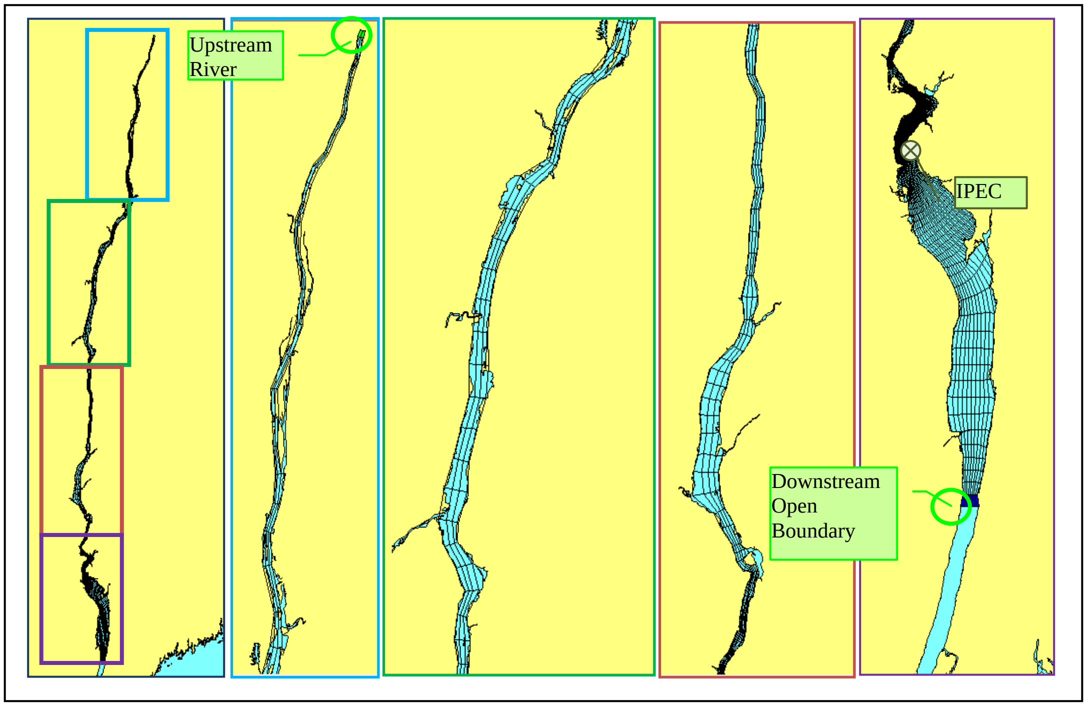

Figure 16-3
Model grid for the IPEC study area (blue shaded cells represent the open boundary at Hastings and the green shaded cells represent the upstream river boundary at Troy)

The river boundaries for the model application are Hastings on Hudson (a USGS station) for the southern boundary, and the dam at Troy for the northern boundary. The northern boundary was forced with River flow from observations at the USGS Lock 1 station, with water temperature based on observations at the USGS Albany station, and the southern boundary was forced based on water surface elevation, temperature and salinity observations at the USGS Hastings on Hudson station. Additional meteorological inputs from the closest airport to IPEC at White Plains were applied at the water surface for use the environmental heat exchange submodel simulating solar and atmospheric radiation exchange, convective and evaporative heat exchange. Finally IPEC loadings including cooling water flow rate and thermal inputs were used at the intake and discharge locations along the River.

Calibration and Verification Results

The purpose of model calibration is to establish model's ability to accurately reproduce observed elevations, currents and temperatures, in this case, using September 2009 data while verification is to check the model's ability to accurately reproduce a separate set of observations, in this case, using July 2010 data. The period chosen for the model calibration was a portion of the 2009 time period, 24-September through 8-October, and the verification period was 8- through 30-July. The statistical parameters used in the analysis included: relative mean error (RME), error coefficient of variance (ECV), squared correlation coefficient (R^2), and skill. Definitions and details are found in [1].

The model calibration did well at achieving the goal metrics [7, 8] with the water surface elevation meeting three guidance values and only slightly exceeded the fourth; the current velocities met two of the guidance values and slightly exceeded two; and the temperature met three of four guidance values. The model verification did well at achieving the goal metrics with the water surface elevation meeting all four guidance values; the current velocities met three of the guidance values and came close to the fourth; and, most importantly, the temperature met two guidance values and did adequately on the other two.

Extreme Environmental Condition Scenario

Both a correlation analysis and a joint probability analysis were performed as search methods to identify and rank the environmental conditions most likely to result in the greatest extent of IPEC's thermal plume. More detail is provided in [1]. Publicly available data from the period 2000 through 2009 was used in the analysis.

The correlation analysis showed that West Point water temperature, White Plains air temperature and Lock 1 upstream River discharge were the factors that had the strongest correlation to surface thermistor temperatures near the IPEC.

The joint probability analysis showed that, from an analysis of the distribution of the three variables, the August 2005 period was extreme because it contained the continuous occurrence of the joint probability condition of at least the 95th percentile exceedance level that was based on an analysis of a 10-yr record of all datasets available (2000 – 2009). Figure 16-4 shows the time variation of the individual probabilities and the three-way joint probability. The three way joint probability actually exceeds the 97th percentile during this period, and frequently ranges to over the 99th percentile. The analysis showed the period 1 through 15 August 2005 had the most extreme set of environmental conditions causing highest River temperatures.

Model Results

The model application to the August 2005 extreme Scenario time frame was performed. Plan view model predicted surface water temperatures, displayed as color coded contours on the map, are presented in Figure 16-5, which shows the downstream extent of the thermal plume at slack before flood and Figure 16-6, which shows the upstream extent for slack before ebb for representative times during the Scenario period. As first observed in the thermistor data, and clearly shown in the figures, the thermal plume tends to hug the eastern shore of the river on both ebb and flood stages of the tide.

The NYSDEC requested that the 8- through 30-July 2010 validation period model results also be processed to determine if the model predicted compliance with the thermal water quality standards. The first analysis was to determine the occurrence of water temperature in the estuary (that included the inferred mixing zone) greater than 90°F. The results of the analysis showed that the variation of the surface area coverage of the 90°F was predominantly semi-diurnal (tidally driven), with two short term events, which peaked at 14.6 acres. These areas were smaller than the 2005 extreme environmental condition results [1] which found a maximum area of under 35 acres. The area coverage for temperatures greater than 90°F complies with the

NYSDEC Thermal WQS by definition, based on the IPEC permit condition of a formulaic inferred mixing zone.

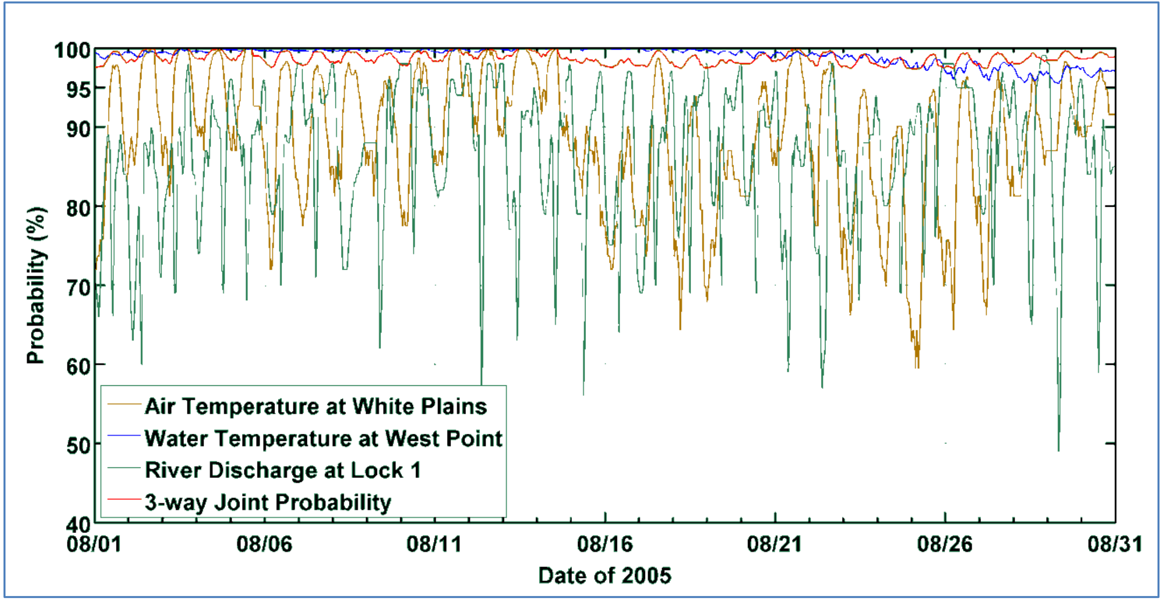

Figure 16-4
Time series of single and joint probabilities for the period August 2005

The 8- through 30-July 2010 validation period results were processed to determine the spatial extent of the cross sectional area and surface width of the 4°F temperature rise to determine compliance. Figure 16-7 shows the percent surface width for a 4°F temperature rise for various transects across the River and that the 4°F surface plume generally repeats itself with tidal cycle regularity at all the cross sections. The maximum surface width occurred at section S3 with a value of 23.9% compared to the allowable maximum of 67%. Similarly, throughout the entire validation period there was no section where the cross-sectional area exceeded 8%, well below the 50% limit.

Conclusions

A triaxial thermal study that consisted of a combination of field work, data analysis and numerical modeling was performed for the thermal discharge from IPEC in the Hudson River. An initial report [1], representing a summary of the 2009 field program, model application and calibration, and selection of an extreme environmental condition time period was documented. Subsequently a second report [2] that described the 2010 field program, model validation and assessment to NYSDEC thermal criteria was prepared. This paper extracted some of the salient material from those reports to define how a successful field and modeling effort can be performed to provide credible information defining the extent of the thermal plume in the River.

The 2-year field program, consisting of an extensive fixed instrument array and mobile studies, was performed to monitor River temperatures and currents at various locations in the River (both downstream and upstream of IPEC) during a six-week period from 24-September through 3-November 2009 and a 10-week period from 5-July to 10-September 2010. The data were analyzed, along with other publicly available River and meteorological observations to first assess the dynamics of the thermal plume resulting from the IPEC discharge, and then to understand the response of the plume to various environmental forcing factors, such as tides, River water temperature and currents, as well as meteorological conditions that substantially effect thermal regimes.

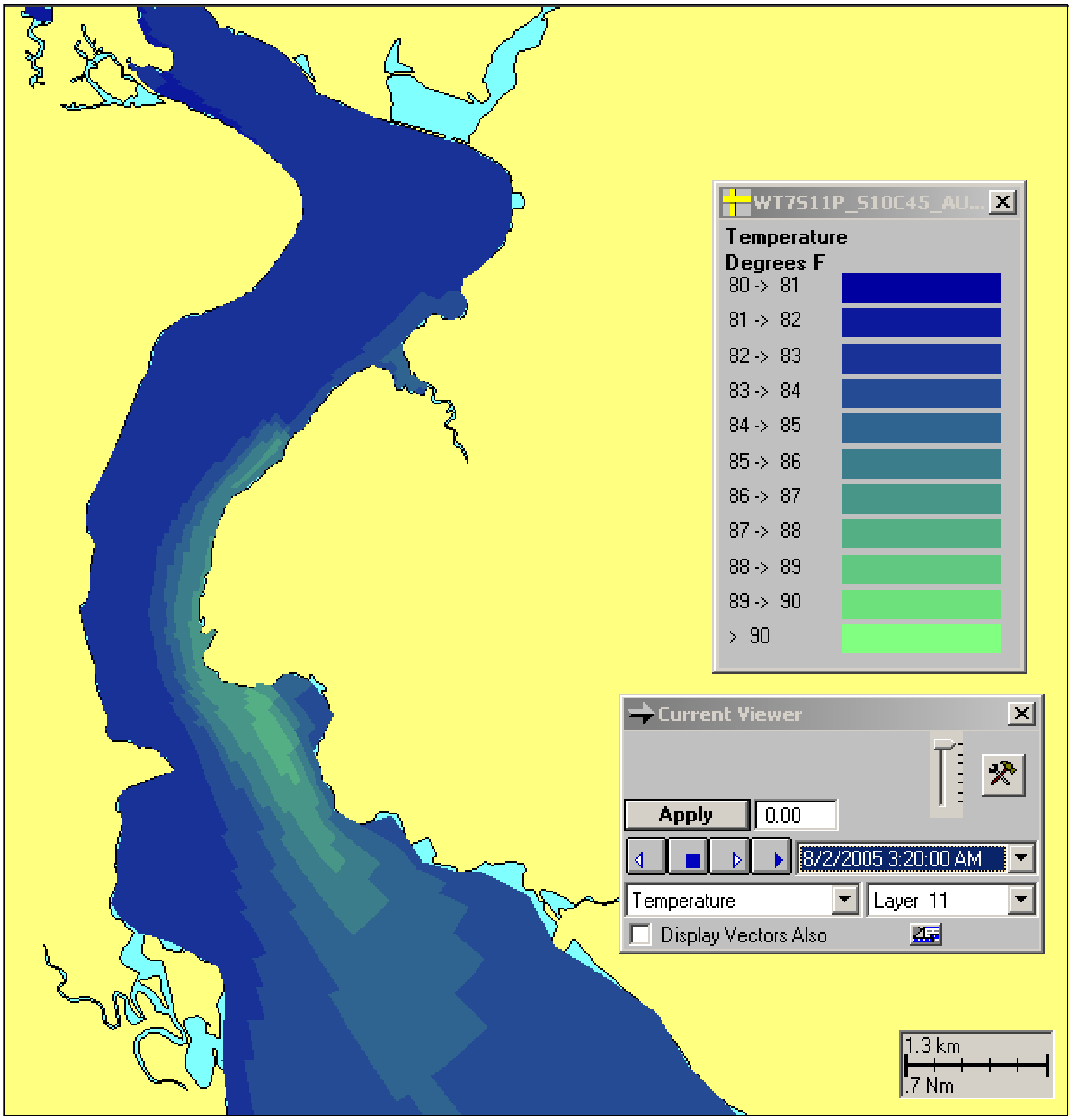

Figure 16-5
Plan view of the model predicted surface water temperatures showing the downstream extent of the plume at slack before flood during the Scenario time period

ASA's BFHYDRO, a three dimensional, baroclinic model was applied to an area that covered the spatial extent from Hastings on Hudson, approximately 20 miles north of the Battery at Manhattan, to the upstream dam at Troy (Study Area). A total of 51,909 cells were used in the model calculation consisting of 4,719 cells in 11 levels. The model application used water surface elevation (tides), water temperature and salinity at the southern boundary (Hastings on Hudson), and River flow and water temperature at the northern boundary (the dam at Troy). Meteorological forcing, including winds, solar radiation and air temperatures, was applied at the water surface. Plant forcing data consisted of intake and discharge temperatures, as well as cooling water flows.

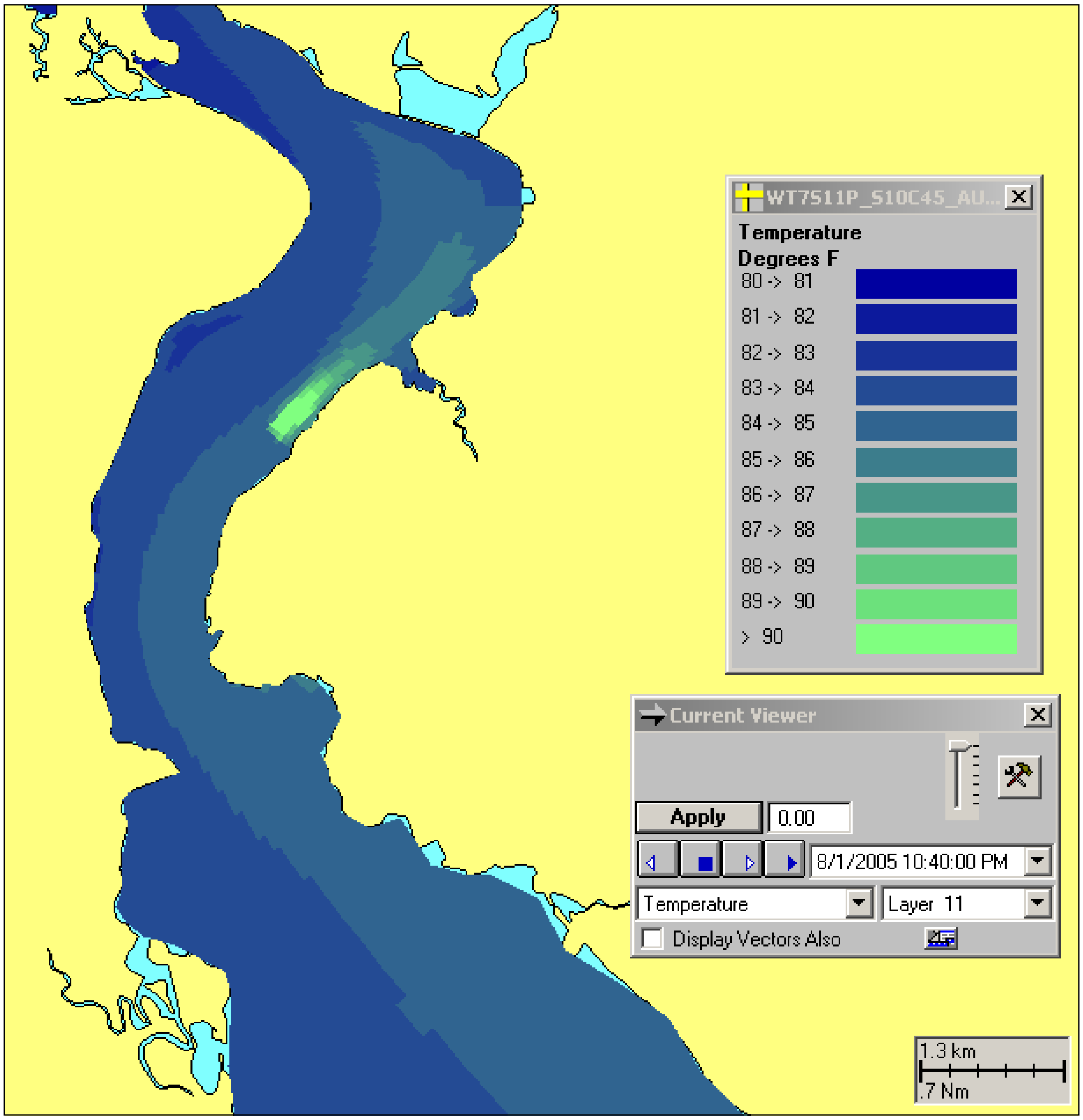

Figure 16-6
Plan view of the model predicted surface water temperatures showing the upstream extent of the plume at slack before ebb during the Scenario time period

The model calibration and validation was successfully performed with both qualitative and quantitative methods that represent the industry standard, providing confidence in model results. Time series comparisons of model vs. observations at the monitoring station locations were successfully established, as well as calculation of quantitative statistics, including relative mean error (RME), error coefficient of variation (ECV), square coefficient of variation (R^2) and model skill. The parameters that were evaluated in the model calibration phase were water surface elevations, currents and temperatures.

The model was then used to run other time periods, particularly extreme environmental conditions, employing the same methodology of model forcing and modeling coefficients. To do so, the model scenario timeframe for simulations was developed, using a ten-year dataset of public information of River and meteorological observations. The goal of developing the scenario timeframe was to ensure that critical environmental conditions which have the largest influence on River temperature (particularly, with respect to the water quality criteria pertaining to spatial extent of the thermal plume) are captured. Based on the detailed results of both the correlation and joint probability analyses used, the critical environmental conditions scenario timeframe was determined to be 1-August through 15-August 2005.

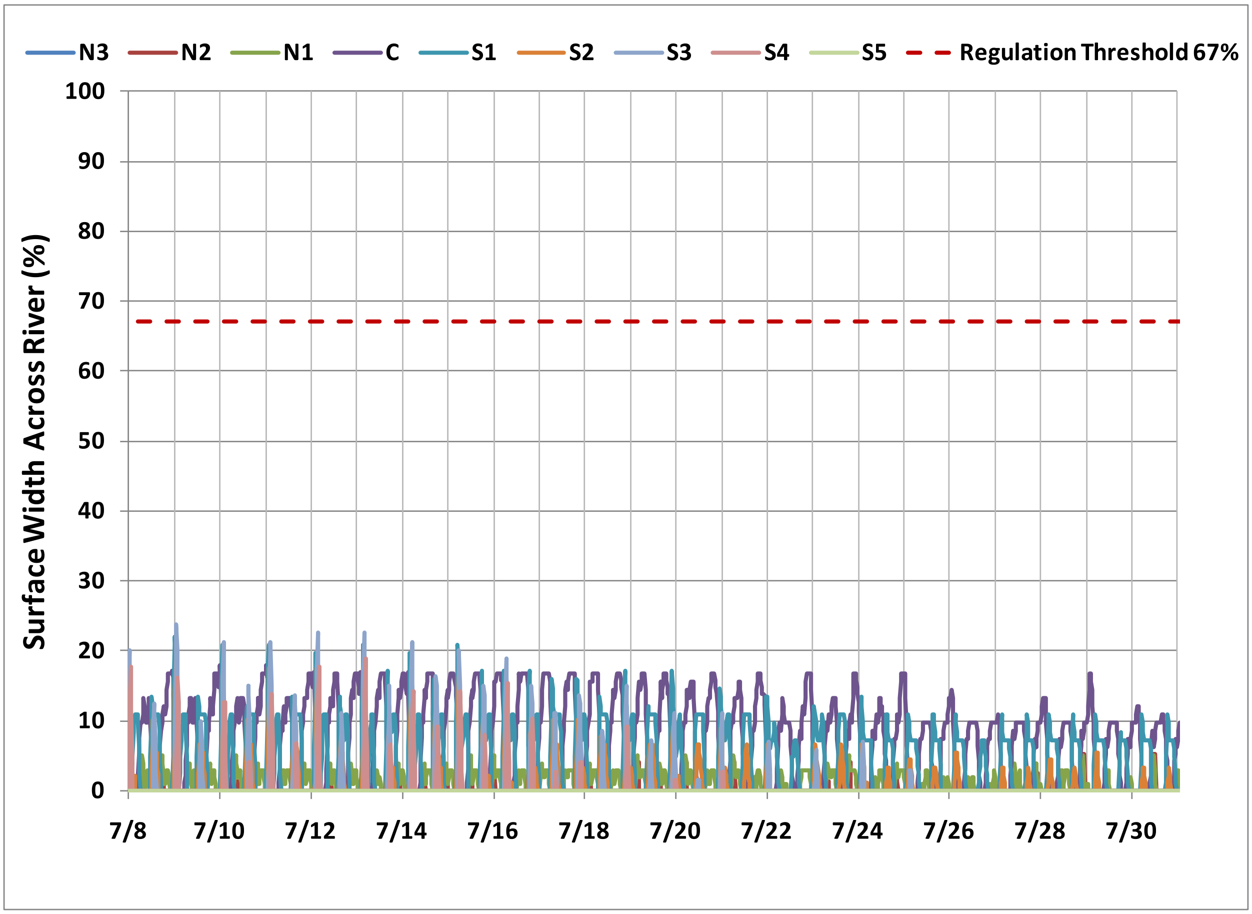

Figure 16-7
Surface width percentage based on a temperature rise of 4°F for all sections during the period from 8 through 30 July 2010. The regulatory threshold of 67% is shown as a dashed line.

In response to a NYDEC requirement to assess compliance using the 2010 validation time period, the 4°F temperature rise analysis showed that the surface width and vertical cross section area percentages generally repeated with tidal cycle regularity at all of the nine transects analyzed. The results for vertical cross section area showed that the maximum extent was 7.8% of the River vertical cross section area. These results are well below the Thermal WQS cross section area limit of 50%. The results for surface width showed that the maximum extent was 23.9% of the River surface width. These results are well below the Thermal WQS surface width limit of 67%.

In conclusion, even under extreme environmental conditions, IPEC was found in compliance with applicable NYSDEC thermal criteria. The model was ultimately used to define a thermal mixing zone for use in a NYSDEC draft permit. Thus a well-designed and executed field program and an appropriate hydrothermal modeling strategy can result in a highly credible analysis that informs client decisions and becomes the basis for regulatory concurrence

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17

SAN MIGUEL RIVER CASE STUDY: INCORPORATING ELEMENTS OF THE CLEAN WATER ACT §316(A) TO DEVELOP SITE-SPECIFIC TEMPERATURE STANDARDS FOR A HIGH ELEVATION, LOW SUMMER FLOW RIVER IN COLORADO

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Abstract

We present a case study where the Colorado Water Quality Control Commission (CWQCC) considered population data and species thermal preference information for both fish and aquatic invertebrates to adopt appropriate stream temperature standards based on elements of the Clean Water Act (CWA) Section 316(a). The San Miguel River in southwestern Colorado, transitions from a mountain stream to a high desert stream. During the summer, agriculture and other water withdrawals divert a substantial portion of the river, often reducing instream flows to less than 10 cfs in the study reach, reducing the river's assimilative capacity for thermal loading. Tri-State Generation and Transmission Association, Inc.'s Nucla Station (100 MW) is located along the lower elevational reaches of the San Miguel River and discharges water used for cooling and other uses to the river. The study reach was originally classified as "cold" water in the 1970s and is adjacent to a downstream segment classified as "warm" water. Over a two year period, Tri-State, EPRI and GEI Consultants, Inc. characterized the existing fish and macroinvertebrate populations and compared them to historical conditions, as well as evaluated the thermal constraints placed on aquatic life use. At multiple sites, both upstream and downstream of Tri-State's discharge, we observed that 96-100% of fish density was comprised of warm water species, and 82-97% of the benthic macroinvertebrate density was comprised of warm eurythermal species. The Colorado Macroinvertebrate Multimetric Index (MMI) indicated that all upstream and downstream sites attained the aquatic life use classification. The aquatic life use attainment, combined with the similarities in species composition related to thermal preferences, indicated that Tri-State's discharge is not adversely affecting the aquatic life community in the San Miguel River. Based on this study, Tri-State successfully re-classified the stream as "warm" water and had site-specific temperature standards adopted for the San Miguel River near the Nucla Station.

Introduction

The San Miguel River near the Tri-State Generation and Transmission Association, Inc. (Tri-State) Nucla Station in southwest Colorado has been monitored over the last twelve years for temperature, with aquatic life studies conducted in 2005, 2008 and 2009. Tri-State, EPRI and EPRI's contractor (GEI Consultants, Inc.) developed a methodology to assess thermal discharge impacts on fish and macroinvertebrate populations of high elevation, low summer flow rivers and conducted a case study of the methodology to determine the possible influence, if any, of the Nucla Station effluent on the aquatic communities of the San Miguel River [1]. The aquatic life studies included detailed field sampling of aquatic biological populations and stream temperatures in 2008 and 2009, along with a re-evaluation of existing data collected in 2005 [2] to determine whether or not the Nucla Station discharge is adversely impacting the aquatic community in the San Miguel River and, if there was no adverse impact, to determine the appropriate stream use-classifications and accompanying instream temperature standards.

Study Background

The San Miguel River has headwaters near Telluride, Colorado, and drains a 1,600 square mile watershed [2]. Over its 129 km length, the San Miguel River descends from an elevation of 9,100 ft to an elevation of 4,760 ft at its confluence with the Dolores River, transitioning from a montane environment to a high desert shrubland [3]. The hydrograph of the San Miguel River in the study area at the Brooks Bridge gage near Nucla, Colorado (USGS gage #09174600) is characterized by late-spring/early-summer snowmelt-driven high flows of 500 to 1,000 cubic feet per second (cfs) and late summer low flows that are often less than 50 cfs [4].

The Nucla Station is a 110 MW electricity generating facility located adjacent to the San Miguel River, near Nucla and Naturita, Colorado in Montrose County (Figure 17-1). The facility uses stream water for cooling and other uses, and returns the water to the river after use, withdrawing on average approximately 3-6 cfs and returning approximately 1 cfs.

The San Miguel River in the vicinity of the Nucla Station was originally classified as "Aquatic Life-Cold," in the 1970s. The river is considered relatively healthy, but human influence has affected its aquatic and riparian ecology [5]. Agricultural users withdraw water from the river from many diversions. Approximately 13 km upstream of the Nucla Station, the Colorado Cooperative (CC) Ditch withdraws as much as 145 cfs from the stream [5], reducing flows through the study reach of the river. These water withdrawals remove a smaller proportion of the water from the stream during peak flows, but during summer low flows the majority of the water is diverted. Heavy grazing over long periods of time have also led to localized effects such as reduced riparian function, bank erosion, and soil compaction. Other localized effects on physical stream morphology include bank stabilization measures such as dikes and rip-rap [5]. These effects and localized channel modifications such as the construction of diversions using stream substrate are present within the study reach of the river.

Regulatory Background

This study evaluated the appropriateness of the current aquatic life use classification of San Miguel River Segment 4b by examining fish and macroinvertebrate communities in accordance with CWA §316(a). The main stem of the San Miguel River is divided into five regulatory segments, and the study area is located in Segment 4 (Figure 17-1). Historically, the upstream end of Segment 4 was located in the mountains approximately 74 km upstream of Naturita, and the downstream end of Segment 4 was located at the confluence of Naturita Creek, which is approximately 5 km downstream of the Nucla Station (Figure 17-1). This entire segment was originally classified as Aquatic Life Cold Class 1 under CWQCC Regulation No. 35. Segment 5 begins at the confluence of Naturita Creek, ends 24 km downstream at the mouth of the San Miguel River, and is classified as Aquatic Life Warm Class 1.

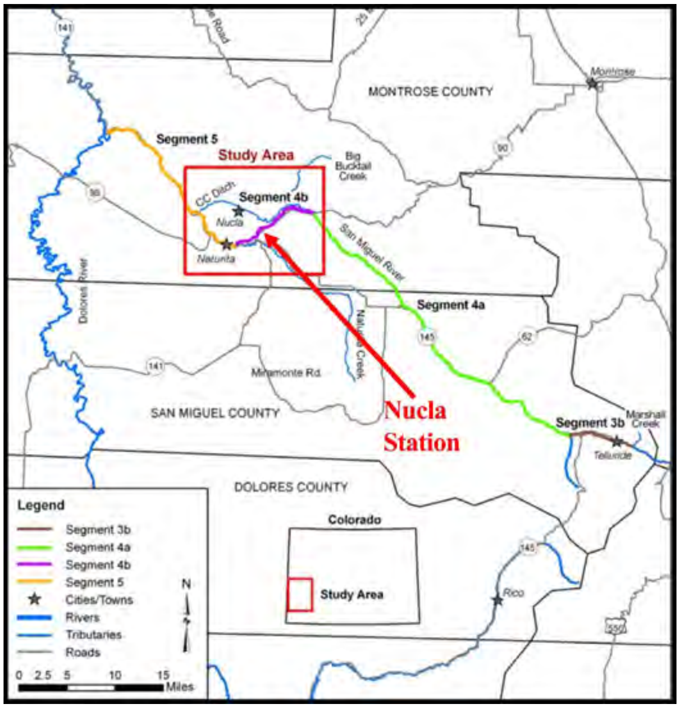

Figure 17-1
San Miguel River near the Tri-State Generation and Transmission Association, Inc. Nucla Station

Study results in 2005 found that an approximately 20 km reach near the downstream end of Segment 4 supported a predominance of warm water species [3]. Evaluation of flow, temperature, and fish assemblage data suggested that this portion of the San Miguel River more resembled a warm water stream than a cold water stream, reflecting the transition to a warm water stream, as is the current classification of the adjacent downstream Segment 5.

As a result of that study, Segment 4 was divided into segments 4a and 4b during the 2006 CWQCC Regulation No. 35 hearings. The upstream end of Segment 4a begins in the same location as the upstream end of the original Segment 4, approximately 74 km upstream of Naturita, and ends at the CC Ditch, upstream of the Nucla Station reflecting the influence of that major diversion structure. This segment retained the original Segment 4 aquatic life use classifications. Segment 4b begins at CC Ditch and ends at the confluence with Naturita Creek. This segment of the San Miguel River was then classified as Aquatic Life Cold Class 2. The CWQCC reevaluated Segment 4b for the appropriate Aquatic Life Use classification in 2010.

In the first hearing (2001), limited instream temperature data were presented showing that there was no possibility of attaining the Aquatic Life Cold Class 1 temperature standards – maximum instream temperatures of 20°C with a footnote recognizing fluctuations – in Segment 4b upstream or downstream of the power plant. The CWQCC did not change the classification or standards, instead a temporary modification of 28°C was applied in the summer and biological studies were requested.

At a second hearing (2006), CWQCC was presented with substantially more instream temperature data from upstream and downstream of the power plant (MWAT values up to 22°C and DM values up to 28°C). Additionally, new data on the fisheries using Segment 4b were presented, where warm water fish accounted for the majority of the species collected at every site and for 96 to 100% of the density of fish; cold water fishes are relatively rare or transient. Again, these data demonstrated that the Aquatic Life Cold Class 2 designation was not attainable within this reach of the San Miguel River. While the CWQCC did not change the aquatic life use classification of Segment 4b, it did adopt a site-specific temporary modification of the temperature standards subject to further studies on the potential impact of the Nucla Station discharge to the San Miguel River. The temporary modification allowed a summer MWAT of 26.3°C (from June to September) that expired in 2011.

In a third hearing (2010), data on the thermal structure of the benthic invertebrate communities were presented in addition to yet more instream temperature data and fisheries data. All of these data reinforced the inability of the San Miguel River to attain the cold water standard. Based on the new information, the CWQCC reclassified San Miguel River segment 4b to Aquatic Life Warm Class 1 in 2010, as summarized in this paper.

Colorado Stream Temperature Standards

Colorado temperature standards associated with cold and warm use classifications are derived using the thermal tolerances of fish species. For example, stream cold water temperature criteria are based on the thermal tolerances of brook trout (*Salvelinus fontinalis*), cutthroat trout (*Oncorhynchus clarkii*), brown trout (*Salmo trutta*), rainbow trout (*Oncorhynchus mykiss*), Arctic grayling (*Salvelinus malma*), mottled sculpin (*Cottus bairdi*), and longnose sucker (*Catostomus catostomus*), while warm water temperature criteria are based on the thermal tolerance of common shiner (*Notropis cornutus*), Johnny darter (*Etheostoma nigrum*), orangethroat darter (*Etheostoma spectabile*), brook stickleback (*Culaea inconstans*), central stoneroller (*Campostoma anomalum*), creek chub (*Semotilus atromaculatus*), longnose dace (*Rhinichthys cataractae*), Northern redbelly dace (*Phoxinus eos*), finescale dace (*Phoxinus neogaeus*), razorback sucker, (*Xyrauchus texanus*), white sucker (*Catostomus commersonii*), and numerous other species.

Further division of the rivers and streams cold and warm water classifications is based on the presence of key fish species as well as their relative life history stages to create a multiple tier structure with different temperature standards for each use classification. For example, cold water streams have a two tier system (Tier I and Tier II) that is applicable at different times of the year, whereas warm water streams have a three tier system (Tier I, Tier II, and Tier III) that is applicable at different times of the year (Table 17-1).

Table 17-1
Stream temperature standards in Colorado, with maximum weekly average temperature (MWAT) and daily maximum temperature (DM) standards applicable in the summer months

Stream Classification	Applicable Months	MWAT °C (chronic)	DM °C (acute)
Aquatic Life Cold Tier I	June – September	17.0	21.7
Aquatic Life Cold Tier II	April – October	18.3	23.9
Aquatic Life Warm Tier I	March – November	24.2	29.0
Aquatic Life Warm Tier II	March – November	27.5	28.6
Aquatic Life Warm Tier III	March – November	28.7	31.8

In the case of the San Miguel River study reach, the most critical time of the year with respect to water temperature and potential effects on aquatic life is during the summer when stream flow is at its lowest level of the year as a result of the instream diversions noted above. Based on the fish species present and its previous classification as a cold water segment, the applicable Cold Water Tier II temperature standards were 18.3°C as a maximum weekly average temperature (MWAT) and 23.9ºC as a daily maximum (DM) from April to October. Based on water temperature data and the aquatic life use data, both fish and macroinvertebrates, it became apparent that the stream segment was not appropriately classified with respect to its Cold Water designation.

While the aquatic life use classification and applicable temperature standards are based on fish, the State of Colorado recently revised their aquatic life use assessment policy in 2010 such that only aquatic invertebrates are considered during aquatic life use attainment evaluations. This new policy [6] is based on a MMI using an ecoregional approach (i.e., mountains, transition zone, plains and xeric). This ecoregional approach largely corresponds to cold and warm water streams, but in some circumstances fails to adequately make that distinction.

Methods and Data Analyses

Site Descriptions

Seven sites were surveyed during the three year aquatic life study. The 2005 study reach covered approximately 20 km of stream and was designed to characterize changes in environmental and stream habitat conditions and the resident fish and macroinvertebrate fauna on a large scale for a major portion of then-Segment 4. The 2008 and 2009 study focused more specifically on the interactions of the Nucla Station discharge with fish communities. Two of the 2005 sites and additional sites bracketing the discharge were sampled to provide better resolution at a smaller scale near the plant (Figure 17-1 and Figure 17-2).

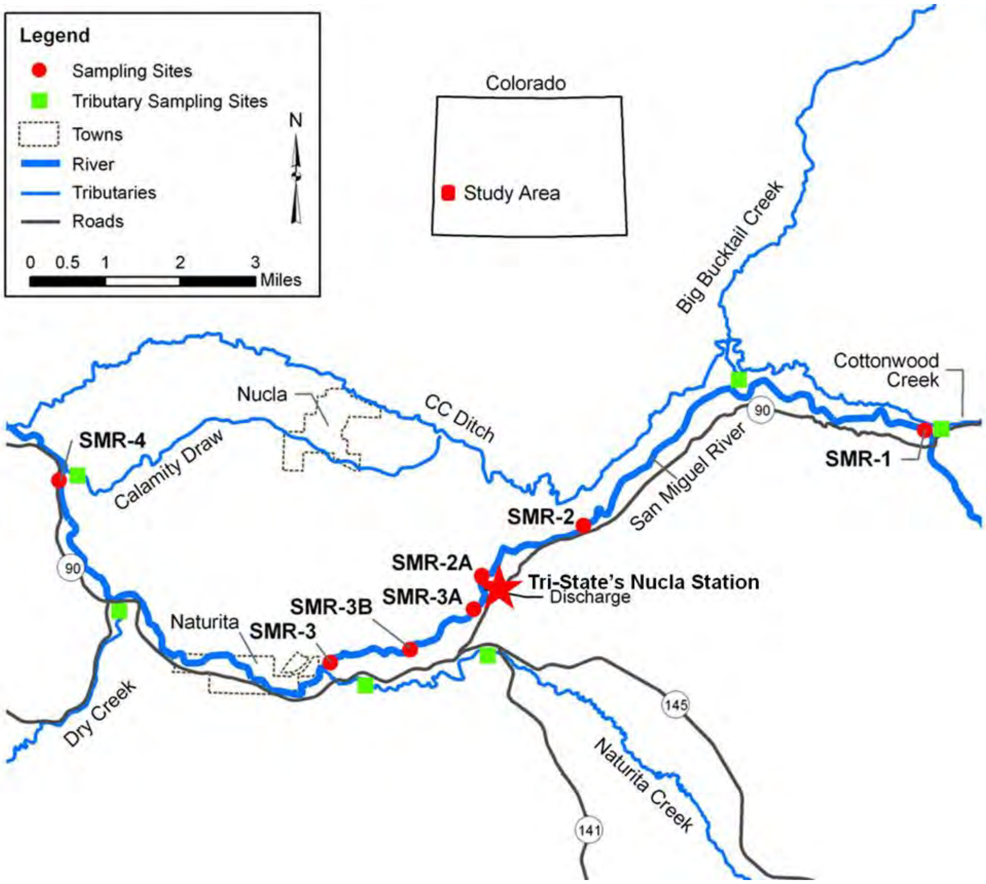

Figure 17-2
San Miguel River with all sampling locations

In addition to the main stem San Miguel River sites, selected tributaries to the San Miguel River (Figure 17-2) were sampled in 2009 to determine if fish utilized these small streams and to further explore how fish abundances are shaped by physical habitat and instream flows. These streams included Cottonwood Creek, Big Bucktail Creek, Naturita Creek, Dry Creek and Calamity Draw. Two sites were sampled on Naturita Creek, with one site near the confluence and the other site just downstream of State Highway 141. All of the other tributary streams were sampled just upstream of their confluences with the San Miguel River.

Fish Population Sampling

Fish populations were surveyed [1] using two-pass electrofishing methods with a bank electrofishing unit and a five-electrode array with population estimates being based on depletion rates. Because the San Miguel River is too large to effectively use block nets, the upstream and downstream ends of the reach were placed at breaks between habitat units to discourage fish from entering or leaving the site during sampling. Captured fish from each pass were retained separately so that quantitative population estimates could be calculated. Individual fish were identified to species, weighed, measured, and released. In 2009, the tributary sampling was performed over approximately 100 m by making a single pass with a backpack electrofishing unit. Larger fish were identified, weighed, measured, and released, and smaller fish were identified and released.

Fish Data Analyses

Estimates of fish density and biomass, length-frequency analyses, species richness, and condition factor analyses were used to compare populations of native bluehead sucker and flannelmouth sucker (both state species of special concern), as well as speckled dace between sites within years and within sites between years, to determine whether differences existed [1]. Population data from 2005, 2008, and 2009 were analyzed to determine whether any of the sites were characterized by interannual variability and to discuss larger-scale trends that could not be addressed with the data collected in 2008 or 2009. Changes in spatial trends over time were also examined.

Tributary surveys allowed us to determine if bluehead suckers and flannelmouth suckers utilized these small systems as refuge habitat for adults during low flow conditions and/or as rearing habitat for juveniles of either species.

Benthic Macroinvertebrate Population Sampling

Benthic macroinvertebrate populations were sampled in 2005, 2008 and 2009 using replicated quantitative methods [1]. In 2005, three samples in riffle habitat with a modified Hess sampler [7] were collected and composited into a single sample. This quantitative composite sample was supplemented by a separate, qualitative multi-habitat sweep sample per site to provide more complete information on the benthic macroinvertebrate taxa composition at each site. In 2008 and 2009, ten replicate quantitative Hess samples were collected in riffle habitat at each site and kept separately [1]. Samples were transferred to individual jars and preserved in the field in 95% ethyl-alcohol for processing at GEI’s laboratory.

Benthic Macroinvertebrate Laboratory Analyses

Samples were processed by sorting, identification, and enumeration of the organisms [1]. Subsampling of quantitative samples (10% minimum) was completed with a subsequent search for rare taxa in the remaining sample [8, 9]. The sorted specimens were identified to the lowest practical taxonomic level, usually genus or species depending upon age and condition of each specimen [10]. These laboratory methods provided benthic macroinvertebrate species lists and estimates of density for each taxon. A suite of population composition metrics was calculated for each site from the macroinvertebrate data for comparison between sites including the Hilsenhoff Biotic Index (HBI, a pollution tolerance index), metrics required for the Colorado MMI, and thermal preference metrics. Methods for calculation of the Colorado MMI and thermal tolerance metrics are presented in a companion paper, Canton *et al*. [11].

Macroinvertebrate Statistical Analysis

Replicate Hess samples allowed the use of statistical tests to compare population composition metrics among sites [12, 13, 14, 15, 16] with a 95% significance level ($\alpha = 0.05$) used for all analyses [1]. One-way analysis of variance (ANOVA) tests or *t*-tests were conducted to determine if significant differences existed among the sites in terms of total density, total taxa richness, EPT taxa richness[1], and the EPT index. If significant differences were detected for parameter values among sites, then the Tukey-Kramer multiple comparison test was performed to determine specifically which sites were different and to compare the differences between those specific sites [17]. The use of the Colorado MMI and the thermal preference data are discussed in depth in Canton *et al*. [11].

Habitat Sampling and Data Analyses

Physical Habitat

Habitat was evaluated qualitatively using the Rapid Bioassessment Protocol (RBP [18]) in 2005. Site lengths, site widths, substrate type, and substrate embeddedness were measured in 2008 and 2009 [1]. In all years, qualitative descriptions of the sampling sites included confinement of stream by banks and/or valley walls, land use, and degree of riparian degradation.

Flow

Monthly and daily flow data for the study reach of the San Miguel River were retrieved from the USGS gage [4] at Brooks Bridge (Gage #09174600), just upstream of Site SMR-2A. Flow data for all years from 2005 through 2009 were retrieved even though biological samples were not collected in 2006 and 2007.

Temperature

Temperature data from 2000 - 2009 from monitoring sites upstream and downstream of the Nucla Station discharge were provided by Tri-State [1, 2]. The thermograph 2,000 ft downstream of the Nucla Station discharge was immediately downstream of the CDPHE regulatory mixing zone. MWAT and DM temperature values were calculated following the CWQCD 303(d) Listing Methodology [19] and compared to potentially applicable refined standards.

Results and Discussion

Fish Results – Population Estimates

Seven fish species, including four native species, and one hybrid, were collected in 2005 from the four sites on the San Miguel River [2]. Coldwater fishes (i.e., trout, and mottled sculpin)

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[1] EPT Taxa Richness is the number of Ephemeroptera (mayfly), Plecoptera (stonefly), and Trichopera (caddisfly) taxa in a sample.

were found only at Site SMR-1, the most upstream site, and comprised only 4% of the density (Table 17-2). The presence of a mixed assemblage of cold- and warmwater species at Site SMR-1 and the absence of coldwater species at the other downstream sites indicated that Site SMR-1 is within the transition zone between cold and warm water. Length-frequency analyses showed an absence of young-of-the-year trout, suggesting little or no successful reproduction by trout in the San Miguel River at or near the Site SMR-1 [2]. The transition to a warmwater stream appeared to have been complete by Site SMR-2, which is upstream of the Nucla Station.

Table 17-2
Estimated densities (# per hectare) of fish captured in the San Miguel River in 2005. Native species are denoted in bold.

Species	SMR-1	SMR-2	SMR-3	SMR-4
Coldwater Fishes				
Brown trout	20	--	--	--
Mottled sculpin	138	--	--	--
Rainbow trout	33	--	--	--
Rainbow trout x cutthroat trout	7	--	--	--
Warmwater Fishes				
Bluehead sucker	164	212	35	19
Flannelmouth sucker	7	57	--	--
Green sunfish	--	--	6	--
Speckled dace	4,039	1,618	1.601	1,433

In 2008, eight species were captured, and four of these species were native (Table 17-3). Native bluehead suckers and speckled dace were the two most abundant species at every site. The biomass and length-distribution results indicate that bluehead suckers successfully reproduce in or near the study reach, even if their abundances were lower at sites SMR-3A and SMR-3. The presence of young-of-the-year (approximately 30 to 60 mm) and adult individuals at all sites indicates that speckled dace reproduce successfully and maintain populations throughout the study reach. Warmwater species accounted for 99 to 100% of the density of fish at the individual sites in 2008.

In 2009, warmwater species accounted for 97% to over 99% of the fish density at the sites. While densities and biomass of bluehead suckers and flannelmouth suckers varied between upstream and downstream sites, the length-frequency histograms indicated a greater proportion of these populations at sites downstream of the Nucla Station were composed of young-of-the-year and juvenile fishes than at the upstream sites. Speckled dace densities did not vary with a clear spatial trend (Table 17-3). Despite differences in biomass between sites, the observed length ranges were similar between sites, and length-frequency histograms indicate that young and adult fish were present at all four sites and show that speckled dace are reproducing at all sites within the study area.

Table 17-3
Estimated densities (# per hectare) of fish captured in the San Miguel River in 2008 and 2009. Native species are denoted in bold.

Species	SMR-2		SMR-2A		SMR-3A		SMR-3(B)	
	2008	2009	2008	2009	2008	2009	2008	2009
Coldwater Fishes								
Brown trout	10	122	--	222	4	30	--	19
Mottled sculpin	3	111	6	263	--	10	--	6
Rainbow trout	--	11	--	8	--	--	--	3
Warmwater Fishes								
Bluehead sucker	269	5,025	364	2,465	44	603	7	1,199
Channel catfish	--	--	--	--	--	--	5	--
Fathead minnow	--	--	--	4	--	--	--	28
Flannelmouth sucker	33	2,570	19	1,267	24	1,300	7	1,355
Green sunfish	5	14	3	33	--	--	--	47
Largemouth bass	--	--	--	--	--	--	2	--
Speckled dace	2,636	1,366	4,518	17,165	2,665	6,810	340	5,454

Fish Results – Condition Factors

The overall health of the fish as measured by fish condition factors (i.e., species weight – length relationships) for speckled dace and relative condition factors for bluehead sucker and flannelmouth sucker were compared between sites using ANOVA and a Tukey-Kramer multiple comparison test [1]. The 2005 data showed the average condition factor of bluehead suckers ranged from 1.29 at Site SMR-4 to 1.62 at Site SMR-3. The average condition factor of speckled dace ranged from 0.93 at Site SMR-1 to 1.17 at Site SMR-4. Average condition factors for speckled dace captured upstream of the Nucla Station were less than 1.0, and average condition factors for speckled dace captured downstream of the Nucla Station were greater than 1.0.

The average condition factors for bluehead suckers in 2008 were nearly identical at all four sites (Table 17-3), with no statistically significant difference between any of the sites ($p > 0.05$). Average condition factors for flannelmouth suckers were highest at Site SMR-2 and lowest at Site SMR-3A (Table 17-4). However, average condition factors were similar at sites SMR-2A and SMR-3A. Condition factors for speckled dace varied throughout the study reach without exhibiting a clear spatial pattern. ANOVA results indicated that speckled dace captured at sites SMR-2 and SMR-3A had significantly higher ($p < 0.001$) mean condition factors than the speckled dace captured at sites SMR-2A and SMR-3 (Table 17-4) – reflecting no trend upstream/downstream of the Nucla Station discharge.

In 2009, while average condition factors for bluehead suckers were highest at Site SMR-2A, the factors at sites SMR-2, SMR-3A, and SMR-3B were comparable (Table 17-5). Average relative weights and average condition factors for flannelmouth suckers followed a similar spatial pattern in that they were highest at Site SMR-2, lowest at Site SMR-3A, and intermediate at the remaining sites. Average relative weights were not significantly different between sites ($p > 0.05$) and were less than optimal throughout the entire study reach in 2009. Condition factors of speckled dace varied without a clear spatial trend in 2009 (Table 17-6).

Table 17-4
Condition indices for commonly-collected fish species in the San Miguel River near Naturita, Colorado, 2008

Index	Site			
	SMR-2	**SMR-2A**	**SMR-3A**	**SMR-3**
Condition Factor				
Bluehead sucker (relative)	1.10	1.09	1.09	1.14
Flannelmouth sucker (relative)	1.06	0.89	0.84	1.01
Speckled dace (standard)	1.08	0.89	0.95	0.89
Relative Weight				
Flannelmouth sucker	107	103	n/a	110

Table 17-5
Condition indices for commonly-collected fish species in the San Miguel River near Naturita, Colorado, 2009

Index	Site			
	SMR-2	**SMR-2A**	**SMR-3A**	**SMR-3B**
Condition Factor				
Bluehead sucker (relative)	1.05	1.12	1.03	1.02
Flannelmouth sucker (relative)	1.41	1.31	1.18	1.24
Speckled dace (standard)	0.89	1.00	0.92	0.90
Relative Weight				
Flannelmouth sucker	98	96	92	96

Fish Results – Tributaries

In 2009, fish were present at five of the six tributary sampling sites (Table 17-6). Cottonwood Creek and Big Bucktail Creek both contained speckled dace and low numbers of mottled sculpin, both native species. Cottonwood Creek had a moderate gradient, substrate consisting of boulders, cobble, and sand, and significant filamentous green algae cover. Big Bucktail Creek was steep, small, and characterized by boulder substrate. Naturita Creek supported native and nonnative species. This site was characterized by a degraded riparian zone. Dry Creek was small and characterized by a mud and boulder substrate. This stream was not flowing, with only standing pools present at the time of sampling. Fish were not found in Calamity Draw, which is steep and is fed by a combination of agricultural return flows and discharge from the Town of Nucla Sanitation District.

Table 17-6
Number of fish captured at each tributary monitoring site in 2009. Native species are indicated by boldface font; non-native species indicated by normal font.

Species	Cottonwood Creek	Big Bucktail Creek	Dry Creek	Naturita Creek		Calamity Draw
				Upper	Lower	
Bluehead sucker	--	--	--	3	5	--
Flannelmouth sucker	--	--	--	4	1	--
Mottled sculpin	1	6	--	--	--	--
Speckled dace	63	185	--	15	22	--
Fathead minnow	--	--	7	46	1	--
White sucker	--	--	--	--	1	--
Green sunfish	--	--	--	6	--	--

Fish Discussion

The presence of coldwater species varied spatially and temporally in the San Miguel River. It appears that coldwater species move downstream into the study area (Segment 4b) from suitable coldwater habitat in Segment 4a which is consistent with other regional based observations [20]. The presence of native warmwater species was more spatially consistent and less variable through time. Warmwater fish accounted for the majority of the species collected at every site and for 96 to 100% of the density of fish. CDOW surveys [21] from 1977 through 2008 confirm the fact that although coldwater fish are present, the majority of the captured fish are warmwater species and Segment 4b of the San Miguel River is a warmwater system.

The observed spatial density patterns indicate that the fish community in the San Miguel River is unaffected by the effluent from the Nucla Station. The variation in spatial density patterns between years indicates that differences in density are not driven by thermal effluent from the Nucla Station. Rather, environmental factors such as climate and stream flow, which affect the entire study reach, and physical habitat, which creates differences between study sites, have a more pronounced effect on fish populations. Spatial patterns in measures of fish condition varied by species and by year, apparently independent of site location. This indicates that a multitude of factors affect fish condition in the San Miguel River and that fish condition is not related to the Nucla Station effluent.

The results of the tributary sampling demonstrate that although bluehead suckers and flannelmouth suckers may utilize the tributaries to the San Miguel River, the majority of adults and juveniles of both species primarily inhabit the main stem of the river. Also, the paucity of adult suckers in the tributaries supports the hypothesis that physical habitat controls the differences in bluehead sucker and flannelmouth sucker densities between river sampling sites. The scarcity of juvenile and young-of-the-year suckers in all of the tributaries also indicates limited utility as nursery areas for native fishes.

Macroinvertebrate Results

Macroinvertebrate data collected in 2005 on the San Miguel River and 2008-2009 are not directly comparable because the populations were sampled using different methods [1, 2]. However, metrics that rely on numeric density data, such as total macroinvertebrate density, the HBI, and temperature preferences could be calculated consistently between years.

Overall, total macroinvertebrate density (Figure 17-3) was usually higher at Site SMR-3A, immediately downstream of the Nucla station, while taxa richness (Figure 17-4), and EPT taxa richness (Figure 17-5), was often lower. In both 2008 and 2009, percent EPT individuals decreased downstream of the Nucla Station, but this was not due to a net decrease in the number of EPT organisms. In fact, in 2009 the absolute number of EPT organisms increased 42%, including the mayfly *Baetis notos*, which increased 63% from Site SMR-2A to Site SMR-3A, and caddisflies in the genera Cheumatopsyche and Hydropsyche, which increased at least 13%. The lower proportion of EPT organisms was instead caused by an accompanying larger increase in non-EPT organisms, particularly the midges *Cricotopus trifascia*, *Eukiefferiella* sp., and *Polypedilum* sp. These six taxa have moderate to high tolerance of pollution [18, 22, 23], and are often considered to be indicators of nutrient enrichment because of their ability to utilize filamentous green algae (FGA) and other periphyton resources as food [24]. Periphyton populations can increase substantially (e.g., the large FGA blooms at Site SMR-3A in 2009) under conditions of low flows, warmer temperatures, and nutrient enrichment.

A critical analysis of these metrics indicated that there was no negative effect of the Nucla station on the San Miguel River, and the invertebrate communities are similar throughout Segment 4b.

The HBI for the benthic macroinvertebrate communities in the vicinity of the Nucla Station had a very narrow range between 4 and 6 for all sites across the three years of the study, consistently ranking in the “Good” to “Very Good” categories (Figure 17-6). This was a very good indication that water quality, except possibly nutrients, was not producing a negative impact on the benthic invertebrate communities in the San Miguel River.

Macroinvertebrate Discussion

These results highlight the consistently healthy benthic macroinvertebrate communities both upstream and downstream of the Nucla Station. Even though the valley widens close to the Nucla Station, and agricultural practices near the stream increase near the Nucla Station. The short distance between Site SMR-2A and Site SMR-3A made it unlikely that nutrients were entering the system from the adjacent agricultural fields, thus likely not a factor in any changes observed in the macroinvertebrate populations downstream of the Nucla Station. Since water in the discharges from the power plant is usually a small proportion of the flow in the river, it was an unlikely source for nutrient enrichment, as well.

Furthermore, *Cheumatopsyche* and *Hydropsyche* caddisflies were abundant both upstream and downstream of the Nucla Station. Therefore, the increase of organisms indicative of nutrient enrichment and the conflicting lack of a source of nutrients led us to conclude that nutrient concentrations in the San Miguel River are similar above and below the power plant, and some other factor was responsible for any observed changes in the composition of the benthic macroinvertebrate community.

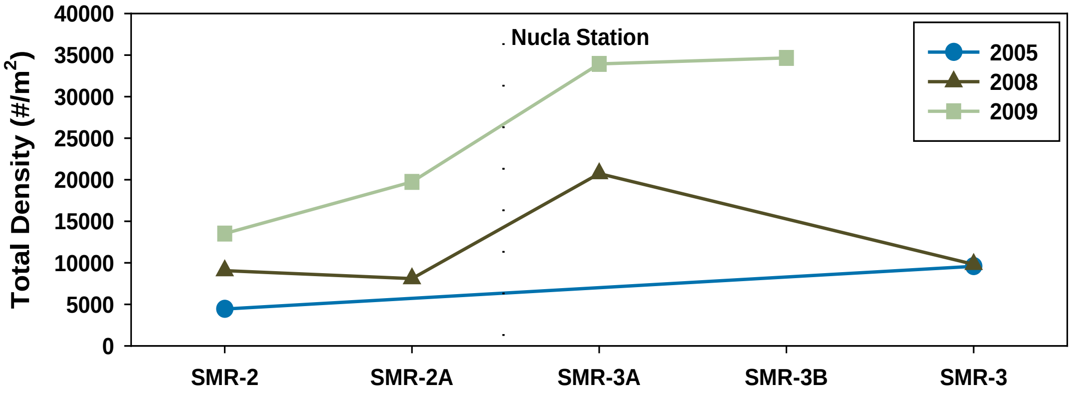

Figure 17-3
Total benthic macroinvertebrate density at sites on the San Miguel River Segment 4b in the vicinity of the Nucla Station

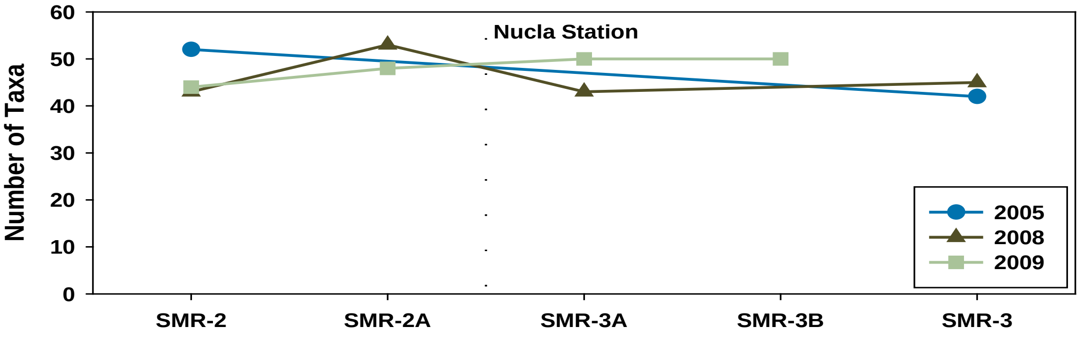

Figure 17-4
Total benthic macroinvertebrate taxa richness at sites on the San Miguel River Segment 4b in the vicinity of the Nucla station

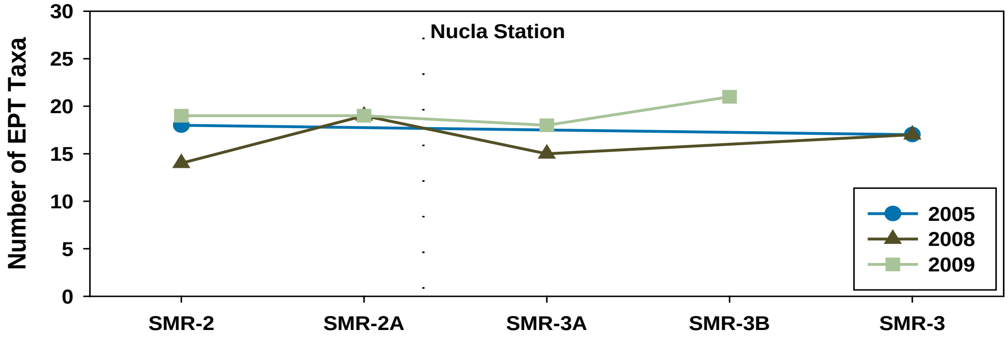

Figure 17-5
EPT taxa richness at sites on the San Miguel River Segment 4b in the vicinity of the Nucla station

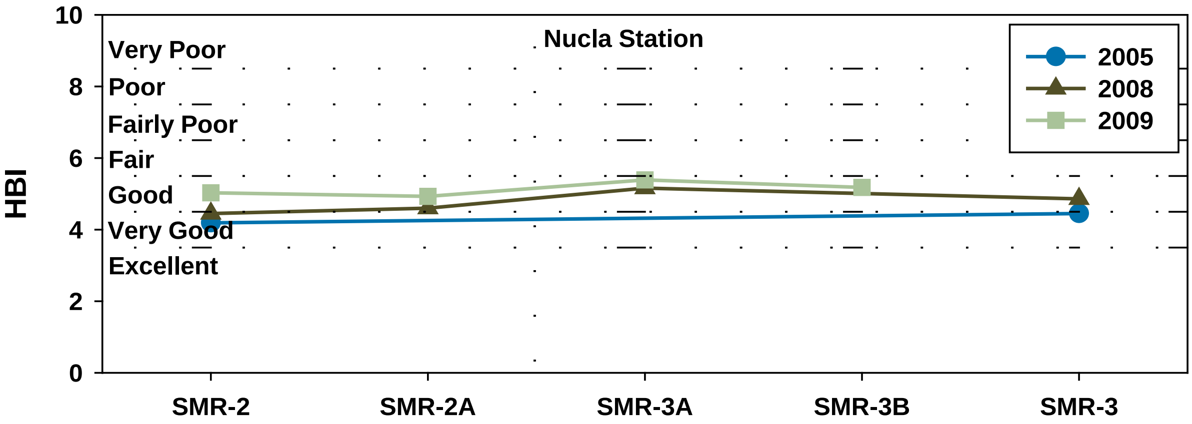

Figure 17-6
Hilsenhoff Biotic Index (HBI) at sites on the San Miguel River near Naturita, Colorado, 2005–2009. Thresholds based on Hilsenhoff (1987) [22].

Habitat Results

Physical Habitat

The 2005 habitat data indicated valley wall confinement and land use changes throughout the San Miguel River within the study reach. Confinement by valley walls was most pronounced at the upstream sites affecting available physical habitat by narrowing the channel, increasing the percentage of pool habitat, and increasing water depths. The downstream site (Site SMR-3) was the least confined. Substrate at all four sites consisted primarily of cobble and gravel, but boulders were present in small numbers at some sites. Embeddedness was highest at Site SMR-3 (40%), indicating that the cumulative effects of cattle grazing and agricultural land use may increase natural erosion rates in this system. All four sites received high scores with the Rapid Bioassessment Protocol (RBP) Habitat Assessment Protocol in 2005.

Qualitative habitat examinations in 2008 and 2009 indicated that pool habitat and average reach depths also varied spatially within the smaller study reach. The two confined sites upstream of the Nucla Station contained a deeper, narrower channel than the two less confined sites downstream of the Nucla Station.

Overall, the physical habitat in the study area was suitable for multiple life stages of native fishes. However, habitat attributes varied by study site and favored different life stages or species of fish over others. Habitat downstream of the Nucla Station was shallower, wider, and characterized by more riffle habitat and less pool habitat. Although these shallow habitats are suitable for smaller fishes such as juvenile suckers and speckled dace, adult suckers would not normally use shallow-water habitat [25, 26], and they were rare at these sites.

Flow

Flows in the San Miguel River follow a typical mountain stream pattern, with high runoff flows in April through June, tapering off to low base flows in August and September. Diversions remove a portion of the water throughout the year, but they are more pronounced during the low flows in August and September, when stream flows are naturally low. The period from 2000 through 2004 had flows less than median flows in most months, including the drought year of 2002. Since 2005, flows in most years have been near or above median flows except for the dry year of 2006 and unusually low flows in August and September, 2009. These low flows in 2009, in conjunction with the wide stream widths, resulted in very shallow stream depths and restricted the amount of available suitable fish habitat at all sites.

Temperature

In both 2008 and 2009, weekly average stream temperatures immediately upstream of the Nucla Station and downstream of Nucla Station's mixing zone exceeded the Cold Stream Tier II temperature standard (Figure 17-7). Weekly average temperature differences (delta *t*) between sites upstream and downstream of the Nucla Station were less than 2°C from 2001 through 2005 [2]. The measured differences in 2008 and 2009 were much less than 2°C, and smaller than the estimated differences from 2001 and 2005 [1].

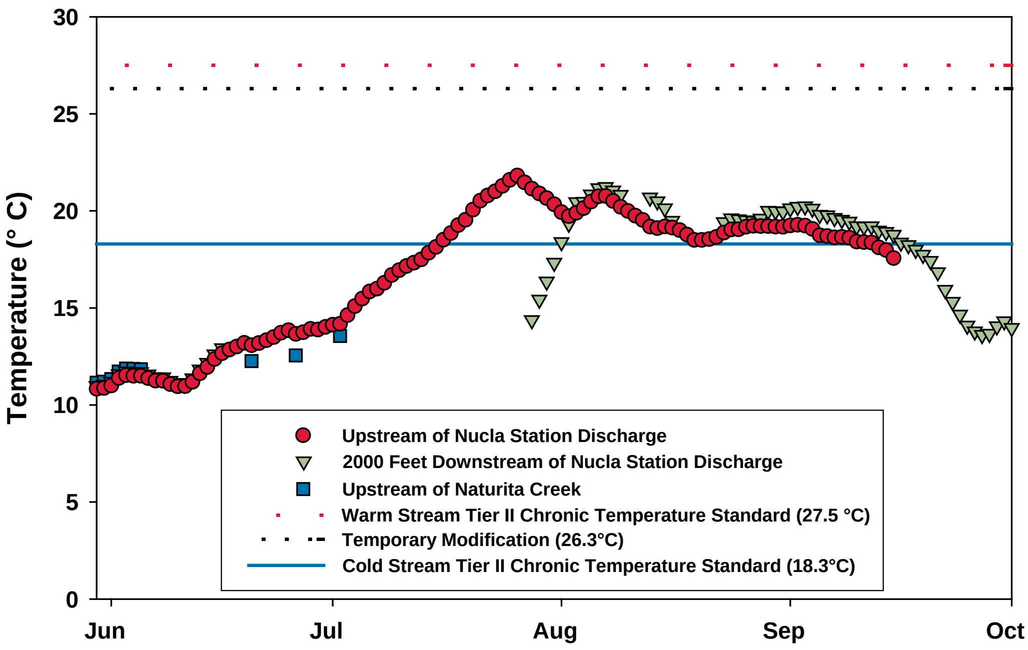

Figure 17-7
Weekly average temperature data summary for the San Miguel River, 2009

The daily maximum temperature values exceeded the Cold Stream Tier II acute standard of 23.9°C at all three thermograph sites in the summer of 2008 and 2009 (Figure 17-8). In 2009, daily maximum temperatures were slightly higher downstream of the mixing zone, likely a function of the extremely low flows observed in August and September when localized, temporary diversions reduced stream flows considerably, especially downstream of the Nucla Station. Shallow, slow-flowing water can increase the susceptibility of the San Miguel River to thermal changes from solar heating.

A 2008 report by Brown and Caldwell described the size of the Nucla Station mixing zone at low flows [27]. At low flows, any reduction in available fish habitat is negligible, and fish can move upstream or downstream past the Nucla Station in the zone of passage on the far bank without encountering water in the mixing zone.

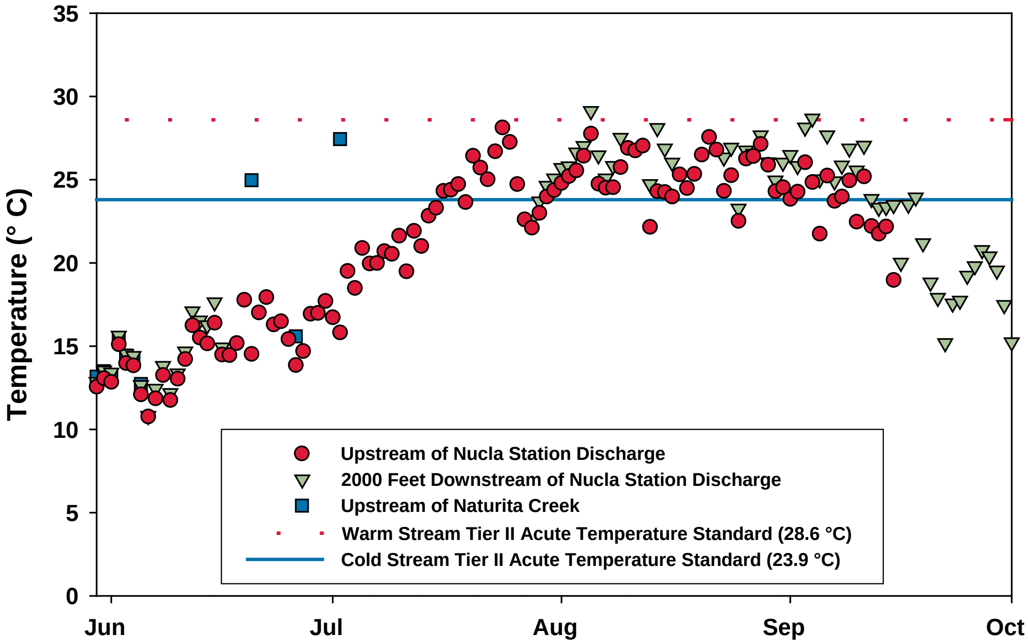

Figure 17-8
Daily maximum temperature data summary for the San Miguel River, 2009

Habitat Discussion

Any effects of water quality changes are likely minimal. The presence of juvenile suckers at the immediately downstream sites (SMR-3A and SMR-3B) indicate that water quality conditions at these sites do not prevent reproduction or site occupancy by this sensitive life stage.

The effects of temperature on fish distribution within the study site also appear to be minimal or absent. The minor temperature differences between sites should not be sufficient to cause avoidance behaviors in bluehead suckers, flannelmouth suckers, or speckled dace. Although tolerance of high temperatures is not well-studied in bluehead suckers or flannelmouth suckers, all three species are eurythermal with temperature preferences between 25°C and 29°C [25, 26, 28].

The primary limitation in the San Miguel River throughout the study reach appears to be the low summer flows and resulting seasonal low habitat availability [29] that forces larger-bodied fish such as bluehead suckers and flannelmouth suckers to take refuge in deep pools, which were more prevalent upstream of the Nucla Station. Lower flows limit habitat diversity, and in some cases, shallow riffles may act as a barrier to migrating bluehead suckers and flannelmouth suckers [26, 28]. Because much of the habitat downstream of the Nucla Station was shallower than this in 2008 and 2009, it is probable that bluehead suckers and flannelmouth suckers take refuge in large, deep pools during summer and that summer long-distance movements within the study reach are restricted by shallow water.

The importance of flow and physical habitat effects on fish distribution and the lack of any substantial difference in temperature, even during the extreme low flows observed in 2009, indicate that temperature effects on the San Miguel River resident fish community are negligible, although they would severely limit cold water fish throughout the study reach.

Conclusions

Based on the results of this study, it was determined that habitat limitations, such as low flow conditions, high summer temperatures, and wide, shallow riffle habitat, rather Nucla Station's discharge, are the driving factors in shaping the aquatic community in the San Miguel River. Regional diversions are the dominant factor resulting in low flow conditions.

The three years of biological data indicate that the study reach is consistently suitable for warmwater fishes and that coldwater fishes are rare or transient. Warmwater fish accounted for the majority of the species collected at every site and for 96 to 100% of the density of fish. The benthic macroinvertebrate assemblage is comprised of 65 to 76% warm eurythermal taxa accounting for 82 to 97% of the density [11].

Use Classification and Temperature Standard

Tri-State presented the fish, macroinvertebrate and habitat data to the CWQCC in December 2010 to address the appropriate aquatic life use classification and temperature standards for the section of the San Miguel River near Nucla Station (Segment 4b). The CWQCC and Division agreed that the Nucla Station discharge was not adversely impacting the aquatic community. The CWQCC determined that the appropriate use classification is Aquatic Life Warm, based on the predominately warmwater fish and benthic macroinvertebrate communities.

Temperature data from sites upstream and downstream of the Nucla Station indicated that the San Miguel River in Segment 4b is incapable of attaining the Cold Stream standards. Tri-State agreed to site-specific instream temperature standards that incorporate the existing Nucla Station effluent limits: weekly average of 23.3°C and daily maximum of 30.9°C from March through October, and weekly average of 9°C and daily maximum of 13°C from November through February.

Acknowledgements

We would like to acknowledge the technical expertise in 316(a) thermal effects studies, support and oversight provided by Robert Goldstein, EPRI, throughout the 2008-2009 study period and report development.

We would also like to acknowledge the complementary report in these proceedings titled "Use of Benthic Invertebrate Thermal Traits to Evaluate Stream Classifications," that provides additional results and discussion on the macroinvertebrate community studied on the San Miguel River.

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18

MOUNT HOPE BAY, BRAYTON POINT STATION AND THE DECLINE OF FISH STOCKS

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Abstract

Mount Hope Bay is a 14 square mile shallow estuary in southeastern Massachusetts. Brayton Point Station is a 4 unit 1600 megawatt coal/oil/gas fired power plant located along the northern shores of Mount Hope Bay. The station began operation in 1963 with a combination of once-through cooling and spray pods. Due to operational problems with the spray pods, the station converted to complete once-through cooling in 1984. As a result, station cooling water flow and thermal discharge to the bay increased by 45%. Simultaneously, aggregate fish abundance declined by over 80% and has remained at that low level of abundance through 2011. Winter flounder (*Pseudopleuronectes americanus*) was one of the species exhibiting the greatest decline. After reviewing the published scientific literature, the U.S. Environmental Protection Agency (EPA) determined that winter flounder was the most thermally sensitive species in Mount Hope Bay, with 24^{o}C being a critical threshold summer water temperature triggering avoidance in juveniles. Utilizing Brayton Point Station's hydrodynamic model, EPA examined multiple discharge scenarios and chose the scenario that would assure protection of winter flounder nursery habitat. This level of operation requires the plant to reduce its thermal impact by approximately 95%. As a result, Brayton Point Station has begun installation of cooling towers, which will become fully operational in the spring of 2012.

Introduction

Brayton Point Station (BPS) is a 1600 megawatt power plant located on the northern shore of Mount Hope Bay in Massachusetts (Figure 18-1). BPS began commercial operation with its first unit in 1963. Units 2, 3 and 4 were added in 1964, 1969 and 1974 respectively. BPS employed once-through cooling for units 1-3 and a closed loop configuration using spray pods to disperse waste heat for Unit 4. Operation of the spray pods resulted in heavy salt deposition on the transmission lines, which lead to problems with arcing. In 1984, BPS switched to complete once through cooling. This change in combination with increased power generation resulted in an approximately 45% increase in cooling water flow and thermal discharge to the bay.

Mount Hope Bay is a shallow estuarine water body hydrologically connected to Narragansett Bay (Figure 18-1). Almost half of the bay is in the Commonwealth of Massachusetts, with the balance being the State of Rhode Island waters. The average water depth of the bay is 18.7 feet, with the upper two thirds of the bay being shallower than 20 feet [1]. The bay has 4 freshwater sources (Taunton, Cole, Lees and Kickamuit Rivers) that feed into the northern part of the bay.

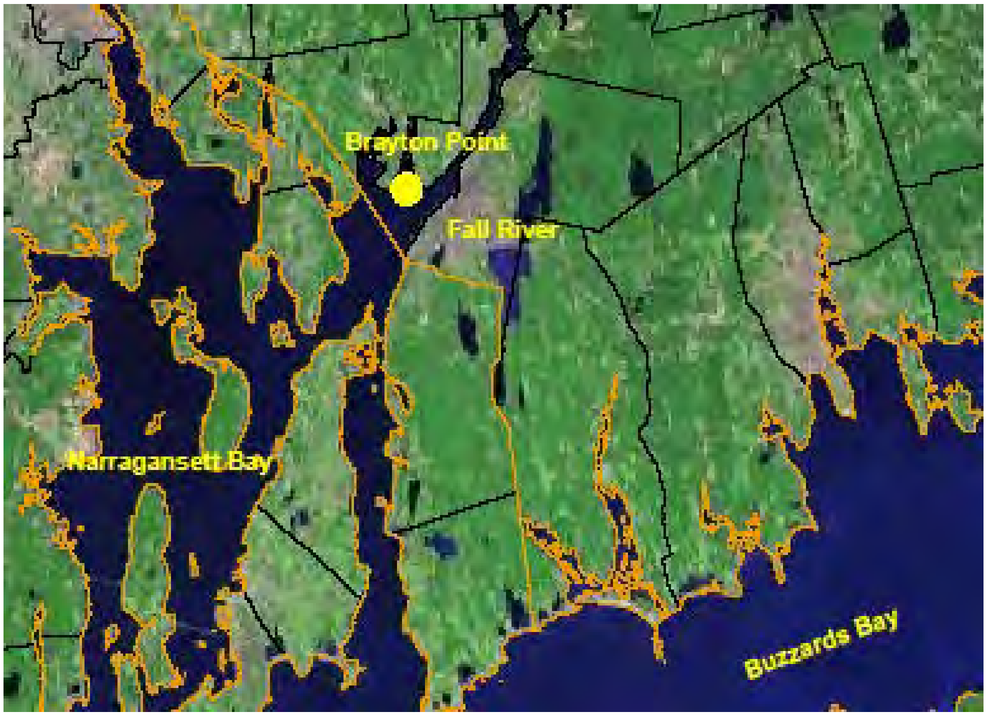

Figure 18-1
Location of Brayton Point Station

As required by their Clean Water Act (CWA) National Pollutant Discharge Elimination System (NPDES) permit, BPS has been conducting extensive monitoring of water quality, fish abundance and other parameters since 1972. Rhode Island Division of Fish and Wildlife (RI DFW) has been collecting fish abundance data for an equivalent period of time in the Rhode Island portion of Mount Hope Bay and in comparable water depths in neighboring Narragansett Bay. In addition, a series of academic researchers from the University of Rhode Island (URI), Brown University, Roger Williams University and the University of Massachusetts at Dartmouth have all collected data on various aspects of the ecology of Mount Hope Bay.

Data from multiple trawl surveys showed a dramatic collapse in aggregate resource abundance (number of fish per tow), beginning in 1984 (Figure 18-2). Mark Gibson of RI DFW analyzed species level abundance data from the BPS trawl survey, the RI DFW trawl survey and the URI trawl survey. These surveys had comparable methods and shared some geographic overlap of sampling areas. Gibson [2] showed that of the 21 species of fish analyzed, 16 were declining at a greater rate in Mount Hope Bay than in adjacent Narragansett Bay. This difference in the rate of decline was statistically significant for four species, winter flounder (*Pseuodpleuronectes americanus*), windowpane (*Scopthalmus aquosus*), tautog (*Tautoga onitis*) and hogchoker (*Trinectes maculates*).

The timing of the collapse correlated with the expansion of plant operations at BPS (Figure 18-3). EPA conducted a thorough review of other stressors (commercial fishing, brown tides, global warming, cormorants, water quality, etc.) that might explain the changes in aggregate resource abundance in Mount Hope Bay, but could not find another factor that would cause a baywide persistent commercial and non-commercial species collapse to the present day. Gibson [2] showed a strong correlation between heat rejection to the bay and fish abundance (R^2>85%).

Independent of the cause, it was evident that a balanced indigenous population (BIP) of fish, shellfish and wildlife was no longer present in Mount Hope Bay.

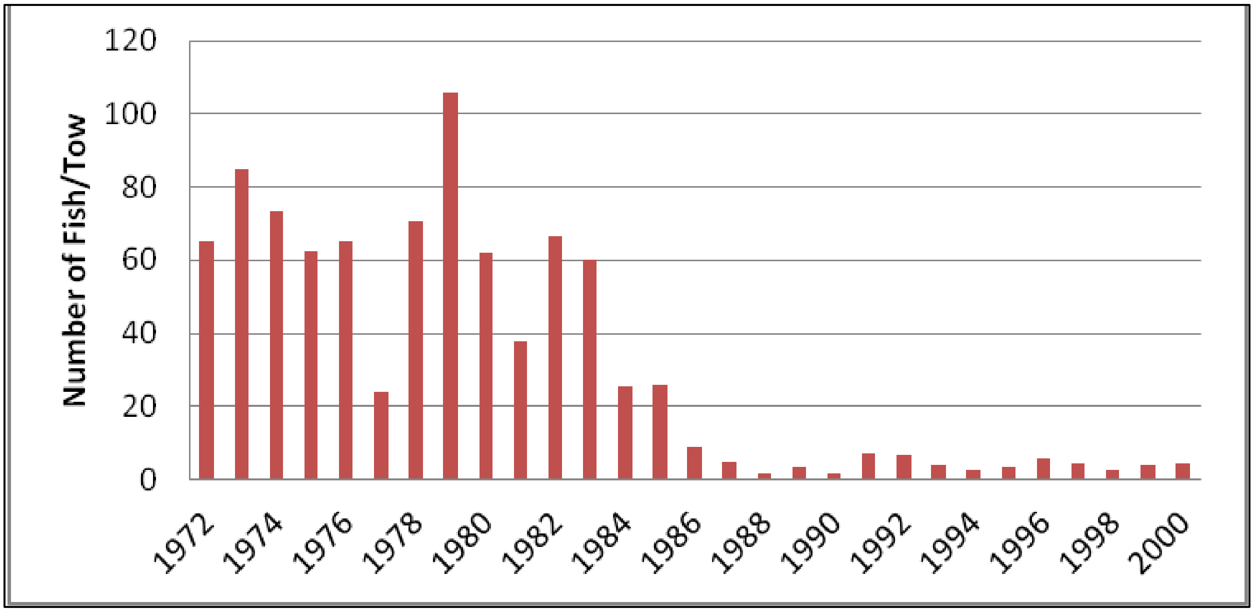

Figure 18-2
Aggregate resource abundance in Mount Hope Bay [11]

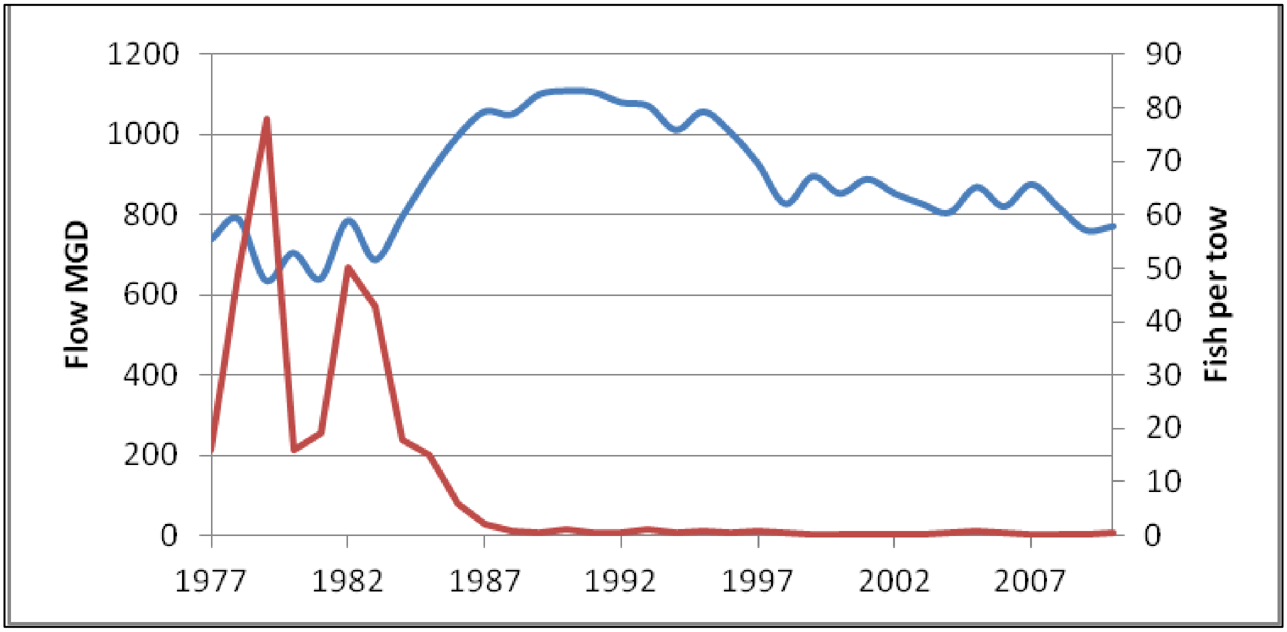

Figure 18-3
Winter flounder abundance in Mount Hope Bay (red line) and flow (blue line) versus year

There were ample indications that the thermal discharge was contributing to the decline of the BIP. Normal fish migration was disturbed for a number of species. Large numbers of striped bass (*Morone saxatilis*) and bluefish (*Pomatomus saltatrix*) would attempt to overwinter in the discharge canal. Schools of young-of-the-year Atlantic menhaden (*Brevoortia tyrannus*) would stay in the bay delaying their normal migration into offshore waters. Menhaden that remained in the bay were weakened by cold water temperatures and tens of thousands of these fish were killed in mass impingement events. Comb jellies or ctenophores, normally a summer/fall visitor to the bay, became a year round resident. Finally, blue-green algae, a nuisance species that thrives on warmer water, were found in large mats on the intake screens.

Hydrodynamic Modeling of the Bay

BPS hired Applied Science Associates (ASA) to develop a hydrodynamic model to predict salinity, velocity and water temperature in Mount Hope Bay. ASA in conjunction with URI developed the Water Quality Modeling and Analysis Program (WQMAP), which divided Mount Hope Bay into 11 depth layers and 3300 individual cells [3].

In the development of WQMAP, data from 10 different field surveys was used. These surveys ranged from single point in time temperature or salinity readings to month long deployments of thermistors at various times of the year. The model underwent a rigorous calibration and validation review. After an optimization process that focused on accurately predicting water temperatures in the mid-field, the model was accepted by all of the state and federal resource agencies.

The model was an invaluable tool that allowed EPA scientists to compare and contrast water temperatures under various operating scenarios at BPS. EPA requested BPS produce maps of summer and winter water temperatures resulting from 5 different specified operating scenarios. These operational scenarios ranged from the current plant operation, to a no plant scenario and three variations in between. The model allowed EPA to predict specific water temperatures at specific geographic locations resulting from differing operating scenarios.

Temperature Thresholds

EPA conducted a thorough literature search on the impacts of thermal discharges to the species on the Representative Important Species (RIS) list. The RIS list included the following:

• Alewife	*Alosa pseudoharengus*
• Atlantic menhaden	*Brevoortia tyrannus*
• Atlantic silverside	*Menidia menidia*
• Bay anchovy	*Anchoa mitchilli*
• Hogchoker	*Trinectes maculates*
• Rainbow smelt	*Osmerus mordax*
• Sand lance	*Ammodyte americanus*
• Seaboard goby	*Gobiosoma ginsburgi*
• Silver hake	*Merluccius bilineris*
• Tautog	*Tautoga onitis*
• Threespine sticklespine	*Gasterosteus acuteatus*

• Weakfish	*Cynoscion regalis*
• White perch	*Morone Americana*
• Winter flounder	*Pseudopleuronectes americanus*
• Quahog	*Mercenaria mercenaria*
• Blue mussel	*Mytilus edulis*
• Eelgrass	*Zostera marina*

Where data was available, the literature search collected information on all life stages of the RIS. Upon reviewing the collected literature, it became apparent that winter flounder (*Pseudopleuronectes americanus*) was the most thermally sensitive species of the RIS. Winter flounder was the ideal indicator species to evaluate thermal impacts of BPS because (1) winter flounder had shown a dramatic decline in abundance that coincided with increases in plant operation (Figure 18-3) and (2) due to winter flounder's ecological and commercial importance, there is an ample quantity of research on its natural history. This includes studies on predator-prey relationships and sublethal effects of increased water temperature. Elevated water temperature has the potential to impact multiple winter flounder life stages.

To better appreciate the threat posed by elevated water temperature to winter flounder, it is important to understand the natural history of this species. Winter flounder is a demersal species that spends large amount of its life in near-shore shallow waters. Adults spawn in the lower part of rivers in the winter time. The timing of spawning is believed to reduce predation on the eggs and larvae, because the major predators on young-of-the-year flounder are either absent or dormant until water temperature warms [4]. In addition, young-of-the-year and juvenile winter flounder use near-shore shallow water habitat as a refuge from predation; EPA's literature review showed that temperatures above 24°C will trigger thermal avoidance in juvenile winter flounder [5, 6, 7].

A comparison of monthly catch rates in shallow (<20 feet) and deep (>20 feet) Mount Hope Bay stations to an identical mix of stations in adjacent Narragansett Bay indicated that winter flounder were avoiding shallow water habitat in Mount Hope Bay. In Mount Hope Bay, only 20% of winter flounder were taken from shallow stations [8]. In contrast, 60% of winter flounder caught in Narragansett Bay over the same time period were from shallow stations [8]. In warmer months, very few winter flounder were taken from shallow stations in Mount Hope Bay (Table 18-1).

Setting the Permit Limits

EPA determined that in order to restore a balance indigenous population to Mount Hope Bay, spawning and nursery habitat must be protected. Brayton Point Station had extensively sampled the lower portion of the rivers feeding into Mount Hope Bay for the presence of juvenile fish in an effort to delineate nursery habitat. EPA estimated the distance from the point of discharge to the closest known nursery habitat. We used this distance as a radius to derive an allowable area of impact (Figure 18-4). This area equated to approximately 10% of the bay. Utilizing the results of the hydrodynamic model runs from 5 different plant operating scenarios, EPA established a relationship between plant operation and its areal impact on the bay (Figure 18-5). EPA plotted the 10% allowable impact area on this curve to derive the final operating conditions. This equated to an annual thermal limit 1.7 trillion British thermal units (TBTU). After a lengthy appeal process (which coincided with a change in plant ownership), the current plant owner (Dominion Energy New England) and EPA agreed on a compliance schedule. This agreement resulted in the installation of cooling towers at BPS thereby allowing the station to meet its thermal discharge permit limit. The towers will be fully operational by the spring of 2012.

Table 18-1
Average water temperature (°C) and percent of total winter flounder catch for Mount Hope Bay (1990–2003) [8]

Month	Water Temperature (°C) Shallow	Water Temperature (°C) Deep	% of Total Winter Flounder Catch Shallow	% of Total Winter Flounder Catch Deep
January	3.65	3.72	46	54
February	3.11	2.79	32	68
March	4.91	4.33	29	71
April	7.82	6.62	15	85
May	14.64	12.57	17	83
June	19.20	16.59	5	95
July	23.23	20.37	2	98
August	23.96	21.51	4	96
September	21.25	19.99	4	96
October	14.59	14.08	6	94
November	9.59	9.85	14	86
December	5.96	5.98	30	70

Conclusions

In order to fully protect fish habitat, it is important to understand the natural history of the species in question, especially how they use the available habitat. It is not sufficient to only consider what water temperatures lead to direct lethality, because this approach will undoubtedly underestimate the ecological impact. It is also important to understand sublethal effects, such as avoidance and thermal attraction, which can disrupt normal migration. These behavioral responses occur at lower temperatures than lethal temperatures and can indirectly lead to higher mortality rates of the target species. Manderson et al. [9] showed that predation risk increased with depth for juvenile winter flounder. Thus, while the avoidance of elevated water temperatures in shallow water may not be a directly lethal response, it can lead to increased mortality. It is also critical to understand the potential changes in predator-prey dynamics that may be altered by temperature. In the case of winter flounder, the elimination of the window of opportunity to spawn prior to its predators becoming seasonally active, could have baywide, population levels effects [10]. In Mount Hope Bay, EPA has attempted to reduce sublethal thermal impacts to winter flounder nursery habitat, by minimizing the area of the bay that would reach or exceed 24°C as a result of the BPS thermal discharge.

In any aquatic system that has been significantly compromised, it is essential to reduce or eliminate impacts on nursery and spawning habitat. Increased survival of early life stages provides the momentum for subsequent increases in adult stocks and ultimately ecosystem recovery. The installation of cooling towers at BPS will allow the continued generation of electricity, while significantly reducing the impact to nearby nursery and spawning habitats.

Acknowledgements

The debate over the impact of BPS on fish populations in Mount Hope Bay carried on for almost 15 years. It involved the hard work of many committed people at a number of agencies. This is by no means a comprehensive list and I apologize to anyone who may feel overlooked. I would like to acknowledge the hard work and contributions of Mark Stein, Mark Gibson, Nick Prodany, Damien Houlihan, Todd Callaghan, Gerald Szal, Jack Schwartz, Dave Johnston, Dave Webster, Sharon Demeo, Tim Lynch, Chris Deacutis, Bob Lawton, Samir Bukhari, Chuck Coutant, Mark Bevelhimer and Mandy Helwig.

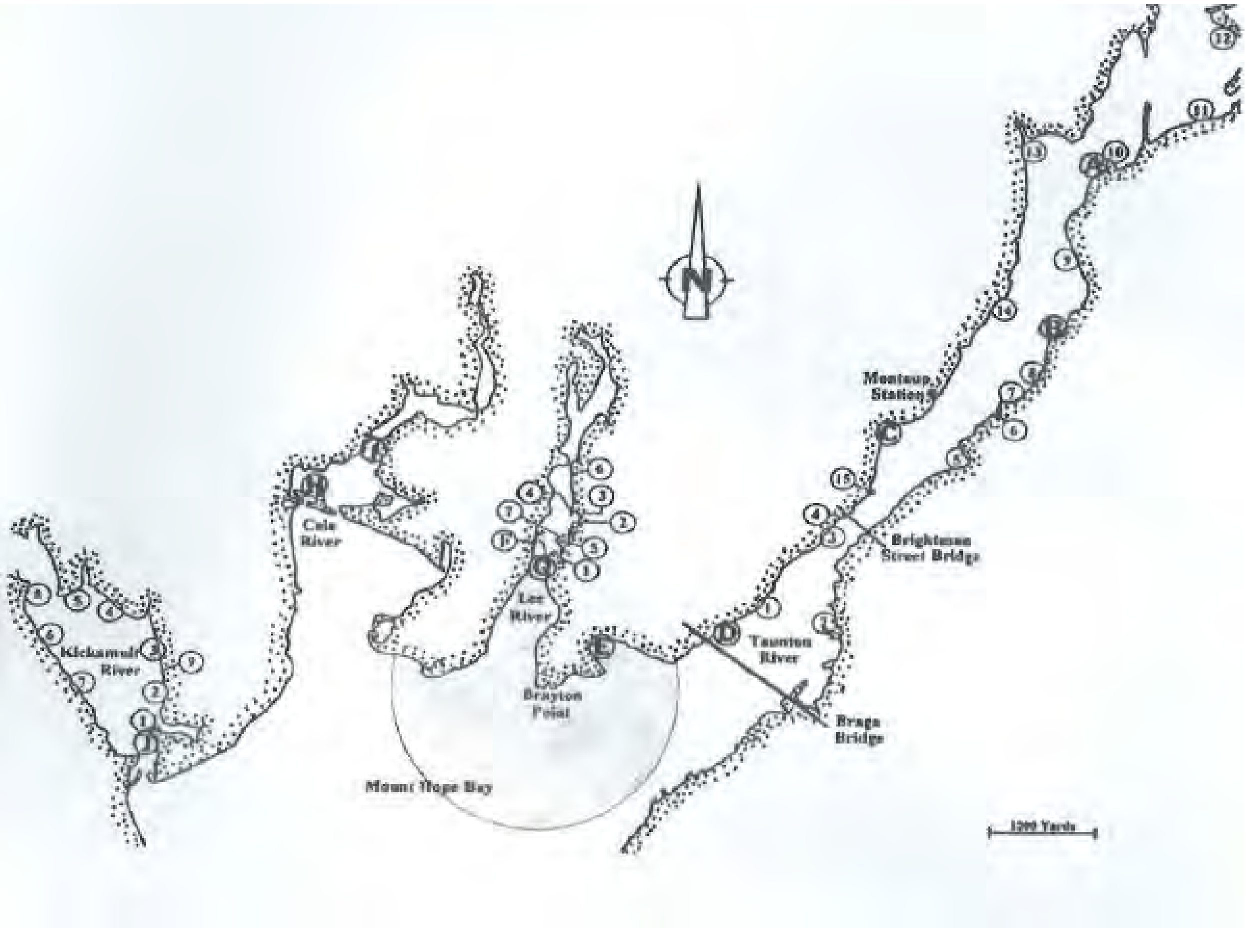

Figure 18-4
Estimated area of thermal impact in relation to location of Young-of-Year Beach Seine Stations in Mount Hope Bay

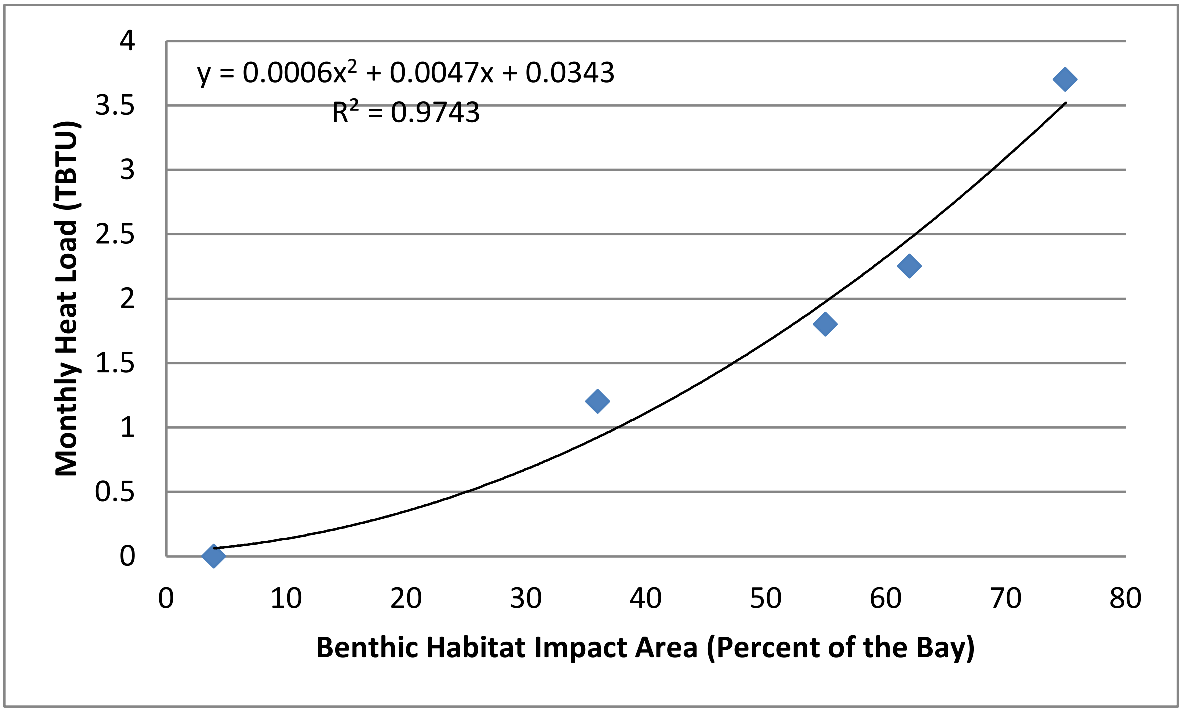

Figure 18-5
Analysis of the relationship between BPS heat load and area of benthic habitat exceeding 24°C

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19

FRESHWATER MUSSEL MONITORING AND ALTERNATE THERMAL STANDARDS

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Abstract

Quad Cities Nuclear Station (QCNS) discharges its thermal effluent into the Mississippi River at River mile 506.4 via a dual diffuser pipe. They are investigating an application for an alternate thermal standard. An Essential Habitat Area (EHA) for *Lampsilis higginsii*, a federally endangered freshwater mussel (unionid) species, occurs a few miles downstream of the diffuser pipe between River miles 503.0 and 505.5. Exelon wanted to ensure that an alternate standard would not affect the indigenous shellfish community under §316(a) of the Clean Water Act (CWA), and identify and mitigate impacts to *Lampsilis higginsii* under Section 10 of the Endangered Species Act (ESA). The unionid life cycle (spawning, glochidia release, fish host activity, fish host infestation period) and behavior (siphoning/feeding rates, burrowing) is temperature dependent, however the thermal triggers and critical thermal maximums for most species are unknown. A unionid monitoring program was established to satisfy Section 316(a) and Section 10 requirements. The area between river mile 495.4 and 515.0 was investigated for unionid communities. The three beds closest to the diffuser (Upstream, Steamboat Slough, and Cordova EHA) were monitored in 2004, 2005, 2006, 2007, and 2008. Temperature probes were placed in the substrate at these three beds to determine actual exposure temperatures. Unionid communities were sampled using quantitative and qualitative techniques to determine density, age structure, mortality, and species composition, and metrics were statistically compared among years. Some community differences were apparent, however differences could be attributed to habitat and zebra mussel infestation rather than or in addition to temperature. Three additional beds were added to the monitoring program in 2007 and 2008 to facilitate impact assessment. Differences in all unionid communities were apparent, but were likely due to habitat differences rather than existing thermal standards. Ambient temperatures in one monitoring year (2006) exceeded water temperature expected with an alternate thermal standard. Some mortality occurred that could be attributed to increased water temperatures, but effects were greater upstream than downstream of the power plant’s diffuser. Data from the mussel monitoring program were used to demonstrate that QCNS would not affect the integrity of the indigenous freshwater mussel community and develop the first freshwater mussel Habitat Conservation Plan under Section 10 of the ESA.

Introduction

Background

Exelon Generation Company operates QCNS on the Illinois bank in Pool 14 of the Upper Mississippi River (UMR) upstream of Cordova, IL. QCNS has been operating since 1972, and since 1984 has obtained cooling water for its operations from and discharged cooling water back into the Mississippi River via a once-through cooling system. Dual diffuser pipes, which extend from the Illinois bank to near the Iowa bank, discharge cooling water into the Mississippi River at approximately Mississippi River mile (MRM) 506.4 (Figure 19-1). Each diffuser pipe has 34 discharge risers. The first nine are closed, which forces the discharge primarily into the main thalweg of the river. The thermal mixing zone extends 152 m (500 ft) downstream of the diffuser pipes. QCNS is currently investigating an application for an alternate thermal standard.

Pool 14 of the UMR harbors a diversity of freshwater unionid mussels. Historically, 53 unionid species have been recorded in the UMR [1]. Of these, 41 have been reported from Pool 14, and 31 have been collected in the past 25 years [1]. Freshwater unionid beds harboring federal, Iowa, and/or Illinois threatened and endangered (T&E) species *Lampsilis higginsii, Plethobasus cyphyus*, *Ellipsaria lineolata*, *Ligumia recta*, *Pleurobema sintoxia*, *Lampsilis teres*, and *Strophitus undulatus* occur upstream and downstream of the QCNS. Additionally, the Cordova Essential Habitat Area (EHA), which is essential for the management and recovery of the federally endangered species *Lampsilis higginsii*, occurs downstream of QCNS along the Illinois bank between MRM 503.0 and 505.5 [2]. Since freshwater unionid mussel species are present within Pool 14, QCNS needed to determine the distribution, species composition, and community characteristics of unionid communities with respect to its discharge, and evaluate how the proposed alternate thermal standard might affect the indigenous shellfish community to satisfy requirements under Section 316(a) of the CWA and identify and mitigate any impacts to federally endangered species under Section 10 of the ESA.

Unionidae Life History and Temperature

Unionidae are bivalves in the order Unionoida. Unionoida are unique among the bivalves in that they have a parasitic stage involving a vertebrate host, their shells are lined with nacre (mother of pearl), and byssal threads (threads used for attachment to substrate) are absent in most adults. Species in North America are in the families Unionidae and Margaritiferidae. These species have glochidium larvae. The only Margaritiferidae in the Mississippi River is *Cumberlandia monodonta*, which is rare in the UMR and has not been found alive in Pool 14 for 25 years [1]. The remaining species are in the family Unionidae. Species in the Mississippi River fall into two subfamilies; Unioninae (tribe Anodontini) and Ambleminae (tribes Amblemini, Lampsilini, Pleurobemini, and Quadrulini) [3].

Unionid beds (aggregations of unionids with several species) typically occur in hydraulically protected areas with stable heterogeneous substrate with sufficient current velocity to prevent accumulation of thick silt, but with shear stress insufficient to scour substrate [6, 7, 8].

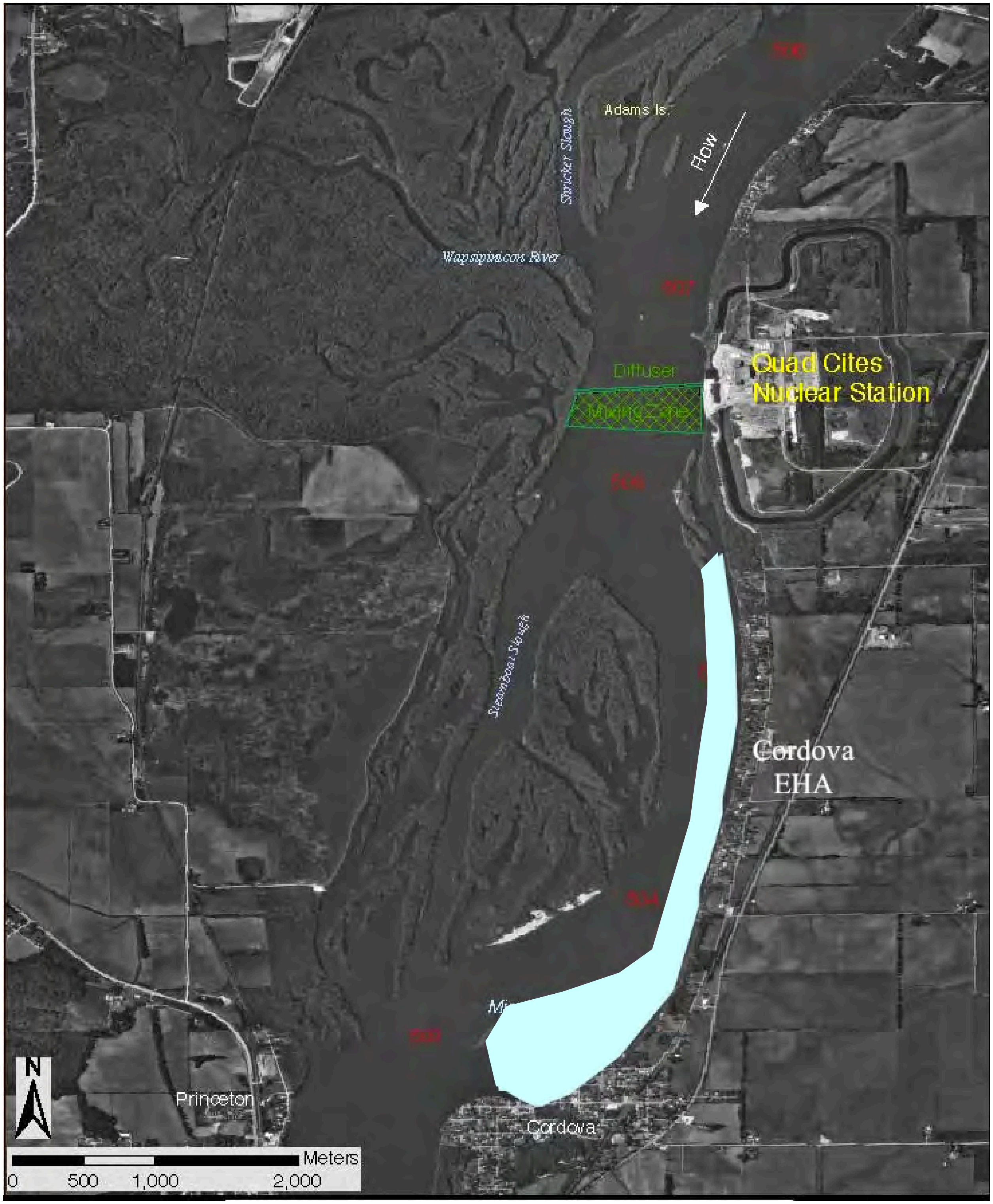

Figure 19-1
Location of Quad Cities Nuclear Station, Pool 14, Mississippi River

Each of the tribes and some species have habitat preferences, although the preferences of most species overlap considerably [4, 5]. Unionids are sedentary animals that live primarily in rivers and streams, although some species are adapted to lentic conditions (primarily Anodontini). Amblemini, Pleurobemini, and Quadrulini (APQ) are thick shelled, and generally robust with corrugations or pustules. These species are particularly adapted to conditions with stable substrate and moderate current velocity; they burrow into the substrate and remain in place for long time-periods [9, 10]. These species are generally the most abundant group in large river unionid beds due to these adaptations. Lampsilini and Anodontini are generally smooth shelled. Elongate, smooth shelled species are adapted for quickly burrowing following displacement by scouring flow (many Anodontini, many Lampsilini and some Pleurobemini) [9, 10]. These species can be found in unionid beds, but also occupy areas with less stable substrate (loose gravel and sand). Lighter shelled species (mostly Anodontini) have a low specific gravity and can live in silty substrate, whereas heavier species would sink into and be smothered by a thick silt layer [9, 10]. Some Lampsilini are more robust (such as *Lampsilis higginsii*) and some Anodontini (*Arcidens confragosus* and *Lasmigona costata*) are sculptured, adaptations for maintaining position in the substrate. These species are generally found with thicker shelled species in unionid beds of larger rivers. Some Lampsilini and Anodontini are complanate and symphynote (*Potamilus alatus*, *Potamilus ohiensis*, *Leptodea fragilis*, *Lasmigona complanata*), which allows them to live in less stable and siltier substrate and under lotic conditions.

Most of the unionid life cycle is temperature dependent, however very little information is available on the thermal maxima of the various unionid life stages. Spawning consists of the male discharging balls of sperm into the water column. The female transfers her eggs into the water tubes of her gills (marsupia). Sperm balls are drawn into the female through her incurrent siphon and eggs are fertilized. The glochidium larvae mature within the marsupia. Amblemini, Pleurobemini, and Quadrulini are short-term brooders (tachytictic). In general, they spawn in the spring and release glochidia in summer (when temperature rises above a threshold). However, *Megalonaias nervosa* [11] and *Quadrula fragosa* [12] release glochidia in the fall, triggered by falling temperature. *Elliptio dilatata* releases in both summer and winter, and release is triggered by both rising and falling temperature [13]. Lampsilini and Anodontini both spawn in summer and species in both tribes have been reported to release glochidia in fall and/or spring [13, 14, 15].

Following the release of glochidia from the female, the glochidia must attach to a fish host. Amblemini, Pleurobemini, and Quadrulini generally stay attached for a few weeks in summer, and Lampsilini may over winter on the host if released in the fall or attach for only a few weeks if released in the spring. Glochidia are encapsulated by the fish and metamorphose into juvenile unionids, which excyst and begin life in the substrate. Amblemini, Pleurobemini, and Quadrulini generally mature at five to ten years old, whereas Anodontini and Lampsilini are generally mature before they reach five years of age. Young Amblemini, Quadrulini, and Pleurobemini generally burrow into the substrate, whereas many young Lampsilini have long byssal threads to attach to substrate particles, debris, and other unionids.

Since unionids are ectothermic animals, temperature affects all aspects of their life history. Temperature is believed to be the most important exogenous factor controlling reproduction [16, 17, 18, 19]. Temperature triggers spawning and the release of glochidia from the female. A decline in temperature triggers the release of glochidia from the female in *Leptodea fragilis* (11°C) and *Pyganodon grandis* (12 to 5°C), while an increase in temperature to near 23°C triggers release in *Amblema plicata* [13]. *Lampsilis higginsii* release glochidia between 20 and 22°C, mainly in the spring [2].

The survival of glochidia between release from the female and attachment to a host is also temperature dependent and species specific [20, 21]. LT50s for glochidia of seven species ranged from 24.2°C (*Potamilus alatus*) to 42.6°C (*Ligumia recta*) after 24 hours [20]. *Anodonta cygnea* glochidia survived 10 to 17 days at 5°C and 2.5 to 5 days at 10 to 16°C, but only 50% survived after 5 days at 18°C [21]. Similarly, *Lampsilis radiata* experienced only 1% survival at 20°C [17] and no *L. higginsii* glochidia survived at temperatures exceeding 25°C [22]. Glochidial development on a host and host immune response also seem to be temperature dependent [21]. Host fish infestation seems to be optimal at 12 to 15°C for *Amblema plicata* and *Megalonaias nervosa* [23].

Release and development of metamorphosed juveniles is also temperature dependent. Fish hosts may avoid areas above a threshold or hosts could remain within the area, but slough off glochidia due to stress. Watters and O'Dee [13] suggest that an upper temperature threshold exists above which glochidia will fail to metamorphose, and a lower temperature threshold exists below which glochidia will not release. The duration of attachment decreases with increased temperature, until an upper thermal limit is reached at which the glochidia release but fail to metamorphose [24]. The minimum temperature seems to apply to species whose glochidia over winter on their fish host (some Lampsilini), while the upper thermal limit seems to apply to summer releasers (most Amblemini, Pleurobemini, and Quadrulini).

Basic functions in unionids, such as metabolic rate and associated functions (heart rate, oxygen uptake rate and feeding rate) are also controlled by temperature. Lampsilinae have a higher metabolic rate than Ambleminae [25]. Metabolic rate increases two to ten-fold in some unionids (*Lampsilis siliquoidea* 1.88 to 4.98; *Pyganodon grandis* 1.27 to 10.35) with a 10°C temperature increase, and neither of these species has the ability to acclimate their metabolic rate with an increase in temperature [26]. *Pyganodon cataracta* metabolic rate (measured as oxygen uptake) also varied directly with water temperature, but *Utterbackia imbecillis* maintained a constant oxygen uptake rate with increase in water temperature [27]. Oxygen uptake for *Actinonaias ligamentina* and *Amblema plicata* was 2.5 and 2.9 times higher, respectively, at 25°C than at 5 to 9°C [25]. Heart rate and food clearance rate also seem to be directly related to water temperature [28]. Changes in filtering rates, respiration rates, excretion and biodeposition rates with increase in water temperature varies with species [29]. *Amblema plicata*, *Fusconaia flava*, *Megalonaias nervosa*, and *Obliquaria reflexa* were classified as thermally tolerant, and *Actinonaias ligamentina*, *Lampsilis cardium*, *Truncilla truncata*, and *Quadrula pustulosa* as thermally sensitive based on their condition at 35°C [29].

The effect of increased water temperature on metabolic rate seems to be greater for juvenile unionids than for adults [30]. Heart rate was measured as less than 5 beats per minute at 10°C and 22 beats per minute at 30°C for adult *Pyganodon cataracta*, whereas juveniles of this species had heart rates of 15 and 70 beats per minute at 10°C and 30°C, respectively [30]. Similar results were observed for *Utterbackia imbecillis*: adult heart rate was less than 5 beats per minute at 10°C and 20 beats per minute at 30°C, whereas juvenile *Utterbackia imbecillis* increased their heart rate from 20 to 50 beats per minute at the two temperatures.

Feeding, growth, and burrowing behavior in unionids are temperature dependent and appear affected by both a thermal minimum and maximum. Maximum feeding rate for *Elliptio* *complanata* was between 13.5 and 18.3°C [31], while *Lampsilis siliquoidea* maximum feeding rate was at temperatures of 21 to 24°C [32]. Some Australian unionoids become inactive, stop growing, and burrow into the substrate at 12°C, and their growth increases with temperature between 13 and 22°C [33]. Unionid burrowing behavior (righting and moving) increased 8 to 10% for each degree of temperature increase from 7 to 21°C, but there may be a thermal maximum after which unionids will not burrow [34].

Few lethal or sublethal upper temperature limits are reported in the literature. Fuller [35] lists the upper lethal temperature of *Anodontoides ferussacianus* as 29°C, but also mentioned this temperature was not lethal to *Pyganodon grandis* or *Lampsilis siliquoidea*. Starkey et al. [36] reported a 96% survival of *Elliptio complanata* when water temperature was increased temporarily to 33.4°C. However, neither Fuller [35] nor Starkey et al. [36] reported the duration during which the unionids that were subjects in their studies were exposed to high temperatures. Bartsch et al. [37] held adult unionids in air temperatures up to 35°C for 15 to 60 minutes, with no apparent harmful effects. Additionally, adult unionids of most thick shelled species can tightly close their valves, switch from metabolism to catabolism under stressful conditions, and remain in this state for extended time periods [35]. Thicker shelled species (Amblemini, Pleurobemini, Quadrulini) can remain closed for longer time periods, as they can more tightly close their valves (reducing exposure) and apparently have a slower metabolic rate. Once conditions are no longer stressful, unionids open their valves, start siphoning, and return to metabolism.

Juvenile unionids would be less likely to survive higher water temperatures, as they have less lipid reserves and a much higher metabolic rate. Dr. Jones (VPI, personal communication) reported that newly metamorphosed juveniles of *Lampsilis fasciola, Cyprogenia stegaria, Dromus dromas*, *Fusconaia cor*, and *Lexingtonia dolabelloides* experienced high rates of mortality during laboratory conditions of 26 to 27°C. Newly metamorphosed juvenile *Utterbackia imbecillis* experienced less than 35% mortality at 30°C, 50% mortality after 96 hours at 31.5°C, and 50% mortality after 48 hours at 34°C [27]. *Pyganodon cataracta* experienced 50% mortality after 96 hours at 33°C, 46% mortality after 48 hours, and 100% mortality at 34°C in 96 hours [27]. Pandolfo et al. [20] reported mean LT50 after 96 hours for seven species of newly metamorphosed juvenile unionids (*Potamilus alatus, Ligumia recta, Ellipsaria lineolata, Megalonaias nervosa, Alasmidonta varicosa, Villosa delumbis*) between 32.5°C and 38.8°C.

The literature suggests there are thermal minimums and maximums for unionid survival, behavior, and most stages of reproduction. Thermal minimums are reported for some species, but information is limited on thermal maximums. At some high temperature adult unionids become inactive, stop feeding, and burrow into the substrate; glochidia may not survive long enough to attach to a fish host, released glochidia may fail to metamorphose, and juvenile metabolism may increase to the point that they cannot survive. High temperature could also cause fish to avoid a mussel bed when glochidia are released or when juveniles excapsulate. Fish may also be stressed if they remain in the mussel bed, causing early release of juveniles. These stresses could result in the lack of unionids in suitable habitat if temperature is high enough, or a change in community characteristics such as density, recruitment, mortality, species richness, or species composition.

If unionids in Pool 14 of the UMR were affected by QCNS, a lack of unionids or difference in unionid community characteristics downstream of the mixing zone would be expected. A sampling program consisting of spatial and temporal references was developed to determine if QCNS was affecting unionid communities, particularly endangered species.

Methods

A phased approach was used to determine how or if unionids would be affected by an alternate thermal standard. Unionid distribution with respect to the thermal plume was determined with a series of reconnaissance spot dives in 2004. Once unionid distribution was determined, a 400 m long area of three beds, one upstream of the diffuser pipe; Upstream Bed (UP Bed), one downstream of the mixing zone, Steamboat Slough Bed (SS Bed), and the Cordova EHA (Cordova Bed) were sampled to determine community characteristics (Figure 19-2). Three additional mussel beds were sampled in 2007 and 2008 (Albany, Hanson's Slough (HS), and Woodwards Grove (WG) beds) to better discern effects of habitat and water quality on unionid communities. Substrate temperature probes were installed in UP, SS, and Cordova beds to determine actual exposure temperature in 2006 through 2008.

Unionid distribution in Pool 14 was determined through literature review, contacting resources agencies, and field reconnaissance studies conducted in July 2004 and June 2007. Unionid distribution upstream of the diffuser pipe and downstream of the mixing zone was estimated from a series of 5-minute reconnaissance dives. Thirteen reconnaissance (recon) dives were conducted at approximately 250 m intervals between 5 m and 1300 m downstream of the mixing zone, and 14 recon dives were conducted between 25 m and 1550 m upstream of the diffuser pipe in July 2004. Five reconnaissance dives were also conducted in the Cordova Bed between approximately MRM 503.5 and 504.5 to identify the best area to sample. A series of reconnaissance dives was also conducted in five beds upstream and seven beds downstream of QCNS in June 2007 to identify three additional sample locations; two upstream and one downstream of QCNS. During each reconnaissance dive, a diver visually and tactilely searched for unionids for five minutes. The diver placed all unionids encountered in a bag, which was retrieved by the surface crew. Unionids were identified and counted, and their ages were estimated either as juveniles (≤3 years old for Lampsilini and Anodontini and ≤5 years old for Amblemini, Pleurobemini, Quadrulini) or adults.

Based on results from the reconnaissance dives, a 400 m section within each mussel bed was selected for unionid community characterization (Figure 19-2). The Albany Bed sample area was along the Illinois bank near MRM 513.5, approximately 14.5 km upstream of the QCNS diffuser. The HS Bed was within Hansons Slough, along the Iowa bank near MRM 509.5, approximately 5km upstream of the diffuser. The UP Bed sample area was near MRM 507 on the Iowa bank near the downstream end of Shricker Slough, approximately 1 km upstream of the diffuser. The SS Bed sample area extended from approximately 900 m to 1.3 km downstream of the mixing zone along the Iowa bank, near MRM 505.6. The Cordova Bed sample area was near MRM 504, 3.3 to 3.7 km downstream of the mixing zone along the Illinois bank. WG bed was along the Iowa bank near MRM 499.5, approximately 10.5 km downstream of the mixing zone.

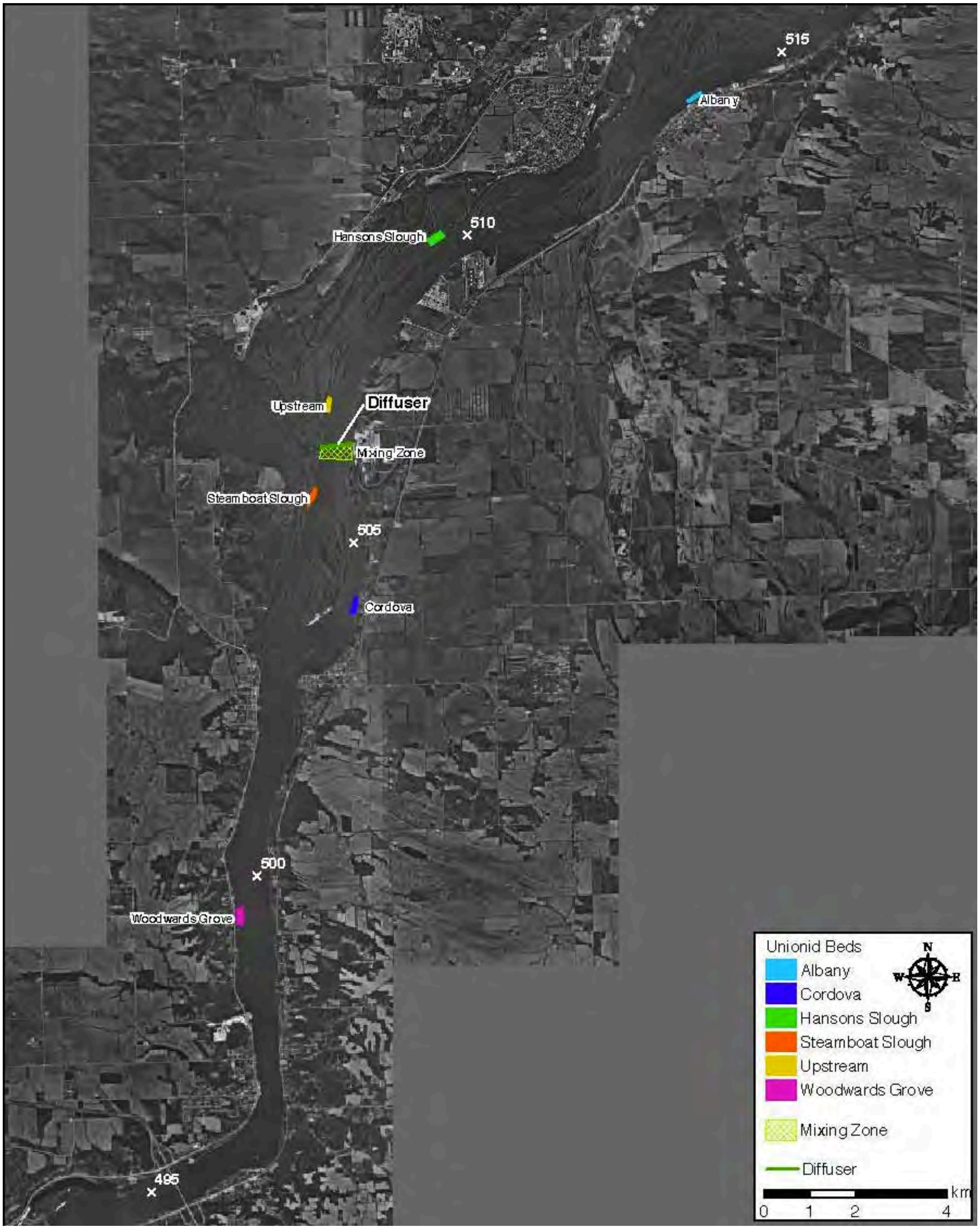

Figure 19-2
Unionid beds sampled upstream and downstream of QCNS

Quantitative and qualitative samples were collected within the UP, SS, and Cordova beds annually between 2004 and 2008. Samples were also collected during extreme low flow, high temperature events in July 2005 and August 2006. Albany, HS, and WG beds were sampled in 2007 and 2008. Quantitative samples are necessary to estimate density, relative abundance, age structure, and mortality. The goal of quantitative sampling was to estimate density within a 95% confidence interval, equal to 25 to 30% of the mean. An initial sample size of 48 randomly located 0.25 m^2 whole substrate quadrat samples was used in 2004. Based on the results of 2004 sampling, sample size was increased to 90 samples in 2005 to 2008. A less intensive sample size of 40 samples was used during the July 2005 and August 2006.

For each quantitative sample, substrate within an area 0.25 m^2 and 10 cm deep was excavated into a 20 L bucket or 6 mm mesh bag and retrieved by the surface crew. Samples were sieved through 12 and 6 mm sieves, and all unionids were sorted from debris. Live unionids were identified, measured (length in mm), aged (external annuli count), and returned to the river within the sample area. Threatened and endangered (T&E) species were hand placed into the substrate by the diver. Freshly dead shells (FD-nacre lustrous, valves intact, with or without tissue; probably dead within the last few months) were identified and counted to estimate mortality [% mortality = no. FD/(no. FD + no. live) * 100]. Density, 95% confidence interval (≈2 standard error units [2SE]), relative abundance of species, age distribution, recruitment (percentage of young unionids), and mortality were estimated from quantitative data.

Qualitative sampling is the best method for determining species richness, as numerous individuals can be collected within a short period of time [38, 39]. Qualitative sample points were selected within each sample area. At each sampling point, the diver located an area where numerous unionids were visible, and held his/her position until water quality, habitat characteristics, and GPS position were recorded. The diver then collected unionids for five minutes using the same techniques as described above for reconnaissance dives. Points were sampled until no additional species were found in at least six consecutive samples in 2004. This required 16 samples in the Cordova Bed, 15 in the UP Bed, and 14 in the SS Bed. Sample size was increased to 25 in 2005 to 2008. As with reconnaissance dives, live unionids were identified and counted as either juveniles or adults. Both quantitative and qualitative data were used to calculate rarefaction species richness.

For all qualitative and quantitative samples, substrate constituents were visually estimated (Wentworth scale) and depth was measured with a pneumatic pressure hose attached to the diver’s umbilical cord. At each qualitative sample point, bottom temperature and dissolved oxygen (DO) were measured with a YSI DO meter or Hydrolab multiprobe, and surface and bottom current velocity was measured with a Marsh-McBirney velocity meter.

In addition to obtaining water temperature data during sampling, temperature recorders were installed in the substrate at the north and south ends of UP and SS beds in July and August 2006, and in UP, SS and Cordova beds in 2007 and 2008. The recorders measured with greater precision temperatures to which unionids were actually exposed. The substrate temperature recorders were installed on May 22, 2007 and removed on October 24, 2007. High river flow in late August and early September 2007 necessitated the removal of temperature recorders between August 20 and September 12, 2007. High river flow in Spring 2008 prevented the installation of temperature probes until July 11, 2008. Recorders were installed in the UP, SS, and Cordova beds on July 11, 2008 and removed October 6, 2008.

Data regarding the mussel bed community characteristics were analyzed using Analysis of Variance (ANOVA). The following parameters were analyzed: differences in total, young and adult density; differences in Lampsilini and Amblemini/Pleurobemini/Quadrulini (APQ) density; and differences in density of freshly dead shells based on sampling dates and bed location. The data were log (x+1) transformed for ANOVAs and significance level was $p<0.05$ for all tests. Bonferroni post-hoc tests were used to detect differences among dates within each site.

Results and Discussion

Temperature

Flow and ambient temperature within the study area during typical low flow/high temperature months (July/August) varied throughout the study period. 2004 discharge was fairly high in early July (100,000 cfs), and fell to a low of 26,800 cfs in August (Table 19-1). Water temperature upstream of the diffuser (within the UP Bed) during July sampling averaged 25.5°C. In 2005, a short period of low flow and high temperature occurred in late July. Flow ranged from 18,030 to 74,820 cfs during July and August, and water temperature during late July sampling in the UP Bed averaged 26.9°C. In 2006, low flow and high water temperature persisted from mid-July through August. Flow ranged from 12,600 cfs to 39,800 cfs, and water temperature in the UP Bed measured in early August averaged 29.6°C. Substrate temperature averaged 27.2°C and ranged from 24.0°C to 30.7°C. July and early August 2007 also experienced low flow and higher water temperatures, but not the extreme experienced in 2006. Additionally, a high water event occurred in mid-August 2007, which reduced the period of higher temperatures. Flow ranged from 18,600 cfs to 123,000 cfs in July/Aug 2007, and substrate temperature in UP Bed from early July to mid-August 2007 averaged 27.2°C and ranged from 23.9 to 29.1°C. July/August 2008 was similar to 2004; flow ranged from 27,200 cfs to 104,150 cfs, and substrate temperature in the UP Bed averaged 26.0°C and ranged from 23.7 to 28.8°C.

Temperature within the SS Bed was slightly higher than in the UP Bed, and temperature within the Cordova Bed varied from slightly warmer to slightly cooler than in the UP Bed (Figure 19-3). In the warmest study year (2006), SS Bed substrate temperature averaged 28.8°C, 1.7°C higher than the UP Bed substrate temperature, and was a maximum of 33.3°C, 2.7°C higher than the UP Bed (Table 19-1). Temperature monitoring probes were not present in the Cordova Bed in 2006, but water temperature measured during monitoring in early August was 0.9°C warmer than in the UP Bed and 0.6°C cooler than in the SS Bed. In 2007, substrate temperature in the SS Bed averaged 1.8°C warmer and was a maximum of 2.9°C warmer than in the UP Bed. This temperature difference was similar to 2006, however duration of warm substrate was shorter in 2007 (Table 19-2). Cordova Bed substrate in 2007 averaged 1.0°C and was a maximum of 2.6°C warmer than the UP Bed. In 2008, SS Bed substrate averaged less than 1.0°C warmer and Cordova Bed substrate averaged only 0.1°C warmer than the UP Bed. At times in 2008, Cordova Bed substrate was cooler than the UP Bed substrate.

Table 19-1
Water and substrate temperatures[1] during July and August, 2004 to 2008

	UP Bed	SS Bed	Cordova Bed
Jul/Aug 2004			
Discharge[2] range 26,800 to 100,000 cfs			
Measured temp. during sampling	25.5 (77.9)	26.5 (79.7)	25.3 (77.5)
Jul/Aug 2005			
Discharge[2] range 18,030 to 74,820 cfs			
Measured temp. during sampling	26.9 (80.4)	29.5 (85.1)	25.3 (77.5)
Jul/Aug 2006			
Discharge[2] range 12,600 to 39,800 cfs			
Measured temp. during sampling	29.6 (85.3)	31.3 (88.0)	30.7 (87.3)
Temperature monitors			
Ave.	27.2 (80.9)	28.8 (83.9)	
Min.	24.0 (75.2)	25.4 (77.7)	
Max.	30.7 (87.3)	33.3 (92.0)	
Ave. difference from UP Bed		1.7 (3.0)	
Max. difference from UP Bed		2.7 (4.8)	
Jul/Aug 2007			
Discharge[2] range 18,600 to 123,000 cfs			
Temperature monitors			
Ave.	27.2 (81.0)	28.9 (84.0)	28.1 (82.5)
Min.	23.9 (75.0)	24.0 (75.2)	23.8 (74.8)
Max.	29.1 (84.3)	31.6 (88.9)	30.9 (87.6)
Ave. difference from UP Bed		1.8 (3.3)	1.0 (1.8)
Max. difference from UP Bed		2.9 (5.2)	2.6 (4.7)
Jul/Aug 2008			
Discharge[2] range 27,200 to 104,150 cfs			
Measured temp. during sampling	26.1 (79.0)	26.8 (80.3)	25.7 (78.3)
Temperature monitors			
Ave.	26.0 (78.8)	26.8 (80.3)	26.0 (78.8)
Min.	23.7 (74.7)	24.4 (76.0)	23.8 (73.9)
Max.	28.8 (83.9)	29.3 (84.7)	28.7 (83.6)
Ave. difference from UP Bed		0.9 (1.6)	0.1 (0.1)
Max. difference from UP Bed		2.3 (4.2)	1.6 (2.9)

[1] °C (°F)

[2] Lock and Dam 14 (LeClaire, IA; MRM 493.3)

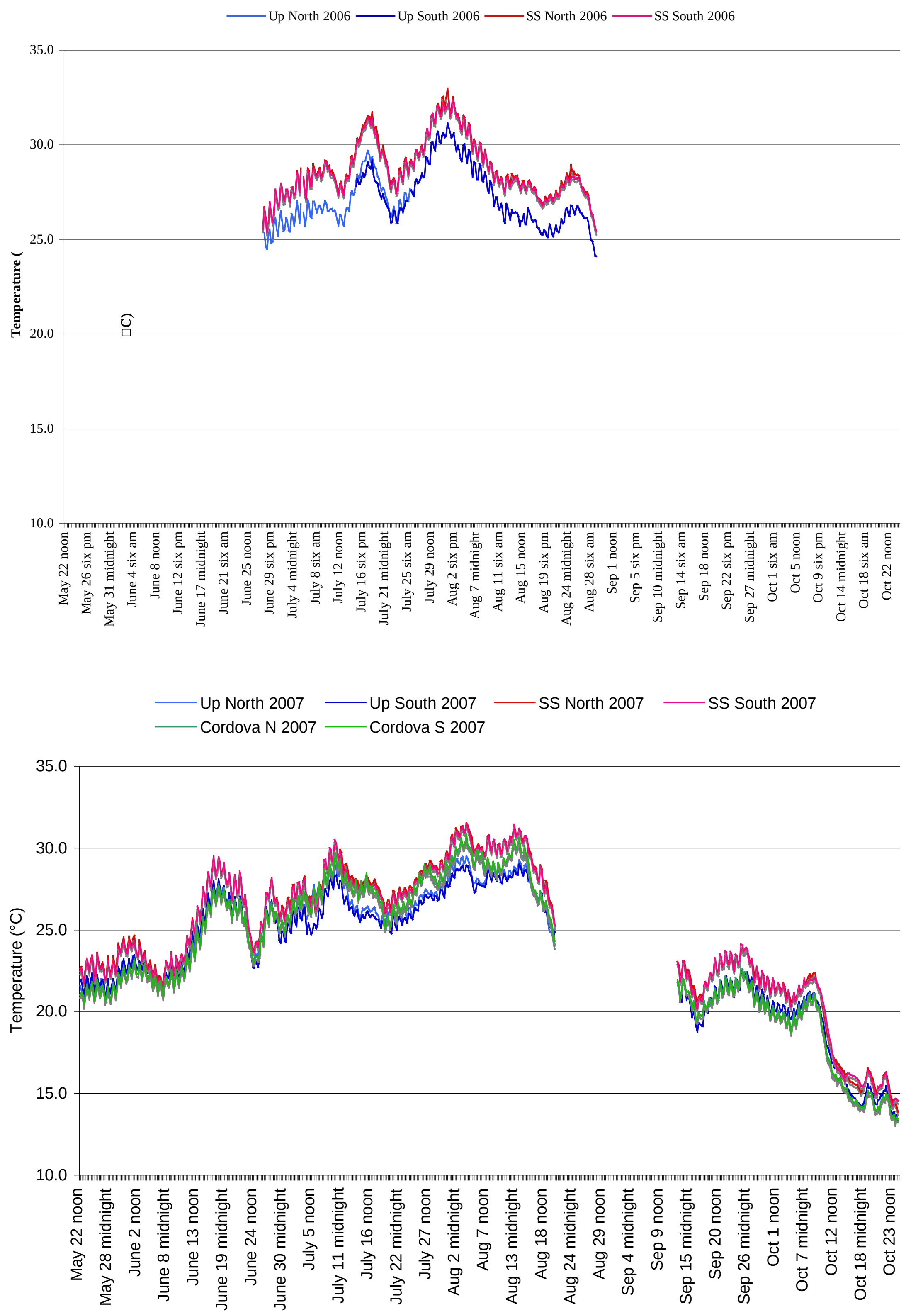

Figure 19-3
Comparison of substrate temperature among unionid mussel beds

Figure 19-3 (continued)
Comparison of substrate temperature among unionid mussel beds

Table 19-2
Hours substrate exceeded extreme temperatures during July and August, 2006, 2007, and 2008

Mussel Bed	Temperature ºC (ºF)				
	>29 (84.2)	>30 (86.0)	>31 (87.8)	>32 (89.6)	>33 (91.4)
2006					
UP Bed	304	86	2	0	0
SS Bed	746	382	185	129	2
2007					
UP Bed (S)	386	0	0	0	0
SS Bed (N)	684	337	106	0	0
Cordova Bed (N)	408	96	0	0	0
2008					
UP Bed (S)	0	0	0	0	0
SS Bed (N)	18.3	0	0	0	0
Cordova Bed (N)	0	0	0	0	0

Habitat

Quantifying mussel habitat has only recently met with any success. Computer models have enabled the evaluation of habitat as a complex suite of river hydraulics [6, 40, 41]. Water depth, mean velocity, substrate type, and substrate stability (measured as shear stress ratio= shear stress at a given flow rate/shear stress at the onset of sediment motion) appear to be the factors influencing mussel distribution and abundance in the UMR [41]. Habitat variables measured in this study included substrate, depth, and current velocity. Differences in these habitat characteristics among the three initial study areas (UP, SS, and Cordova beds) could contribute to differences in unionid communities. UP Bed substrate was primarily sand and clay, depth averaged 3.4 m, and current velocity averaged 0.2 m/sec (Table 19-3). Substrate in the SS Bed consisted of predominantly sand and silt. The higher silt load in this bed could be due to discharge from the Wapsipinicon River that discharges into the Mississippi River upstream of the QCNS discharge. Depth averaged 2.2 m, and current velocity averaged 0.2 m/sec. Cordova Bed substrate consisted of gravel, sand, silt, and zebra mussel (*Dreissena polymorpha*) shells. Both average depth (2 m) and current velocity (0.1 m/sec) were less than either the UP or SS beds.

Table 19-3
Average substrate, depth, and current velocity within mussel beds, 2007 and 2008

	Albany	HS	UP	SS	Cordova	WG
Substrate						
% Bedrock	3	0	0	0	0	0
% Boulder	1	0	0	1	2	0
% Cobble	7	0	<1	1	2	2
% Gravel	21	1	5	1	22	8
% Sand	30	82	63	52	20	32
% Silt	3	10	6	44	19	30
% Clay	1	6	23	1	3	18
% Detritus	0	1	<1	1	1	0
% Shell	35	0	3	<1	29	11
% Vegetation	0	0	<1	0	3	0
Depth (m)						
Average	1.8	1.6	3.4	2.2	2.0	3.3
Range	0.6 to 4.6	0.6 to 2.7	0.6 to 6.4	0.9 to 3.4	0.6 to 4.6	0.3 to 5.5
Bottom current velocity (m/sec)						
Average	0.1	0.2	0.2	0.2	0.1	0.1
Range	>0 to 0.3	>0 to 0.3	>0.1 to 0.4	>0 to 0.4	0 to 0.4	>0 to 0.3

Due to the habitat differences in the three initial study areas, three areas were added to the study to facilitate evaluation of habitat versus temperature effects on unionid communities. Albany Bed was most similar in habitat to the Cordova Bed, with gravel, sand, and zebra mussel shell substrate, a depth range of 0.6 to 4.6 m, and current velocity range of greater than 0 to 0.3 m/sec during sampling in 2007 and 2008. Both the Albany Bed and Cordova Bed were also heavily infested with zebra mussels. HS Bed was intermediate in habitat to the UP and SS beds. It was located within a side channel similar to SS Bed, substrate was primarily sand with some silt and clay, and current velocity averaged 0.2 m/sec. However, depth was less than either UP or SS averaging 1.6 m. WG Bed was downstream of Steamboat Slough. Substrate consisted of sand, silt, and clay. Average depth was similar to the UP Bed at 3.3 m, but current velocity was slower and was more similar to Albany and Cordova Beds.

Unionid Distribution and Community Characteristics

Temperature in Steamboat Slough downstream of the mixing zone did not appear to limit unionid colonization. Unionids were found from downstream of the mixing zone to the upper end of Steamboat Slough. Unionid abundance was greatest between 750 m and 1300 m downstream of the mixing zone. Interestingly, zebra mussels were scarce downstream of the mixing zone.

Species composition and other community metrics varied among the mussel beds in this study. UP and Cordova beds consist of over 50% Lampsilini, whereas less than 40% of the community in the HS Bed, SS Bed, and WG Bed were Lampsilini (Table 19-4). When only the three initial study sites were considered, it appeared that the lower percentage of Lampsilini in the SS Bed could be attributed to the higher temperature in this bed. However, the HS bed (upstream) and WG bed (further downstream) also had a lower relative abundance of Lampsilini, suggesting that factors other than the higher temperature downstream of the diffuser may be affecting species composition. The temperature tolerant species *Amblema plicata* and *Obliquaria reflexa* were abundant (>15% and 8% of the community, respectively) in all of the study areas. *Amblema plicata* dominated the Albany Bed (upstream) and the SS and Cordova beds (downstream of the diffuser). *Obliquaria reflexa* dominated the UP bed. *Quadrula p. pustulosa*, considered temperature sensitive [29], dominated the HS Bed, and *Quadrula quadrula* dominated the WG Bed. T&E species were found in all beds. *Lampsilis higginsii* (federally endangered) was collected in all beds, but was most abundant in the Cordova Bed. *Ligumia recta* (Illinois threatened species) was also collected in all beds, but was most abundant in the Albany and Cordova beds. *Ellipsaria lineolata* (Illinois and Iowa endangered species) was collected in all beds, but was most abundant in the Albany and HS beds. *Pleurobema sintoxia* (Iowa endangered species) was found in the HS, SS, and WG beds. *Lampsilis teres* (Iowa endangered) was found in all but the Albany and Cordova beds. *Strophitus undulatus* (Iowa threatened species) was only found in the Albany, HS, and Cordova beds.

Table 19-4
Relative abundance (%) of unionid species within mussel beds

	Albany	HS	UP	SS	Cordova	WG
Margaritiferidae						
Cumberlandia monodonta	SF	-	-	-	-	-
Unionidae						
Amblemini						
Amblema plicata	23.8	16.2	21.6	28.0	33.9	17.6
Pleurobemini						
Cyclonaias tuberculata	SF	-	-	-	SF	SF
Elliptio crassidens	SF	-	-	-	-	-
Elliptio dilatata	SF	-	-	-	SF	WD
Fusconaia ebena	-	-	WD	SF	WD	WD
Fusconaia flava	4.0	5.5	5.0	3.0	2.0	0.7
Plethobasus cyphyus	SF	-	-	-	-	SF
Pleurobema sintoxia	-	0.4	WD	X	WD	X
Quadrulini						
Megalonaias nervosa	1.2	0.2	0.1	X	2.8	3.6
Quadrula metanevra	-	-	0.1	-	WD	SF
Quadrula nodulata	0.4	5.1	1.2	11.8	0.2	6.8
Quadrula p. pustulosa	13.9	33.5	8.3	5.8	5.4	1.8
Quadrula quadrula	2.8	5.9	6.5	12.3	1.9	28.7
Tritogonia verrucosa	SF	-	WD	-	WD	SF
Total APQ	**46.0**	**66.9**	**42.7**	**60.9**	**46.1**	**59.1**
Lampsilini						
Actinonaias ligamentina	-	0.2	X	X	0.4	-
Ellipsaria lineolata	0.8	0.8	0.3	0.2	0.2	0.4
Lampsilis cardium	9.9	7.2	7.5	3.7	7.4	1.4
Lampsilis higginsii	0.8	0.6	0.1	X	2.4	X
Lampsilis siliquoidea	-	-	-	-	X	-
Lampsilis teres	-	X	0.4	X	WD	0.4
Leptodea fragilis	7.5	1.5	6.1	2.1	17.8	8.2
Ligumia recta	5.2	0.4	0.9	0.4	4.1	0.4

Table 19-4 (continued)
Relative abundance (%) of unionid species within mussel beds

	Albany	HS	UP	SS	Cordova	WG
Lampsilini (CONTINUED)						
Obliquaria reflexa	11.9	15.4	29.5	22.6	8.5	11.5
Obovaria olivaria	1.6	1.3	2.3	0.6	0.6	X
Potamilus alatus	1.6	0.4	0.2	0.4	1.9	1.1
Potamilus capax	-	-	WD	-	-	-
Potamilus ohiensis	0.4	1.3	1.0	4.3	0.4	4.7
Toxolasma parvus	2.0	0.2	0.5	WD	3.3	WD
Truncilla donaciformis	6.7	2.3	4.5	2.8	3.5	5.0
Truncilla truncata	WD	0.6	0.6	0.2	0.6	X
Total Lampsilini	**48.4**	**32.3**	**53.9**	**37.2**	**52.9**	**33.0**
Anodontini						
Arcidens confragosus	0.4	X	0.3	0.2	0.2	2.2
Lasmigona c. complanata	0.4	0.4	1.9	0.9	0.7	1.4
Lasmigona costata	-	-	-	-	-	SF
Pyganodon grandis	2.4	0.4	0.4	0.7	0.9	2.2
Strophitus undulatus	0.4	X	WD	-	0.2	-
Utterbackia imbecillis	2.0	-	0.8	X	0.9	2.2
Total Anodontini	**5.6**	**0.8**	**3.4**	**1.9**	**3.0**	**7.9**

Numbers represent % that species represents in quantitative samples. X=not collected in quantitative samples, but found in qualitative samples; FD = freshly dead shell, WD = weathered shell, SF = subfossil shell

Other community characteristics also varied among beds, but were not consistently higher or lower with respect to upstream or downstream of the diffuser (Table 19-5). For example, overall density was significantly higher in the HS Bed than in other beds both upstream and downstream, but did not differ significantly among the Albany, SS, Cordova, and WG beds. Lampsilini density was highest in thee UP Bed and lowest in the SS Bed. APQ density was highest in the HS Bed and lowest in the Cordova Bed.

Temperature Effects on Unionid Communities

Most density metrics (total adult, total young, total APQ, APQ adults, APQ young, Lampsilini adults, and Lampsilini young) either were not significantly different among sampling events or fluctuated over time (Table 19-6). However, significant differences in some community metrics (total density, total density of freshly dead shells, total Lampsilini density, and density of freshly dead Lampsilini) were apparent and corresponded with prolonged period of high water temperature and low discharge experienced in the summer of 2006. The density of freshly dead shells (total and Lampsilini) was significantly higher in the UP Bed one month after the period of low flow and high temperature, suggesting that Lampsilini upstream of the diffuser were affected by prolonged high ambient water temperature. Higher density of freshly dead shells was also seen in the Cordova Bed in 2006, one month following the high temperature and low discharge. Freshly dead shells were also more abundant in the Cordova Bed in 2004, when zebra mussel encrusted most of the unionids. The higher morality of Lampsilini could be due to their inability to tightly close their valves when disturbed, making them more susceptible to the effects of higher temperatures. Three of the species (*Actinonaias ligamentina*, *Lampsilis cardium*, *Truncilla truncata*) listed as sensitive to temperature [29] are in the Lampsilini tribe. In contrast, density of freshly dead shells did not significantly increase downstream of the mixing zone in the SS Bed. This may have been due to the lower density of Lampsilini in the SS Bed compared to the UP Bed. Rather, total density and Lampsilini and APQ density in the SS Bed was significantly higher in August 2006 than in other sampling events. Density of both young APQ and Lampsilini young was somewhat higher in 2006, but not significantly higher than all other events. This increase is puzzling, as recruitment (% young individuals) was fairly low in the preceding years.

Periods of high water temperature were also observed in 2005 and 2007, however no changes in density or mortality were observed. Additionally, the increase in 2006 mortality in the UP and Cordova beds did not result in a decline in total density or Lampsilini density in the following years.

Conclusions

The approach to this study included both temporal and spatial references, and the evaluation of several community metrics for each site. This approach was necessary to discern between normal variability in metrics both spatially and temporally and the effects of temperature on unionids. Unionids beds were found downstream of the diffuser, indicating the temperatures downstream of the mixing zone are not a deterrent to unionid colonization. Differences in species composition and community characteristics were observed among beds in the study area, however these differences are likely due to a variety of factors including substrate stability, substrate type, current velocity, fish host availability, and water quality.

The higher mortality observed in the UP Bed following a prolonged period of high ambient water temperature indicates that prolonged high water temperature can affect unionids, particularly Lampsilini species, which seem to be more sensitive to higher temperatures. However, the increased mortality was insufficient to reduce density. The apparently higher sensitivity of Lampsilini to high temperature would suggest that the lower abundance of Lampsilini in the SS Bed is due to the slightly higher temperatures in this bed. However, Lampsilini are also lower in abundance in the HS Bed, which is upstream of the QCNS diffuser, and in the WG Bed, which is further from the diffuser, suggesting factors other than temperature are driving unionid community characteristics in the study area.

Results of this study were used demonstrate that the existing operation and the proposed alternative thermal standard would not affect the indigenous shellfish community in Pool 14 of the Mississippi River in a §316(a) demonstration. Results were also used in developing a Habitat Conservation Plan (HCP), which demonstrated that the proposed alternative standard would not jeopardize the *Lampsilis higginsii* community in Pool 14 of the UMR. A monitoring plan was included in the HCP, which will be used along with existed data to detect any changes in unionid communities that might occur due to operation under the proposed alternate thermal standard.

Table 19-5
Comparison of average community characteristics among unionid beds

	Albany^{4}	HS^{4}	UP^{5}	SS^{5}	Cordova^{5}	WG^{4}
Ave. no./m^{2,1}	5.6±1.2^{C}	10.5±2.1^{A}	9.3±1.2^{B}	4.4±0.5^{C}	4.4±0.5^{C}	6.2±1.1B^{C}
Ave. no. live/FD species^{2}	20.5	23.5	21.4	16.3	20.4	22.5
Cum. live/FD species	22	25	25	24	25	23
Rarefaction richness^{3}						
100	14	13	14	11	14	15
250	17	15	17	14	17	17
500	19	17	20	15	19	20
Ave. no. young/m^{2,1}	2.4±0.6^{AB}	3.5±0.7^{A}	3.0±0.5^{A}	1.1±0.2^{C}	1.6±0.3B^{C}	2.6±0.5^{A}
Ave. no. adults/m^{2,1}	3.2±0.8^{C}	7.1±1.8^{A}	6.2±1.0^{AB}	3.3±0.4^{C}	2.9±0.4^{C}	3.6±0.7^{BC}
% young^{1}	42.9	32.9	32.6	25.2	35.0	41.2
% of species w/ ≤5 yrs^{1}	78.0	70.2	69.2	58.9	62.5	71.3
Ave. no. FD/m^{2,1}	0.4±0.2^{AB}	0.4±0.2^{AB}	0.7±0.2^{A}	0.2±0.1^{B}	0.7±0.2^{A}	0.2±0.1^{AB}
% Mortality^{1}	6.3	3.2	6.7	3.8	12.9	3.8
% adult mortality	8.9	4.8	6.5	4.0	13.7	5.7
% juvenile mortality	2.7	0.0	11.5	4.0	11.3	0.9
APQ						
Ave. no./m^{2,1}	2.6±0.7^{BC}	7.0±1.4^{A}	4.0±0.6^{B}	2.7±0.4^{BC}	2.0±0.3^{C}	3.7±0.8^{B}
Ave. no.≤5yrs/m^{2,1}	1.0±0.4^{BCD}	2.4±0.6^{A}	1.4±0.3^{B}	0.7±0.2^{CD}	0.6±0.2^{D}	1.2±0.4^{BC}
Ave. no.>5yrs/m^{2,1}	1.6±0.5^{BC}	4.7±1.2^{A}	2.5±0.4^{B}	1.9±0.3^{BC}	1.4±0.2^{C}	2.5±0.6^{B}
% young^{1}	38.8	33.4	36.2	27.9	29.7	32.1
Ave. no. FD/m^{2,1}	0.1±0.1^{AB}	0.2±0.1^{AB}	0.1±0.1^{AB}	0.1±0.0^{B}	0.2±0.1^{A}	0.0±0.1^{AB}
% Mortality^{1}	4.1	2.2	3.2	1.8	8.8	1.2
% adult mortality	5.3	3.2	2.6	1.5	5.5	1.8
% juvenile mortality	2.2	0.0	5.8	2.4	14.0	0.0
Lampsilini						
Ave. no./m^{2,1}	2.7±0.7^{BC}	3.4±0.8^{AB}	5.0±0.7^{A}	1.6±0.3^{C}	2.3±0.3^{BC}	2.0±0.5B^{C}
Ave. no.≤3yrs/m^{2,1}	1.2±0.4^{AB}	1.1±0.3^{AB}	1.5±0.3^{A}	0.4±0.1^{C}	0.9±0.2^{B}	1.1±0.3^{AB}
Ave. no.>3yrs/m^{2,1}	1.5±0.5^{BC}	2.3±0.7^{AB}	3.5±0.6^{A}	1.3±0.2^{C}	1.4±0.2^{BC}	0.9±0.3^{C}
% young^{1}	43.4	31.4	30.2	21.6	40.0	55.4
Ave. no. FD/m^{2,1}	0.3±0.2^{AB}	0.2±0.1^{AB}	0.5±0.2^{A}	0.1±0.1^{B}	0.4±0.2^{A}	0.2±0.1^{AB}
% Mortality^{1}	9.0	5.6	8.4	6.1	14.9	7.1
% adult mortality	12.7	7.9	8.3	6.7	19.1	14.6
% juvenile mortality	3.6	0.0	16.7	5.1	6.6	0.0

[1] Quantitative data only

[2] Quantitative and Qualitative combined

[3] Qualitative data only

[4] Average of October 2007 and August 2008

[5] Average of all monitoring events 2004 to 2008

Different letters within a row indicates a significant difference (ANOVA, $p<0.05$)

Table 19-6
Temporal and spatial comparison of unionid density

	Jul-04	Jul-05	Oct-05	Aug-06	Sep-06	Oct-07	Aug-08
Total FD							
UP	0.6 ± 0.5^{A}	0.1 ± 0.2^{A}	0.4 ± 0.3^{A}	0.6 ± 0.5^{A}	2.0 ± 0.8^{B}	0.4 ± 0.3^{A}	0.3 ± 0.2^{A}
SS	0.2 ±0.2^{A}	0.1 ±0.2^{A}	0.1 ±0.2^{A}	0.1±02^{A}	0.5±0.3^{A}	0.1 ± 0.1^{A}	0.1 ± 0.2^{A}
Cordova	1.8 ±1.6^{A}	0.8 ±0.9^{AB}	0.2 ±0.2^{B}	0.6±0.5^{AB}	1.4±0.6^{A}	0.2±0.2^{B}	0.2 ± 0.2^{B}
Lampsilinae FD							
UP	0.4 ± 0.5^{A}	0^{A}	0.2 ± 0.2^{A}	0.4 ± 0.4^{A}	1.5 ± 0.6^{B}	0.1 ± 0.2^{A}	0.2 ± 0.2^{A}
SS	0.1 ± 0.2^{A}	0.1 ± 0.2^{A}	0.1 ± 0.1^{A}	0^{A}	0.3 ± 0.2^{A}	0.0 ± 0.1^{A}	0.1 ± 0.1^{A}
Cordova	1.5±1.2^{A}	0.4±0.5A^{B}	0^{B}	0.2±0.3^{BC}	0.9±0.5^{AC}	0.0±0.1^{B}	0.1 ± 0.1^{B}
Total Density							
UP	8.1±3.1^{A}	6.9±3.1^{A}	11.2±2.6^{A}	8.3±4.2^{A}	11.0±4.3^{A}	8.7±2.1^{A}	8.3 ± 2.7^{A}
SS	3.4±2.0^{A}	4.1±1.2^{A}	4.2±0.9^{A}	9.0±2.6^{B}	4.2±1.0^{A}	4.1±1.0^{A}	3.6 ± 1.0^{A}
Cordova	5.7±1.9^{A}	3.0±1.3^{AB}	5.8±1.5^{A}	3.7±1.4^{AB}	3.0±1.1^{B}	4.7±1.2^{AB}	4.6 ± 1.0^{AB}
Total APQ							
UP	3.3±1.6^{A}	2.2±1.3^{A}	4.6±1.4^{A}	3.6±2.1^{A}	5.0±1.8^{A}	3.9±1.2^{A}	3.7 ± 1.3^{A}
SS	2.1±1.4^{A}	2.5±1.0^{AB}	2.6±0.7^{A}	5.5±2.2^{B}	2.3±0.7^{A}	2.5±0.7^{A}	2.4 ± 0.8^{A}
Cordova	2.3±1.1^{A}	1.8±1.1^{A}	2.3±0.8^{A}	1.5±0.8^{A}	1.5±0.7^{A}	2.1±0.8^{A}	2.5 ± 0.7^{A}
Total Lampsilini							
UP	4.8±2.0^{A}	4.6±2.1^{A}	6.1±1.5^{A}	4.4±2.1^{A}	5.5±2.5^{A}	4.5±1.2^{A}	4.4 ± 1.7^{A}
SS	1.3±0.9^{A}	1.4±0.8^{A}	1.6±0.6^{A}	3.4±1.3^{B}	1.9±0.7^{AB}	1.6±0.6^{A}	1.0 ± 0.5^{A}
Cordova	3.3±1.2^{A}	1.1±0.6^{B}	3.3±1.0^{A}	1.8±0.9^{AB}	1.5±0.6^{B}	2.4±0.8^{AB}	2.0 ± 0.6^{AB}
Total Adults							
UP	6.8 ±2.5^{A}	5.4 ±2.8^{A}	7.5±1.9^{A}	4.5±2.4^{A}	7.2±3.6^{A}	5.9±1.7^{A}	5.3 ± 1.8^{A}
SS	3.3 ±1.9^{AC}	3.7 ±1.2^{ABC}	3.8 ±0.9^{A}	7.2±2.3^{B}	2.7±0.8^{AC}	2.8±0.8^{AC}	1.9 ± 0.7^{C}
Cordova	3.5 ±1.4^{A}	2.4±1.2^{A}	3.7 ±0.9^{A}	2.6±1.3^{A}	2.2±0.9^{A}	3.0±0.9^{A}	2.6 ± 0.7^{A}
Total Young							
UP	1.3 ±0.9^{B}	1.5 ±0.9^{AB}	3.7 ±1.1^{A}	3.8±2.2^{AB}	3.8±1.2^{AB}	2.8±0.9^{AB}	3.0 ± 1.1^{AB}
SS	0.2 ±0.2^{A}	0.4 ±0.4^{AB}	0.4 ±0.2^{A}	1.8±0.8^{C}	1.5±0.5^{BC}	1.3±0.5^{BC}	1.8 ± 0.6^{C}
Cordova	2.2±1.0^{AB}	0.6 ±0.5^{AB}	2.1 ±0.9^{AB}	1.1±0.6^{AB}	0.8±0.4^{A}	1.6±0.7^{AB}	2.0 ± 0.6^{B}

APQ=Amblemini, Pleurobemini, Quadrulini

FD=freshly dead shells

Different letters within a row indicates a significant difference (ANOVA, $p<0.05$)

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20

ASSESSMENT OF EFFECTS OF INTERACTION OF PUMPED STORAGE POWER STATION OPERATIONS AND THERMAL PLUME ON MIGRATION OF AMERICAN SHAD, ALOSA SAPIDISSIMA, IN CONOWINGO POND ON THE LOWER SUSQUEHANNA RIVER

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Abstract

Potential individual and interactive effects of once-through cooling Peach Bottom Atomic Power Station (PBAPS) thermal discharge (approximately 3,350 cfs) and Muddy Run Pumped Storage Station (MRPSS) operations on migration of American shad (both pre-spawned and post-spawned), *Alosa sapidissima*, were assessed in Conowingo Pond on the Lower Susquehanna River. The two power stations are approximately five miles apart with PBAPS located on the west side of Conowingo Pond and MRPSS located on the east side. In general, the configuration and the size of the thermal plume, its attendant temperature, and the magnitude of heat dissipation are dependent upon prevailing hydrological-meteorological conditions. The plume size is smaller and confined to the west bank at high river flows and spreads across Conowingo Pond at low flows.

Pre-spawned American shad migrate upstream through Conowingo Pond in April to early June and post-spawned shad migrate downstream in late May through July. Upstream movement of the thermal plume (indexed by ΔT rise of 1°F near PBAPS intake) only occurs at natural river flows of less than 10,000 cfs and continuous 12 hours (typical is 7- 8 hr) pumping of MRPSS; however, during generation, the thermal plume is advanced downstream. The probability of migrating American shad encountering upstream plume movement at river flows less than 10,000 cfs is 0% in April, less than 0.1% in May, 9.2% in June, and 35.4% (approximately 11 days for a proportion of post-spawned shad population migration) in July. A vast area (water temperature less than 86°F and velocities less than 7.0 ft/s) for unimpeded migration remains

available both for upstream and downstream migrants; most migration occurs during the day time when MRPSS is in a generation mode thus further minimizing potential interactive effects of power stations. Almost the entire population of radio-tagged (80-91%) pre-spawned American shad successfully migrated past the two stations whether PBAPS was shut down or operating with minimal delay; the release location distance from MRPSS also did not influence migration passage rates. Estimated travel speed (4.0 to 6.7 mi/day) of upstream migrants was similar to that reported for other water bodies. Near-field and far-field velocities at MRPSS were within the prolonged and sustained swim speed capacity of American shad (≤ 7.0 ft/sec).

Among a host of factors, spikes in natural river flows causing spillage over 25,000 cfs at Holtwood Dam with high turbulence, velocities, turbidity, and inefficient passage pose significantly greater impedance to American shad migration than the operation of either power station individually or synergistically.

Introduction

Numerous long-term field and laboratory investigations [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17] contributed significantly to a better understanding and prediction of fish behavioral responses to thermal discharges. In general, these studies indicated that fishes are capable of eliciting positive (preference or attraction) or negative (avoidance or escape) responses depending upon prevailing water temperatures and site-specific characteristics. [8] reported on multi-year behavioral responses of adult American shad, *Alosa sapidissima*, on the Connecticut River relative to the heated discharge from the Connecticut Yankee Atomic Power Plant and noted the ability of American shad to migrate under or around the thermal plume . Similarly, studies related to assessment of effects of pumped storage facilities on fishes and other biota have been published [18, 19, 20, 21, 22]. However, we are not aware of any report or publications assessing the potential interactive effects of a large thermal discharge and operations of a pumped storage facility on rivers targeted for restoration of migratory fishes, particularly American shad. This may be, perhaps in part, a function of the absence of close proximity of these types of facilities on American shad bearing fresh waters. Conowingo Pond on the Lower Susquehanna River (Figure 20-1) provided an opportunity to examine the potential interactive effects, if any, of thermal plume from the once-through cooling PBAPS and operations of MRPSS on migrating American shad. The two power stations are about five miles apart with PBAPS (RM 17) on the west shore and MRPSS (RM 22) on the east shore of Conowingo Pond (Figure 20-1).

Intensive efforts have been underway since the early 1980s to establish a self-sustaining population of two million American shad to the upper Susquehanna River by 2025 [23 ,24]. These efforts have included installation of fishways between 1991 and 2000 at the four hydroelectric stations on the Lower Susquehanna River (Figure 20-1) to facilitate upstream migration of American shad to historical spawning grounds, supplemental production with release of hatchery reared larvae from different river systems, and in-river fishery moratorium/ regulations.

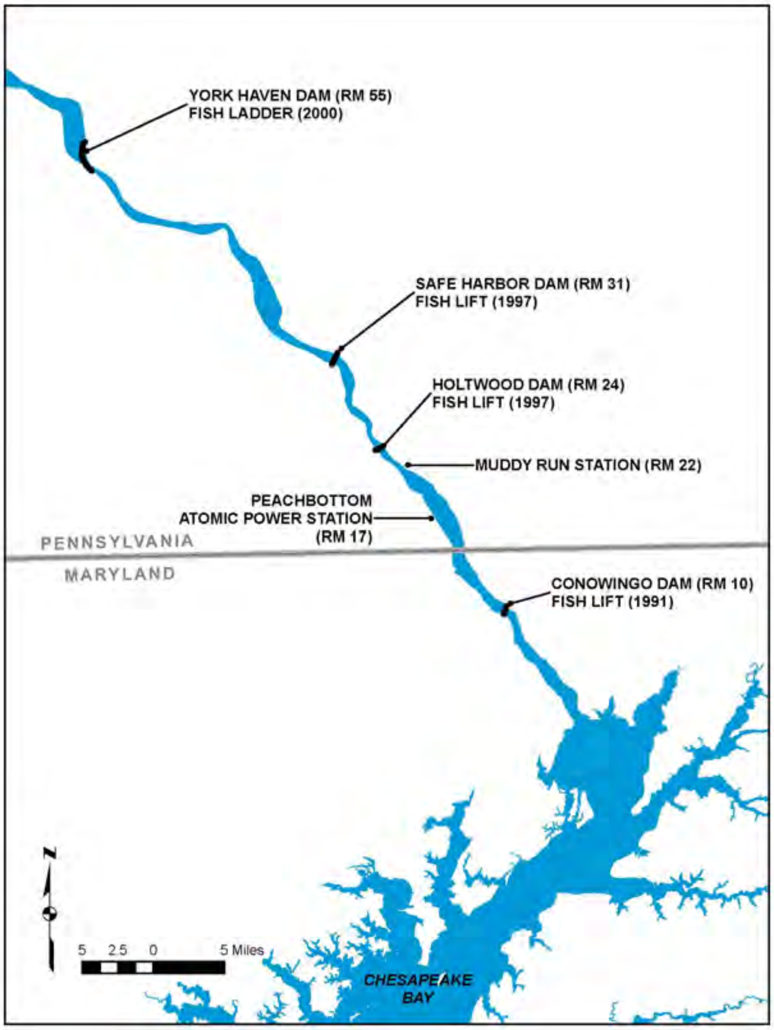

Figure 20-1
Location map of power stations and fishways at hydroelectric stations on the lower Susquehanna River

Though river-specific characteristics may vary, virtually all the east coast rivers including the Susquehanna River bear multiple fishways to allow American shad to reach its historic upstream spawning grounds. A primary concern has been the low number and proportion of the American shad population passing each successive upstream fishway [25, 26]. On the Susquehanna River, though year to year variations occur, the proportion of American shad counts at Holtwood Dam has averaged 33% of those at the Conowingo Fish Lift (Table 20-1); passage rates decline substantially between the other two upstream fishways. Because of a failure of a large proportion of American shad population to pass the Holtwood Fish Lift, a concern arose that operations of MRPSS and PBAPS thermal plume individually or synergistically may be interfering with the upstream migration of American shad. This concern is based on the belief that the pumping operations of MRPSS could shift the PBAPS thermal plume upstream in such a way as to contribute to disorientation or “confusion” of migrating American shad resulting in delays. Also, concern arose that the discharge from MRPSS during generation could form a velocity “barrier” such that a proportion of the population fails to negotiate the area in a timely manner to reach Holtwood Fish Lift and thus add to migration delay.

Table 20-1
Number of American shad passed and 90% run completion date at the Conowingo East Fish Lift and Holtwood Fish Lift

	Conowingo			Holtwood			
Year	Total Shad Passed	90% Passage Date	Daily Average Water Temperature at 90% Passage (°F)	Total Shad Passed	Percent of Conowingo Counts	90% Passage Date	Daily Average Water Temperature at 90% Passage (°F)
1997	90,071	24-May	64.4	28,063	31	3-Jun	69
1998	39,904	25-May	73.4	8,235	27	3-Jun	77.3
1999	69,712	18-May	69.9	34,702	50	22-May	71.2
2000	153,546	16-May	69.6	29,421	19	8-Jun	67.4
2001	193,574	20-May	70.7	109,976	57	22-May	65.4
2002	108,001	28-May	65	17,522	16	3-Jun	75.6
2003	125,135	21-May	61.4	25,254	20	22-May	61.9
2004	109,360	15-May	73.4	3,428	3	24-May	72.9
2005	68,926	22-May	67.1	34,189	3	31-May	66.8
2006	56,899	21-May	64.1	35,968	63	26-May	67.2
2007	23,492	20-May	67.8	10,338	44	27-May	73.6
2008	19,914	29-May	69.4	2,795	14	3-Jun	72.5
2009	27,235	24-May	71.2	10,896	40	27-May	73.2
2010	37,757	20-May	65.7	16,472	44	28-May	73.8
Totals	1,123,526			367,259	33		

Daily average water temperatures recorded at Holtwood Dam.
Sources: [27, 28, 29]

Some laboratory flume studies [30, 31] have suggested that velocities exceeding 10.0 ft/sec may form a passage barrier to 25% of migrating American shad population. Although studies in confined flumes may not replicate actual in-river field conditions with myriads of velocities initially, this criterion may be useful to identify areas of potential passage impediments. Since the American shad peak upstream migration in the lower Susquehanna River occurs within approximately 30 days and little successful spawning occurs in Conowingo Pond it is important that factors influencing migration failure be delineated. Significant reduction in passage rates, regardless of source(s), can have adverse effects on recruitment potential and eventually on the success of restoration efforts.

The objectives of this assessment are to provide a synthesis of existing biological and hydrological data to: (1) identify the hydrological conditions at which the PBAPS thermal plume moves upstream due to MRPSS pumping operations and depending upon its timing whether this condition would impede migration of American shad, (2) quantify the longitudinal, horizontal, and vertical dispersion of the thermal plume relative to American shad migration at specific pumping and generating rates and duration , (3) assess the influence of MRPSS discharge velocity on upstream migration of American shad, (4) identify areas in Conowingo Pond that may impede upstream and downstream migration, and (5) bracket the time interval over which the American shad population can be exposed to risks attributable to operations of MRPSS or PBAPS individually or synergistically. Most American shad migrate upstream through Conowingo Pond at river flows under 50,000 cfs and water temperatures between 56°F and 70° F [27]. Ninety percent of the shad run is complete by late May, generally at water temperatures less than or equal to 73°F (Table 20-1). Downstream migration of post-spawned shad mostly occurs in late May through July at water temperatures 73-80°F and river flows less than 25,000 cfs [32, 33].

Study Area

Conowingo Pond

We assessed the individual and interactive effects of the two power stations on the migration of American shad in Conowingo Pond, a 9,000 acre impoundment on the lower Susquehanna River (Figure 20-1). It is 14 miles long, averages 1 mile in width with an average depth of 20 feet and a maximum depth of 90 feet behind Conowingo Hydroelectric Dam and in some channels in the upper Pond. It is bounded upstream by Holtwood Hydroelectric Station and downstream by Conowingo Hydroelectric Station. Both are peaking facilities with a mandated continuous minimum flow requirement at Conowingo Dam but there is no such requirement at Holtwood at present. The volume and flow rates of the Pond are complex because of the variability in inflows and outflows that occur on a daily basis.

Peach Bottom Atomic Power Station (PBAPS)

PBAPS Units 2 and 3, located on the west shore of Conowingo Pond (Figure 20-1), commenced operation in 1974. Each unit (1,182 MW), is base-loaded and operates at a full power level except during periods of start-up and scheduled forced shutdowns. Both units were shut down between March 1987 and July 1989 during which time when three radio telemetry studies were conducted providing baseline data for assessing conditions with and without the thermal plume. Cooling water is provided by three 250,000 gpm (558 cfs) pumps per unit, with a total capacity of 1,500,000 gpm (approximately 3,350 cfs). During passage through the condensers, the water temperature is designed to increase up to 22°F at full load. Thus, at ambient temperatures of 50 to 70°F in spring months (American shad upstream migration period) the water temperature immediately at the point of discharge can range from 72 to 92°F at full load. The heated water is discharged into a 4,700 foot long discharge canal and eventually into Conowingo Pond via a submerged “jet” discharge structure located at the end of the discharge canal, with velocities of 5-8ft/sec [34]. The high discharge velocity in combination with high temperature minimizes entry of fishes into the canal.

Muddy Run Pumped Storage Station (MRPSS)

MRPSS is an 800MW peaking power station located about 5 miles upstream of PBAPS on the east shore of Conowingo Pond (Figure 20-1) and became fully operational in 1968. The pumping capacity of the station is about 28,000 cfs while discharge can reach up to 32,000 cfs during generation. Continuous pumping up to the upper storage reservoir generally occurs during non-peak times (typically for 7-8 hour duration), and continuous generation typically occurs twice a day for 5 or 7 hour duration. Since MRPSS pumps water from Conowingo Pond some proportion of the PBAPS thermal plume may be subjected to upstream shift at low river flows. The extent of the upstream movement of the thermal plume generally depends upon the river flow, volume, and duration of continuous pumping operation [35]. When MRPSS is generating, the PBAPS thermal plume may shift downstream. Consequently, the magnitude of thermal plume dispersion (longitudinally, horizontally, and vertically) with its attendant increased temperature may vary with the inflows, outflows, and ambient temperature with corresponding variability in potential exposure to fishes.

Methods

Radio Telemetry Studies

We utilized radio telemetry techniques [8, 36, 37, 38, 39, 40, 41, 42, 43] to assess the individual and synergistic effects of the two power stations on migration patterns of American shad. Figure 20-2 shows the number of American shad radio tagged and released far-field and near-field of power stations between 1987 and 2008. Although we conducted several migration studies [32, 33, 44, 45, 46] of gastric-implanted radio tagged adult American shad of unknown river origin due to the Susquehanna River population being comprised of hatchery-reared returns from out of basin rivers and a remnant Susquehanna River population, data from four studies [32, 33, 44, 45, 46] are used more extensively in the present assessment than others. However, where deemed relevant, particular migration information on post-spawned American shad from other studies is also discussed.

Studies were conducted over a wide range of hydrological conditions utilizing American shad in various stages of sexual maturity (Table 20-2). Sexual maturity of each fish tagged and released was determined from physical condition, date, and prevailing water temperature. Depending upon the objectives of each study, we employed different release methods (e.g., holding net pen or free release, or within the flume of Conowingo East Fish Lift), tag type (ATS or Lotek), and monitoring/tracking techniques (e.g., boat-based mobile, aerial, and fixed location continuous receivers). Details of these radio telemetry studies are given in [32, 33, 44, 45, 46].

Experimental design (multiple releases representing early, mid, and late run segments of pre-spawned radio-tagged American shad) of the [33] study allowed for statistical analyses of data to detect differences (P=0.05) between migration patterns of early, mid, and late segments. A generalized linear model (GLM) was used to develop relationships between travel times and environmental variables. Chi-square tests were used to detect differences between proportion of run segments migrating to and past MRPSS. Additionally, the [33] study included a release of 50 fish equipped with depth sensing tags. These fish were monitored by a continuous receiver installed at MRPSS to assess migrating fish depth. Additionally, weekly mobile tracking was conducted to record depth and velocity at locations occupied by each detected fish in Conowingo Pond.

We utilized two primary metrics (travel time/swim speed and proportion of tagged fish migrating past power stations) as indicators of successful migration past the power stations. Travel time was calculated from release time to first detection at an upstream location; swim speed was estimated by dividing the travel time by linear distance between two locations. The proportion of tagged fish successfully migrating past each power station was calculated from the number of fish detected upstream of each station divided by number of fish detected downstream.

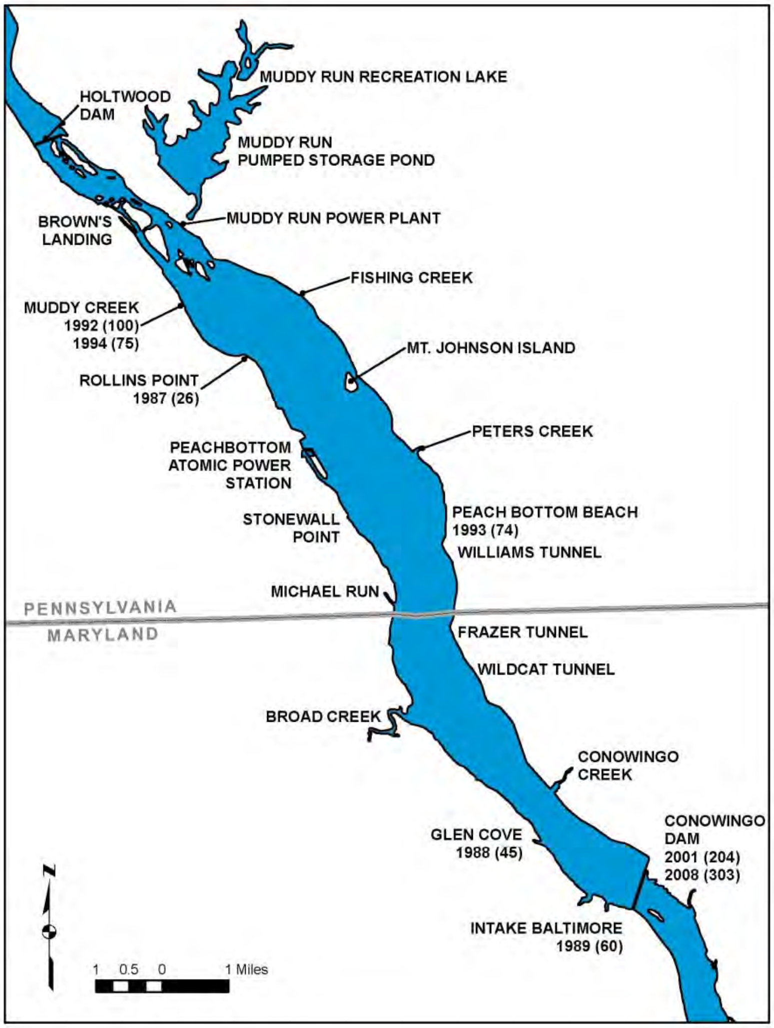

Figure 20-2
Locations and number (in parentheses) of radio tagged American shad released in Conowingo Pond, 1987-2008

Table 20-2
Summary of radio tagged American shad released far-field of Muddy Run Pumped Storage Station in Conowingo Pond, 1987-2008. River flows and water temperature measured during tracking period. PBAPS was shutdown in 1987-1989. Sexual maturity stage field determined based on physical condition of fish, date, and prevailing water temperature.

Year	Release Location	No. Released	Distance to MRPSS (mi)	Release Dates	River Flow (kcfs)	Water Temp (°F)
1987	Upstream of PBAPS[1]	26*	6	22-May	10.6-31.9	65.8-72.0
1988	Glen Cove[1]	45**	11	6–13 Jun	4.3-20.8	68.2-71.1
1989	Baltimore City Intake[2]	60***	11.5	25 Apr–6 Jun	17.7-223.0	58.6-72.5
1993	Peach Bottom Marina	74****	6	11–27 May	13.5-52.2	62.6-73.4
2001	Conowingo East Fish Lift[3]	204****	12	2–23 May	12.3-32.7	60.0-72.0
2008	Conowingo East Fish Lift[3]	317****	12	22 Apr–30 May	13.7-66.4	57.4-80.4

*Pre-spawned, late running, or post-spawned; **Post-spawned; ***Pre-spawned, partially spent, or post-spawned; ****Pre-spawned

[1] Boat-based mobile tracking; [2] Boat-based and fixed location tracking; [3] Fixed location monitoring

Sources: [32, 33, 44, 45, 46]

Near-Field Velocity Profiles at MRPSS

Water velocity and bathymetry profiles were measured along 30 transects in the MRPSS tailrace during MRPSS generation (26,000-32,000 cfs) and pumping (24,000-26,000 cfs) modes for comparison with prolonged and sustained swim speed of American shad and identification of passage impediments, if any. Holtwood was releasing between 27,000 and 31,000 cfs during these surveys. Velocity measurements were collected with a 1-MHz Sontek Acoustic Doppler Current Profiler meter (ADCP).

Development of Hydrothermal Model

Due to the complexity of the effects of the three hydro plants on Conowingo Pond hydraulics, a 3-D time varying hydrothermal model (Generalized Environmental Modeling for Surfacewaters Systems, or GEMSS®) was developed. The goals of the model were to:(1) identify the threshold river flow below which the PBAPS thermal plume migrates upstream dispersion occurs, (2) calculate velocity profiles of the upstream moving thermal plume, (3) study the behavior of the plume at the cessation of MRPSS pumping, and (4) study the behavior of thermal plume during MRPSS generation. The model included: (1) Susquehanna River inflow and water temperature, (2) MRPSS pumping and generation, (3) PBAPS discharge rate and water temperature rise, and (4) Conowingo Dam flow release rate. The model is currently being calibrated based on a multi-year field measurement program. Thus, at the time of this paper, the model results are only available for July 2010 (period of post-spawned American shad downstream migration) at incoming river flow of 10,000 and 20,000 cfs and water temperature of 82-84°F (both measured at Holtwood Dam) and are discussed herein. For completeness, inferences on thermal plume characteristics in May and June (pre-spawned and post-spawned migration periods) are drawn based on July modeling results.

Assumptions

The following assumptions were made in the present assessment:

- Detectable interactive effects of the two power stations are possible only when American shad migration coincides with hydrological conditions conducive for upstream thermal plume movement due to MRPSS pumping operations;
- Magnitude of the interactive effects of the two power stations on migrating American shad would vary with the duration of the co-occurrence of above hydrological events and power station operating scenarios;
- A 1°F rise (ΔT) at PBAPS intake is indicative of upstream shift in thermal plume;
- Upstream thermal plume movement is negligible at river flows higher than 10,000 cfs as indicated by model results to date;
- Since the incoming water temperatures are lower and river flows are higher in May (average temperature 64°F, average daily river flow 47,200 cfs) and June (average temperature 75°F, average daily river flow 30,300 cfs) than those in July (average temperature 81°F, and average river flow 17,000 cfs) ΔTs at various depths would be lower during the months of May and June than those presented here for July 2010;
- Although laboratory determined avoidance temperature (≥ 86°F) for juvenile American shad was found in the literature [2, 12], corresponding estimate was not found for the adult American shad. Consequently, the same avoidance temperature of greater than or equal to 86°F was also assumed for adult American shad;
- Velocities greater than 7.0 ft/sec could pose a barrier for a proportion (≥ 25%) of both upstream and downstream migrants though swim speeds of pre-spawned American shad in excess of 7.0 ft/sec have been estimated in confined channel/flumes [8, 30, 31, 42] suggest swim speed of post-spawned and pre-spawned American shad to be similar;
- Migratory pattern of American shad captured, radio tagged, and released inside or outside of a fishway is representative of non-tagged migrating shad; and
- The duration of pumping is conservatively taken as 12 hours, although 7-8 hours is typical.

Results

One of the objectives of our assessment was to delineate the extent and magnitude of the upstream dispersion of the thermal plume due to MRPSS pumping and hydrological conditions at which such phenomenon occur. Figure 20-3 shows predicted thermal plume configuration at river flows of 10,000 cfs and 20,000 cfs during pumping and generating with incoming water temperatures of 82-84°F in July and MRPSS continuously pumping 20,000 cfs for 12 hours (typical is 7-8 hours). The joint probability occurrence of river flows less than or equal to10,000 cfs and water temperatures greater than or equal to 81°F is 0.1% in May and 3.8% in June. Consequently, there is little likelihood that migrating American shad would encounter thermal plume upstream dispersion in these months. In July, the joint probability occurrence of river flows less than or equal to 10,000 cfs and water temperature greater than or equal to 81°F is 31.3% and of river flows greater than or equal to 20,000 cfs and water greater than or equal to 81°F is 6.6%.

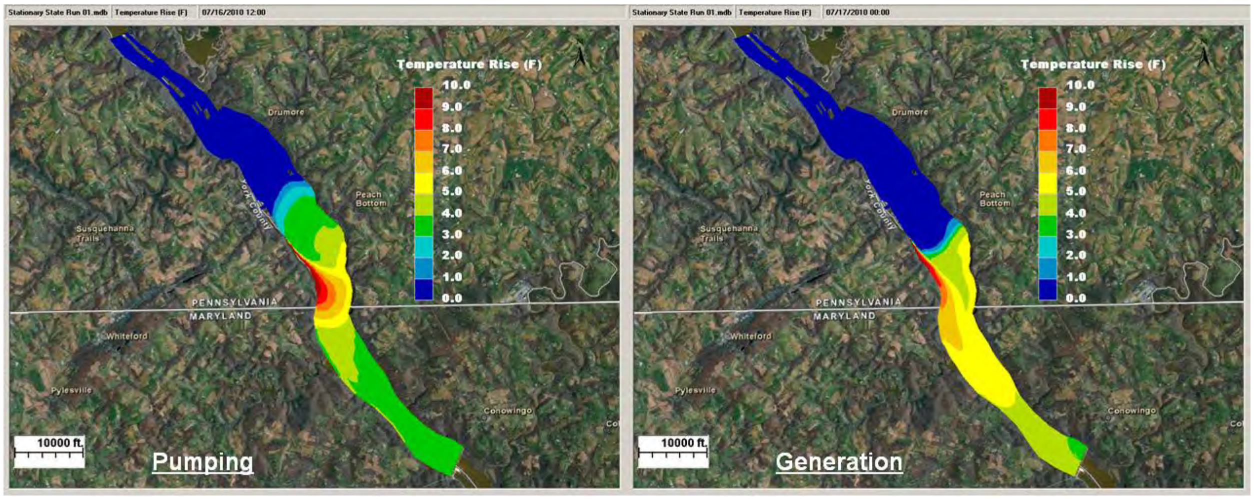

Figure 20-3
PBAPS thermal plume at 10,000 cfs Susquehanna River flow during pumping and generation cycles of MRPSS

At 10,000 cfs river flow, the thermal plume moves upstream a short distance, approximately 1,000 feet upstream of PBAPS intake (Figure 20-3) with a rise (ΔT) in surface temperature ranging from 2 to 3°F above the incoming water temperature (or absolute temperatures of 84 to 87°F). However, the rise in temperature at greater depths is much lower and most of the area upstream of PBAPS intake shows water temperatures under 86°F, well within the tolerance range of American shad.

During MRPSS generation (≥ 25,000 cfs) at incoming river flows of 10,000 cfs and 20,000 cfs modeled for July, no rise in water temperature upstream of the PBAPS intake was observed, and the plume size decreased in the downstream direction (Figure 20-4). Since post-spawned American shad migrate downstream during the day time [8, 42] when MRPSS is expected to be in a generation mode, migration should be unimpeded and may even be enhanced past the station. A higher rate (48.8%) of radio-tagged fish migrated past the MRPSS during generation than during pumping (36.1%) [33].

Figure 20-5 shows velocity distribution by depth of the moving thermal plume at river flows of 10,000 cfs with MRPSS continuously pumping for 12 hours. Although the direction of the change in velocity is towards MRPSS, all surface velocities upstream of PBAPS intake were less than 0.3 ft/sec with decreasing magnitude from a depth of 5 feet to the bottom depths and elsewhere. It is unlikely that the magnitude of change in velocity predicted herein would elicit adverse reaction by post-spawned American shad. [47] reported that a minimum increase of 1.4 ft/sec in water velocity per approximately 3.1 feet of linear distance was needed at the exit of an experimental louver system at the Hadley Falls Station on the Connecticut River to elicit an avoidance response by post-spawned American shad.

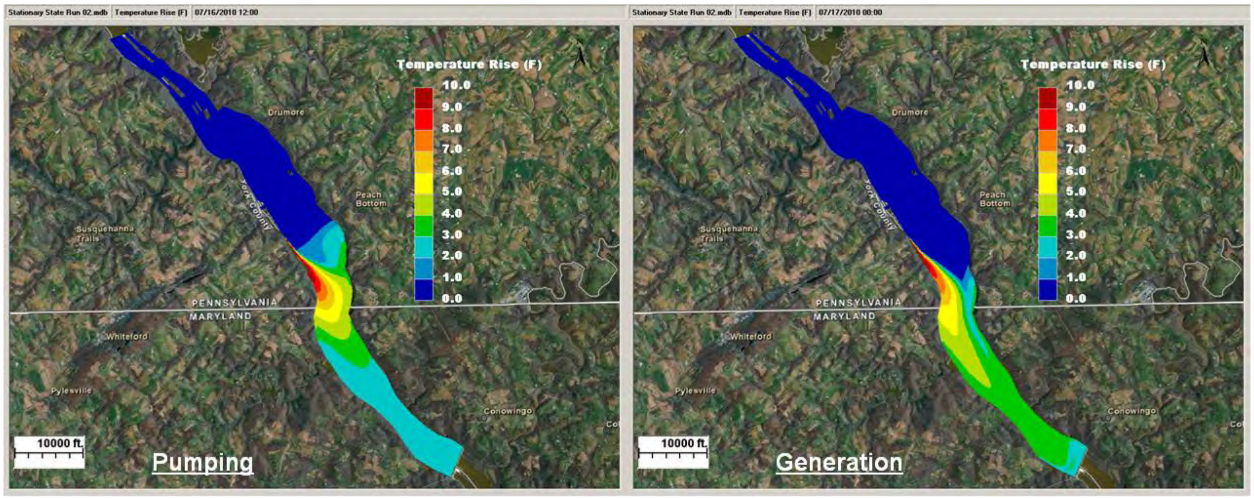

Figure 20-4
PBAPS thermal plume at 20,000 cfs Susquehanna River flow during pumping and generation cycles of MRPSS

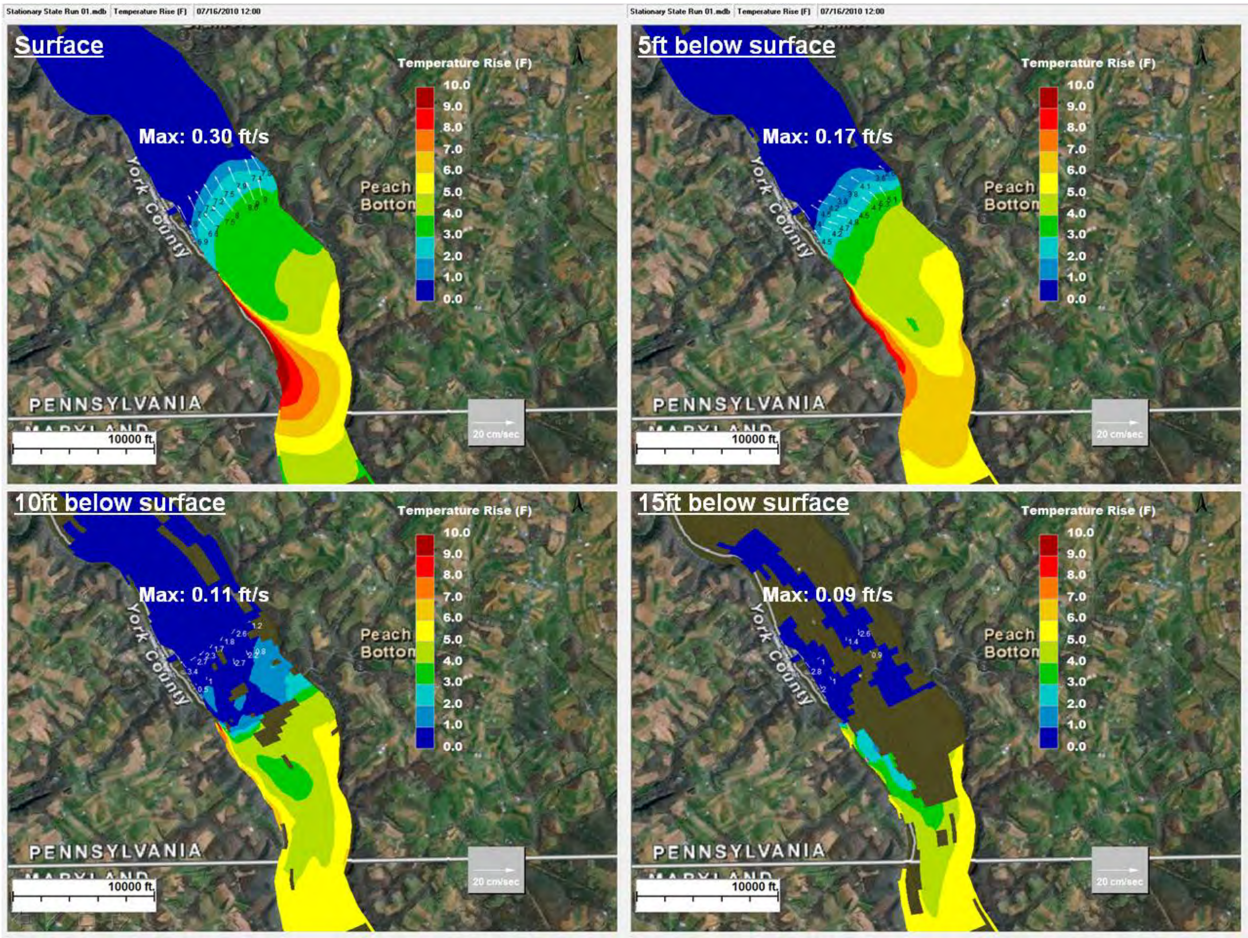

Figure 20-5
PBAPS thermal plume and velocities at 10,000 cfs Susquehanna River flow during pumping

Since PBAPS was in a shutdown mode in 1987-1989 when many post-spawned radio-tagged American shad were released, we can only draw inferences on the effect of changes in velocity of upstream movement of water due to MRPSS pumping operations. Assuming that the changes in velocity would be the same due to MRPSS pumping operations, we expect no adverse reaction by post-spawned American shad. Tracking of radio-tagged American shad indicated that post-spawned American shad freely migrated upstream past MRPSS and then many returned downstream at river flows between 4,300 and 20,800 cfs [44, 45].

No obvious migration impediments, either due to operations of the two stations individually or synergistically were detected. The proportion of fish detected either at MRPSS or upstream past the MRPSS was high for all years. It ranged from 80 to 91% [32, 33, 45, 46]. It appears that the entire migrating American shad population does not encounter MRPSS operations and a certain proportion may migrate far field towards the west shore of Conowingo Pond. Radio tracking of American shad over several years suggests that migrating shad tend to utilize the entire river for migration but not necessarily in equal proportions.

Velocity profiles taken near the MRPSS during both pumping and generation support the above conclusion. The velocity data collected in the MRPSS tailrace during generation are shown in

Figure 20-6. All velocity measurements were within the range of American shad prolonged and sustained swim speed of 2.4 ft/sec and 7.0 ft/sec, respectively with most measurements less than 3.0 ft/sec; substantial areas of lower velocity should provide ample migration passage zone with minimal delay.

Though a cautionary note is warranted in making interannual comparisons because no two years may be hydrologically identical, the shutdown of PBAPS in 1987-1989 allowed an opportunity to compare passage rates past the stations with and without the PBAPS thermal plume. The proportion of pre-spawned American shad migrating past the PBAPS site without thermal plume and upstream of MRPSS was similar between years with and without the thermal plume. In 1989, without the thermal plume, out of 60 shad, 43 (72%) migrated past PBAPS and utilized the entire Pond [45]; of these 43 shad, 28 (65%) were detected at the MRPSS monitor, and 11 (26%) were detected upstream of MRPSS for a total upstream passage rate of 91% (39 of 43). The proportions migrating past MRPSS were approximately 86% in 1993 [46]; 80% in 2001 [32]; and 84.5% in 2008 [33]. Considering that a certain proportion of American shad fails to migrate upstream after capture, radio tagging, and release, these proportions migrating past MRPSS are high. The post-spawned American shad also moved extensively between Conowingo Dam and Holtwood Dam (past MRPSS) in 1987 and 1988 [44]. In fact, contrary to expectation, 24 to 69.6% of presumably post-spawned fish migrated past MRPSS [44].

A spike in natural river flows accompanied with high turbulence, velocity, and turbidity can be a significant impediment to American shad migration [45, 48]. [48] reported that a flood event in Connecticut River flushed all sonic tagged away. Apparently, these fish had left the study area for good. A similar situation occurred in Conowingo Pond in 1989 and 2008 [33, 45]. We had detected 42 radio-tagged fish upstream of MRPSS prior to a high flow event between 6 and 21 May 1989; and only four fish were still present after flows subsided (Figure 20-7). An additional group of 22 radio tagged fish was released between 22 and 24 May. Seven of these fish migrated past the MRPSS. Rates of migration and departure for these seven fish were rapid and similar to those shown in other years. These seven fish reached MRPSS in 1 to 2 days and left the area within 1 to 7 days indicating unimpeded migration past MRPSS.

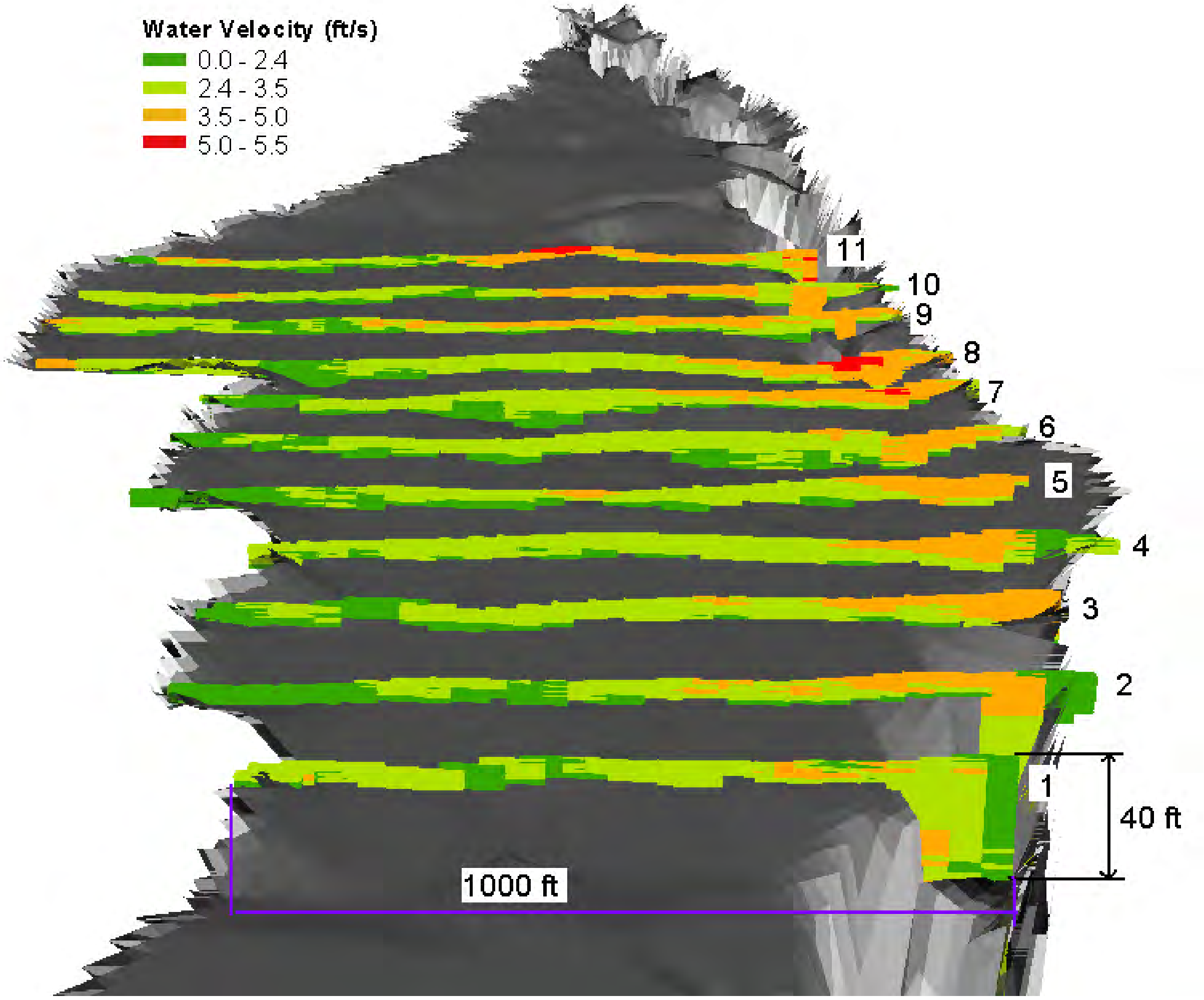

Figure 20-6
Distribution of velocity measurements in the MRPSS tailrace during generation

In a later study [33], release of radio-tagged American shad during the mid-season migration period was followed by a spike in river flow, displacing most tagged fish out of the surveillance area. As a result, significant differences (P = 0.002) between run segments migrating from Conowingo Dam past MRPSS were noted. The passage counts at the Holtwood Fish Lift followed the same pattern as observed for the radio tagged shad during this period; high passage counts were observed on either side of the river flow spike.

MRPSS generation did not appear to affect migration of pre-spawned American shad past MRPSS [33]. A greater percentage (48.8%) of radio-tagged American shad migrated past the station during generation than during pumping mode (36.1%). Although passage occurred at all generation conditions of MRPSS, most shad migrated past MRPSS at river flows less than 50,000 cfs and in the upper 10 feet of the water column; little passage occurred at higher river flows.

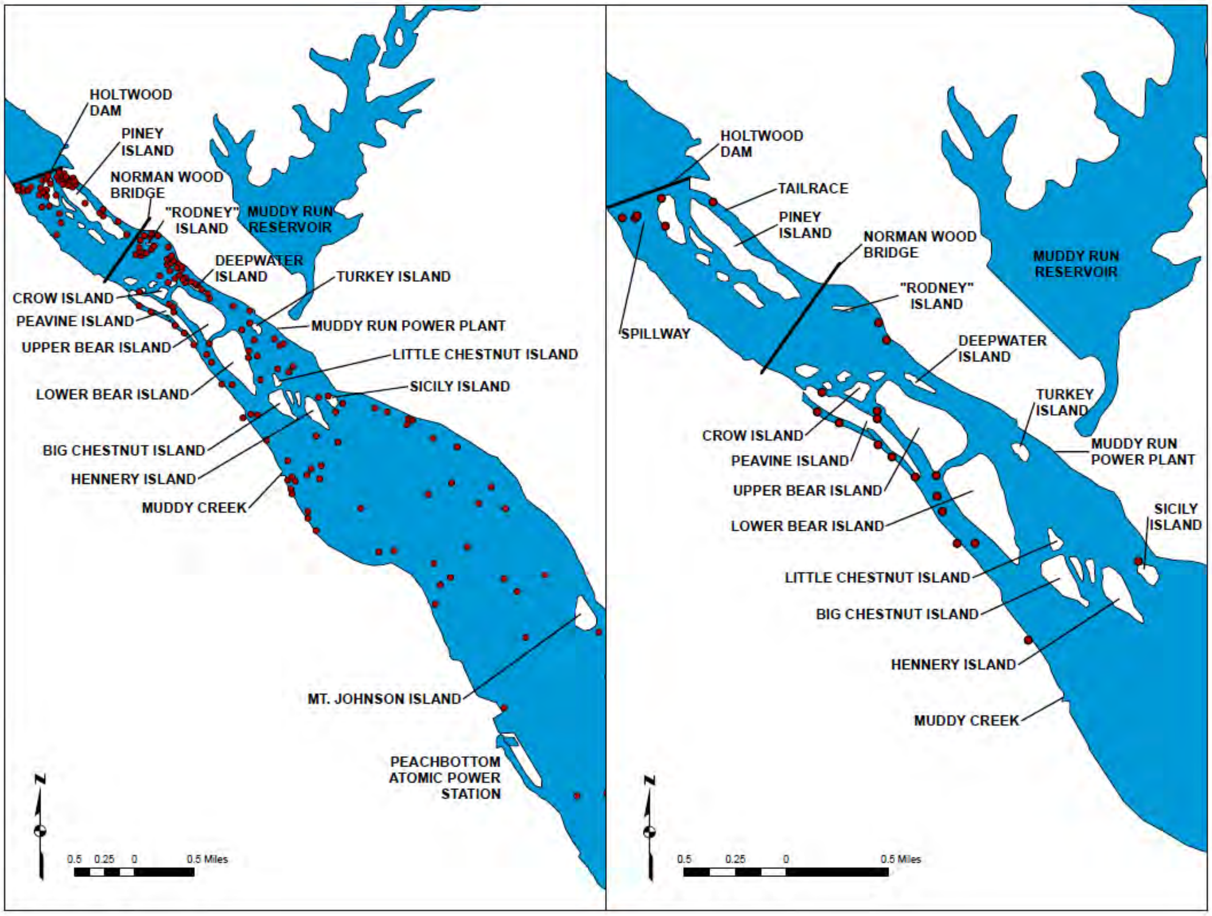

Figure 20-7
Comparison of detections of radio tagged American shad at Holtwood spillage of < 25,000 cfs (left) and at spillage > 25,000 cfs (right)

No consistent relationships of predictive value ($r^2 < 0.25$, or <25% variance explained) could be found between travel times and with any of the environmental variables included in the regression analysis [33]. Although some individual significant ($P < 0.05$) correlations ($r^2 < 0.25$ or <25%) between travel time and environmental variables were noted, they were inconsistent. As an example, travel time of early run migrants from the Conowingo release site to past MRPSS was positive, significantly ($P = 0.001$) correlated with river flow and Holtwood spillage. However, travel time of late run migrants was negatively correlated with these variables. Similarly, travel time of early migrants that was negatively correlated ($P = 0.009$) with water temperature, was positive for late migrants ($P = 0.0001$), and non-significant ($P = 0.105$) for mid run migrants. No combination of variables included in multiple regression models produced a meaningful predictive model ($r^2 \leq 0.15$ or < 15% variance explained).No significant differences ($P > 0.05$) were detected in median travel times from Conowingo to past MRPSS between pumping, generating, or shutdown. Median travel times from Sicily Island (approximately 0.7 mi downstream, deemed a staging area) to past MRPSS were non-significant as well.

Although release sites and methods differed between years, estimated average travel times and speeds of most pre-spawned fish past MRPSS were similar with PBAPS operating or shut down and comparable to those reported by others. The average travel times to migrate past MRPSS were 1.3 to 2.5 days or travel speed of 0.2 to 0.4 mph. These estimated travel speeds are within the range (0.1 to 0.6 mph) of those reported in other river systems [38, 40, 41, 42]. The cited investigations were conducted on primarily pre-spawned radio-tagged shad and released into more of a riverine type habitat rather than in impoundments and at water temperatures generally less than 60° F.

Principal Findings and Conclusions

The primary objectives and assumptions established for our assessment were met to a large extent. We identified that the thermal plume moves a short distance, approximately 1,000 feet upstream of the PBAPS intake (ΔT rise of 1°F above ambient at surface) after the MRPSS has been continuously pumping 20,000 cfs for 12 hours (typical is 7-8 hours) at a river flow of less than or equal to 10,000 cfs in July. The probability occurrence of river flow of less than or equal to 10,000 cfs is 35.6% (approximately 11 days) in July and, thus, only the post-spawned American shad could potentially encounter this condition for a short duration with moderate probability of occurrence. Since post-spawned American shad migrate primarily during the day [8, 47] and MRPSS pumping occurs mostly at night, the probability of co-occurrence of these two events further lowers probability of exposure risk. The joint probability occurrence of river flows less than or equal to 10,000 cfs and water temperature greater than or equal to 81°F in May is 0.1% and 3.8% in June. Consequently, there is little likelihood that migrating American shad would encounter thermal plume upstream dispersion in these months; the incoming water temperature varied between 82 and 84°F.

It is unknown, pending additional model calibration, whether the extent of the upstream thermal plume movement would be negligible at a lower MRPSS pumping flow volume (< 20,000 cfs) or shorter duration (<12hr). Nor can we definitively estimate from the available data the proportion of down migrating American shad that could encounter this condition. However, we think that that it is likely a small proportion of the population since the downstream migration through Conowingo Pond begins in late May and is completed by July.

Extensive movements by partially spent and post-spawned American shad within Conowingo Pond suggested little, if any, significant adverse effects of the two power stations acting alone or in synergism. Most shad freely migrated past MRPSS and then many migrated downstream at river flows ranging between 4,300 and 20,800 cfs. Systematic weekly tracking of radio tagged American shad in May through August 2010 did not reveal change in movement direction even though river flows less than 10,000 cfs occurred 100% of the time in July 2010.

The surface velocity within the upstream migrating thermal plume is ≤ 0.3 ft/s due to MRPSS pumping operation and is less than the minimum change in velocity (> 0.4ft/s per linear foot distance) needed to elicit an avoidance response by American shad [47]; change in velocities at 5ft and deeper depths is negligible. American shad tend to travel at deeper depths [33, 49] where the velocity change is negligible due to MRPSS pumping. In the absence of turbulence, American shad can swim for short distances through velocities exceeding 10.0 ft/s [30, 31].

Our assumption that a velocity of > 7.0 ft/s may occur and could form a “barrier” for migrating American shad was rejected because no velocity measurements along the American shad travel path approached this velocity level. The highest velocity measured in the MRPSS tailrace was approximately 5.5 ft/s and was restricted to a small area; most of the tailrace area showed velocities <3.0 ft/s and were well within the prolonged and sustained swim speed of American shad (≤7.0 ft/s). Both pre-spawned and post-spawned American shad routinely enter fishways with attraction velocities between 4 and 7 ft/s [27]. [37] noted that a velocity of 6.3 ft/s did not repel migrating American shad in the Hadley Falls tailrace on the Connecticut River. Also, observations have indicated both pre- and post-spawned shad are capable of traversing velocities >5-7.0 ft/s even after turbine passage [36, 50]. There was little evidence of congregation of radio-tagged American shad near the MRPSS.

The estimated travel speeds (0.2-0.4 mph) were within the range (0.1-0.6 mph) of those reported in other investigations on migration of American shad. Other investigations were conducted in more of a riverine type habitat than in impoundments at water temperatures generally < 60°F.

Our assumption that a water temperature of over 86°F would be avoided by migrating American shad was likely conservative. Tracking of radio tagged shad indicated that some shad occupied areas with water temperature as high as 90°F, though for short duration (<1.5 hr). This was also corroborated to a certain extent by presence of radio tagged post-spawned shad in Conowingo Pond in July 2010 at temperatures exceeding 86°F and active utilization of fishways at water temperature over 80°F.This would suggest a larger area of migration passage corridor exists than based on assuming avoidance temperature of less than or equal to 86°F.

Even though the upstream movement of the thermal plume occurs, the temperature rise associated with the predicted thermal plume shift was restricted to a small area and well within the thermal tolerance of migrating American shad [8, 12]. This conclusion was supported by an extremely high (80-91%) proportion of radio-tagged American shad successfully migrating past both PBAPS and MRPSS with minimal delay.

Absence of individual effect of PBAPS thermal discharge on migration of American shad was demonstrated by similarity in successful passage rates past MRPSS during PBAPS shutdown (1989) and after shutdown (2001 and 2008). The respective passage rates were 91%, and 80 to 84.5%. The respective travel times were 2.5, 1.8 and 1.3 days.

The assumption that the behavior of radio tagged American shad is representative of non-tagged also appeared to be satisfied. In 2001, 74.3% (136 of 183) radio-tagged American shad were detected at Holtwood Dam and 46 (34%, 46 of 136) eventually utilized the fish lift [32]. Although the proportion of radio tagged fish passing the Holtwood Fish Lift did not mirror that of non- tagged fish, peak passage of both radio tagged and non-tagged fish occurred on the same days [31]. This proportion of tagged shad detected was higher than the non-tagged shad counted (57%) at Holtwood Fish Lift. The exact reasons for this discrepancy are unknown, but it was thought that some tagged shad released near their spawning time may have spawned and lost a strong urge to migrate as those migrating early in the season [32].

In a subsequent study, the passage counts of untagged shad at Holtwood Fish Lift as a percentage of Conowingo East Fish Lift shad counts were similar to that of radio tagged fish passage. Normandeau Associates, Inc. and Gomez and Sullivan (2009) [33] reported that 14% of the radio tagged fish utilized the Holtwood fish lift, the same percentage as the non-tagged fish. The pattern of passage counts at Holtwood Fish Lift due to a spike in river flow was similar for tagged and non-tagged fish. Passage counts declined with high river flows and increased as river flows subsided, a trend exhibited by the radio tagged fish.

In conclusion, analysis of multiple sources of site-specific data collected over a long period of time and widely varying hydrological conditions and literature review suggest that operations of

MRPSS and PBAPS individually or jointly contribute little, if any, to the failure of a high proportion of upstream migrating American shad to utilize Holtwood Fish Lift. Other uncontrollable factors such as natural high river flows (> 25,000 cfs spillage at Holtwood Dam) with their associated high velocity, turbulence, and turbidity or fish lift mechanical failures pose greater impediments than the operations of the two power stations either individually or synergistically.

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21

COST AND PERFORMANCE CONSEQUENCES OF CLOSED-CYCLE RETROFIT

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Abstract

This paper presents the results of an analysis of the costs of retrofitting those existing steam-electric power plants, which were designed for, built with, and are currently operating on once through cooling, with closed-cycle cooling systems. The motivation for this is regulatory activity subsequent to Section 316(b) of the Clean Water Act (CWA) under which some once-through cooled plants will be required to retrofit closed-cycle cooling equipment.

The paper develops an estimate of the national capital cost of retrofitting all what were formally known as “Phase II” facilities (utilizing > 50 MGD cooling flow) among power generation plants. Three other significant cost elements were estimated. These are the cost of replacement energy during the time that plants are unable to operate during the retrofit process, the annual cost of additional operating power required for closed-cycle cooling and the cost of heat rate penalties resulting in reduced plant efficiency and output incurred because of thermal limitations of closed-cycle cooling.

A cost estimating methodology is developed in which plant retrofits are categorized according to a “degree of difficulty” analysis. A cost estimating relationship is derived for each category. The costs range from approximately $180/gpm to $570/gpm for fossil plants and $275/gpm to $645/gpm for nuclear plants. The national capital cost of retrofit is estimated at just over $62 billion. A major additional cost is that of plant downtime during retrofit for which a total national cost of just over $17 billion is estimated.

In addition, the concept of “seasonal operation”, in which the retrofitted closed-cycle system would be used only during certain periods of the year, such as the “spawning season”, while once-through cooling could continue to be used for the rest of the year is analyzed. The potential benefits of seasonal operation include a possible reduction in retrofit system cost if a smaller cooling tower can be used during the cooler springtime months. In addition, the increase in operating costs normally accompanying a retrofit to closed-cycle systems is reduced for two reasons. First, the increased pumping power and cooling tower fan power is not required during the period of the year when once-though cooling can continue to be used. Second, once-through cooling could be used during the hottest summer periods eliminating the efficiency and output penalties often incurred with closed-cycle cooling during the summer months.

Introduction

In 1972, Congress passed the CWA and §316(b) which applies directly to regulating the impacts of cooling water intake structures (CWIS) on aquatic life. Specifically, §316(b) requires EPA to ensure that "the location, design, construction and capacity of cooling water intake structures shall reflect the best technology available for minimizing adverse environmental impact." [1, 2] EPA issued a Rule in 1977 to implement the CWA §316(b) requirements. However, because of legal challenge, the regulation was remanded. EPA took no follow-up action to correct the issues raised by the litigation. Permitting authorities subsequently issued §316(b) permits in various ways including following EPA guidance provided or using best professional judgment (BPJ). In 1994, a coalition of environmental groups sued EPA over failure to promulgate national standards enforcing CWA §316(b) requirements. As a result, EPA entered into a consent decree to develop in phases final regulations for both existing and new facilities that use CWIS. A Phase I Rule for new facilities was issued in 2001 [3]. The Phase I Rule essentially requires closed-cycle cooling systems or comparably performing intake technologies as best technology available (BTA) to minimize adverse environmental impact. In 2004, EPA promulgated a Phase II Rule [4] to implement regulations for existing power plants that withdraw more than 50 million gallons per day (MGD) of cooling water. This regulation was subsequently challenged and later remanded for revision.

On April 20, 2011, EPA proposed a revised §316(b) Rule [5] for existing power plants and other industrial facilities using cooling water. Performance standards and monitoring requirements are proposed for reducing impingement and entrainment mortality. Relative to entrainment, the compliance standard is determined by the permitting authority on a "case-by-case" basis. To support this determination, facilities withdrawing more than 125 MGD actual intake flow must submit a number of studies that characterize the presence of early life stages in the source water that are susceptible to entrainment, the extent of entrainment mortality caused by the plant, and an evaluation of entrainment reduction options as well as their environmental impacts and benefits. A final existing facility Rule will be promulgated on or before July 27, 2012.

Relative to the requirement to evaluate entrainment reduction options, the proposed Rule specifically requires that permit applicants consider the technical feasibility, cost, environmental impacts, and benefits of closed-cycle recirculating systems, such as natural draft cooling towers, mechanical draft cooling towers, hybrid designs, and compact or multi-cell arrangements. Related EPRI research has examined the technical feasibility, cost, economic impacts and environmental and social impacts of complete retrofit of mechanical draft cooling towers [6, 7, 8, 9] to power plants with once-through cooling. The technical feasibility and cost associated with seasonal deployment of some type of cooling towers during periods when fish and shellfish eggs and larvae are abundant, however, has not been previously explored.

This paper addresses two related, but separate topics. The first is an analysis of the national costs of retrofitting with closed-cycle cooling systems those existing steam-electric power plants which were designed for, built with and are currently operating on once-through cooling. The second explores the potential benefits of "seasonal operation" in which a retrofitted closed-cycle system is used only during certain periods, such as the spawning season, and the plant continues to use once-through cooling during the remainder of the year.

National Cost Study

The primary objective of the national cost study is to develop an estimate of the national capital cost of retrofitting all the eligible facilities among power generation plants. Three other significant cost elements were estimated. These are the cost of replacement energy during the time that plants are unable to operate during the retrofit process, the annual cost of additional operating power required for closed-cycle cooling, and the cost of heat rate penalties resulting in reduced plant efficiency and output incurred because of thermal limitations of closed-cycle cooling.

The national cost estimates include the capital, downtime, operating and penalty costs for 428 plants, of which 39 are nuclear plants and 389 are fossil plants fueled with coal, oil or gas, which withdraw more than 50 million gallons per day (MGD) from the surface waters of the United States. Figure 21-1 shows the distribution of these plants across the country.

Table 21-1 lists the total plant capacity in megawatts and the total cooling water flow withdrawn for the families of fossil and nuclear plants.

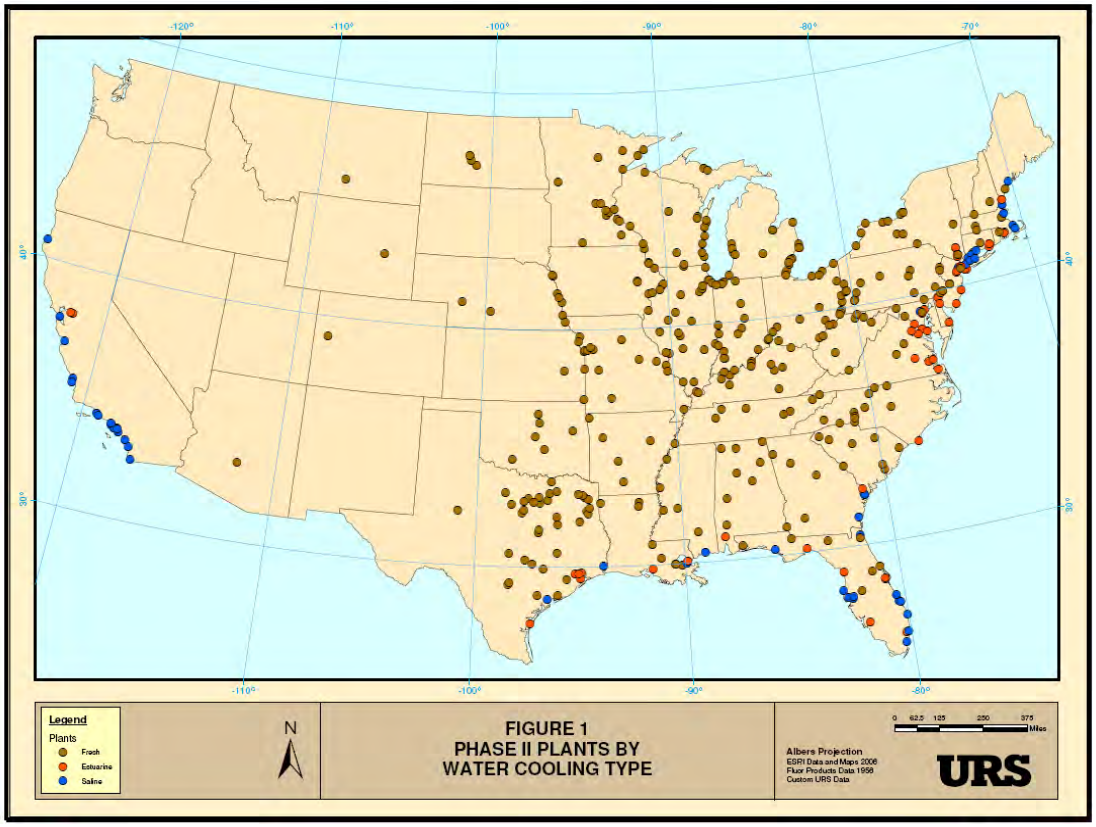

Figure 21-1
Plants included in cooling system retrofit cost study [7]

Table 21-1
Plant capacity and cooling water flow of plants included in analysis

Plant Type	No. of Plants	Total Capacity MW	Total Circulating Water Flow gpm[1]
Fossil	389	252,000	139,507,000
Nuclear	39	60,000	42,789,000
Total	428	312,000	182,296,000

[1] gpm = gallons per minute

Closed-cycle Cooling Retrofit

Figure 21-2 shows schematically a general approach to retrofitting a once-through cooled plant with closed-cycle cooling. The existing once-through cooling arrangement in most cases is left largely intact with the same condenser, the same set of circulating water pumps and intake discharge lines and operates at the same circulating water flow rate. The hot water from the condenser is discharged into a sump from which a new set of circulating water pumps draws the hot water and pumps it to a new cooling tower. The cold water from the cooling tower then drains by gravity from the cold water basin back to an intake bay from which the original circulating water pumps draw water to be pumped to the condenser. The existing intake and discharge facilities are modified or eliminated and provisions for both makeup and blowdown from the closed-cycle system must be made.

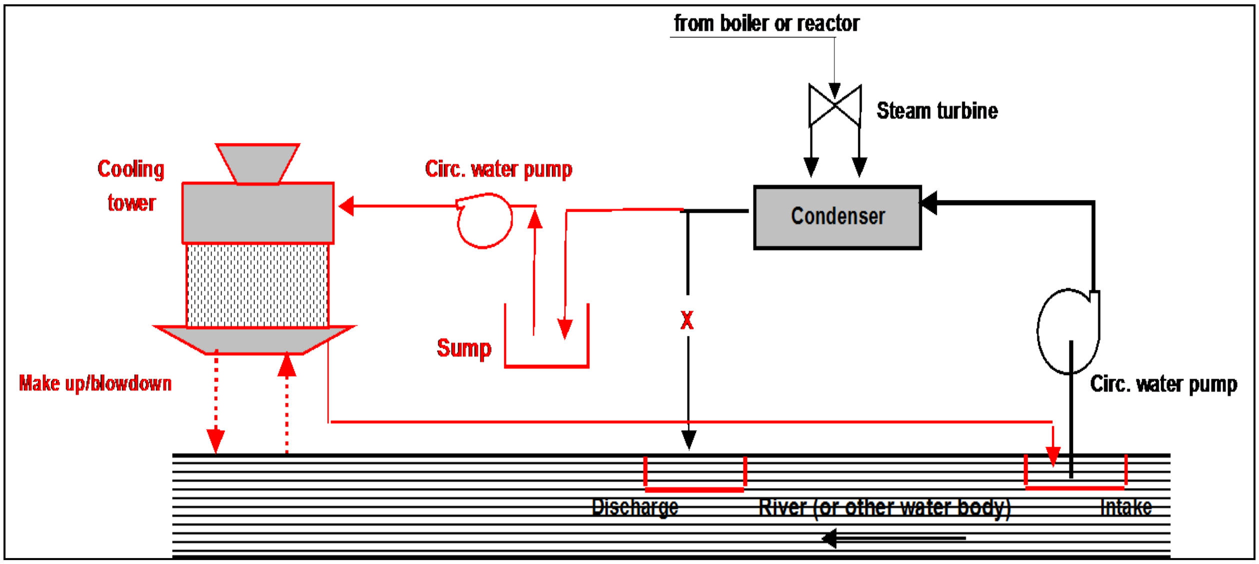

Figure 21-2
Schematic of retrofitted cooling system

Many variations on this retrofit arrangement are possible. Depending on the existing type of intake and discharge systems, it may be possible to use existing intake or discharge bays or canals in place of a new sump for the withdrawal and discharge points of the new circulating water loop to and from the tower. In some cases, it is possible to modify the existing circulating water pumps so that the cooling water can be pumped through the condenser and then directly to the top of the tower without the need for a second set of pumps or an intermediate sump. In some cases, it may not be possible to find a location for the tower which permits gravity return of the cold water. In that case, additional return pumps would be required. However, all of these modifications retain the basic premise of the retrofit; i.e., that the existing condenser and cooling water flow rate are retained and a cooling tower is, in some sense, simply inserted into an existing cooling loop in order to recirculate cold water to the condenser and, by so doing, to significantly reduce the continuous withdrawal rate of water from the environment.

Significantly different approaches to closed-cycle cooling system retrofits are sometimes considered. Examples include the use of natural-draft cooling towers in place of mechanical-draft towers, the use of hybrid, or even all-dry, cooling in place of wet cooling and a complete re-optimization of the existing system to a different cooling water flow rate and condenser configuration. The discussion in this paper is confined to retrofits to all-wet cooling using mechanical-draft cooling towers.

Methodology

A methodology was developed to account for the highly site-specific nature of cooling system retrofit costs in a determination of total national costs. Retrofitting of existing once-through cooled plants with closed-cycle cooling is typically significantly more costly than the installation of closed-cycle cooling at new, greenfield facilities. The cost is highly dependent on the characteristics of the site and of the existing plant layout.

The methodology consists of three steps. The first two address the estimation of cost at individual plants; the third aggregates and extrapolates individual plant estimates to a national total:

Step 1 establishes a likely range of capital costs for a plant simply as a function of the circulating water flow rate in the original once-through cooling system. Independent information on actual, or independently estimated, retrofit costs at over 80 plants yielded likely ranges of costs for individual plant retrofits as a function of cooling water flow rate. It can be noted in Figure 21-3 that these costs can be clustered in to low, average, high and very high cost groupings. These groupings are assumed to correspond to retrofit projects of varying degrees of difficulty, characterized as “Easy”, “Average”, “Difficult” and “More difficult”. Separate equations in the form of

Retrofit Capital Cost, $ = Cost coefficient, $/gpm x Circulating water flow, gpm

were developed for fossil and nuclear plants.

The linear cost relationships are shown along with the individual cost points in Figure 21-3. The full set of correlation coefficients is given in Table 21-2.

Step 2 places an individual plant cost within the likely range of costs on the basis of the perceived degree of difficulty of a retrofit at that plant. The degree of difficulty is based on site-specific information obtained from a cost-estimating worksheet survey of over 185 facilities. Eleven factors characterizing the plant and site, listed in Table 21-3, were considered in establishing the likely degree of difficulty for any individual plant. Estimates are made for approximately 125 facilities and a distribution of the family of Phase II facilities over a range of degrees of difficulty from “Easy” to “More Difficult” (for fossil plants) and “Less Difficult” to “More Difficult” (for nuclear plants) is extrapolated.

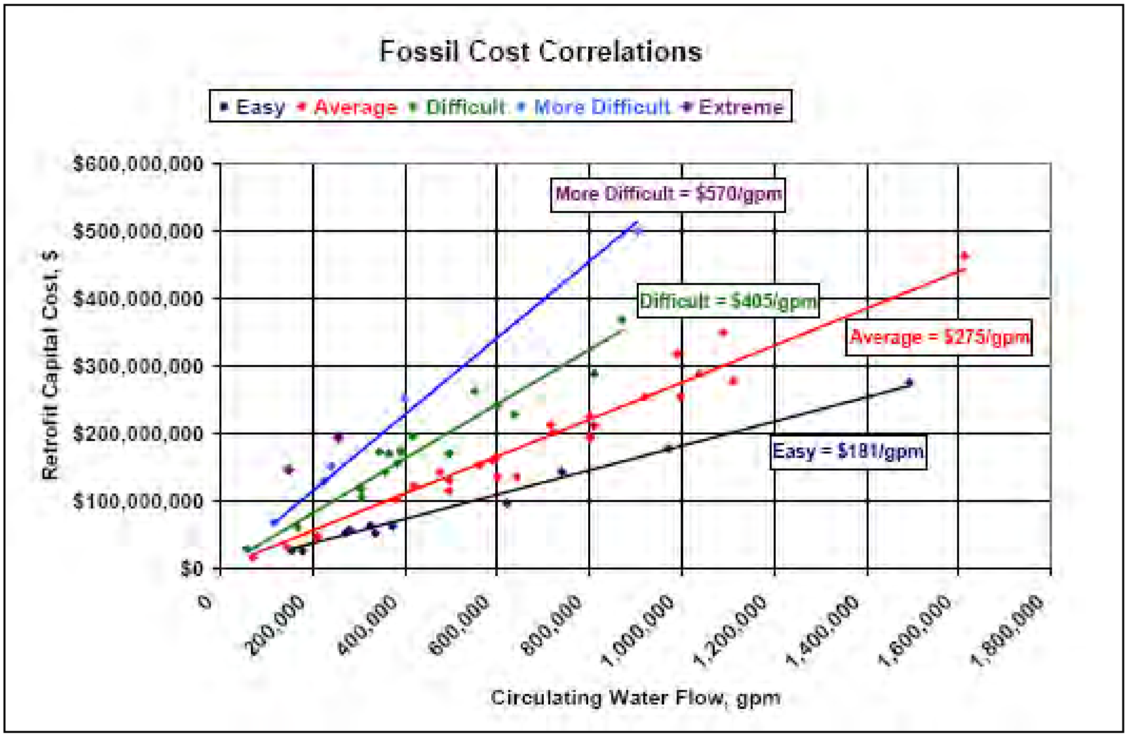

Figure 21-3
Cost information and correlating equations for fossil plant retrofits

Table 21-2
Cost coefficients for differing degrees of difficulty

Fossil Plants	
Degree of Difficulty	**Normalized Cost, $/gpm**
Easy	$181
Average	$275
Difficult	4405
More difficult	$570
Nuclear Plants	
Less difficult	$274
More difficult	$644

Table 21-3
Factors influencing degree of difficulty

Factor	Description
1	The availability of a suitable on-site location for a tower
2	The separation distance between the existing turbine/condenser location and the selected location for the new cooling tower
3	Site geological conditions which may result in unusually high site preparation or system installation costs
4	Existing underground infrastructure which may present significant interferences to the installation of circulating water lines
5	The need to reinforce existing condenser and water tunnels
6	The need for plume abatement
7	The presence of on- or off-site drift deposition constraints
8	The need for noise reduction measures
9	The need to bring in alternate sources of make-up water
10	Any related modifications to balance of plant equipment, particularly the auxiliary cooling systems, that may be necessitated by the retrofit
11	Re-optimization of the cooling water system or extensive modification or reinforcement of the existing condenser and circulating water tunnels

Figure 21-4 provides an indication of how well the estimating procedure described in Steps 1 and 2 compares with independently provided costs at individual plants for which sufficient plant and site information was available to permit a careful assessment of the factors in Table 21-3 and to assign an estimated degree of difficulty. The comparisons are shown for 25 plants. They represent both fossil and nuclear plants and cover a wide range of plant sizes, cooling water flow rates, source water types and degrees of difficulty. The agreement for all but a few plants is within +/-25% with no evidence of any systematic bias in the methodology.

Step 3 applies these cost correlations to all 428 eligible plants to determine the national cost which would be incurred if all were retrofitted (Table 21-4). The plants were divided into degrees of difficulty in the same proportion as was determined for the 125 plants for which individual, site-specific analyses were conducted.

In addition, estimates were made of three other significant cost elements. These were the cost of energy replacement during the time a plant is down for retrofitting, the annual cost of additional operating power for the cooling system pumps and fans and the annual cost of a heat rate penalty resulting from thermal limitations of the closed-cycle cooling system. The distribution of retrofit costs by source water type and cost element is shown in Table 21-5.

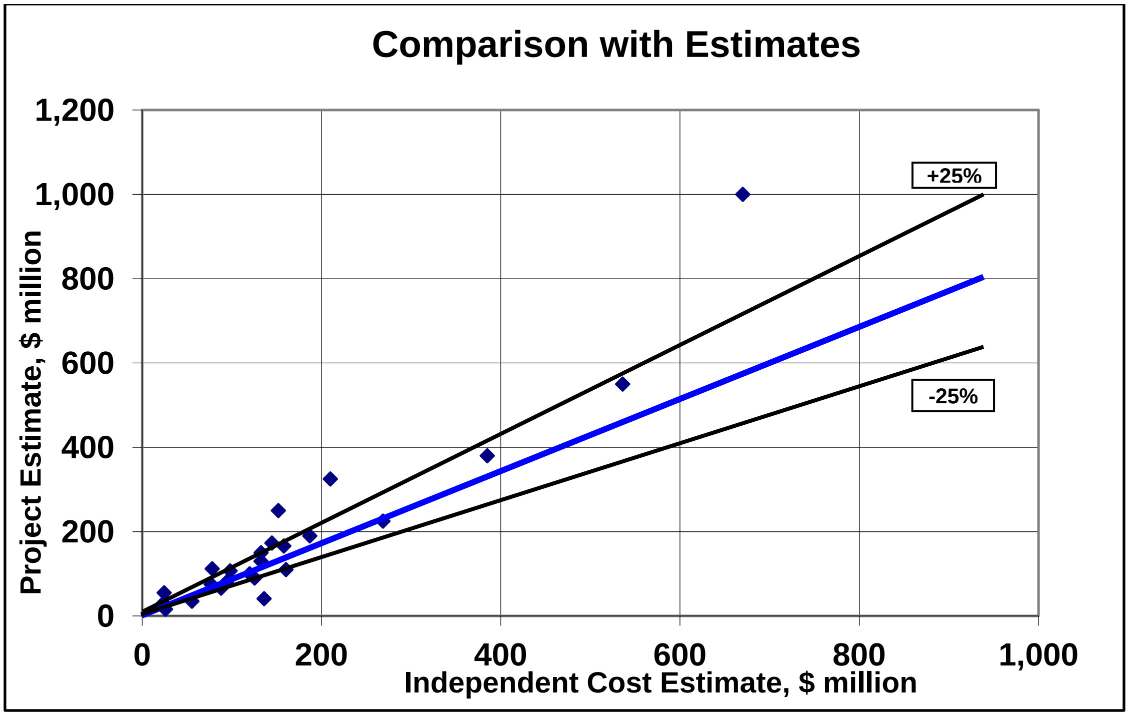

Figure 21-4
Comparison of estimates with independent cost information

Table 21-4
Distribution of capital costs by degree of difficulty

Plant Type	Degree of Difficulty	Allocation %	Capacity MW	Flow gpm	Cost $ Millions
Fossil	Easy	22%	55,440	30,691,540	$5,560
	Easy to Average	10%	25,200	13,950,700	$3,180
	Average	26%	65,520	36,271,820	$9,970
	Average to Difficult	13%	3,270	18,135,910	$6,170
	Difficult	24%	60,480	33,481,680	$13,560
	More Difficult	5%	12,600	6,975,350	$3,980
Total Fossil		100%	252,000	139,507,000	$42,420
Nuclear	Less Difficult	25%	15,000	10,697,000	$3,520
	More Difficult	25%	15,000	10,697,000	$8,270
	Intermediate	50%	30,000	21,394,000	$7,860
Total Nuclear		100%	60,000	42,788,000	$19,650
Total All Plants			312,000	182,295,000	$62,070

Table 21-5
Distribution of retrofit costs by source water type and cost element

Plant Type	Source Water	Capacity MW	Water Flow gpm	Costs ($ millions)					
				Capital	Operating Power	Heat Rate Penalty	Downtime	Annualized Cost	Net Present Value
Nuclear	Great Lakes	6,000	3,840,000	$1,760	$13	$16	$740	$200	$2,860
	Lakes/ Reservoirs	20,000	13,990,000	$6,420	$46	$60	$2,700	$740	$10,430
	O/E/TR	22,000	17,615,000	$8,090	$58	$75	$3,400	$940	$13,140
	Rivers	12,000	7,344,000	$3,370	$24	$31	$1,420	$390	$5,480
	Total Nuclear	60,000	42,789,000	$19,640	$141	$182	$8,260	$2,270	$31,910
Fossil	Great Lakes	27,000	14,242,000	$4,330	$44	$54	$920	$480	$6,450
	Lakes/ Reservoirs	61,000	32,831,000	$9,980	$100	$124	$2,120	$1,110	$14,890
	O/E/TR	70,000	41,923,000	$12,750	$128	$158	$2,710	$1,410	$19,010
	Rivers	94,000	50,511,000	$15,360	$155	$191	$3,260	$1,700	$22,910
	Total Fossil	252,000	139,507,000	$42,420	$427	$527	$9,010	$4,700	$63,260
All	Total All Plants	312,000	182,296,000	$62,060	$568	$709	$17,270	$6,970	$95,170

Note: O/E/TR: Oceans, estuaries and tidal rivers

Estimated Cost of Downtime

Individual site-specific estimates of the duration of the downtime required for a cooling system retrofit are beyond the scope of this study. Information was gathered from two sources. The first was the experience with actual retrofits at a few mid-sized fossil plants for which the approach to retrofit was as described earlier and illustrated in Figure 21-2. In this type of retrofit, the tower can be built and the new circulating lines and pumps installed while the plant is on-line. The only downtime is required in during the change-over when the new circulating loop to the tower is tied into the existing circulating loop through the condenser. Downtime for the plants ranged from 3 to 6 months. For plants with lengthy scheduled outages or for low capacity factor plants with long periods of non-operation, the actual "downtime" when the plant cannot operate for reasons solely related to the retrofit can be further reduced or, perhaps, eliminated.

On the other hand, special considerations apply at baseload plants with high capacity factors and long remaining life, as, for example, most nuclear plants and new, large coal plants. In such cases, the preferred retrofit may involve a "re-optimization" of the cooling system. Typically, this includes reducing the cooling water flow and modifying the steam condenser in order to enable the use of a smaller, more effective cooling tower and requires less operating power for the pumps and fans.

The procedure requires the removal, modification and replacement of the steam condenser which requires that the plant be off-line for an extended period. Estimates of downtime for re-optimization have been independently estimated at several plants to last at least 6 months and, in one case, for over eighteen months.

Conservative assumptions were made for the purpose of developing a national cost. It was assumed that all nuclear plants and coal plants with greater than 75% capacity factor and a remaining life of more than 5 years would require 6 months downtime. Of the remaining coal plants, all those ranked as "Easy" or "Average" retrofits were assumed to have no downtime; the "Difficult" plants, 4 months; the "More Difficult", 6 months. The lost energy output was evaluated at $35/MWh.

Additional Operating Power

The additional operating power required by a closed-cycle cooling system using a wet, mechanical-draft cooling tower consists of two parts: pumping power and fan power. The pumping power for the retrofitted system consists of both the power used by the original once-through cooled system, which remains essentially unchanged in most cases, and the added power required to pump the circulating water from the condenser exit to the top of the cooling tower. From there it is assumed that the water returns to the intake of the original circulating water pumps by gravity. A small amount of additional power is required to provide make-up to the closed-cycle system and to discharge blowdown form the system. However, these flows are a small fraction (typically less than 5%) of the recirculating flow, and this additional power is neglected in these estimates.

Consistent with that approach, the additional pumping power required is a function simply of the circulating water flow rate and the head required to convey the water from the condenser discharge sump to the distribution deck of the cooling tower, which is made up of the elevation change from the condenser discharge sump to the distribution deck plus the frictional pressure drop in the circulating water line to the tower. Both of these vary depending on the circulating water flow rate of the existing once-through system and the layout of the newly installed closed-cycle system. Using a plausible range of circulating water flows, tower heights, site elevation profiles, and separation distances between the cooling tower and the turbine hall, a range of additional pumping power requirements of from 0.3% to 1.1% of plant output was determined.

Similar assumptions can be used to estimate the amount of fan power required. The number of cells in the cooling tower varies with a number of factors including circulating water flow, the cooling range, the site climatological characteristics, the make-up water quality and the space available in which to place the tower. All of these factors influence the water loading per cell, the air flow per cell and fan horsepower required. Different, internally consistent sets of plausible values can lead to a wide range of fan power estimates. An average fan power of 0.6% of plant output was derived from many individual cases and is adopted for the purposes of developing a national estimate of additional operating power.

When added to average additional pumping power developed above, a total average operating power of 1.3% of plant output is used for the national cost estimates.

Heat Rate Penalty Cost

Conversion of a once-through cooling system to a closed-cycle cooling system using a wet cooling tower frequently results in an increase in the achievable turbine backpressure for most of the year and a corresponding loss of plant efficiency and output. In most circumstances, this loss is greatest during the hottest period of the year at precisely the time that the power requirement of the electrical network is at its peak.

A proper determination of the heat rate penalty requires a calculation of the plant output throughout the year on both the original once-through cooling system and the retrofitted closed-cycle system. This begins with a calculation of the condensing pressure as a function of the source water temperature in the case of once-through cooling and ambient wet bulb temperature in the case of the closed-cycle system. The variation in plant efficiency and output can then be calculated from the variation in condensing pressure, and the difference in plant performance both on an annual average basis and during the hottest period of the year can be determined.

These differences can vary widely from site to site as a function of several factors, the most important of which are source water temperature variation compared to atmospheric wet bulb temperature variation and steam turbine performance characteristics relating turbine output to turbine exhaust pressure. A large number of individual cases were analyzed and described in an EPRI report [6]. For purposes of developing a national cost estimate, an average value of 2% for 10% of the year was assumed for the hottest hours, and 1% for the remainder of the year.

Seasonal Operation

As noted earlier, the technical feasibility and cost associated with seasonal use of closed-cycle cooling during periods when fish and shellfish eggs and larvae are abundant, while using once-through cooling for the rest of the year, has not been previously explored. This study assesses the differences in system cost and annual performance between seasonal and full-time operation of closed-cycle cooling for a range of site and plant characteristics.

Seasonal operation is postulated to have two benefits in comparison to full-time closed-cycle operation while providing acceptable environmental protection. These are

- Reduced capital cost of cooling system retrofit and
- Reduced negative impact on plant efficiency and output

when compared to the cost and impact which would be incurred with a full-time closed-cycle system.

The reduction in capital cost results from the fact that a cooling tower design for springtime design conditions can be smaller and cheaper that one designed for summertime conditions. The reduction in performance penalties results from two factors:

- The cooling water available from the natural source used for once-through cooling during the summertime is typically colder than the water available from a cooling tower at the same location, and
- The additional operating power for the pumps and fans in a closed-cycle system is required for only part of the year.

The magnitude of these benefits is determined by both site and plant characteristics. The important site characteristics are:

- The difference between the peak springtime and summertime wet bulb temperatures.
- The comparative variability in source water temperature and ambient wet bulb temperature during the year, and particularly during the hottest periods in the summer.

The important plant characteristics are

- The variation in turbine efficiency and output as a function of turbine exhaust pressure
- The design and operating parameters of the existing once-through cooling system including the cooling water flow rate, the cooling water temperature increase and the condenser size and capability.

Approach

The study is conducted in several steps. These are:

1. The plant and site characteristics which affect the differences in cost and performance between seasonal and full-time closed-cycle cooling are identified.
2. Seven sites are selected to cover the range of these important plant/site characteristics. The plant and site characteristics are tabulated in Table 21-6.
3. For each site, closed-cycle cooling systems are chosen for both full-time and seasonal operation and the annual performance of each is determined as well as the baseline performance achieved with once-through cooling.

Table 21-6
Plant/unit and site characteristics of selected cases

Once-through Design Values	Plant A		Plant B	Plant C		Plant D	Plant E	Plant F	Plant G
	Units 1-3	Unit 4	Unit 1	Units 1-2	Units 3-4	Units 1-4	Units 1-2	Unit 1	Units 1-3
Gross Output, MW	100	500	595	385	660	833	1244	202	623
Heat Load, MMBtu/hr	522	2,398	3,900	1,900	3,021	4,200	8,525	950	3,767
Circ Flow, gpm	66,500	181,000	404,188	190,000	318,000	336,000	1,100,000	100,000	209,292
Design Inlet Temp., °F	80	60	56	69	70	57	74	49	46
Design Cond. Temp., °F	101	101	92	92	94	92	120	101	84
Design BP, "Hg	2	2.0	1.5	1.5	1.6	1.5	3.5	2.0	1.2
Cond Range, °F	15.7	26.5	19.3	20.0	19.0	25.0	15.5	19.0	36.0
Cond TTD, °F	5.7	14.9	16.47	2.8	4.9	10.0	30.0	33.0	2.0

Note: Output, heat load and circ. water flow values are for each unit at multi-unit plants

4. The reduction in gross plant output due to cooling system limitations on turbine output and the further reduction in net plant output resulting from cooling system operating power requirements are calculated throughout the year and are summed to determine the plant's annual energy output with each cooling system.
5. The reduction in plant output from both turbine output limitations and additional operating power requirements is assessed for each of the three cooling systems at each site.
6. Differences in retrofit costs are estimated and discussed.

Analysis and Assumptions

Analyses are made of the performance and yearly operating profiles for year-round once-through cooling, full-time closed-cycle cooling and seasonal of closed-cycle cooling.

Some general assumptions are:

- The basic design and operating parameters of the original once-through system are unchanged in either retrofit.
- The performance comparisons will be made on the basis of plant operation at full load for the entire year.
- The turbine and its performance characteristics are unchanged by the retrofit.
- Seasonal operation is defined as closed-cycle cooling during the months of March through June at all sites.
- The cooling towers for the full-time and seasonal systems will be designed to deliver the same cold water temperature; that is, the cold water temperature from the seasonal tower at the highest wet-bulb temperature during March through June will be the same as the cold water temperature from the full-time tower at the annual 0.4% wet bulb temperature.
- The design cold water temperature will be either the existing cooling system design temperature or, if this cannot be achieved at the summer design wet bulb, then a tower with a 5°F approach will be chosen for the full-time design.

The analysis consists of:

- An hour-by-hour calculation of the turbine exhaust pressure and turbine output with the existing once-through cooling systems. Monthly and annual output is determined.
- Comparable calculations of the turbine exhaust pressure and turbine output for a full-time closed-cycle cooling system with a tower designed to "summertime" conditions for each month of the year.
- The additional operating power required to provide the additional circulating water head rise and the cooling tower fan operation is determined and the associated reduction in net unit output is calculated for each month and summed for the year.
- Similar calculations for a seasonal closed-cycle cooling system designed to "spawning season" conditions for the months of March through June.

- The annual output for the seasonal system is determined assuming closed cycle operation during March through June and once-through cooling for the rest of the year.

Performance Results

Once-through Cooling

Once-through cooling is used as the baseline against which the two closed-cycle systems are compared.

- The once-through cooling systems are assumed to have been designed to allow full turbine output at the design source water temperatures listed in Table 21-6. During periods of the year when the source water temperature is higher than the design temperature, the turbine output will be reduced in accordance with the turbine heat rate curves. The results are listed in Table 21-7.
- In one case (Plant A 1-3) there is a slight increase in annual output. This results from the fact that the heat rate curve for this particular turbine shows a slight increase in output for turbine exhaust pressures below the design point.
- No penalty is assessed for once-through cooling operating power. Operating power penalties for the closed-cycle systems will be evaluated for operating power requirements in excess of the power consumed by the once-through cooling system.

Table 21-7
Once-through cooling performance

Site/Unit	Unit Capacity MW	Cooling Water Flow gpm	Normalized Flow gpm/MW	Baseline Output[1] MWh	OTC Heat Rate Penalty MWh	Actual Output MWh	Penalty as % of Baseline %
Plant A 1-3	100	66,500	665.0	876,000	-4,764	880,764	-0.54%
Plant A 4	500	181,000	362.0	4,380,000	14,191	4,365,809	0.32%
Plant B	595	404,188	679.3	5,212,200	15,760	5,196,440	0.30%
Plant C 1,2	385	190,000	493.5	3,372,600	159	3,372,441	0.00%
Plant C 3,4	660	318,000	481.8	5,781,600	237	5,781,363	0.00%
Plant D 1 & 4	811	336,000	414.3	7,104,360	13,539	7,090,821	0.19%
Plant D 2 & 3	833	336,000	403.4	7,297,080	6,898	7,290,182	0.09%
Plant E 1-2	1244	1,100,000	884.2	10,897,440	84,530	10,812,910	0.78%
Plant F	202	100,000	495.0	1,769,520	2,009	1,767,511	0.11%
Plant G 1-3	623	209,292	335.9	5,457,480	11,606	5,445,874	0.21%

[1] "Baseline output" equals design capacity for 8,760 hours

The reduction in plant output as a result of once-through cooling system limitations is consistently small and always less than 0.32% with the exception of Plant E 1-2 which has a 0.78% reduction. Plant E 1-2 is a two-unit nuclear plant with turbine characteristics that is very sensitive to increased turbine exhaust pressure.

Full-time Closed-cycle Cooling

The reduction in annual output as a result of a retrofit to closed-cycle cooling operated year-round is tabulated in Table 21-8. The additional auxiliary power required for increased pumping power and for the cooling tower fans varies from just over 0.8% to just over 2.3% of plant output. The heat rate penalty for reduced gross turbine output varies from essentially zero (Plant C) to almost 2% (Plants B and F). The total output reduction varies from 1% (Plant G) to almost 3.5% (Plants B and E), which are both nuclear plants. The average reduction for all cases is 1.86%

Table 21-8
Full-time closed cycle performance

Site/Unit	Unit Capacity MW	Add'l Aux. Power kW	Aux. Power Penalty MWh	Aux. Power as % of Capacity %	Heat Rate Penalty MWh	Ht. Rt. Penalty as % of OTC Output %	Total Output Reduction MWh	Total as % of OTC Actual %
Plant A 1-3	100	1,402	12,282	1.40%	1,984	0.23%	14,266	1.62%
Plant A 4	500	4,417	38,693	0.88%	16,015	0.37%	54,708	1.25%
Plant B	595	9,863	86,400	1.66%	94,831	1.82%	181,231	3.49%
Plant C 1,2	385	4,636	40,611	1.20%	381	0.01%	40,992	1.22%
Plant C 3,4	660	7,760	67,978	1.18%	518	0.01%	68,496	1.18%
Plant D 1 & 4	811	7,082	62,038	0.87%	31,618	0.45%	93,656	1.32%
Plant D 2 & 3	833	7,082	62,038	0.85%	18,173	0.25%	80,211	1.10%
Plant E 1-2	1,244	28,842	252,656	2.32%	114,211	1.06%	366,867	3.39%
Plant F	202	2,440	21,374	1.21%	30,398	1.72%	51,772	2.93%
Plant G 1-3	623	5,107	44,737	0.82%	12,314	0.23%	57,051	1.05%

Seasonal Closed-cycle Cooling

Performance results for closed-cycle systems with seasonal operation are shown in Table 21-9. The auxiliary power penalty exists only for the operating period of March through June and is zero for the remaining 8 months of the year. The heat rate penalty is equal to that for the once-through cooling system for 8 months of the year and equal to the penalty for closed-cycle operation only during the months of March through June. The total output reduction, as a percentage of actual once-through cooling operation varies from a low of 0.25% (Plant A 1-3) to

1.85% (Plant E 1-2). The average total output reduction is 1.04% of the once-through cooing output.

The last column in Table 21-9 shows the benefit of seasonal operation compared to year-round closed-cycle cooling expressed as a percentage of once-through cooing output. The benefit varies from 0.48% (Plant G) to 1.83% (Plant B) with an average benefit for all cases of just over 1%.

Cost Estimates

The cost comparisons between a retrofit designed for full-time operation vs. seasonal operation are estimated using the results of the previous study [10] of national retrofit costs for guidance.

- Cooling tower cost reductions are highly variable ranging from no savings to as much as a 50% cost reduction at sites where the summer time conditions are much hotter and more humid than the spawning season conditions [11].
- Cooling tower costs, however, make up typically only from 15 to 30% of the total retrofit costs, so the total retrofit savings would typically be less than 10%.
- The other retrofit costs could be increased by the additional complexity required to allow switching back and forth between once-through and closed-cycle operation. It was not possible to quantify or generalize these costs.
- The effect on plant downtime required to complete the retrofit might be reduced if the existing intake/discharge structures were left untouched in the retrofit.

Conclusions

Performance Effects

- Both full-time and seasonal closed-cycle cooling systems incurred a significant operating penalty in comparison to once-through cooling.
- For full-time closed-cycle systems, the reduction in gross turbine output averaged over the course of the year varies from essentially zero to almost 2%. The effect is generally higher for nuclear plants than for fossil plants.
- The additional operating power for closed-cycle system operation is a function of the normalized cooing water flow expressed as gpm/MW and varies from 0.8% to 2.3% as the normalized cooling water flow increases from 300 to 900 gpm/MW.
- The total reduction in plant output, expressed as a percentage of annual output with once-through cooling ranges from 1% to 3.5% for full-time closed-cycle operation and from 0.25% to 1.8% with seasonal operation. Again the greatest effect in both cases is for the nuclear plants which have both more sensitivity to turbine exhaust pressure and higher cooling water flows per unit capacity than do fossil plants.

Table 21-9
Seasonal closed-cycle cooling performance

Site/Unit	Unit Capacity MW	Additional Auxiliary Power Penalty Jan, Feb, Jul-Dec MWh	Additional Auxiliary Power Penalty Mar-Jun MWh	Heat Rate Penalty Jan, Feb, Jul-Dec MWh	Heat Rate Penalty Mar-Jun MWh	Total Output Reduction MWh	Total as % of OTC Actual %	Benefit vs. Full time MWh	Benefit as % of OTC Actual %
Plant A 1-3	100	0	4,104	-2,648	736	2,192	0.25%	12,074	1.37%
Plant A 4	500	0	11,171	11,733	9,710	32,614	0.75%	22,094	0.51%
Plant B	595	0	24,945	14,995	45,969	85,909	1.65%	95,322	1.83%
Plant C 1,2	385	0	14,706	43	143	14,892	0.44%	26,100	0.77%
Plant C 3,4	660	0	19,626	47	179	19,852	0.34%	48,644	0.84%
Plant D 1 & 4	811	0	20,737	11,335	22,422	54,494	0.77%	39,162	0.55%
Plant D 2 & 3	833	0	20,737	5,924	13,730	40,391	0.57%	53,265	0.75%
Plant E 1-2	1,244	0	67,888	67,394	64,655	199,937	1.85%	166,930	1.54%
Plant F	202	0	6,172	3,194	12,112	21,478	1.22%	30,294	1.71%
Plant G 1-3	623	0	12,917	10,827	7,331	31,075	0.57%	25,976	0.48%

Retrofit Costs

- Retrofit costs for full-time closed-cycle systems were taken from the results of a recent EPRI study on national retrofit costs [6]. Cost estimates are highly dependent on the site-specific characteristics of the plant to be retrofitted, range from $181/gpm to $570/gpm for fossil plants and from $274/gpm to $644/gpm for nuclear plants.
- Capital costs savings from seasonal rather than full-time closed-cycle system designs, resulting from the ability to use a smaller cooling tower consistent with lower wet bulb temperatures during the spawning season compared to the summer would typically be no more than 10%.
- The other retrofit costs could be increased by the additional complexity required to allow switching back and forth between once-through and closed-cycle operation. It was not possible to quantify or generalize these costs.
- The effect on plant downtime required to complete the retrofit might be reduced if the existing intake/discharge structures were left untouched in the retrofit.

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22

APPLICATION OF THERMAL IMAGERY TO OPTIMIZATION OF COOLING LAKE PERFORMANCE

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Abstract

The surface area of a power plant cooling lake is the primary determinant of how many megawatts of waste heat it can dissipate while keeping maximum temperatures below regulatory and/or biologically significant limits. Optimization of lake cooling performance requires placing the cooling water inlet and discharge in locations that minimize flow configurations that lead to bypassing of significant parts of the lake. Thermal imagery is an excellent tool for understanding flow configuration in existing cooling lakes because areas being bypassed by the discharged cooling water as it flows to the intake will appear as cool zones in the imagery. This paper presents several examples of thermal images of power plant cooling lakes and other aqueous thermal dissipation systems collected by the Department of Energy's (DOE) Multi-spectral Thermal Imager (MTI) satellite. MTI has sufficient spatial resolution (20 m) in thermal wave bands to resolve temperature distributions created by discharge of thermal effluent on the scale typical of US power plants. The actual thermal imagery is compared to 3-D hydrodynamic simulations performed by the Savannah River National Laboratory (SRNL) to help explain the observed temperature distributions. Additional simulations will be presented in which the locations of the cooling water discharge, intake or flow baffles have been changed to make better use of the total lake surface area. (These modifications are hypothetical and illustrative; they were not requested or endorsed by the power plant owners.) The improvement in performance will be quantified in terms of reduced average cooling water inlet temperature and equivalent potential increase in operating power.

Background

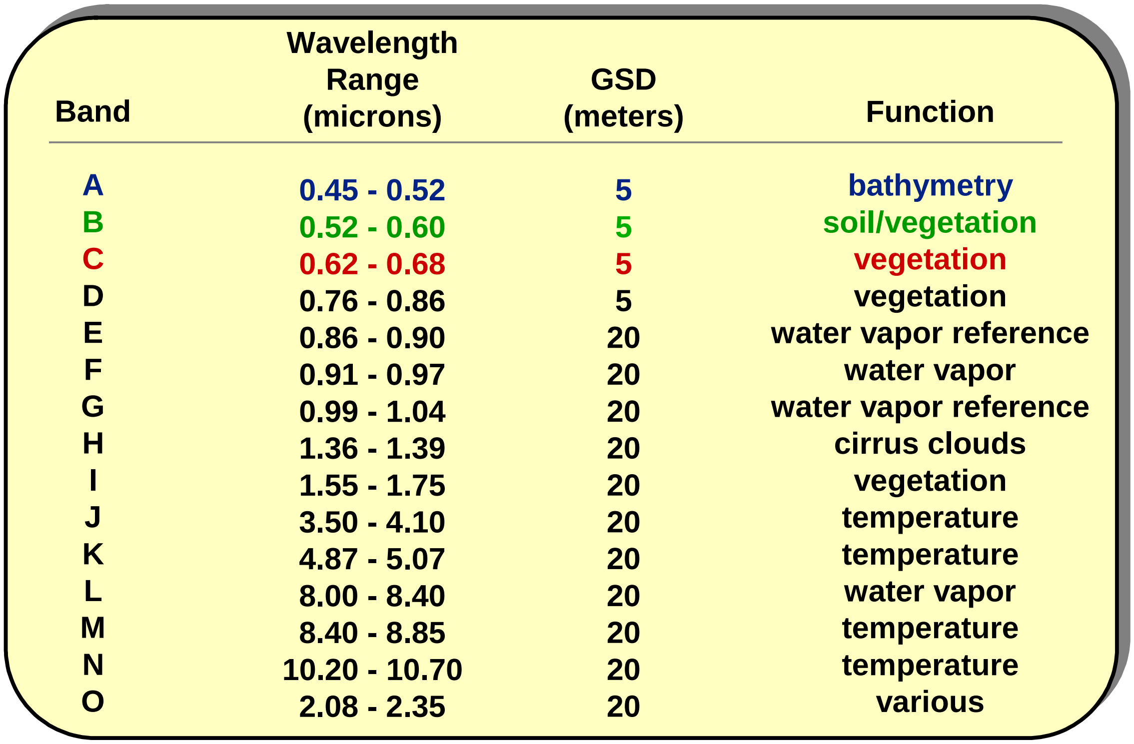
SRNL has performed research on applications of thermal imagery to analyses of power plant operations for more than 20 years. SRNL developed methods to use thermal images to remotely measure temperatures and to estimate heat losses from cooling lakes, cooling towers (natural and mechanical draft) and from direct thermal discharges to rivers and the ocean [1, 2, 3, 4, 5, 6]. Much of this research was a part of DOE's MTI satellite project [7], done to demonstrate the value of high resolution multi-spectral imagery to environmental monitoring and to conduct analyses relating to nuclear proliferation. Additional research since the MTI Project has been supported by the National Nuclear Security Administration (NNSA). Aspects of this research might be useful in analytical studies directed at optimization of cooling lake performance.

Cooling lake dynamics and heat transfer are tightly coupled because temperature gradients in a heated lake produce water density gradients and currents that tend to spread heated effluent over entire lake via a 3-D circulation. This implies that a simulation that reproduces an accurately calibrated thermal image must be an accurate simulation of 3-D circulation, thermal heat load and rate of heat loss to atmosphere. Factors that can cause suboptimal use of lake surface area are lake geometry and intake/discharge locations and effluent discharge structure. "Hydraulic short-circuits" occur when cooling water bypasses parts of the lake as it flows from discharge to intake. Underutilized areas can be detected through use of thermal imagery taken either from a satellite or aircraft. Typically, 20 to 30 images taken in different weather conditions over several months to a year will lead to a more complete understanding of underutilization.

Multi-Spectral Thermal Imager (MTI) Project

The MTI satellite is a DOE project created to develop precise radiometric remote sensing techniques. A key feature of the MTI satellite, thermometry, is performed using multiple bands. MTI was launched on March 12, 2000, and is still operational. Many targets were imaged by MTI, including several power plants. At these sites two years of imagery and ground truth were collected for use in model validation.

The MTI satellite measures upwelling radiance from the earth in 15 wavebands that span the visible, near infrared, mid-wave and long-wave (thermal) parts of the electromagnetic spectrum. Figure 22-1 lists those wavebands and the reasons they were selected. The first four wavebands have spatial resolution of 5 m, whereas the other 11 have a resolution of 20 m, a high resolution compared to any other commercially available satellite. For example, NASA's Landsat has a resolution of 60 m in its thermal wavebands.



Band	Wavelength Range (microns)	GSD (meters)	Function
A	0.45 - 0.52	5	bathymetry
B	0.52 - 0.60	5	soil/vegetation
C	0.62 - 0.68	5	vegetation
D	0.76 - 0.86	5	vegetation
E	0.86 - 0.90	20	water vapor reference
F	0.91 - 0.97	20	water vapor
G	0.99 - 1.04	20	water vapor reference
H	1.36 - 1.39	20	cirrus clouds
I	1.55 - 1.75	20	vegetation
J	3.50 - 4.10	20	temperature
K	4.87 - 5.07	20	temperature
L	8.00 - 8.40	20	water vapor
M	8.40 - 8.85	20	temperature
N	10.20 - 10.70	20	temperature
O	2.08 - 2.35	20	various

Figure 22-1
MTI wavebands, ground sampling distance (GSD, also pixel size) and waveband function

SRNL was the DOE laboratory with primary responsibility for MTI ground truth collections. SRNL selected 14 MTI “core” ground truth collection sites based on validation requirements for MTI science algorithms. These sites are owned and managed by DOE, other government agencies and electric power utilities. SRNL developed collaborative relationships with these organizations, in which MTI imagery was exchanged for site access and support (plant operating data, monitoring of SRNL instrumentation). Four of those sites were selected for this presentation to illustrate MTI’s capabilities and hypothetical alterations to their cooling system configuration that would make them more efficient at dissipating waste heat. These four sites with their type of aqueous thermal discharge are as follows:

- H. B. Robinson, South Carolina – cooling lake with long discharge canal
- Comanche Peak, Texas – cooling lake
- Turkey Point, Florida – cooling canals
- Pilgrim, Massachusetts – ocean discharge

One additional site, a subject of a DOE-funded research project but not part of the MTI project, was selected for inclusion in this presentation:

- Midland, Michigan – cooling lake (ice formation)

H. B. Robinson

The H. B. Robinson (HBR) Power Plant, near Hartsville, South Carolina, consists of one 750 MWe nuclear unit and one 170 MWe fossil unit. Waste heat is dissipated in the environment by a 2280 acre (9.2 km^2) cooling lake with a 6.2 km discharge canal. The cooling lake is long and shallow (Figure 22-2).

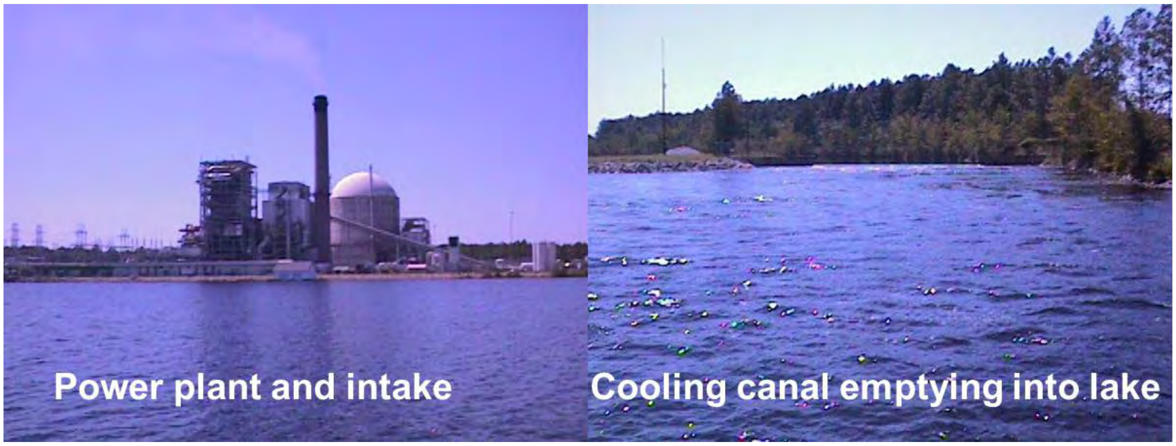


Figure 22-2
H. B. Robinson Power Plant and Cooling Lake

The upper end of the lake is separated by a road from the rest of the lake that is barely discernible in a thermal image because it is much cooler. Only a small part of the heat from the HBR power plant reaches that part of the lake because the channel under the road is narrow. The road and bridge that separate the upper part of the HBR cooling lake from the main body of the lake can be seen in the false color image on the left side of Figure 22-3. This image of the HBR site and cooling lake was created from the 5 m MTI wavebands. Figure 22-3 also compares an MTI thermal image (Band N) to a simulated thermal image created from a hydrodynamic simulation by a code developed by SRNL [4, 5, 6]. The gradual cooling of the water (yellow is hottest; red, cooler; black, coldest) is apparent as it flows from the end of the discharge canal to the cooling water intake at the lower end of the lake. The color in the simulated image was scaled in a way that excluded the discharge canal (white). This was done to match temperatures in the simulated image to the corresponding temperatures and colors in the MTI thermal image. The discharge canal is about 20 m wide, the width of one MTI pixel. For this reason, the canal is not well-resolved by MTI, so the radiance from the warm discharge water mixed with the radiance from the cooler adjacent land pixels, resulting in a canal that looks cooler than it actually was. This problem did not exist for the simulated image, so it was necessary to exclude the discharge canal from the scaling of the simulated image for the rest of the two images to match.

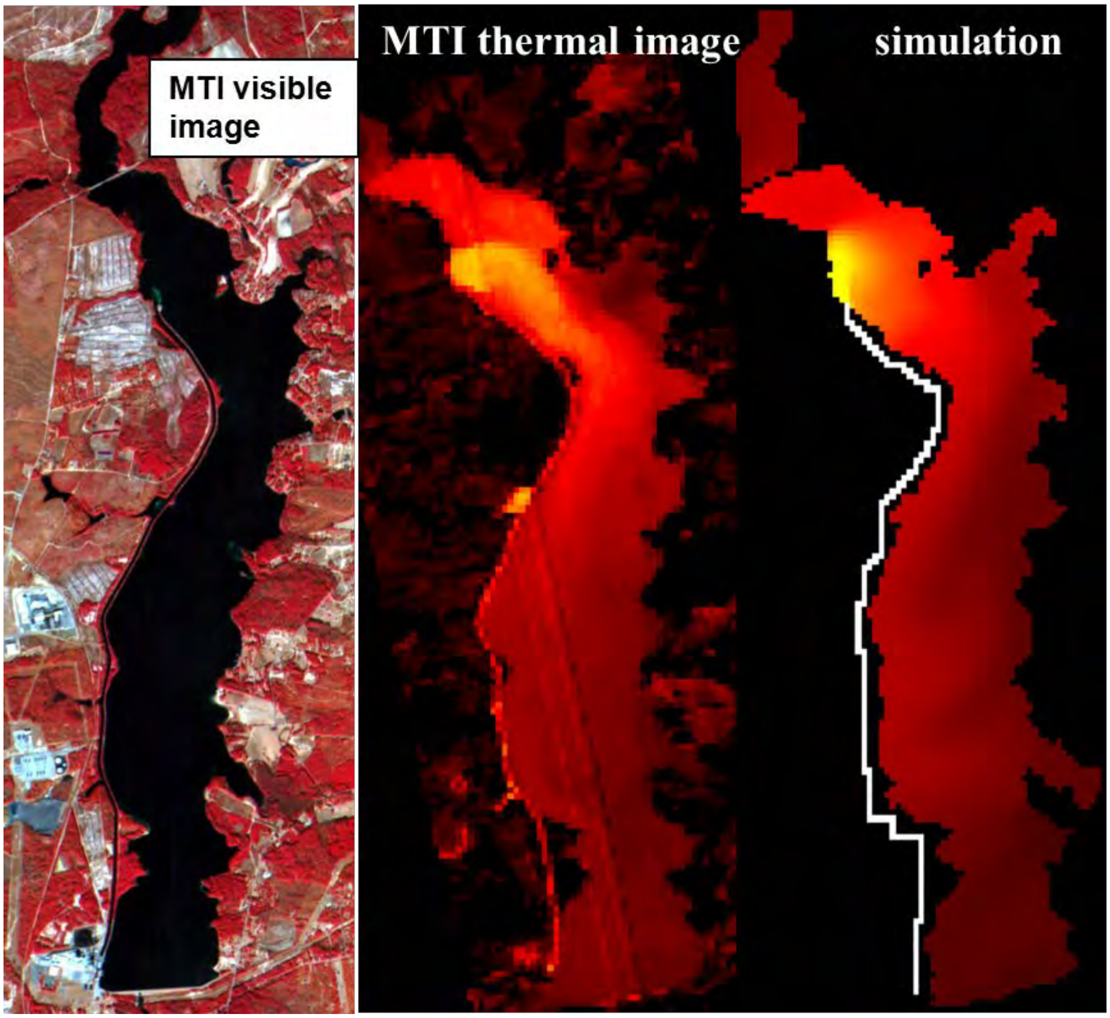
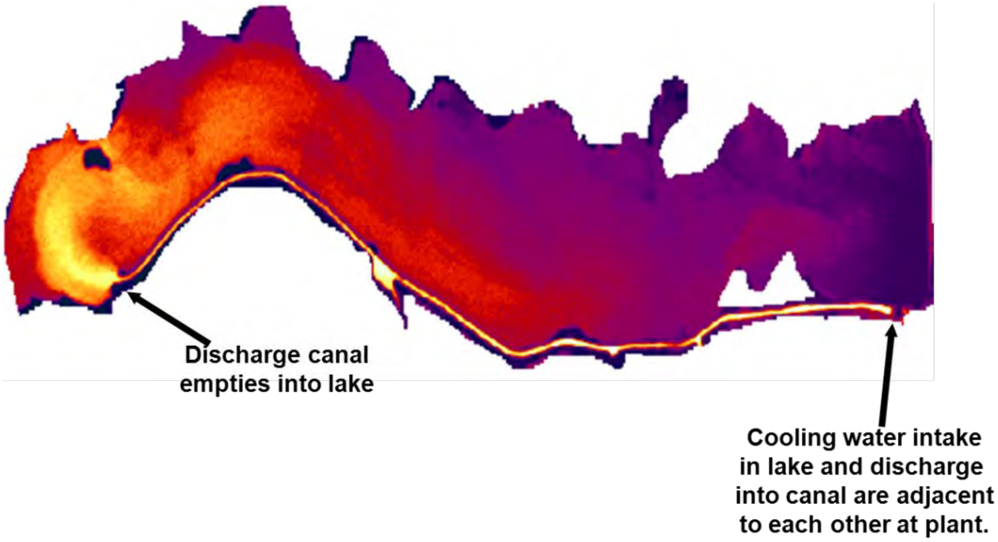


Figure 22-3
MTI visible image (road and bridge crosses upper part of lake), thermal image and simulated thermal image of HBR cooling lake. Heated water is discharged into canal at power plant on lower left corner of lake. Heated water enters lake at end of canal at location most clearly seen in simulated image.

Although a satellite with thermal imaging capabilities is the most convenient way to take thermal images of a large cooling lake, high resolution thermal images can also be created from mosaics of thermal images taken from an aircraft. Figure 22-4 is an example of a mosaicked thermal image of the HBR cooling lake created by SRNL from several images taken of the lake from a helicopter that hovered at an elevation of several thousand feet. Software to mosaic images is available, but the process is somewhat laborious. The images taken to produce Figure 22-4 were all collected within a few minutes, so no discontinuities were along the edges of the individual frames that were combined to produce the image of the entire lake.



Discharge canal empties into lake

Cooling water intake in lake and discharge into canal are adjacent to each other at plant.

Figure 22-4
Thermal image of HBR cooling lake created by combining several thermal images taken from a helicopter into a single mosaic

Since the HBR cooling lake makes use of a long discharge canal to empty its heated water into the lake at a location far from the cooling water intake, the lake is most likely efficiently making use of most of the surface area for cooling. However, as noted above, the upper end of the lake is almost separated from the rest of the lake by a bridge that has a narrow (10 m) channel underneath that connects the two parts of the lake. To investigate the potential improvement in cooling efficiency by relocating the cooling water discharge further up the lake, 3-D hydrodynamic simulations of the period from October 1, 2000, to January 2, 2002, were performed. The MTI satellite imaged the cooling lake during this period about 20 times. Based on plant operating data, a constant heat load of 1536 MW, a 582,000 gpm cooling water flow, 10ºC cooling water temperature rise between inlet and discharge except for outage were used to perform the simulation along with the local weather data from the National Weather Service.

Using the actual lake outfall location, average simulated versus measured cooling water inlet and discharge temperatures were as follows:

	Measured	**Simulated**
CW Discharge	31.5°C	31.9°C
CW Inlet	21.9°C	22.6°C

Figure 22-5 compares hourly measured cooling water inlet temperatures to corresponding simulated temperatures from late 2000 through most of 2001. The agreement is generally constant with occasional deviations of 2 to 3°C. Some of these discrepancies can be attributed to short-term variations in cooling water flow rate and temperature since only average values were used in the simulation. The others can be attributed to input inaccuracies and model limitations relative to the real system.

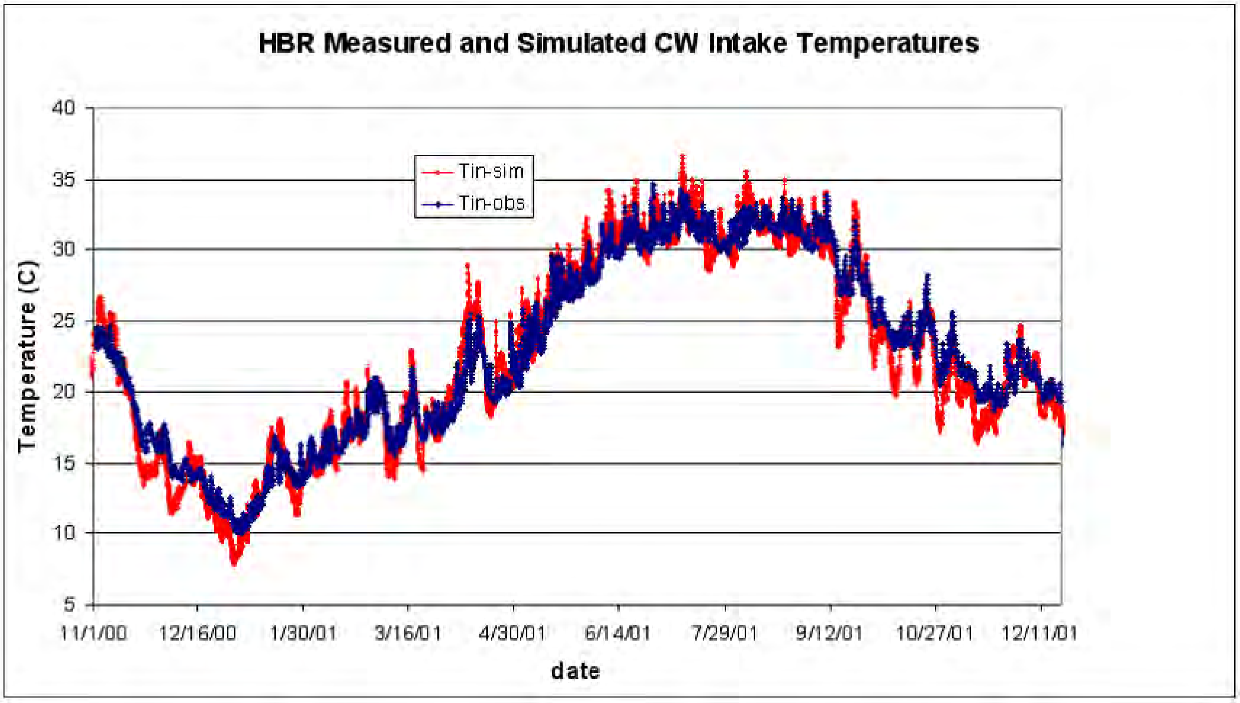


Figure 22-5
Comparison of Measured and Simulated Cooling Water Inlet Temperatures for HBR Cooling Lake from November 1, 2000, to December 15, 2001

Figure 22-6 compares hourly measured cooling water discharge temperatures to corresponding simulated temperatures for late 2000 through most of 2001. The agreement is again generally constant, with occasional discrepancies similar to those in Figure 22-5.

Figure 22-6 clearly shows an apparent outage in April 2001. The agreement between measured and simulated temperatures in Figure 22-5 and Figure 22-6 is steady enough to imply that the code can be used to explore the effects of possible alterations in the discharge location.

Two modified discharge points were then simulated: (1) halfway to road at upper end of lake, and (2) discharge into upper lake on far side of road. The first modification only lowered the temperature at the cooling water inlet by 0.1ºC. The second modification lowered the average temperature at the cooling water inlet by 0.4ºC. Figure 22-7 presents these results graphically. This relatively modest improvement in cooling lake performance is attributed to the already optimized locations of the cooling water discharge and intake structures.

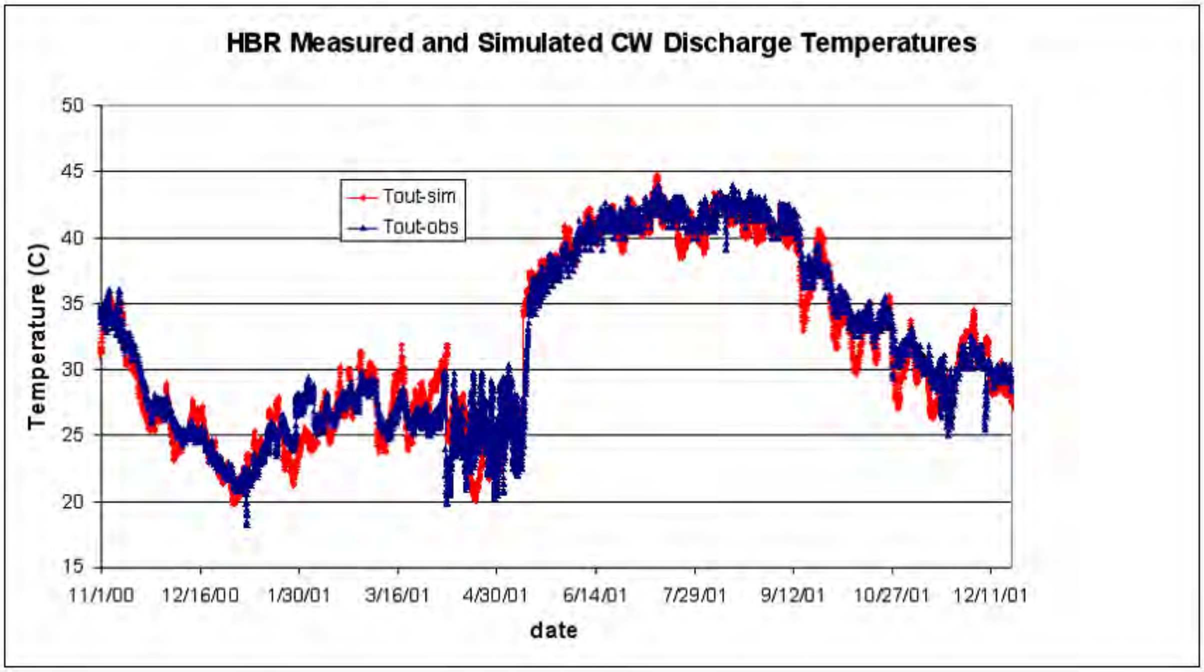


Figure 22-6
Comparison of Measured and Simulated Cooling Water Discharge Temperatures for HBR Cooling Lake from November 1, 2000, to December 15, 2001

Comanche Peak

The Comanche Peak Nuclear Power Plant is in north central Texas, southwest of Fort Worth. The two 1150 MWe units discharge approximately 4500 MW of waste heat into the cooling lake (Squaw Creek Reservoir). The cooling lake has an area of 3270 acres and a cooling water flow rate of 2.2×10^6 gpm. The power plant discharges heated water into one of the arms of the lake and draws cooling water from the inlet structure on the other side of the arm (Figure 22-8). Relative to the HBR cooling lake, more potential exists for short-circuiting of parts of the lake and lower cooling efficiency.

Figure 22-9 compares a calibrated MTI thermal image to the corresponding simulation on September 3, 2000. Surface velocity vectors are superimposed on the color-coded temperature field in the simulated image. These velocity vectors show that pressure gradients created by the temperature gradients in the lake tend to force the heated water over the entire surface area of the lake.

Figure 22-10 shows simulated temperatures and velocity vectors from the simulation at a depth of 9 m. The 3-D circulation created by the forced flow from the discharge and intake and the density-driven currents that arise from the temperature gradients includes a subsurface return flow that enters not only the cooling water inlet but also returns up the arm of the lake where the discharge is located.

An obvious option for improving the cooling efficiency of this lake is to move the cooling water inlet to the upper end of the lake. This simulation was run for the summer months of 2000. The result was a fairly large 1.5°C decrease in the average cooling water inlet temperature.

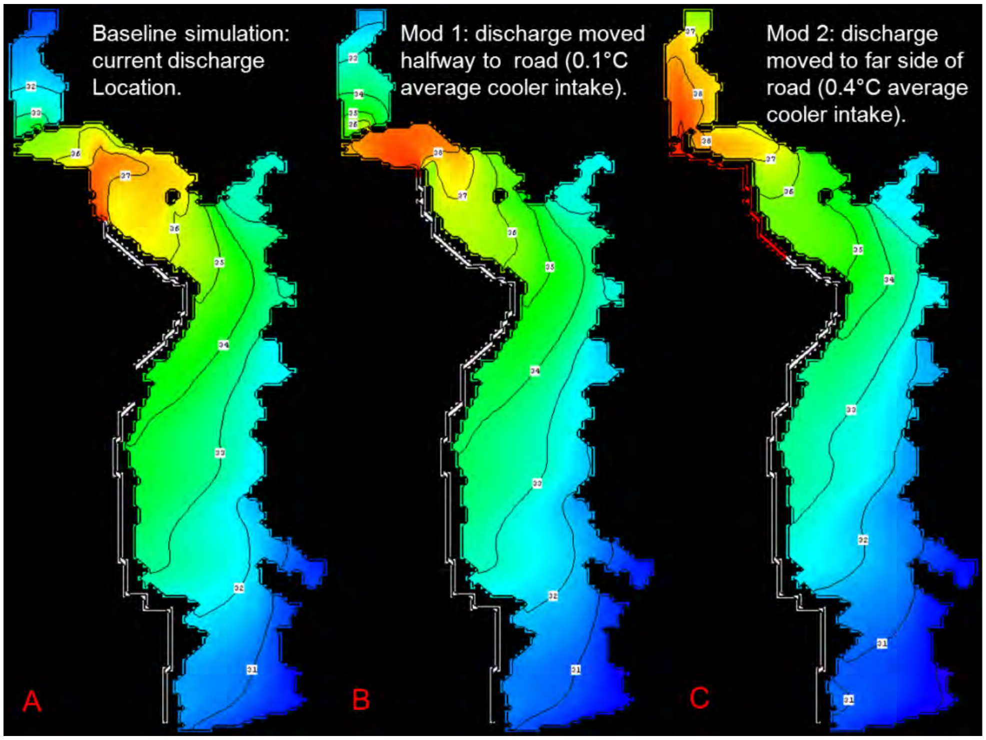


Figure 22-7
Comparison of HBR cooling lake simulations with (A) current discharge location, (B) discharge moved further up lake but below bridge, (C) discharge moved to far side of bridge

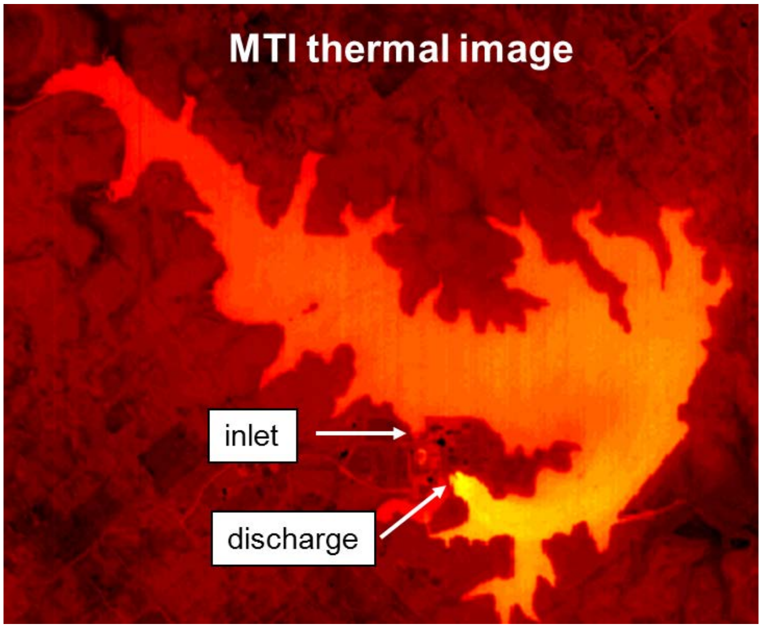


Figure 22-8
Comanche Peak Nuclear Power Plant Cooling Lake. Cooling water discharge and inlets are on different sides of a major side arm of the lake.

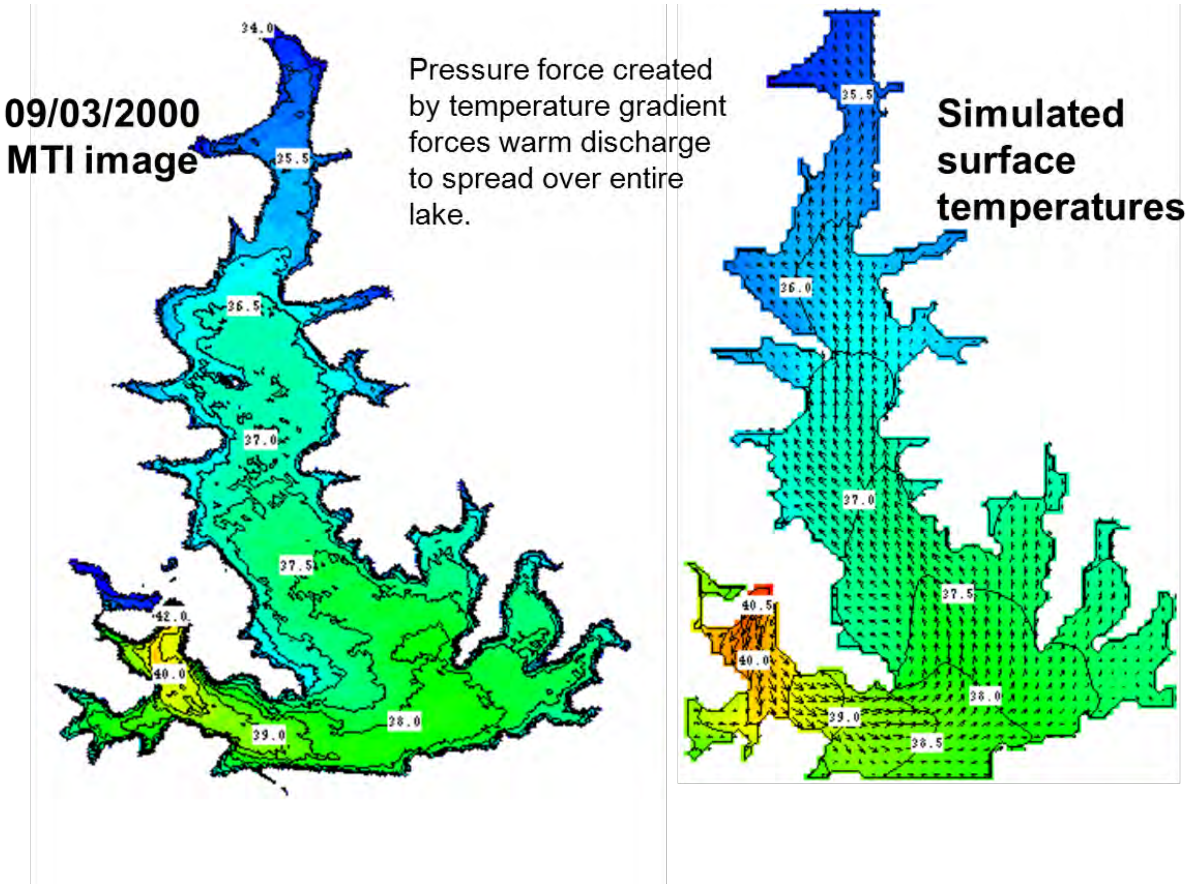


Figure 22-9
Comparison of calibrated MTI thermal image taken on September 3, 2000, to simulated image. Simulated surface velocity vectors are plotted on the simulated temperature field to show pressure force from temperature gradient forces heated water to spread over entire lake.

Turkey Point Power Plant

The Turkey Point combined nuclear and fossil-fuel power plant is on the edge of Biscayne Bay, Florida, south of Miami. The plant consists of two 720 MWe nuclear units and two 405 MWe fossil units. The cooling system is an 8.4 km by 3.6 km area with 31 shallow cooling canals, each 60 m wide (Figure 22-11). Flow into individual canals is controlled by varying the width of the entrances.

Figure 22-12 displays an MTI image and a mosaic created from several images taken from a helicopter. The MTI and mosaic images were taken on different days. Note some indication of flow mal-distribution occurs with cooler water apparent in the lower left part of the images. This implies some flow bypass was occurring because the cooling water collects in the transverse canal at the bottom of the system and returns to the power plant via the several canals on the right side of the images separated from the rest of the array by a wider dike accommodating vehicle traffic.

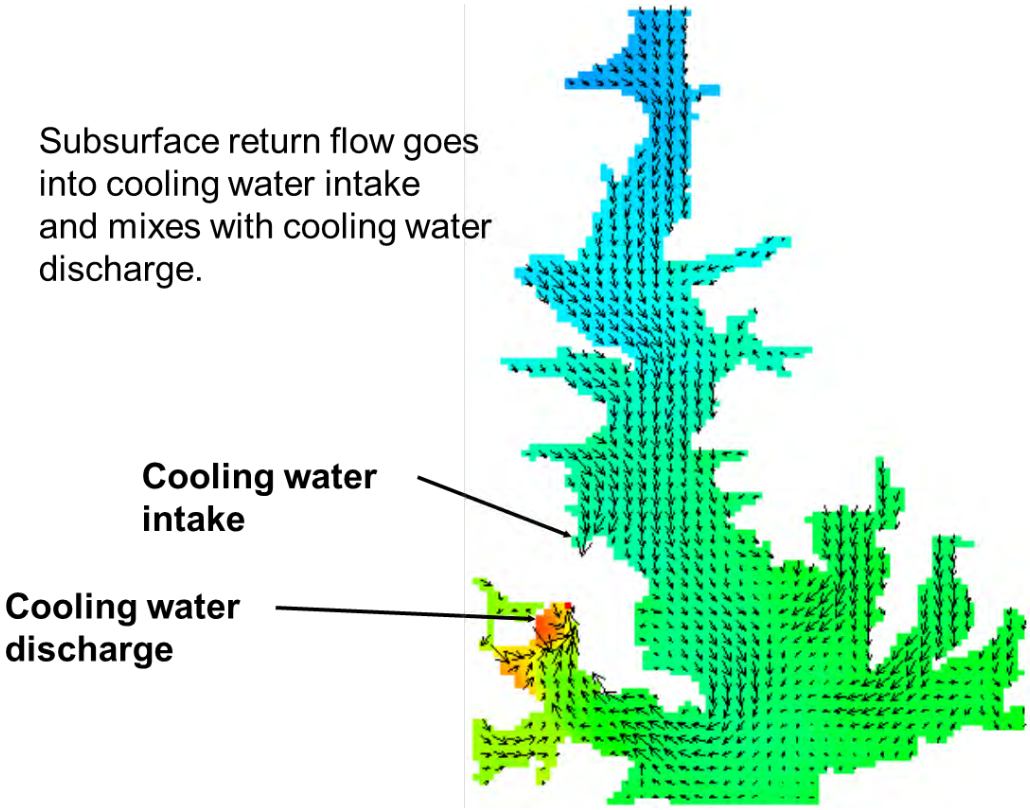

Subsurface return flow goes into cooling water intake and mixes with cooling water discharge.

Figure 22-10
Simulated Temperatures in Comanche Peak Nuclear Power Plant cooling lake at a depth of 9 m with velocity vectors superimposed

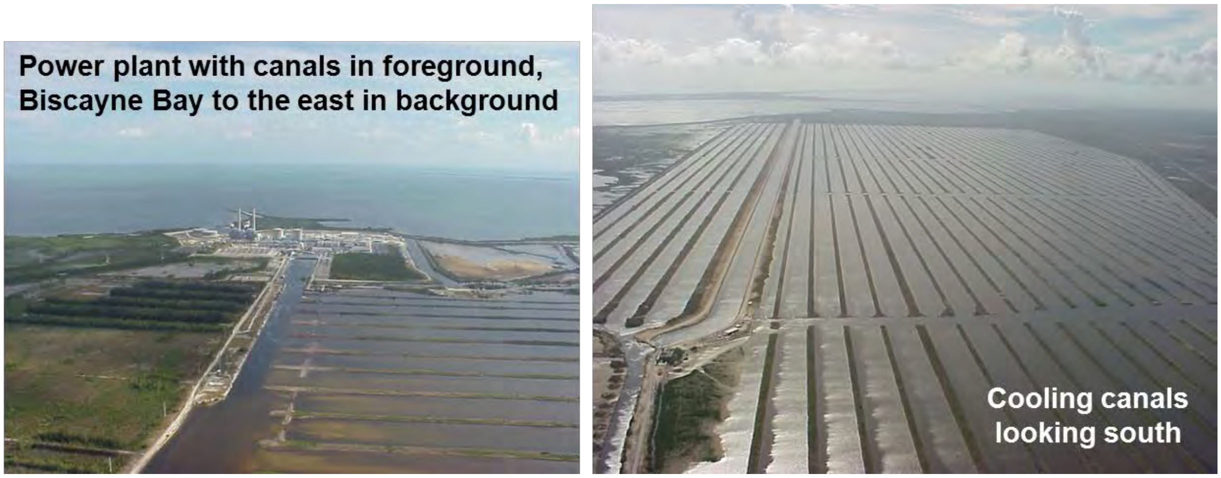


Figure 22-11
Turkey Point Power Plant with cooling canals in foreground (left) and view of entire system of cooling canals (right)

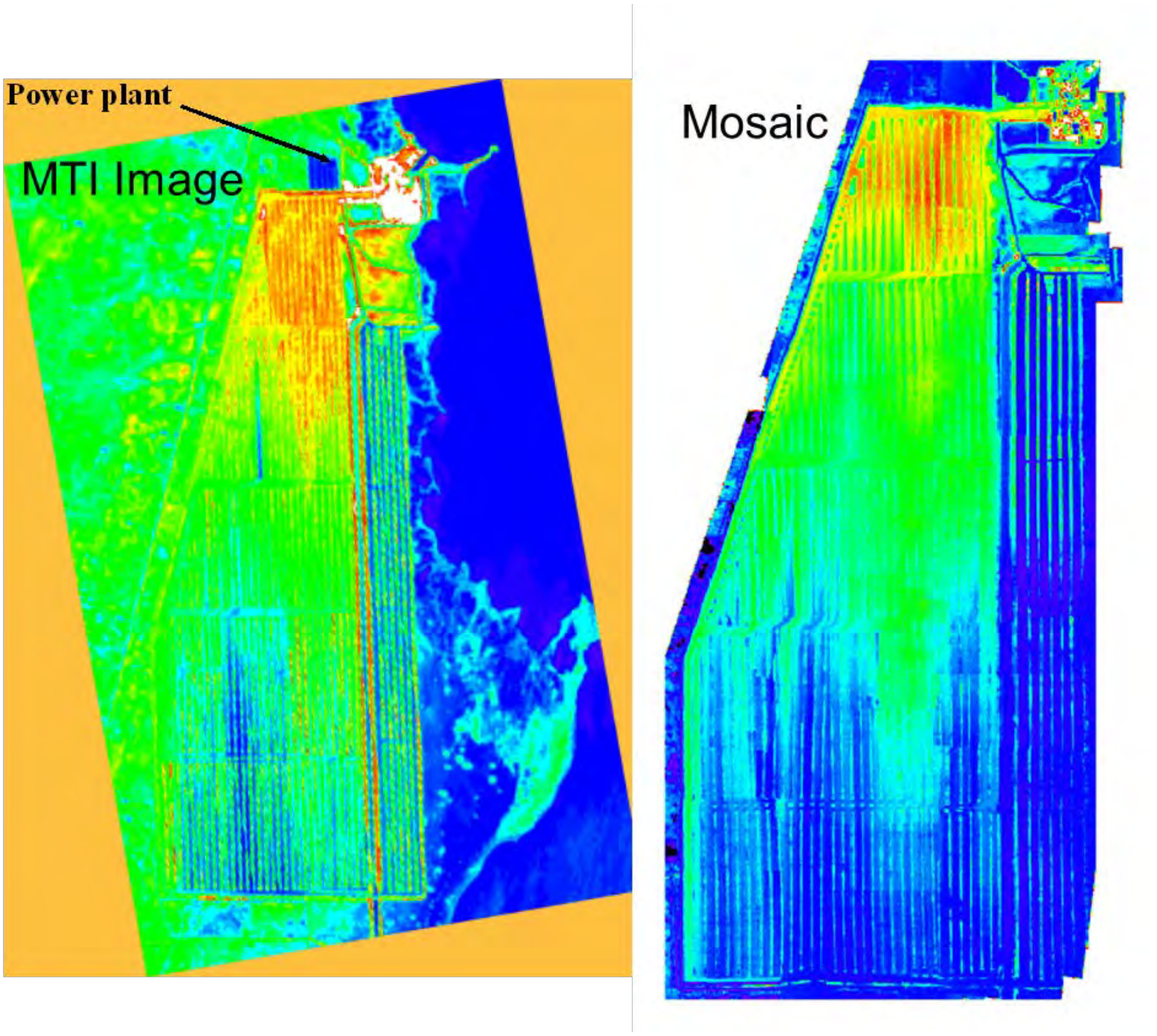


Figure 22-12
MTI thermal image and mosaic image of Turkey Point Power Plant cooling canal system. Cooler water in lower left parts of images (particularly MTI image) suggests some flow mal-distribution and bypass.

Maintaining even flow distribution in this complex system of canals is difficult. A possible alternative configuration consists of a series of baffles that allow only one pathway for the flow, but fewer in number, which increases the total surface area available for heat loss to the atmosphere. Testing this hypothetical reconfiguration first required reproducing the observed flow and temperature pattern with the hydrodynamic code. Figure 22-13 shows the result of this simulation (A) and also the result when the simple set of baffles replaces the complex system of parallel canals (B). The simulation with the actual canal configuration reproduces the cooler water in the lower left part of the domain.

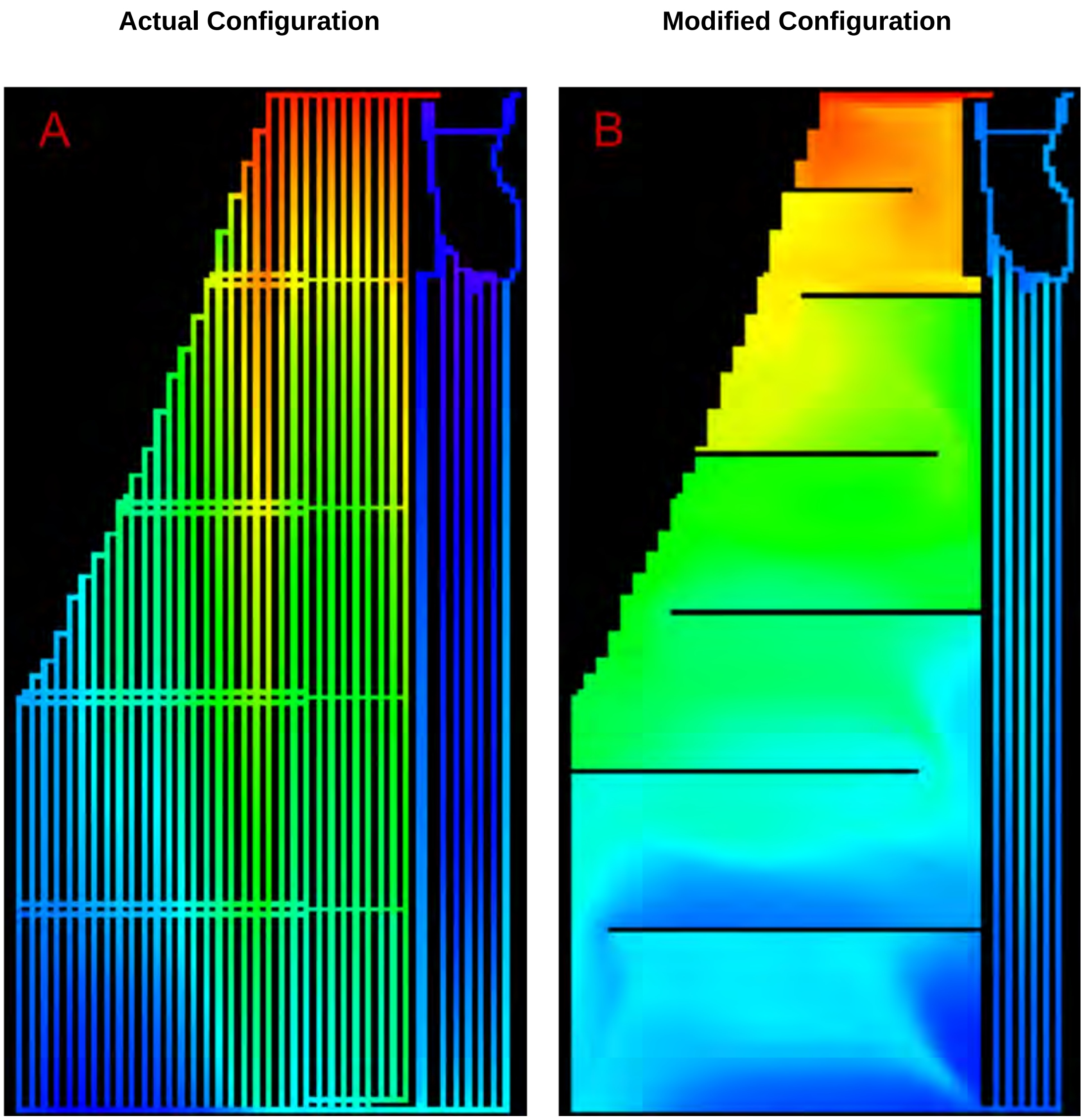


Figure 22-13
Simulation of Turkey Point Power Plant cooling canal system using (A) current canal configuration and (B) hypothetical alternative configuration that uses a smaller number of baffles to direct the flow

The temperature field from the simulation that used the baffles indicates still some limited flow bypass. However, the increase in water surface area more than compensated for this. Figure 22-14 displays time series of computed cooling water inlet temperatures from the two simulations. The modified design always led to a lower cooling water inlet temperature. On the average, the modified canal configuration produced an inlet temperature 1.2°C colder than the existing design. The average cooling water inlet temperature is slightly cooler than the average air temperature. This is possible because the average dew point temperature was 16.5°C, well below the 20.7°C average inlet temperature for the modified configuration. The average inlet temperature can be cooler than the average air temperature because most heat of the heat loss from a cooling lake is via evaporation, which is a function of the difference between the dew point temperature and the water surface temperature.

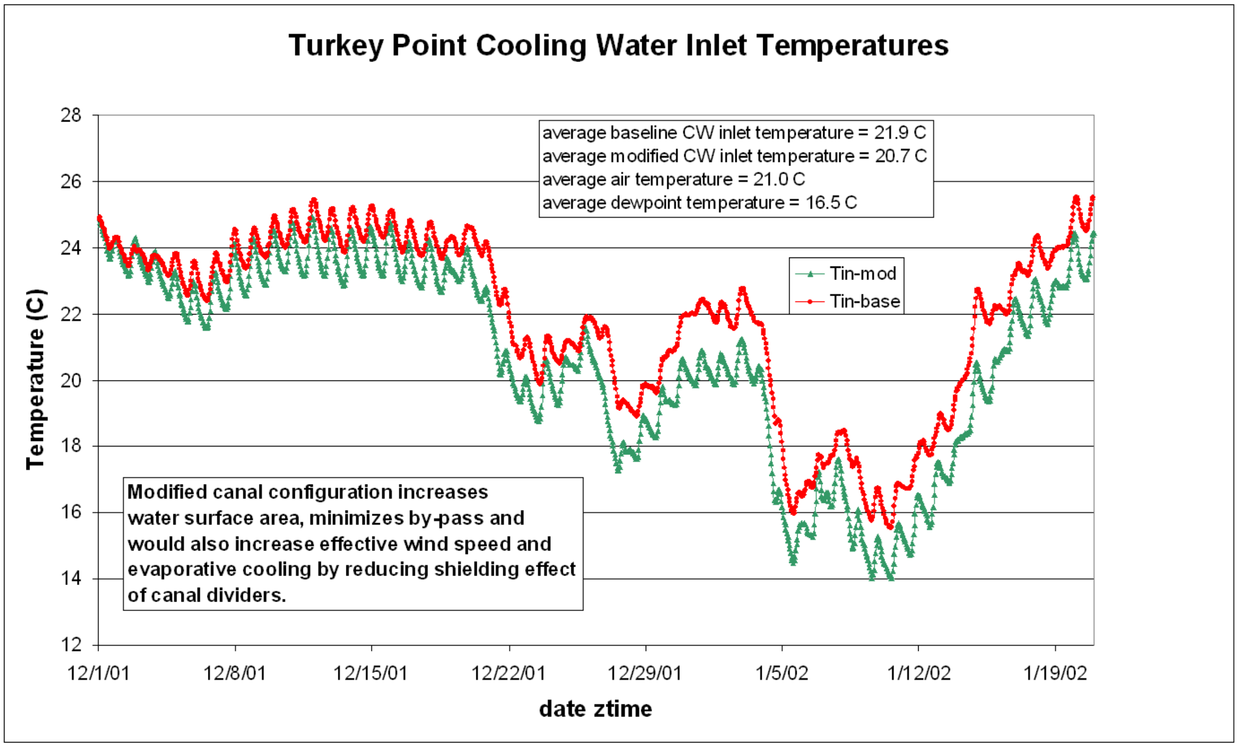


Figure 22-14
Comparison of time series of computed cooling water inlet temperatures for Turkey Point Power Plant current canal configuration and hypothetical configuration shown in Figure 22-13B

Pilgrim Power Plant

Pilgrim Power Plant (PPP) is a single unit (690 MWe) nuclear power plant on Massachusetts Bay just south of Plymouth, MA. The power plant uses seawater for once-through cooling (Figure 22-15) to discharge approximately 1400 MW of waste heat to the ocean.

The cooling water inlet bay is protected by breakwaters that protect it from large waves created by winter storms. The breakwater can be seen in Figure 22-15 and Figure 22-16, showing the discharge canal and the protected intake bay. Although PPP is in an area that experiences large tidal amplitudes of approximately 3 m, the local currents that dissipate the thermal plume from the plant are controlled by the wind rather than tidal currents. This is the case because PPP is on a point where both the incoming and ebbing tidal currents converge to produce a stagnation point; i.e., a location where the tidal component of the current is weak. As a result, wind stress is the primary forcing for the movement of the thermal plume.

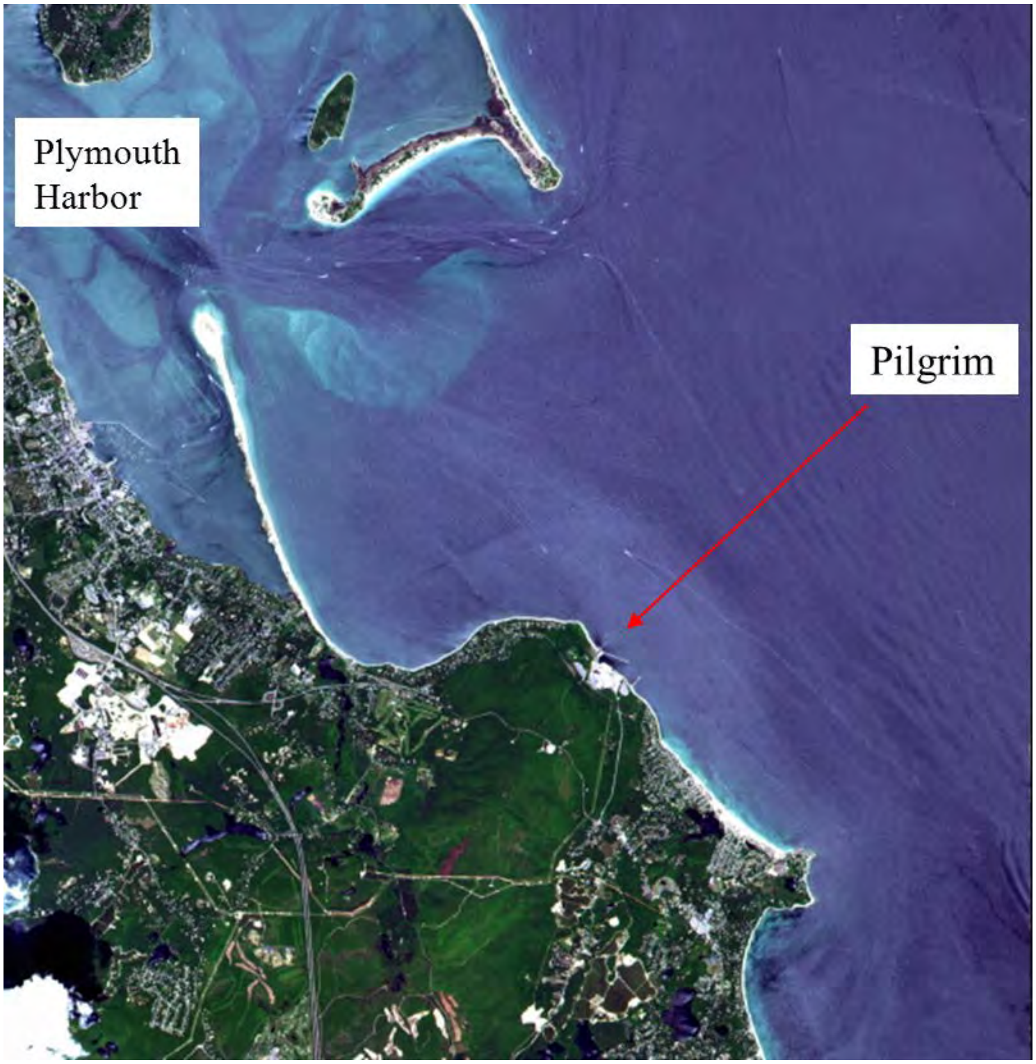


Figure 22-15
Pilgrim Power Plant, just south of Plymouth, Massachusetts

Figure 22-17 compares calibrated MTI images of thermal plumes from PPP to simulations on days when the wind-generated currents blew the thermal plume from left to right across the image domain (left images) and when the wind-generated current blew the thermal plume directly offshore (right images). In both cases, the simulation did a suitable job of reproducing the actual thermal plume, including recirculation of some of the heated water back into the cooling water intake. This recirculation is actually more pronounced in the MTI images than in the simulation, largely because the simulations did not include the full amount of time that the thermal plume was passing by the entrance to the intake bay. This recirculation is difficult to quantify or even identify in thermocouple data, because the temperature rise caused by recirculation is smaller in magnitude than the daily change in temperature caused by the solar heating/nocturnal cooling cycle and variation caused by intermittent upwelling and random fluctuations. The entrainment of heated water from the discharge back into the intake is obvious when the entire temperature field can be seen in a high resolution thermal image such as those taken by MTI.

Figure 22-16
Photographs of Pilgrim Power Plant cooling water intake bay and discharge canal into Massachusetts Bay

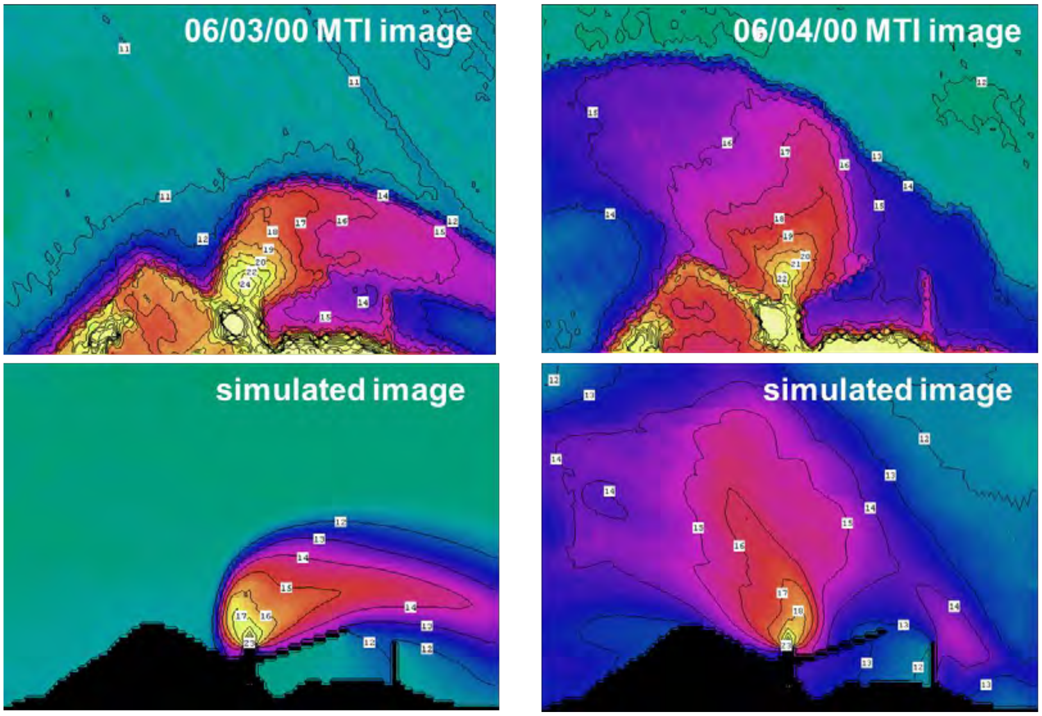


Figure 22-17
Comparison of calibrated MTI images of thermal plumes from PPP on days when the wind-driven current carries the plume from left to right (left side images) and straight offshore (right side images). Images show recirculation of heated discharge water back into intake bay.

Given the successful replication of the MTI images, modifications of the breakwater were attempted to reduce the recirculation of the thermal plume on days when the wind-driven current carried it past the opening in the breakwater. None of these modifications were successful because the flow into the intake bay forced by the cooling water intake overwhelmed any deflection of the plume produced by alternations in the breakwater design. The only viable approach to eliminating the recirculation at PPP appears to be relocation of the cooling water inlet line offshore at a significant depth. A simulation which explored this possibility reduced the average intake temperature by 0.7°C, and larger reductions are probably possible.

Midland Co-Generation Plant

The Midland Co-generation Plant (MCP) is near Midland, Michigan. This power plant burns natural gas to generate both electricity and steam. It discharges about 500 MW of waste heat into its dedicated cooling lake with an area of 880 acres (Figure 22-18). The dike that extends from the power plant down into the middle of the lake separates the cooling water discharge (left side of dike) from the intake (right side). The lake is somewhat large relative to the heat load, because MCP was originally a nuclear site that was changed to natural gas. For this reason, the lake partially freezes during much of the winter. The amount of freezing depends on the variable heat load and the weather.

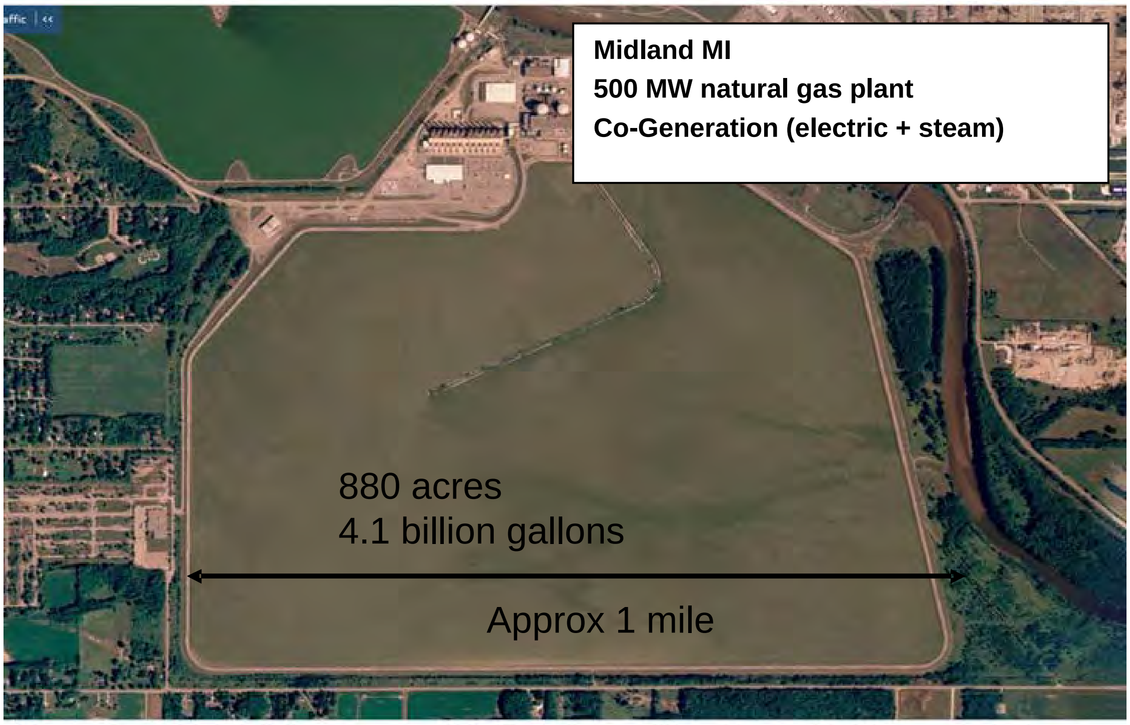


Figure 22-18
Photograph of Midland Co-Generation Plant with dike that forces more complete coverage of the lake by heated water from the plant. Discharge is on left side of dike, intake is on right side.

Figure 22-19 is an aerial photograph of the cooling lake taken on February 24, 2008, when the lake was partially frozen. The discharge side of the lake is ice-free and the rest of the lake is covered by ice. Some evidence of limited flow bypass is in the lower left corner of the image where an icy area is nearly separated from the main region of ice on the right side of the lake.

Figure 22-19
Visible photograph of Midland Co-generation Plant cooling lake on February 24, 2008, when lake was partially frozen. Warmer (discharge) side of the lake is not frozen and appears black in this image. Frozen part (intake side) is either pure white (snow on ice) or stippled (uneven ice with ridges).

Although the MCP is typically not troubled by high cooling water inlet temperatures, the presence of ice on the lake provides an opportunity to show how both thermal and visible imagery can be used to understand the dynamics and thermodynamics of cooling lakes. To simulate this lake, an ice formation model had to be added to the SRNL hydrodynamic code. After this had been completed, simulations such as the one shown in Figure 22-20 were now made possible. The image in Figure 22-20 was taken on February 19, 2010, when the temperature was a typical -7°C and the lake was about 70% ice-covered. The thermal image is a mosaic of images taken by Rochester Institute of Technology (RIT) personnel from an aircraft. The simulation reproduced the ice-water distribution to a fairly close degree of approximation. In both the real and simulated images, the ice-free areas are lighter shades of grey.

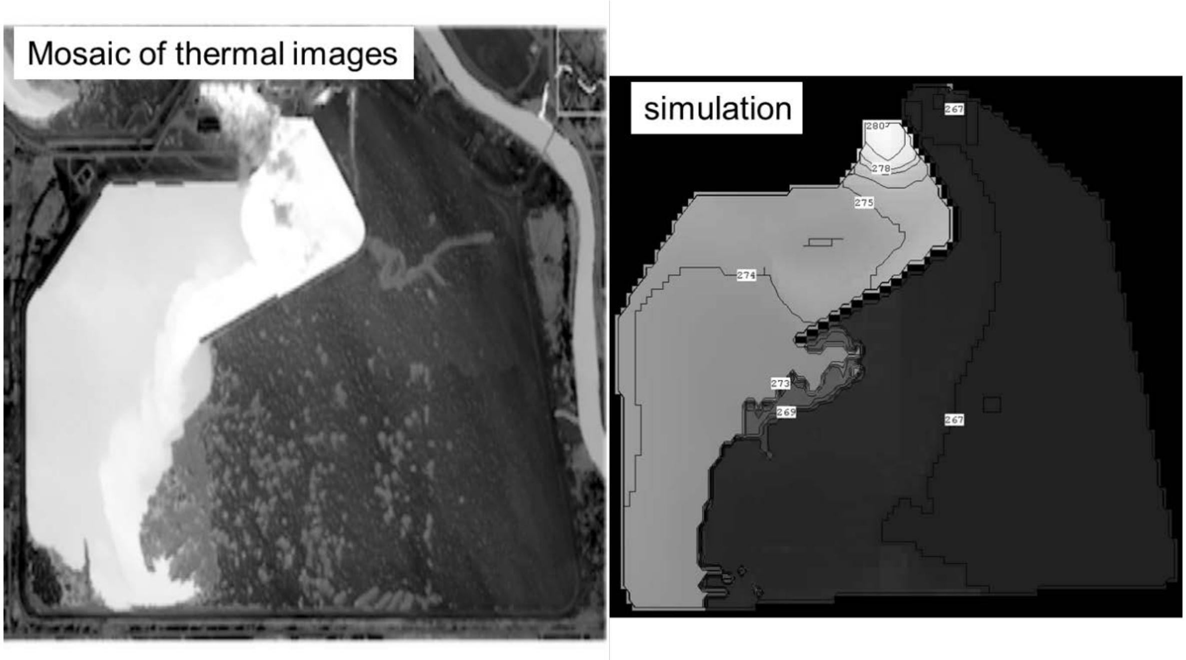


Figure 22-20
Thermal mosaic of Midland Co-generation Plant cooling lake when it was approximately 70% ice covered (left) and corresponding simulation (right). Ice-free areas are lighter grey.

When the weather is extremely cold or the heat load on the lake is low or both, most of the lake freezes (Figure 22-21). The simulation indicates the ice surface was warmer closer to the discharge where the simulated ice was thinner. This is not apparent in the mosaic because the grey scale extended over a wider range of temperatures (included hot plant components).

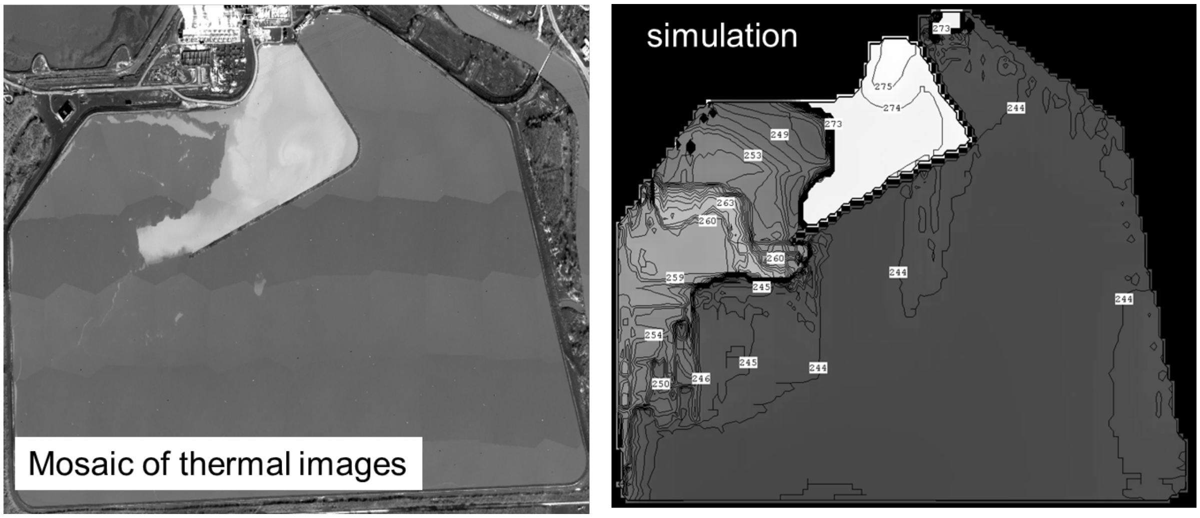


Figure 22-21
Thermal mosaic of Midland Co-generation Plant cooling lake when it was approximately 93% ice covered (left) and corresponding simulation (right). Ice-free areas are lighter grey.

Figure 22-22 compares measured ice fractions for the MCP cooling lake derived from imagery to simulated ice fractions as a function of time during the winter of 2008 – 2009. Solid correlation is shown between measured and simulated ice fractions.

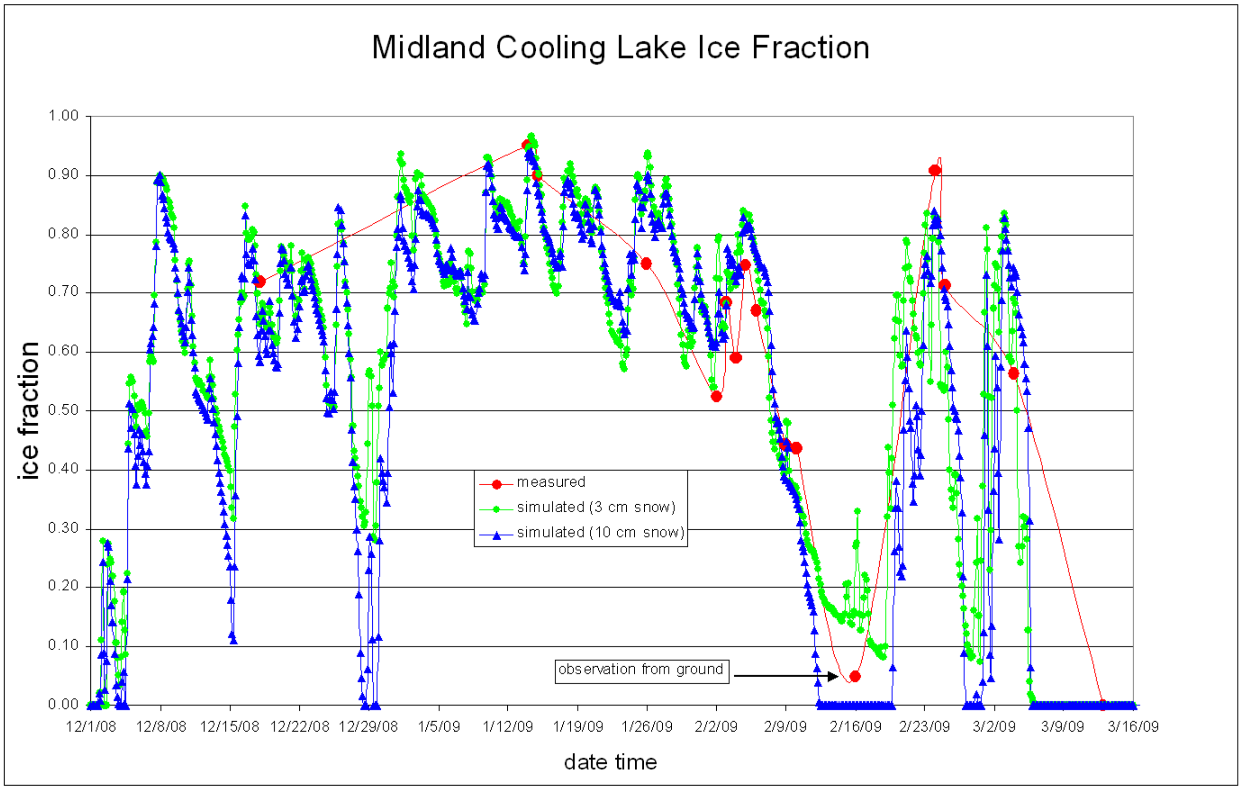


Figure 22-22
Comparison of measured to simulated Midland Co-Generation Plant ice fractions during the 2008 – 2009 winter

Given the reliability of the combined hydrodynamic–ice formation model, a hypothetical gap in the dike was created and the simulation of the winter of 2008 – 2009 was repeated. Figure 22-23 compares images from the original simulation to an image for the same time from the simulation with the gap in the dike. Ice-covered parts of the lake are color-coded blue. As would be expected, the warm water takes the shortcut and flows directly into the cooling water intake, keeping that area ice-free. Although this hypothetical change in the dike might not have any practical use, it shows that different schemes for changing the ice distribution on a partially frozen cooling lake can be explored with a validated code that includes the necessary physics.

Summary

The combination of high-resolution thermal imagery and 3-D hydrodynamic modeling with heat transfer constitutes an effective method for understanding how efficiently a cooling lake or other aqueous systems dissipate power plant waste heat. The hydrodynamic model must first duplicate temperature distributions in calibrated thermal imagery. Time series of images (20 to 30) taken over a year or more lead to a more complete understand of cooling lake dynamics and thermodynamics than a single image. Hydrodynamic codes validated with calibrated thermal imagery should be reliable tools for assessing proposed modifications to improve cooling lake efficiency. Thermal imagery can be acquired either from a satellite or by creating mosaics from images taken from an aircraft. The MTI satellite is the only satellite currently available with adequate resolution for this type of analysis, although thermal images can be created by combining thermal images taken from an aircraft into a mosaic. DOE would probably be receptive to requests for tasking from representatives of the electric utility industry.

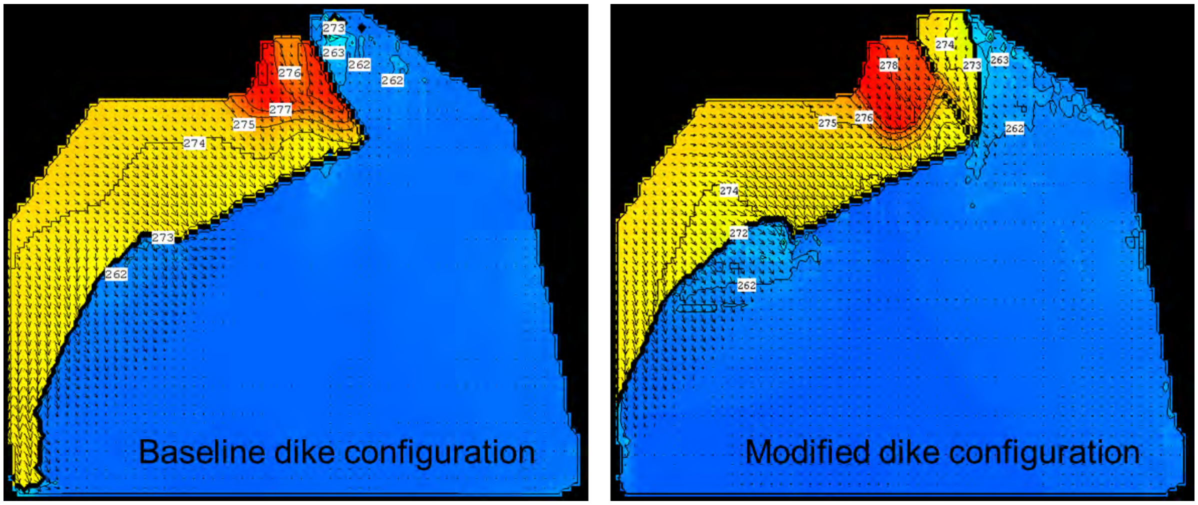


Figure 22-23
Comparison of simulations with actual dike (left) and modified dike with gap near discharge (right). Bypass of flow through gap keeps cooling water inlet ice-free.

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23

ESTIMATING FORCED EVAPORATION FROM SURFACE WATER

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Abstract

Forced evaporation from water surfaces driven by heat from thermoelectric power plants is an important, poorly quantified component of U.S. water consumption. Published estimates of forced evaporation from a variety of methods range from 0.015 to 4.5 liters per kilowatt-hour (L/kWh) for cooling ponds and 0.45 to 12 L/kWh for once-through cooling, and some of the methods used to arrive at these estimates leave out known thermodynamic constraints. Existing studies of the physics of heat loss from water surfaces provide the basis for an improved method to apportion the dissipation of heat from a power plant to the processes of evaporation, conduction, and radiation. The share of the added heat dissipated by forced evaporation depends only on the water temperature and the wind speed, but estimating the heated water temperature also requires estimates of the natural water temperature, air temperature, and humidity. The method also estimates the heat discharged through the condenser of a power plant and the ratio of forced evaporation to net generation. Using this method with reasonable assumptions for plant efficiency and average environmental conditions, forced evaporation from cooling ponds is estimated to be 1.2 to 1.4 liters per kilowatt-hour (L/kWh) for fossil-fueled plants and from 1.5 to 1.8 L/kWh for nuclear plants. Published coefficients used as the basis for estimates of thermoelectric water needs include several that fall well outside these ranges, indicating that thermodynamic constraints should be incorporated into future methods for estimating forced evaporation.

Introduction

Although water consumption by once-through cooling of thermoelectric power plants is important [1-3], there is no consensus on its magnitude or an optimal method of estimation. Published coefficients [3-10] for average forced evaporation in the U.S. range from 0.015 to 4.5 L/kWh for cooling ponds and 0.45 to 12 L/kWh for once-through cooling in lakes and rivers (0.004 to 1.2 gallons per kilowatt-hour (gal/kWh) and 0.12 to 3.1 gal/kWh, respectively). The lack of consensus among these estimates reflects the variety of estimation methods used and suggests that some of them must be in error. Most published coefficients are presented as average or “typical” nationwide values for broad technological categories of power plants and do not reflect climatic and seasonal differences in the rate of forced evaporation or the effects of variability in plant efficiency within each technological category. There is a need for a transparent, verifiable method to estimate forced evaporation based on environmental conditions and physical constraints. This paper summarizes some of the issues surrounding forced evaporation and presents modifications to a previously published method to overcome known deficiencies.

Background

Forced evaporation from surface water occurs when heat is added by human activities, such as the cooling of thermoelectric power plants, and can be a substantial consumption of water, in the sense of making water unavailable for other human uses. Thermoelectric water consumption, including forced evaporation and evaporation from cooling towers, was estimated in 1995 to be about 3 percent of human water consumption in the U.S. [11]. Forced evaporation in natural surface-water bodies occurs outside the plant boundary and cannot be directly measured by the plant operator, but it is an unavoidable result of using lakes and rivers as components of cooling systems. In some cases, forced evaporation has been deemed insignificant on the scale of the stream it occurs in [12], but in river basins where water allocation has become a legal and political issue, thermoelectric forced evaporation may substantially affect the overall water budget [2].

Forced evaporation is constrained by the characteristics of individual power plants. The heat available to drive evaporation in the environment is the heat extracted from the steam by the condenser (“condenser duty”). Condenser duty excludes the heat transformed into electricity, discharged in flue gases, or conducted to the atmosphere from plant equipment. High thermal efficiency, which is limited by thermodynamic constraints and the high capital cost of high-efficiency plants, tends to produce low ratios of forced evaporation to condenser duty; low efficiency, which is constrained more loosely by the high operating costs of low-efficiency plants, tends to produce high ratios of forced evaporation to condenser duty.

Published national averages of forced evaporation have been presented using either of two types of consumption coefficients:

1. the ratio of water evaporated to net electric generation, a water-balance approach at the level of the power plant
2. the percentage of the condenser duty that is lost to the atmosphere as evaporation, a thermodynamic approach at the level of the cooling system

Because all such national-average coefficients are presented as constants for a given combination of fuel and cooling system type, they cannot be used to address plant-to-plant differences in efficiency and environmental conditions. Published regional and national constant percentages of condenser duty driving evaporation (such as 75 [4], 60 [7, 13], or 40 percent [1]) also fail to express the variability due to environmental conditions.

Models in which forced evaporation varies with environmental conditions date from Harbeck’s [14] pioneering study applying heat transfer theory to Lake Colorado, a cooling pond in Texas. For once-through or pond cooling in general, Harbeck [15] demonstrated that from 20 to 75 percent of the added heat may be lost by evaporation, depending only on water temperature and wind speed. Harbeck suggested that air temperature is an adequate surrogate for water temperature where water temperature data are not available. He presented his results as a chart, and did not suggest that the heat transfer equations be solved for each case. Huston [16] used Harbeck’s method to estimate annual averages of forced evaporation from 37 to 54 percent of condenser duty over 18 major continental-U.S. river basins. Majewski and Miller [17] discussed heat loss and evaporation in detail, presenting 9 wind functions for comparison. They adopted the same approach as Harbeck, though entirely in SI units and using a different wind function, and developed a chart similar to his. Ward [18, 19] developed linear approximations of Harbeck's heat transfer formulae, proposed the optional substitution of other wind speed functions, and analyzed the errors in forced evaporation that would result from the linear approximation and from errors in the estimated temperature of the heated water.

Harbeck's use of air temperature as a surrogate for water temperature has been identified as his model's main deficiency. Boyer [20] commented that the use of air temperatures as a surrogate for lake temperatures would lead to considerable errors in forced evaporation for some lakes. Brady and others [21, 22] used the same underlying equations as Harbeck to estimate percent forced evaporation, improving the treatment of the equilibrium water temperature and the wind function, and estimated 64 percent forced evaporation for a wind speed of 4 meters per second (m/s; 9 miles per hour (mph)) and a water temperature of 27°C (80°F) under summer conditions in Chesapeake Bay. Hu and others [23, 24] determined that predictions based on the method of Brady and others gave a higher and more accurate estimate of water consumption than Harbeck's method.

Williams and Tomasko [25] applied the same underlying physics as Harbeck, Brady, Majewski, and others to the problem of forced evaporation in Chesapeake Bay and the Potomac River. Williams and Tomasko assumed that forced evaporation is directly proportional to the increase in plume temperature above ambient water temperature, implicitly treating the heat transfer equations as linear with respect to water temperature. Their estimates are based on the assumed area and heated water temperature of the plume, and condenser duty is not used to constrain forced evaporation. As a result of the difficulty in estimating plume characteristics, their two example calculations yield thermodynamically unrealistic results of 2 percent forced evaporation in one case and 200 percent in the other.

Forced-Evaporation Model

The method proposed here for estimating forced evaporation is based on that of Ward [18], with a few key revisions:

1. A natural water temperature is estimated based on available water-temperature data rather than air temperature data. Typical water-temperature data sources include previously measured river temperature upstream from the plant, or in nearby lakes and streams,
2. A heat loading (i.e. condenser duty per area) is estimated or measured and used to solve the relevant equations iteratively to estimate a heated water temperature, and
3. The percent forced evaporation is given by the ratio of the difference in evaporation at the two temperatures to the difference in the sum of evaporation, conduction, and radiation at the two temperatures.

Equations for heat loss can be solved for both the natural and heated water temperatures, with the estimated heated-water temperature adjusted iteratively until the difference in heat loss at the two temperatures is equal to the added heat from the power plant. Monthly-average values are used for environmental variables, and monthly estimates of the percent of condenser duty that drives evaporation are produced, tracking seasonal changes in water consumption. In the following equations, the units used by Ward are preserved to facilitate comparison to his and Harbeck's publications.

The total heat loss from a water surface is the sum of heat loss through evaporation, conduction, and radiation expressed in terms of energy flux per unit area.

$$H(T) = E(T) + C(T) + R(T) \tag{1}$$

where $H(T)$ is heat loss from the water surface, $E(T)$ is heat loss through evaporation, $C(T)$ is conduction, and $R(T)$ is radiation, all in calories (cal) per square centimeter per day.

Evaporation is given by:

$$E(T) = \rho L f(W)[e(T) - e_a] \tag{2}$$

where ρ is water density in g/cm^3, L is the latent heat of vaporization in cal/g, $e(T)$ is the saturation vapor pressure in millibars at water-surface temperature T, and e_a is the vapor pressure of the overlying atmosphere in millibars, and

$$f(W) = 7.0 * 10^{-8}(W) \tag{3}$$

where W is wind speed in miles per hour.

Conduction is given by:

$$C(T) = f(W)\frac{\rho p c_p}{\epsilon}(T - T_a) \tag{4}$$

where p is atmospheric pressure in millibars, c_p is the specific heat of air at a constant pressure, 0.24 cal/(g °K), ϵ is the molecular weight ratio of water vapor to dry air, and T_a is air temperature in °C.

Radiation is given by:

$$R(T) = \epsilon_r \sigma (T + 273)^4 \tag{5}$$

where σ is the Stefan-Boltzman constant ($1.17*10^{-7}$ cal/(cm^2 °K^4 day)) and ϵ_r is the emissivity of the water surface, 0.97.

The difference between heat loss at the natural water temperature and at the heated water temperature is:

$$H(T_H) - H(T_N) = [E(T_H) + C(T_H) + R(T_H)] - [E(T_N) + C(T_N) + R(T_N)] \tag{6}$$

where T_H is the heated water temperature and T_N is the natural water temperature, both in ºC.

The difference in the heat loss at the two temperatures $(H(T_H) - H(T_N))$ is set equal to the added heat from the power plant (condenser duty) by iteratively adjusting the heated water temperature (T_H).

The ratio of forced evaporation to condenser duty is given by:

$$FE = [E(T_H) - E(T_N)]/[H(T_H) - H(T_N)] \tag{7}$$

Ward [18] demonstrates that additional heat losses through evaporation, conduction, and radiation are approximately linear functions of an imposed increase in water temperature, and based on this approximation the ratio of increased evaporation to the total increase in heat loss is a function of only water temperature and wind speed. These linear approximations are not needed if the equations for evaporation, conduction, and radiation are evaluated at the natural water temperature and the heated water temperature. If the imposed heat load is distributed over an assumed area, the heated temperature can be solved for iteratively, and the share of evaporation in the increased heat dissipation can be calculated directly.

Solution of these equations over a range of environmental conditions demonstrates that *forced* evaporation is insensitive to air temperature and humidity, although these variables strongly affect the *overall* evaporation rate. Plotted results approximately reproduce Harbeck's [15] chart (Figure 23-1). Errors in either the natural water temperature or the estimated heat loading produce an error in the heated water temperature, and, as discussed by Ward [18], each degree Celsius error in heated water temperature produces an error of about 1 percent of condenser duty in forced evaporation.

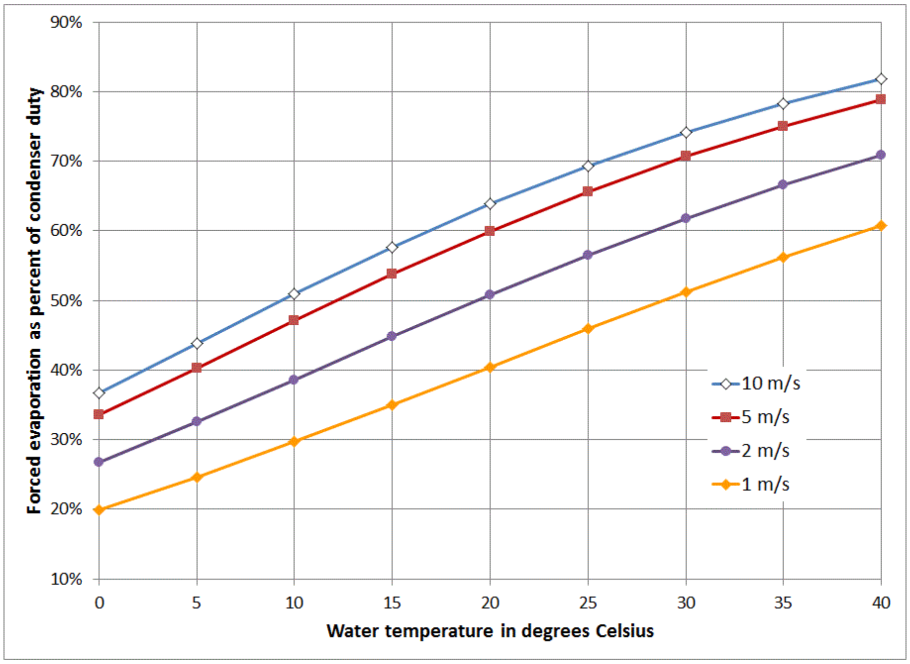

Figure 23-1
Forced evaporation as percent of condenser duty as a function of heated-water temperature and wind speed

Because all three forms of heat loss increase about linearly with increasing water temperature, the change in water temperature because of added heat and the corresponding increase in forced evaporation are proportional to the heat added per unit area. For water starting near 0°C, forced evaporation increases about 15 percent for each megawatt (thermal) added per hectare; for water starting near 30°C, it increases about 4 percent for each megawatt (thermal) added per hectare (Figure 23-2). Selection of a different wind function can shift the relation of forced evaporation to water temperature by several percent at a given wind speed (Figure 23-3). Therefore, the selection of the appropriate wind speed function for once-through cooling remains an important open question.

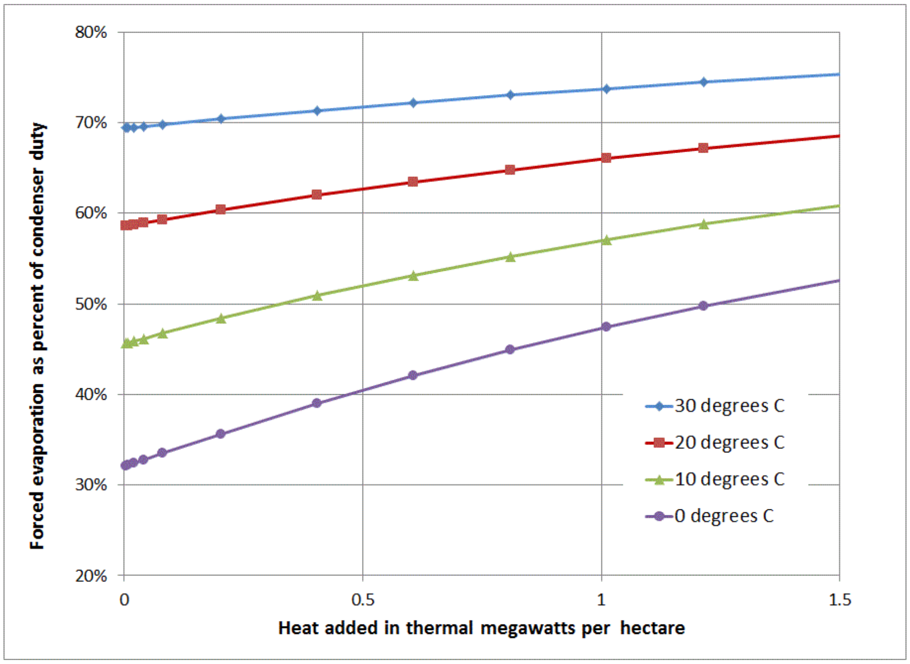

Figure 23-2
Effects of heat loading on forced evaporation at 4 m/s (9 mph) wind speed and four natural water temperatures representative of the continental U.S.

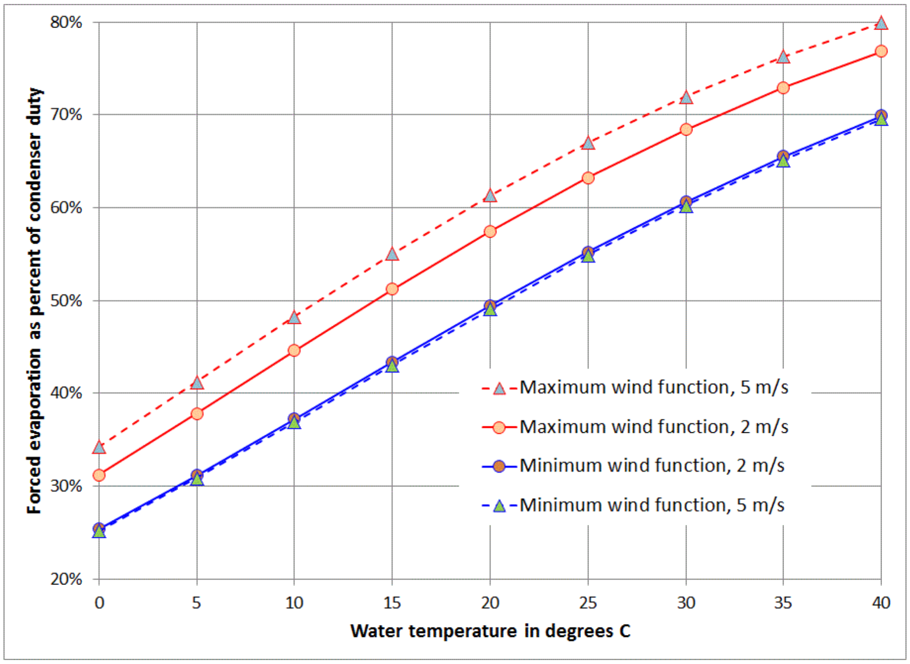

Figure 23-3
Relation of forced evaporation to water temperature for the largest and smallest values of wind functions reviewed by Majewski and others, 1979, at wind speeds of 2 and 5 meters per second

The ratio of forced evaporation, a thermodynamic consumption coefficient, can be used to produce a corresponding water-balance forced-evaporation coefficient by combining it with estimated characteristics of the power-plant heat budget: the thermal efficiency of net electric generation, the boiler efficiency, and the (small) percentage of fuel heat lost directly to the air by plant equipment.

The dimensionless ratio of condenser duty to the energy embodied in net electrical generation is given by:

$$\frac{CD}{NG} = (BE - TE - AL)/(TE) \tag{8}$$

where CD is condenser duty, NG is net electrical generation, BE is boiler efficiency, TE is the thermal efficiency of net electrical generation, and AL is heat lost to the air from plant equipment.

The water-balance forced-evaporation coefficient FEC, in L/kWh, is given by

$$FEC = \left[\left(\frac{CD}{NG}\right) * FE\right] / H_{vap} \tag{9}$$

where H_{vap} is the heat of vaporization of water at the natural water temperature in kWh/L.

Discussion

The proposed method can be applied at scales from the individual plant to the nation. For individual plants where the necessary environmental variables and plant heat-budget characteristics can be estimated, it provides a “first cut” estimate of forced evaporation that can be refined using more detailed modeling and locally collected data. Huston [16] provides an example of a regional model that might be updated. The application of this model at the national scale, using average values of environmental variables and plant characteristics, can provide a first-approximation thermodynamic test of the published water-balance coefficients of forced evaporation that identifies those that are thermodynamically implausible.

For example, assume the typical value of annual average wind speed over the eastern U.S.– the geographic area in which cooling ponds are relatively common – to lie between 3 and 5 m/s, and the average cooling pond temperature to lie somewhere between 15°C and 20°C. Reasonable assumptions for average plant characteristics are 33 percent net thermal efficiency for both nuclear and fossil-fueled plants, 89 percent boiler efficiency and 3 percent heat loss outside the cooling system for fossil-fueled plants, and 100 percent nominal boiler efficiency and 1 percent heat loss outside the cooling system for nuclear plants. Condenser duty under these assumptions would be about 5700 kilojoule per kilowatt-hour (kJ/kWh; 5400 British thermal units per kilowatt-hour (Btu/kWh)) for fossil-fueled plants and 7100 kJ/kWh (6700 Btu/kWh) for nuclear plants. Forced evaporation from cooling ponds under these environmental conditions would be 50 to 60 percent of condenser duty, or from 1.2 to 1.4 L/kWh (0.31 to 0.37 gal/kWh) for fossil-fueled plants and from 1.5 to 1.8 L/kWh (0.39 to 0.46 gal/kWh) for nuclear plants.

Coefficients for consumption at plants with cooling ponds that have been used as the basis for estimates of present and future thermoelectric water needs include some statistically estimated coefficients [8, 9] that fall outside these ranges. These departures from thermodynamic plausibility suggest that the assumptions of the statistical analysis need to be reassessed.

The method proposed in this article has three major sources of uncertainty:

1. The estimation of a natural water temperature in the absence of added heat
2. The estimation of heat loading in a lake or river plume
3. The selection of a wind function

Increased collection of water temperature data and thermal models that accurately estimate natural temperatures in lakes and streams could be used to reduce errors in the assumed baseline water temperature. Plumes could be modeled to better estimate thermal loading. The differences among published wind functions suggest potential for improvement, and perhaps wind functions that depend on the characteristics of the water body could be developed. Existing wind speed functions were developed from studies of lakes and ponds, not rivers, and it may be difficult to define a wind speed function for rivers on the basis of empirical water-balance studies. Case studies of water and heat budgets for thermal plumes and cooling ponds may help reduce all three types of uncertainty. Applications of this model should include evaluation of the choice of a wind speed function and the level of uncertainty in the input wind speed and water temperature; results should be presented with an explicit discussion of their precision.

Conclusion

As noted previously, published national-average forced-evaporation coefficients cover a range so broad that they cannot all be accurate. Unreliable estimates of forced evaporation at individual plants may lead to flawed assessments of the plant’s environmental effects; application of invalid coefficients of forced evaporation can distort regional and national assessments of choices among cooling technologies. This paper shows that thermodynamic constraints on forced evaporation can be quantified. Such constraints should be considered in future estimation of forced evaporation and used to evaluate the plausibility of existing forced-evaporation coefficients.

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A REVIEW OF THE 2011 EPA PROPOSED CLEAN WATER ACT §316(B) REGULATION FOR EXISTING POWER PLANTS AND ITS POTENTIAL IMPACT ON THERMAL DISCHARGE

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Abstract

On April 20, 2011, the U.S. Environmental Protection Agency (EPA) proposed a revised Rule implementing §316(b) of the Clean Water Act (CWA) for existing power plants and other industrial facilities that use once-through cooling water. Section 316(b) of the CWA requires that National Pollutant Discharge Elimination System (NPDES) permits for facilities with cooling water intake structures ensure that the location, design, construction, and capacity of the structures reflect the best technology available to minimize harmful impacts on the environment. There are three components to the proposed regulation: (1) existing facilities that have a design intake flow of over 2 million gallons per day (MGD) would be subject to either an annual and monthly impingement mortality limit or the facility could reduce their intake velocity to 0.5 feet per second; (2) existing facilities that withdraw more than 125 MGD actual intake flow would be required to conduct studies to help their permitting authority determine whether and what site-specific controls, if any, would be required to reduce entrainment mortality of early life stages of fish and shellfish; and (3) new units that add electrical generation capacity at an existing facility would be required to add technology that is equivalent to closed-cycle cooling. The site-specific studies to evaluate the need for entrainment technology controls requires that facilities examine a suite of technologies from fine mesh traveling screens to closed cycle cooling including wet mechanical draft and natural draft towers, dry cooling and hybrid systems. The assessment also requires an analysis of how the different technology options would affect the facilities thermal discharge and its impact. EPA plans to promulgate a final Rule on or before July 27, 2012. In general, compliance activities could result in no effect on a plant's thermal discharge or requirements for closed-cycle cooling could completely eliminate the plant's thermal discharge and the need for 316(a)-related permitting. This paper reviews in detail the Rule's requirements and the potential compliance activities that will affect thermal discharge.

Introduction

In 1972, Congress passed the CWA and §316(b) applied directly to regulating the impacts of cooling water intake structures (CWIS) on aquatic life. Specifically, §316(b) requires EPA to ensure that "the location, design, construction and capacity of cooling water intake structures shall reflect the best technology available for minimizing adverse environmental impact." The

EPA issued a Rule in 1977 to implement the CWA §316(b) requirements. However, because of legal challenge, the regulation was remanded. EPA took no follow-up action to correct the issues raised by the litigation. Despite the remand, most states subsequently issued §316(b) requirements in NPDES permits in accordance with the remanded Rule's requirements. In 1994, a coalition of environmental groups sued EPA over failure to promulgate national standards enforcing CWA §316(b) requirements. As a result, EPA entered into a consent decree to develop in phases final regulations for both existing and new facilities that use CWIS. A Phase I Rule for new facilities was issued in 2001 [1]. The Phase I Rule essentially requires closed-cycle cooling systems or comparable performing intake technologies as best technology available (BTA) to minimize adverse environmental impact. In 2004, EPA promulgated a Phase II Rule [2] to implement regulations for existing power plants that withdraw more than 50 million gallons per day (MGD) of cooling water and later a Phase III Rule for existing power plants withdrawing less than 50 MGD and all other industrial facilities that use cooling water. Both regulations were subsequently challenged and later formally remanded (Phase II) or voluntary withdrawn for revision.

On April 20, 2011, EPA proposed a revised §316(b) Rule [3]; http://water.epa.gov/lawsregs/lawsguidance/cwa/316b/index.cfm] for existing power plants and other industrial facilities using cooling water (a combined Phase II and III regulatory action). Technical development documents that provide details on EPA analyses and support the Rule's provisions can be downloaded at: http://www.regulations.gov/#!searchResults;rpp=10;po=0;s=EPA-HQ-OW-2008-0667. Performance standards and monitoring requirements were proposed for reducing impingement and entrainment mortality. EPA provided a 120-day period to support state agency, nongovernmental organization, the power industry and the public to review and comment on the proposed regulation. The public comment period closed August 18, 2011. A final existing facility Rule is planned for promulgation on or before July 27, 2012. This paper briefly reviews the content of the proposed rule and, more importantly, the impacts the proposed rule could have on thermal discharges.

Review of Proposed Rule

The EPA evaluated four regulatory options and selected the option as subsequently reviewed. The Rule affects all existing facilities withdrawing more than 2 MGD design intake flow. Fixed standards are proposed for reducing impingement mortality while entrainment mortality compliance is determined on a case-by-case basis. This Rule also has requirements for new units that add electrical generation capacity at an existing facility equivalent to requirements for new facilities as promulgated in the 2001 Phase I Rule. This paper focuses only on the Rule as it affects existing facilities.

Regulatory Options Considered

EPA developed and evaluated four primary options for the proposed rule. Three of the options would require the same impingement mortality standards as the proposed option, but would vary the approach to entrainment mortality controls. The fourth option would allow both impingement and entrainment mortality controls to be established on a site-specific Best Professional Judgment (BPJ) basis for facilities with a design intake flow (DIF) less than 50 MGD and the impingement mortality standards and BPJ entrainment control for facilities with DIF ≥ 50 MGD. The following regulatory options were considered:

- Option 1 – uniform impingement mortality controls at all existing facilities; site-specific entrainment controls for existing facilities (other than new units) that withdraw over 2 MGD DIF (this was selected as the proposed option).
- Option 2 - impingement mortality controls at all existing facilities that withdraw over 2 MGD DIF; require flow reduction commensurate with closed-cycle cooling by facilities greater than 125 MGD DIF.
- Option 3 - establish impingement mortality controls at all existing facilities that withdraw over 2 MGD DIF; require flow reduction commensurate with closed-cycle cooling at all existing facilities over 2 MGD DIF.
- Option 4 -- uniform impingement mortality controls at existing facilities with design intake flow of 50 MGD or more; BPJ permits for existing facilities with design intake flow between 2 MGD and 50 MGD DIF and site-specific entrainment controls for facilities withdrawing more than 2 MGD DIF

EPA proposed Option 1 as “best technology available” (BTA) for minimizing adverse environmental impact under Section 316(b) of the CWA. EPA rejected the other three for various reasons including availability, costs and the amount of harm that would be reduced to the aquatic environment. Relative to closed-cycle cooling, four factors in particular with unfavorable consequence led EPA to reject it as a uniform standard including energy reliability, air emissions permits, land availability, and remaining useful plant life. Although Options 2 through 4 were rejected by EPA, because they were proposed and because they explicitly requested public comments on them, EPA could adopt them in whole or part in the final rule to be released on or before July 27, 2012. The potential impacts of each option on thermal discharge are subsequently discussed following a brief review of the content of the proposed option which immediately follows.

Compliance Standards in Proposed Option

Compliance standards were proposed to control impingement of fish and shellfish trapped on 3/8 inch mesh traveling water screens and for entrainment of fish and shellfish in early life stages that pass through the screen and the power plant to be discharged in the heated effluent. Each of these proposed standards are subsequently reviewed.

Impingement Mortality

Facilities using more than 2 MGD DIF have two options to achieve compliance:

- Option 1 – Demonstrate that impingement mortality does not exceed 31% monthly and 12% annually. EPA identified Ristroph-modified traveling water screens as BTA and developed the standards from the available survival database for these screens.
- Option 2 – Reduce the maximum design through screen velocity not to exceed 0.5 fps during minimum source water levels. Additional requirements may apply including:

- Entrapment - facilities with long intake canals, intake tunnels, forebays, barrier nets or other intake conditions that could result in fish entrapment behind the net or high velocity field, must either provide a means for fish to escape or modify traveling screens with smooth mesh, low pressure screenwash, fish guards on collection buckets and a fish return and rotate screens continuously. The Rule does not require monitoring the performance of the modified screens.
- Shellfish – facilities located on oceans or tidal waters must also reduce shellfish mortality to a level achieved by a properly deployed and maintained barrier net. Use of cylindrical wedgewire screens, drum screens, dual flow screens and similar devices are also considered in compliance with this requirement.
- Traveling Screens – if traveling screens are used to meet the velocity reduction requirement, they must be modified as described for entrapment with fish protection measures and a fish return system.

Entrainment Mortality

Facilities using more than 2 MGD DIF are also subject to reducing entrainment mortality, however, only facilities withdrawing more than125 MGD actual intake flow (AIF) must submit a Comprehensive Entrainment Characterization Study, evaluate entrainment reduction technologies (including closed-cycle cooling) as well as their environmental impacts and benefits (9 specific factors must be evaluated). Compliance is determined by the permitting authority on a “case-by-case” basis and could result in a determination ranging from the existing CWIS being deemed BTA to a requirement to retrofit with closed-cycle cooling.

Information Requirements

The Rule contains extensive information submittal requirements. All facilities with a flow greater than 2 MGD DIF must submit the information required at 122.21(r)(2) through (8) that includes source waterbody physical data, cooling water intake structure data, source water baseline biological characterization data, cooling water system data, Impingement Mortality Reduction Plan, performance data (impingement and entrainment survival data) and operational status information.

Facilities using more than 125 MGD AIF must also submit an Entrainment Mortality Data Collection Plan, a Comprehensive Technical Feasibility and Cost Evaluation Study (facilities must evaluate closed-cycle cooling systems and fine mesh screens), Benefit Valuation Study (both monetized recreational and commercial fish benefits as well as non-use ecological benefits) and Non-water Quality and Other Environmental Impacts Study. All entrainment information must be peer reviewed.

Monitoring Requirements

Impingement Mortality

Compliance by demonstrating that impingement mortality does not exceed 31% monthly and 12% annually requires monthly monitoring in the fish return system and holding fish for 24 hours to 48 hours to determine survival. Any fish removed with debris and screen carryover must be counted as dead fish. Compliance by reducing the through-screen velocity to not exceed 0.5

fps can either be demonstrated by providing engineering design information or by twice weekly velocity monitoring.

Entrainment Mortality

Entrainment mortality verification monitoring is determined on a case-by-case basis depending on the compliance method.

Schedule

Impingement Mortality

Power plants withdrawing more than 50 MGD must submit the information described at 122.21(r)(2) through (8) within 6 months of the effective date of the Rule and the results of the Impingement Mortality Reduction Plan within 3.5 years. Facilities withdrawing between 2 MGD and 50 MGD have up to 3 years to submit the 122.21(r)(2) through (8) information. All existing facilities must be in compliance within 8 years from the effective date of the Rule.

Entrainment Mortality

Facilities withdrawing more than 125 MGD AIF must also submit the Entrainment Mortality Data Collection Plan within 6 months, complete peer review of the plan within 1 year and submit the study results within 4 years of the effective final Rule date. The remaining documents at 122.21(r)(10) through (12) must be submitted within 5 years. The permit authority will establish the requisite compliance schedule for meeting the site-specific entrainment standard.

Impacts on Thermal Discharge

Although intimately linked in Section 316 of the CWA and because intake of water directly affects discharge, it is somewhat surprising how little mention there is in the 116 pages and over 100,000 words included in the Federal Register notice on the proposed §316(b) regulatory action on potential impacts on §316(a) or thermal discharge issues and permitting. The following are summary observations on where either "§316(a)" or "thermal discharge" is noted in the proposed Rule:

- "§316(a)" is not mentioned in the Rule
- "§316(a)" is noted 3 times in preamble (all in same short section)
- "Thermal discharge" is noted 3 times in the Rule
- "Thermal discharge" is mentioned 20 times in the Rule's preamble (13 times in one section as subsequently discussed)

In a section of the Rule's preamble [3] on the *National Benefits of Today's Considered Options*, EPA has a subsection on "Assessment of Thermal Discharge Impacts." In this subsection (page 22246 FR 76[76]) EPA notes that:

> Since thermal discharges are a product of once-through cooling water systems, the impacts of thermal discharges are a relevant consideration when assessing appropriate technologies to reduce the effects of cooling water intakes. Thermal pollution has long been recognized to cause harm to the structure and function of aquatic ecosystems.

> Concerns about the impacts of thermal discharges are addressed by provisions of CWA Section 316(a) regulations. NPDES permits are required to limit thermal discharges in order to ensure that that there is no appreciable harm to a balanced, indigenous population of shellfish, fish and wildlife. Permit requirements, however, may not totally eliminate all adverse impacts in all cases. In addition to reducing total I&E mortality, closed cycle cooling reduces thermal pollution. Most retrofit installations of cooling towers at electric generating facilities have been required by NPDES permits for the sole purpose of reducing thermal discharges.
>
> EPA did not quantify nationally the impacts of thermal discharges. However, numerous studies have shown that thermal discharges may substantially alter the structure of aquatic communities by modifying photosynthetic, metabolic, and growth rates. Thermal discharges also harm aquatic life by reducing levels of dissolved oxygen, altering the location and timing of fish behavior such as spawning, aggregation, and migration, and may cause thermal shock-induced mortality for some species. Adverse temperature effects may also be more pronounced in aquatic ecosystems that are already subject to other environmental stressors such as high levels of biochemical oxygen demand, sediment contamination, or pathogens. Within mixing zones, which often extend several miles downstream from outfalls, thermal discharges may impair efforts to restore and protect the waterbody. For example, permit requirements to limit nitrogen discharges in a watershed, and thereby reduce harmful algal blooms, may be counteracted by thermal discharges which promote growth of harmful algae. Thermal discharges may have indirect effects on fish and other vertebrate populations through increasing pathogen growth and infection rates.
>
> Thermal discharges may thus alter the ecological services, and reduce the benefits, of aquatic ecosystems that receive heated effluent. The magnitude of thermal effects on ecosystem services is related to facility-specific factors, including the volume of the waterbody from which cooling water is withdrawn and returned, other heat loads, the rate of water exchange, the presence of nearby refugia, and the assemblage of nearby fish species. Again, EPA emphasizes that thermal impacts are supposed to be minimized through implementation of Section 316(a), but to the extent that any impacts remain after the requirements in 316(a) have been satisfied, replacing once-through cooling with closed-cycle cooling may provide additional benefits.

There is no additional substantive discussion provided by EPA in the proposed Rule on either thermal discharge or the potential impacts of §316(b) compliance options or installed technologies on §316(a) permitting. The following are the author’s projections on the potential impacts of each of the EPA regulatory options on thermal discharge – this includes the EPA preferred option and the three options EPA rejected (though any of which could be adopted in the final Rule).

Effects of Impingement Compliance

All facilities with a DIF greater than 2 MGD would be subject to the proposed impingement reduction requirements and, theoretically, also the site-specific entrainment analysis; however, only facilities that withdraw more than 125 MGD AIF would need to conduct the entrainment studies. This somewhat implies, subject to the decision of the permit authority, that facilities withdrawing more than 2 MGD but less than 125 MGD AIF will only have to deal with the impingement requirements. If a facility decided to pursue Option 1 by demonstrating that impingement mortality is reduced 69% monthly and 88% annually they would need to modify their existing traveling screens or install new screens such that they are “fish-friendly” or Ristroph modified and, accordingly, conduct monthly biological monitoring. New or otherwise modified traveling water screens will have no effect on either the volume of water discharged or the temperature of the discharge plume and, therefore, no §316(a)-related issues will result. Power plants will, however, need to return the fish and shellfish to a location in the source waterbody that maximizes survival. This means they need to consider the location relative to the thermal discharge. For some facilities this would require transporting the fish a long distance to avoid thermal plume entrainment.

Relative to the impingement compliance alternative 2, which involves reducing the design through screen velocity to less than 0.5 fps, because of the very high costs involved in re-configuring intakes (e.g., a facility with a current design through-screen of 1.0 fps would need to more than double the existing intake profile), the only facilities likely to pursue this option are those with existing velocities very close (e.g., ~0.6 fps) to the EPA criteria. One possible approach to reduce the velocity would be to reduce the flow volume by changing pumps or installing variable frequency drives (VFD)[4]. This would result in a smaller and hotter thermal plume with resulting implications to §316(a) permitting. The number of facilities that may consider this approach is unknown to EPRI.

Effects of Entrainment Compliance

Entrainment compliance is determined by the permitting authority on a “case-by-case” basis and could result in a determination ranging from the existing CWIS being deemed BTA to a requirement to retrofit with closed-cycle cooling. The former determination would result in no change to the existing thermal discharge while the latter would eliminate thermal discharge as an issue. Facilities withdrawing more than 125 MGD AIF would have to conduct a number of studies to aid the permitting authority in the “case-by-case” decision-making process. These studies and their scope include:

1. <u>Entrainment Mortality Data Collection Plan</u> (122.21(r)(9)): this study would include a plan for collecting entrainment mortality data, requires a peer review process, and then requires the owner or operator of the facility to carry out the data collection. This study would provide data necessary to evaluate entrainment mortality for that facility.
2. <u>Comprehensive Technical Feasibility and Cost Evaluation Study</u> (122.21(r)(10): the owner or operator of the facility would submit an engineering study of the technical feasibility and incremental costs of candidate entrainment mortality control technologies. The study would include an evaluation of technical feasibility of closed-cycle cooling and fine mesh screens with a mesh size of 2 mm or smaller, as well as any other entrainment reduction technologies identified by the applicant or requested by the Director. This study would include: a description of all technologies and operational measures considered (which could include alternative designs of closed-cycle recirculating systems such as natural draft cooling towers, hybrid designs, and compact or multi-cell arrangements); documentation of factors that make a candidate technology impractical or infeasible for further evaluation.

3. Benefits Evaluation Study (122.21(r)(11): the owner or operator of the facility would submit a detailed discussion of the magnitude of water quality benefits, both monetized and non-monetized, of the candidate entrainment mortality reduction technologies evaluated in 122.21(r)(10), including incremental changes in the impingement mortality and entrainment mortality of fish and shellfish; and monetization of these changes to the extent appropriate and feasible using the best available scientific, engineering, and economic information. NOTE: included in this evaluation are the benefits associated with reduced thermal discharges (including impacts to T&E species and critical habitat and residual impacts to migratory species as EPA discussed in the preamble to the proposed Rule).
4. Non-Water Quality and other Environmental Impacts Study (122.21(r)(11): The owner or operator of the facility would submit a detailed discussion of the changes in non-water quality factors attributed to technologies and/or operational measures considered. These changes may include, but are not limited to, increases or decreases in energy consumption; thermal discharges including an estimate of increased facility capacity, operations, and reliability due to relaxed permitting constraints related to thermal discharges; air pollutant emissions and their health and environmental impacts; noise; safety such as the potential for plumes, icing, and availability of emergency cooling water; grid reliability including an estimate of changes to facility capacity, operations, and reliability due to cooling water availability; consumptive water use: and facility reliability such as production of steam and impacts to production based on process unit heating or cooling.

The following is a brief review of the potential candidate entrainment reduction technologies or CWIS re-design approaches and their potential impact on thermal discharge. A detailed review of all technologies is provided in EPRI 's Fish Protection Technology Reference Manual [5] (Note: an updated version of the manual is planned for release in late 2012). The following entrainment reduction technologies will not affect thermal discharge when used at the existing CWIS location:

- Fine mesh traveling screens – screens with mesh size of 2.0 mm or smaller must be evaluated. These screens collect and transfer to a fish return system the eggs, larvae and juvenile life stages of fish and shellfish that are physically prevented from passing through the fine mesh screens.
- Narrow slot wedge wire screens (cylindrical or flat panel) – these screens also physically exclude eggs, larvae or juvenile life stages, however, the excluded larvae are not collected but swept downstream or away from the intake by a sweeping current.
- Aquatic filter barrier – this technology is essentially a barrier net with a woven fabric material that may be perforated (e.g., 0.5 mm or larger) to increase through-flow. It also physically excludes eggs, larvae and juvenile life stages.
- Modular inclined screen (MIS) – this screen uses a narrow slot inclined wedge wire panel to physically exclude eggs, larvae and juvenile life stages and direct them to a fish return system.

The following technologies or approaches can change the volume or temperature of a thermal discharge as discussed:

- CWIS location change – physically moving a CWIS to a new location with a lower density of entrainable life stages can result in a significant reduction in entrainment. Generally, such an opportunity is limited to power plants located on ocean coasts or the Great Lakes. The new intake location could be a velocity cap or an offshore arrangement of cylindrical wedge wire screens. The new location may also offer the opportunity to access cooler water. Such a reconfiguration of the CWIS would also involve installation of new circulating water pumps, therefore, the entire character – volume and temperature – of the thermal plume will change.

- Variable frequency drives (VFD) – is a technology that can reduce entrainment and impingement of aquatic organisms by incremental reductions in circulating water intake flows. A VFD is a controller that adjusts the power delivered to a motor, allowing the motor to operate at different speeds. VFDs are often used in fans, ventilation systems, conveyor belts, and other industrial equipment. VFDs allow the operator of a power generating facility to decrease the circulating water flow by operating the circulating water pumps at less than full capacity. Assuming a linear relationship between the planktonic behavior of eggs and larvae and intake flow, entrainment can be reduced with reductions in flow provided by VFD operation. This flow reduction will result in a smaller and hotter thermal plume when the flow is reduced.

- Cooling towers – retrofit of cooling towers would eliminate thermal discharge as an issue. A point of note is that while several existing facilities have retrofitted once-through cooling systems with closed cycle systems, this action has never been conducted to minimize or eliminate impingement and entrainment. Retrofits have been conducted to eliminate thermal discharge issues.

- Seasonal cooling towers – this would involve the use of closed-cycle units during the period when entrainable life-stages are abundant which is typically during the local aquatic life spawning season. The once-through cooling system would be used during the rest of the year. Based on available entrainment data, EPRI [6] recently estimated the seasonal signal for different regions and waterbodies across the U.S. Generally, the seasonal signal and period when cooling towers could be temporarily deployed ranges from 2 to as many as 8 months with the shortest periods occurring in northern regions. This deployment approach is based on the premise that the towers could be used during the cooler period of the year (i.e., lower wet bulb temperatures) and, therefore, would be smaller with lower capital cost and less financial impact on plant operation. EPRI [7] recently examined this premise based on an assumed deployment of seasonal towers during the period of March through June – a typical spawning period in the northern half of the U.S. east of the Mississippi. EPRI found that the capital costs savings resulting from the ability to use a smaller cooling tower consistent with lower wet bulb temperatures during the spawning season compared to the summer would typically be no more than 10% and that the total reduction in plant output, expressed as a percentage of annual output with once-through cooling, ranges from 1% to 3.5% for full-time closed-cycle operation and from 0.25% to 1.8% with seasonal operation. EPRI also found but did not quantify challenges associated with maintaining both systems when they were not operating and with installing and maintaining a valve system to re-direct cooling flow to each system. If deployed, however, the thermal plume would be eliminated during the local spawning period and remain unchanged for the rest of the year.

Numerous power plants currently use helper cooling towers to meet thermal mixing zone requirements on a year-round or seasonal basis. There is no requirement in the proposed Rule or potential compliance action that would preclude or otherwise affect helper tower use.

EPA Rejected Regulatory Options

As previously noted EPA rejected three compliance options; however, as also noted, because they were presented for public review and comment, they could be adopted in whole or part in the final Rule scheduled to be issued on or before July 27, 2012. The three rejected options and their potential impact on thermal discharge include:

- Option 2 - impingement mortality controls at all existing facilities that withdraw over 2 MGD DIF; require flow reduction commensurate with closed-cycle cooling by facilities greater than 125 MGD DIF. If adopted, this option would eliminate thermal discharge as an issue for all facilities with a DIF greater than 125 MGD. Facilities with DIF less than 125 MGD would comply with the impingement reduction requirements as previously discussed. Re-design of the CWIS to attain 0.5 with installation of new pumps or by using VFDs could change the volume or temperature of the thermal discharge.
- Option 3 - establish impingement mortality controls at all existing facilities that withdraw over 2 MGD DIF; require flow reduction commensurate with closed-cycle cooling at all existing facilities over 2 MGD DIF. If adopted, this option would eliminate thermal discharge as an issue at all in-scope facilities.
- Option 4 - uniform impingement mortality controls at existing facilities with design intake flow of 50 MGD or more; BPJ permits for existing facilities with design intake flow between 2 MGD and 50 MGD DIF. If adopted, the potential implications of this option are similar to those discussed for Option 1. The only difference is that impingement reduction requirements for facilities with DIF between 2 and 50 MGD would be determined on a case-by-case basis.

Summary

EPA released a proposed Rule for implementing §316(b) of the CWA on April 20, 2011. A final Rule is planned for release on or before July 27, 2012. The final Rule will specify the requirements for reducing impingement mortality (entrapment of fish and shellfish on intake screens) and entrainment (mortality caused by passage of eggs, larvae and juvenile life stages through the power plant cooling system). EPA examined four regulatory approaches and selected a preferred option; however, any of the three rejected options could be adopted in the final Rule. Two of the rejected options involved retrofit of closed-cycle systems to plants with design intake flows greater than 2 MGD or 125 MGD – both of which would have eliminated thermal discharge as an issue for in-scope facilities. The third option rejected by EPA would have dealt with impingement reduction on a case-by-case basis for facilities with DIF less than 50 MGD and require selecting one of the impingement reduction alternatives for facilities withdrawing 50 MGD or greater DIF. The third option also included entrainment control on a case-by-case basis for all facilities with DIF greater than 2 MGD. The effect on thermal discharge for this option, therefore, is essentially similar to the EPA proposed option. Relative to the proposed option, impingement compliance requirements will likely have minimal impact on thermal discharge except those facilities that either re-build CWIS and possibly install new circulating water pumps or use VFDs to attain a design through-screen velocity of 0.5 fps. Entrainment compliance could have the greatest potential effect on thermal discharge and this will be decided on a case-by-case basis by permit authorities. Under the case-by-case approach for entrainment reduction, the existing CWIS could be determined as BTA or requirements for closed-cycle cooling – either a complete retrofit or seasonal tower use – could be required. The latter would completely eliminate the thermal discharge or at least during the seasonal period that towers are used. Use of VFDs to reduce entrainment could also result in a smaller and hotter thermal discharge and changes in intake location may also affect the character of a plant's thermal discharge. As of preparation of this paper, EPA is expected to release in January or February 2012 an update on §316(b) regulatory options they are considering; however, this is expected to be directed at impingement compliance approaches and will have little to no impact on the information presented herein.

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BENEFICIAL USES OF EXCESS HEAT

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Abstract

EPRI's thermal ecology workshop focused on the impacts of heated discharges on the environment. As an alternative to disposing of heat via cooling water discharges, there is value to considering recycle and reuse options for the excess heat. In addition to lowering the ecological impacts of heated discharges, reuse of heat for secondary purposes could be cost-neutral or actually provide some income back to the power company. This paper describes several technologies and practices that can take advantage of excess heat and put that heat to some other use. Some examples of the technologies that are investigated include heating of buildings, desalination of salty water/wastewater, aquaculture and greenhouse operations, industrial processes, and small-scale power generation using Organic Rankine Cycle (ORC) technology.

Introduction

Steam electric power plants operate by using fuel to boil water into steam. The steam is passed through a turbine that in turn spins a generator. The spent steam is condensed back to the liquid water phase – at nearly all U.S. steam electric plants, cool water is passed through condensers to cool the steam. Through that process, the cooling water increases in temperature. In closed-cycle systems, the heated water is returned to a cooling tower, pond, or other structure that enables the water to cool off then is recirculated to the condenser. In once-through cooling systems, the heated cooling water is discharged to a nearby surface water body.

Many power plants using once-through cooling systems discharge more than 100 million gallons per day (MGD) of heated water, and a few larger plants discharge several billion gallons (BGD) per day. Heated cooling water discharges can pose advantages and disadvantages to the receiving water bodies. In cold weather times of the year, the warm effluent serves as an attractant for many fish. This provides targeted fishing opportunities for anglers in the off-season. One of the workshop participants noted in a side conversation that he had heard of kayak clubs practicing boat-rolling techniques in warm water plumes during winter time.

In spite of some advantages to warm water discharges, the input of vast quantities of heat and potentially high water temperatures can influence whole ecosystems as well as individual species and populations. Section 316(a) of the Clean Water Act (CWA) acknowledges the potential impact of thermal discharges, but also introduces flexibility in how permit writers set thermal discharge limits. The provisions of section 316(a) have given rise to billions of dollars of aquatic ecological studies in the water bodies around power plants with warm water discharges. EPRI's decision to hold this thermal ecology workshop, nearly 40 years after the CWA was passed, gives a good indication of the contemporary importance of warm water discharges.

Terminology

The large amount of heat found in power plant cooling water discharges has historically been thought of as a burden or problem that confers a high management and permitting cost to the power company. In this context, the heat is often referred to as “waste heat”. The clear connotation is that this heat is not desirable and must be disposed of or dealt with in some manner.

One of the goals of this paper is to promote greener thinking about the heat. To the extent that there are viable opportunities to put the heat to a secondary beneficial use, the heat now has value. In this light, it is far more palatable to refer to the heat as “excess heat”. Seemingly insignificant details, such as how to refer to the heat, can affect the way in which power companies and regulators think about putting excess heat to some other use. Therefore, throughout this paper, the term “excess heat” is used to promote forward and enlightened thinking about heat.

Some Caveats

Most of the papers presented at EPRI’s thermal ecology workshop represent summaries of extensive studies or projects previously conducted by the authors or their colleagues. Those authors are personally familiar with the subject matter and the specific details of the facilities or water bodies that make up their papers. Conversely, this paper is not the results of a prior technical study conducted by the author. Instead, it is an introduction to a subject ancillary to the theme of the workshop.

During the workshop planning discussions, the author suggested to the workshop chairman, EPRI’s Bob Goldstein, that a paper examining the beneficial reuse opportunities for heat would be interesting. Dr. Goldstein invited the author to make a presentation on that subject and subsequently prepare a written paper. While having general familiarity with recycling of water and waste materials, the author had not previously investigated the reuse of excess heat from a power plant, and therefore had no existing report on which to base his talk and paper.

Given the manner in which this paper topic was selected, the author relied on past experience and internet research to identify five potential beneficial reuse opportunities for heated discharges from a power plant. Some of the options included are actual examples of current or past heated water reuse. Other examples represent options that have some potential but which have never been used before. The second group of options might be practical or might not.

Evaluation of Reuse Options

Before a power company and any potential partner undertake a project to reuse heated cooling water, a careful feasibility evaluation should be undertaken. At least four separate evaluations should be done before moving forward with the project.

- *The practicality and technical feasibility of an option must be assured*. For example, if a proposed reuse requires extensive piping, and the site does not have sufficient space to install the piping and pumps, the option is not physically practical.
- *The federal, state, and local regulatory requirements must be reviewed thoroughly to make sure the proposed option is not prohibited*. In the case that the regulations are silent

on the reuse opportunity, regulators should be consulted to make sure they are receptive to permitting the proposed reuse option.

- *The management at the power company must be comfortable with the proposed reuse option and must not have serious concerns about any long-term liability that could result from the selection of an option*. For example, if the heated cooling water was used to support an operation that grows food, and the use of the cooling water unintentionally introduces a contaminant into the food crop, the power company could be held liable.
- *The costs of implementing an option in a way that meets all applicable regulatory requirements should be estimated*. It is important to review and quantify all cost components when doing this analysis. To the extent that the total costs remain cost-effective to the company, the project can move forward.

Reuse Options

Five primary options are reviewed and discussed below. Some of these can be implemented in more than one way. The descriptions are necessarily qualitative in nature but they still illustrate potential opportunities. The primary options include:

- *Heating of buildings*. The heat could be used to provide heating to onsite buildings in cold weather portions of the year.
- *Desalination technologies that use waste heat*. The heat would be used to purify onsite wastewater, saline groundwater, or seawater.
- *Aquaculture*. The heat would be used to enhance growth rates of fish and other seafood for consumption, algae for biofuel feedstock, and plants/vegetables for ornamental or food use.
- *Industrial processes*. The heat would be used for enhancing in-plant processes.
- *Small scale Organic Rankine Cycle plants that have been developed to take advantage of medium temperature geothermal sources*. The heat would be used to generate additional power.

Pros and Cons are suggested for each option described below.

Heating of Buildings

Buildings can use excess heat in at least two different ways.

Direct Heating Using Hot Water

Portions of the cooling water effluent stream can be piped to nearby buildings where the excess heat can serve to warm the buildings during cold weather months. The heat can be transferred from the water to the building using radiators, under floor piping for radiant heating, or air handlers to transfer heat to an air stream. According to the International Energy Agency Heat

Pump Centre's website[1], the typical delivery temperature for water used in radiators is 45-55° C, for under floor heating 30-45° C, and for air heating is 30–50° C.

Pros

- Reuses excess power plant heat
- Reduces heating bills for the users
- Reduces the heat load discharged to the receiving water body

Cons

- Only viable for cold weather months
- Requires additional piping, pumps, and heat exchangers/radiators
- Still need to discharge residual cooling water

Heating Using Steam

Rather than using the heated cooling water as the heat-carrying fluid, this approach uses steam. Conceptually, the steam would be removed from the steam loop at a point following the turbine exit and before the condenser. The steam could be moved into dedicated steam lines and sent to nearby buildings for district heating. Many older urban power plants were set up with district heating via steam in mind. Retrofitting a power plant that was not specifically designed for steam reuse may or may not be practical.

As a result of removing some of the steam before the condenser, the cooling provided by the condenser would be changed. If the same discharge temperature is desired, this could allow a decrease in the volume of new cooling water required to be withdrawn. Conversely, if the cooling water volume passed through the condenser is kept the same, the cooling water effluent stream will have a somewhat lower temperature. Both of these are desirable endpoints, assuming that the performance and efficiency of the power plant are not affected by removing the steam.

Pros

- Reuses excess power plant heat
- Reduces heating bills for the users
- Reduces the heat load discharged to the receiving water body

Cons

- Only viable for cold weather months
- Requires additional piping, pumps, and steam return lines

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[1] IEA Heat Pump Centre website http://www.heatpumpcentre.org/en/aboutheatpumps/heatpumpsinresidential/Sidor/default.aspx; accessed on October 18, 2011.

- Need to return spent steam from the district heating system to the power plant boiler or add large quantity of very clean water for boiler makeup

A case example of using steam for district heating is provided in the box below.

Case Example for District Heating Using Steam: Kendall Power Station, Cambridge, MA

Kendall Station was built by Cambridge Electric Light Company in 1949. The plant was designed to provide power and steam to local users. During the 1960s, the local steam demand increased, and the plant added two steam boilers. In the late 1990s, through deregulation of the power industry, the electricity and steam portions of the plant were sold to different owners.

In 2002, the steam plant owner, GenOn, repowered the plant to give 265 MW capacity using residual oil, natural gas and distillate, but had backup boilers using heavy fuel oil. In 2005, Veolia Energy acquired the steam distribution network in Cambridge and two steam boilers at Kendall Station. The boilers were upgraded to produce low emissions. The new facility was designed to supply 150,000 tons of steam a year to its industrial customers and property owners in the Cambridge region. The steam system consists of 4 miles of concrete pipe carrying superheated steam at 200 psi.

The plant historically distributed some of the steam for district heating of commercial buildings. Plans are now underway to use more of the excess heat for district heating. Through upgrades and construction of a new steam pipeline to send more steam across the river to Boston, the Kendall Station's thermal discharge and cooling water withdrawals are reduced by about 95%.

Sources:

1) Veolia Energy, http://www.districtenergyaward.org/download/awards2011/Modernization_United%20States_Cambridge_2011.pdf ,

2) U.S. EPA Region 1, http://www.epa.gov/region1/npdes/mirantkendall/. Both accessed on October 19, 2011.

Desalination

As the demand for fresh water supplies grows, one approach is to treat salty water to remove the salt. Desalination is being used to produce drinking water from seawater and to treat industrial wastewater with high total dissolved solids (TDS). Both of these applications are described below.

Desalination of Seawater for Drinking Water

Some large municipal drinking water plants throughout the world use seawater as their source water. Desalination can be accomplished using several technologies. Many of the older plants used thermal distillation, which heats saline water to steam then condenses the steam back to a fresh water stream and a concentrated brine stream. Having a warmer starting temperature (by using heated cooling water) would reduce the energy input to heat the water to boiling.

Many of the newer plants use reverse osmosis, in which salt water is pushed under pressure against a membrane with very small pores. The sodium and chloride ions are blocked by the membrane while the water passes through. The author was unable to find information in the literature concerning whether reverse osmosis performs more efficiently when the source water is warmer than ambient water temperatures.

Pros for Desalination for Drinking Water

- Reuses excess power plant heat
- Reduces the volume of cooling water and therefore the heat load discharged to the receiving water body
- Unlike use for heating, desalination is a year-round activity

Pros for Co-Locating Desalination Plants with Power Plants

- The power plant site is already zoned for a compatible land use and has suitable security procedures for a water supply operation
- The existing infrastructure for feed water intake and brine discharge can save from 5% to 20% in desalination costs
- The desalination plant has the potential to purchase power at prices below retail rates

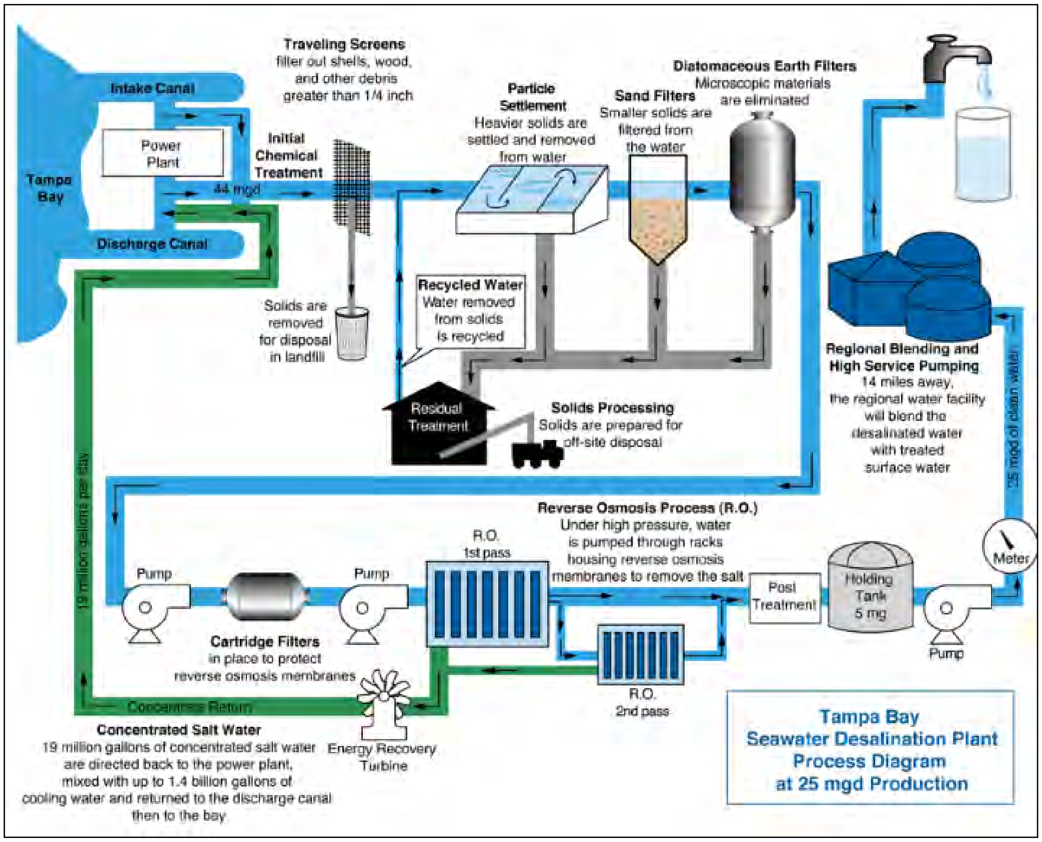
Cons

- Requires additional piping, pumps – this can be minimized by co-locating the desalination plant near the power plant.
- New once-through cooled plants are not being built
- Existing coastal once-through cooled plants may not have the physical space to add on a large new industrial operation and may face local permitting challenges

New municipal drinking water desalination plants are often co-located with power plants to provide both power and hot water. The case example for this section is the Tampa Bay Seawater Desalination plant.

<u>Case Example for Desalination for Drinking Water</u>: Tampa Bay Seawater Desalination Plant, Tampa FL

The Tampa Bay Seawater Desalination plant is located next to Tampa Electric's Big Bend Power Station in Tampa, FL. The power plant uses up to 1.4 BGD of seawater from Tampa Bay as once-through cooling water. The drinking water plant removes approximately 44 MGD of the heated cooling water to produce 25 MGD of fresh water, leaving 19 MGD of concentrated seawater that is directed back to the power plant and mixed with the cooling water in the discharge canal and returned to the Bay.



Source: Tampa Bay Water website, http://www.tampabaywater.org/facilities/desalination_plant/index.aspx, accessed on October 19, 2011.

Desalination of Oil and Gas Produced Water

In most parts of the United States, onshore oil and gas operations are not allowed to discharge the salty produced water that comes to the surface with the oil and gas. However, in some locations, coal bed methane produced water (this often has brackish or near fresh salinity) and hydraulic fracturing flowback water and produced water from shale gas development (which typically has very high TDS) has been treated and discharged [1].

If the TDS concentration in the flowback water or produced water exceeds 40,000 ppm, reverse osmosis and most other desalination processes are no longer cost effective. Only thermal distillation and crystallization processes can treat these wastewaters that can be as salty as 300,000 ppm TDS [2]. Thermal distillation and crystallization processes require heat, and operators look for sources of excess heat. A large natural gas company is using an EVRAS (Evaporative Reduction and Solidification) system to evaporate all of the flowback and produced water from a gas field in Fort Worth, TX. The resulting solids are crystallized. The system utilizes waste heat from an adjacent gas processing plant for evaporation.

In September 2011, the author had a conversation with a representative of a flowback water treatment company in northern Pennsylvania. The representative noted that his company was undergoing discussions with a local power company about using excess heat from the plant cooling water as a heating source for the flowback water desalination plant. Because the negotiations were not concluded at that time, the company representative was unable to share details.

Pros

- Reuses excess power plant heat
- Reduces the volume of cooling water and therefore the heat load discharged to the receiving water body
- Unlike use for heating, desalination is a year-round activity
- Can lower the cost of treating the high-TDS flowback water

Cons

- Requires additional piping, pumps – this can be minimized by co-locating the desalination plant near the power plant.
- May not have oil and gas activity near the power plant
- Heat requirements for produced water desalination are probably small compared to full-scale power plant heat load.

Aquaculture

Most aquatic plants and animals have a temperature tolerance range. Within that range, they tend to grow faster as the temperature rises, up to a critical threshold, beyond which growth diminishes and eventually stops. During times of the year when the water temperature is lower than optimal, commercial aquaculture operators can benefit from finding a warmer water source that promotes faster growth within the tolerance range.

With this in mind, some aquaculture operators have co-located at power plants to take advantage of heated cooling water. Cooling water can be used as the sole source or can be blended to keep the water at a desired temperature. During the 1980s, several Maryland power companies voluntarily operated hatcheries for striped bass. Some plants had onsite outdoor growing ponds that may or may not have received heated cooling water during the cold months. The author visited several of the aquaculture facilities as part of his responsibilities as a National Pollutant Discharge Elimination System (NPDES) permit writer and manager at the time.

Pros

- Reuses excess power plant heat
- Can accelerate growth rates of cultured species at commercial aquaculture facilities

Cons

- Requires additional piping, pumps – this can be minimized by co-locating the aquaculture plant near the power plant
- Only viable for cold weather months
- Need to ensure that cooling water does not introduce any undesirable substances into aquaculture operations
- Heat requirements for produced water desalination are probably small compared to full-scale power plant heat load

Other power companies and even some other industrial facilities also put their heated effluent to beneficial use in helping to warm hatchery/aquaculture operations and shorten growing times. Three case examples are described below.

Heating Greenhouses

A related application to aquaculture is use of heated cooling water in greenhouses during cold periods of the year. Like aquatic animals, plants will grow more quickly when the temperature is warmer, up to a critical threshold. The author assumed that this was a common practice, but while preparing the slide presentation for the workshop, was unable to identify any current uses of heated cooling water by greenhouses. However, during the workshop, Sean Ramach of EPA Region 5 noted during his presentation that at least one power company within Region 5 was considering using some of its heated cooling water for greenhouse warming.

Case Examples for Using Heated Cooling Water to Supplement Hatchery/Aquacultural Operations:

C.P. Crane Power Plant, Baltimore, MD

Baltimore Gas & Electric (now Constellation Energy) opened a striped bass hatchery in 2003 at the C.P. Crane power plant near Baltimore, MD. The facility was designed to conduct aquaculture and economic research to determine the feasibility of producing striped bass using intensive culture techniques and discharge water containing waste heat from the adjacent electric generation facility. Later the mission was shifted to raise striped bass hatchlings to fingerling size for subsequent transplanting into the Chesapeake Bay.

Chalk Point Power Plant, Aquasco, MD

Potomac Electric Power Company (now GenOn), operated several hatcheries and fish growing ponds at the Chalk Point plant and at a nearby research laboratory in Benedict, MD. Initially, the operations focused on raising striped bass for transplanting into the Chesapeake Bay. Later, the Maryland Department of Natural Resources requested that the hatchery switch to other species. During a site visit in 1999, the author visited a sturgeon rearing operation at the Chalk Point plant. The photo shows some of the young sturgeon.

Photo Source: J. Veil

ICDAS Iron and Steel Complex, Biga, Turkey

The ICDAS Iron and Steel Complex in Biga, Turkey includes a fish farm that produces 25 tons of sea bream and sea bass each year. The water supply for the fish farm is taken from the cooling water discharge of the mill. The harvest period is expected to be as short as 9 months compared to 12 to 16 months in conventional open sea units, taking advantage of supply water temperature being ideal for fish species in addition to inherent higher dissolved oxygen levels.

Source: http://www.icdas.com.tr/icdas/haber_devam_en.asp?id=66, accessed October 20, 2011.

Pros

- Reuses excess power plant heat
- Can accelerate growth rates of plants

Cons

- Requires additional piping, pumps – this can be minimized by co-locating the greenhouse near the power plant, but large commercial greenhouse operations with multiple buildings are not typically located near power plants
- Only viable for cold weather months
- Individual greenhouses would not need much heated water

Use in Industrial Operations

Many industrial processes either require heat or can become more efficient if heat is introduced. Heat can be used to preheat materials before combustion or reaction or to improve the kinetics of a reaction. Although heat is used widely throughout industrial operations, it often is generated onsite by the company at significant expense. Heated cooling water from power plant operations can help supplement or replace the heating requirement. One example of this is in-house use of heat to dry coal that will subsequently be burned at the same power station. This is highlighted below as a case example.

A second potential application was discussed in a presentation at the 2nd EPRI thermal ecology workshop in 2007. Proposals to construct coastal liquefied natural gas (LNG) terminals were popular at that time. The presentation [3] discussed the opportunity to co-locate an LNG terminal with a coastal power plant. The LNG arrives at a very cold temperature and must be heated to return the gas to a gaseous state. One way of warming the LNG is to use seawater at ambient temperature, then discharge the temperature several degrees cooler. This type of operation would perfectly complement a power plant’s cooling water. Each facility’s discharge would have thermal properties that met the other facility’s need. With the rapid increase in interest in shale gas, however, most of the proposals for coastal LNG terminals have been withdrawn.

Pros

- Reuses excess power plant heat
- When opportunities are available at or near a power plant, both parties can benefit

Cons

- Requires additional piping, pumps – this can be minimized by finding industrial partners located onsite or nearby
- Hopefully the industrial operation can use the excess heat year-round

Case Example for Using Heated Cooling Water Support an Industrial Operation: Lehigh University Study on Coal Drying

The U.S. Department of Energy's National Energy Technology Laboratory funded Lehigh University to evaluate using heated cooling water to dry low-rank coal to reduce water consumed in pulverized coal power plants. Low-rank coals contain significant amounts of water – subbituminous and lignite coals contain 15-30% and 25-40% respectively. Drying the coal prior to combustion can improve the plant efficiency, and in return reduce overall air emissions. In addition, lowering the temperature of the return cooling water reduced evaporative loss in the cooling tower, thus reducing overall water consumption by 5 to 7 percent, depending on ambient conditions.

Information from this project was used to design a full-scale coal drying system at Great River Energy's 546 MW lignite-fired Coal Creek Power Station in Underwood, ND. The Lehigh researchers found that there is enough low-grade excess heat at Coal Creek Station to remove 4.2 million pounds of water from 9,100 tons/hour (83 million tons per year) of lignite using the fixed bed dryer technology. When the sole source of excess heat is heated cooling water, the dryer requires an increase in station service power needs due to the high fluidization air flow rates needed by the relatively low-temperature drying system. Due to relatively high capital costs and high station service power costs for this configuration, the return on investment is negative for all moisture levels. On the other hand, when excess heat is taken from both heated cooling water and boiler flue gas, the economics are more favorable.

Source: Reference [4]

Use in Low Temperature Power Generation

Traditional steam electric power plants boil water to make steam. The boiling point of fresh water is 100°C. ORC power generation uses an alternate working fluid that moves from liquid phase to gaseous phase at a temperature lower than 100°C. ORC systems are receiving attention for use with geothermal water sources with temperatures slightly below 100°C.

The typical temperatures of heated cooling water effluent are well below 100°C (rarely much higher than 50°C). They may not contain sufficient temperature to operate an ORC generator. Power plant effluent has not previously been used as a heat source for such a system. A more detailed analysis by mechanical engineers and thermodynamic specialists would be needed to determine whether this is a viable reuse opportunity for heated cooling water.

In a previous section of this paper, the concept of using spent steam as a heat source was discussed. Theoretically, spent steam would have a temperature sufficiently hot to power an ORC generator. Another alternative would involve reduced cooling water volumes used in the main power cycle, leading to higher ΔTs and higher exit temperatures that better support small-scale power production.

Pros

- Reuses excess power plant heat to generate additional power

Cons

- Requires additional piping, pumps – this can be minimized by co-locating the ORC generator onsite
- Has never been used with heated cooling water
- Needs secondary cooling system to condense vaporize working fluid
- May not be thermodynamically viable
- May have excessive cost

Case Example for Low Temperature Power Generation: Naval Petroleum Reserve, central Wyoming

DOE's Rocky Mountain Oilfield Testing Center in Wyoming conducted research using an Ormat ORC generator with nominal 250 MW capacity. The working fluid was isopentane. The cooling system was an air-cooled condenser. The water source was produced water from an oil well. The design inlet temperature was 170°F, but the actual water temperature ranged from 195 to 198°F.

Over a period of about two and one half years, the total power produced from the unit was 2,181 megawatt hours of power from about 500 million gallons of hot produced water.

Source: Reference [5] and RMOTC website (photo source), http://www.rmotc.doe.gov/geothermal.html, accessed on October 20, 2011.

Final Thoughts

Excess heat can be an expensive power plant waste product or can be considered as a potentially useful byproduct. Several reuse options, with different degrees of practicality and feasibility, are described in the presentation. Persons interested in reusing excess heat should conduct a series of evaluations to make sure that the reuse opportunity is viable and cost-effective.

This paper is a qualitative introduction to the subject. Rather than being a definitive treatise, it is intended to make readers think about other ways in which excess heat can be put to work.

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26

INTEGRATED SITE SCALE REMOTE SENSING AND MODELING FOR REGULATORY MANAGEMENT OF THERMAL PLUMES

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Abstract

We have developed novel methods for cost effective design, evaluation, inspection, permitting, maintenance, and repair of wastewater disposal infrastructure. Our approach integrates site scale remote sensing for field data collection using a tethered helium balloon and desktop computers for hydrodynamic simulation modeling for outfall design and evaluation. Wastewater diffusers are needed to meet minimum dilution requirements within a regulatory mixing zone, a limited region around the discharge structure where the initial dilution occurs. We have created new methods for the CORMIX software system to provide comprehensive analysis of point source mixing zones. The CorHyd internal diffuser hydraulics simulation tool is intended for design and analysis of multiport diffuser discharges. We have developed new methods to assess diffuser infrastructure physical condition using various remote sensing technologies. Our patent-pending aerial remote sensing platform monitors mixing zone water quality and provides assessment of outfall physical condition through diffuser performance monitoring. Our approach integrates hydrodynamic simulation modeling and sensor networks to provide advanced information technology on wastewater disposal infrastructure to designers, consultants, regulators, facility managers, and maintenance crews.

Introduction

Wastewater disposal infrastructure design and management is increasingly important worldwide. The management of effluents such as municipal wastewater, desalination brines, thermal cooling waters, or industrial discharges requires better methods to mitigate negative impacts, protect human health, ensure regulatory compliance, and minimize costs.

Environmental regulations worldwide often include the concept of a mixing zone. Ambient water quality standards need not be met at the end of a pipe if a mixing zone is allowed by the regulatory authority (EPA, 1984). A regulatory mixing zone (RMZ) is a limited region or area around the discharge where the initial dilution occurs. Figure 26-1 shows a plan view representation of a RMZ for a point source discharge. Dischargers must demonstrate sufficient dilution at the edge of the mixing zone to comply with water quality standards. Mixing zones are typically determined by mathematical modeling, however sometimes field dilution studies are required (EPA, 1991). Mixing zones typically encompass the hydrodynamic near-field where outfall design and physical condition can have a strong influence on mixing.

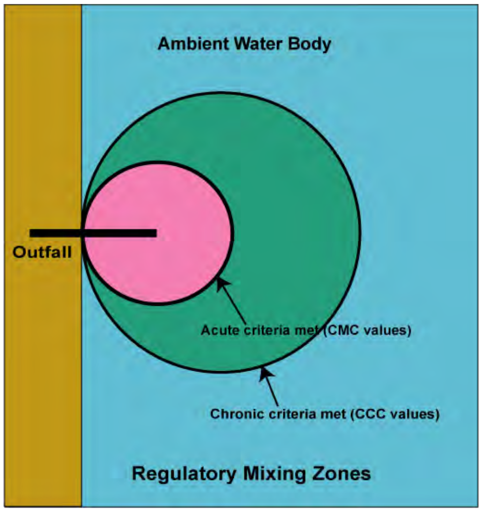

Figure 26-1
Regulatory Mixing Zones (RMZ). The discharge must meet minimum dilution at the edge of the regulatory mixing zone.

CORMIX-CorHyd Multiport Diffuser Hydraulic Modeling

The CORMIX modeling system has been in development since 1986 to simulate mixing zones of point source discharges [1, 2]. The present system now incorporates several hydrodynamic simulation codes for single port, multiport diffuser and shoreline discharge sources [3-9]. Effluents modeled include conservative, non-conservative (1st order decay), thermal, brine, and sediment sources. It contains several pre- and post-processor system and computer-aided-design (CAD) tools including 3-D graphics for source specification and mixing zone visualization, sensitivity analysis tools, time-series simulations, performance benchmarking, and case validation [9-14].

Figure 26-2 shows the space and times scales of the RMZ with respect to physical mixing processes and available simulation models. Figure 26-2 illustrates that most RMZ occur within the hydrodynamic far-field, but in the beginning of the far-field, shortly after boundary plume boundary interaction. CORMIX is the only available mixing zone model which explicitly simulates the physical mixing processes of the near-field, boundary interaction, and the far-field to give a comprehensive approach to predicting the RMZ.

The newest CORMIX feature integrates the CorHyd simulation tool for multiport diffuser internal hydraulics design [15]. CorHyd computes energy requirements, port flowrate, and diffuser head loss for multiport diffusers. A definition diagram for CorHyd appears in Figure 26-3. CorHyd can be used to specify pipe dimensions, head requirements, port/riser configurations, and line source characteristics. It has features to assist in the design of port/riser groups to specify a uniform port discharge flow along the diffuser. This ensures an efficient line source discharge. CorHyd analysis, used in conjunction with CORMIX dilution predictions, can assist in the design of unidirectional, staged, and alternating diffuser configurations to optimize near-field mixing within the RMZ.

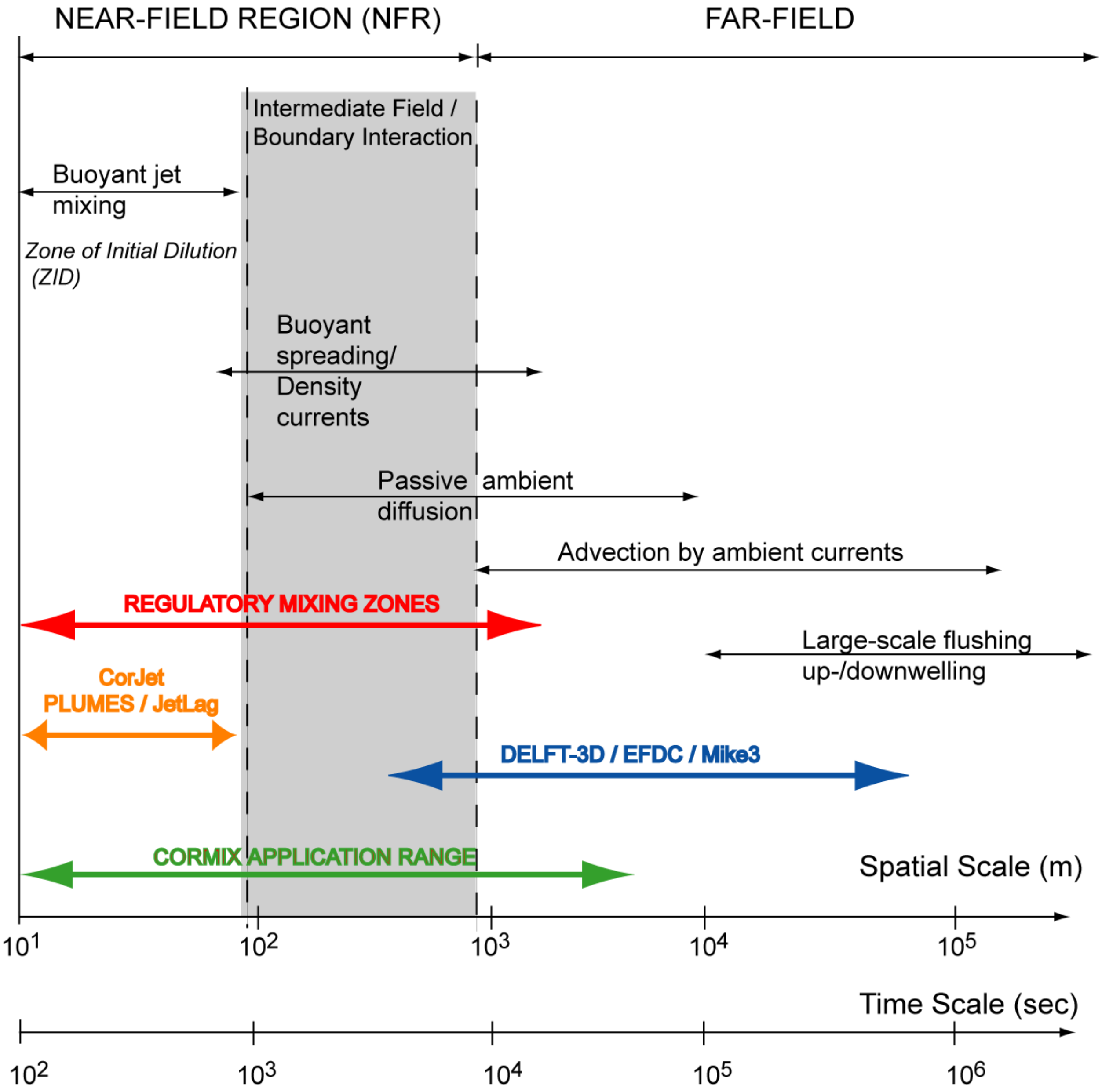

Figure 26-2
Space and times scales of physical mixing processes, hydrodynamic models, and the regulatory mixing zone

Remote Sensing of Mixing Zones

With U.S. Environmental Protection Agency (EPA) support, we have developed a remote sensing system for water quality monitoring in mixing zones [16, 17]. This system includes an aerial platform and several in-stream sensors.

Our patent-pending aerial system includes a tethered-balloon aerial platform with several sensors including infrared (IR) and visual cameras to collect site scale data.

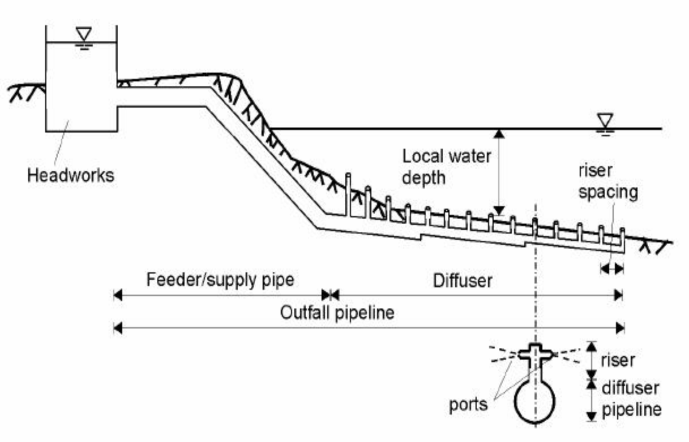

Figure 26-3
CorHyd definition sketch. CorHyd calculates energy loss and flow rate along the diffuser manifold. Line source behavior simulated by CorHyd is essential for diffuser infrastructure design, maintenance, and rehabilitation.

Infrared remote sensing of mixing zones can be considered wherever a temperature difference (ΔT) between effluent and ambient temperature is present. However, aerial IR sensors detect surface temperatures only. Thus, the variation in subsurface temperatures which may occur in deeper stratified flows cannot be detected. Therefore, our system concentrates on remote sensing of shallow layer flows. However, our platform may still be used in other situations with surfacing plumes. CORMIX modeling of surface plume characteristics is part of mission planning / feasibility analysis for IR remote sensing.

Aerial remote sensing has the potential to collect data over large regions in real time without disturbing or influencing the properties measured. However, currently available aerial remote sensing platforms are very expensive or not well suited for many mixing zone management issues [18]. Direct measurement of biophysical information such as temperature is dependent on the scale of the phenomena. To properly resolve mixing zone spatial scales with the Nyquist frequency limits requires resolution not readily available through space-based platforms and is limited to low-altitude helicopter or fixed-wing aircraft operations [19]. Both the helicopter and fixed-wing aircraft platform have enjoyed widespread successful application in remote sensing of the spatial distribution of surface water temperature values in mixing zones [20, 21]. However availability is limited, extensive operator training is required, and their costs are relatively high. Because of these limitations, conventional aircraft are not well-suited for rapid or routine deployment at a fixed location where hourly sampling may be required over an extended time.

There are several advantages to using balloons or blimps as platforms for aerial remote sensing. Balloons can be deployed quickly. Extensive operator training is not required. Tethered balloons can be moved and relocated easily, providing a more flexible method to collect data. Tethered balloons can be deployed on small boats in rivers to conduct water quality surveys over several stream miles.

Figure 26-4 illustrates the application of our remote sensing system. Platform sensors (Figure 26-4B) include visual and IR cameras, digital compass (platform x-y-z position and bearing to true and magnetic north), temperature/humidity sensor, and laser rangefinder (distance to target). Our ground station laptop computer uses our custom application ZoneView to communicate with the aerial platform via a wireless network. ZoneView monitors and positions the pan/tilt camera mount and captures sensor data. The aerial platform transmits visual and infrared images to the ground station in "near" real time, about once every second. All captured image data is stored locally on the laptop database which is tagged with GPS position information and other sensor readings.

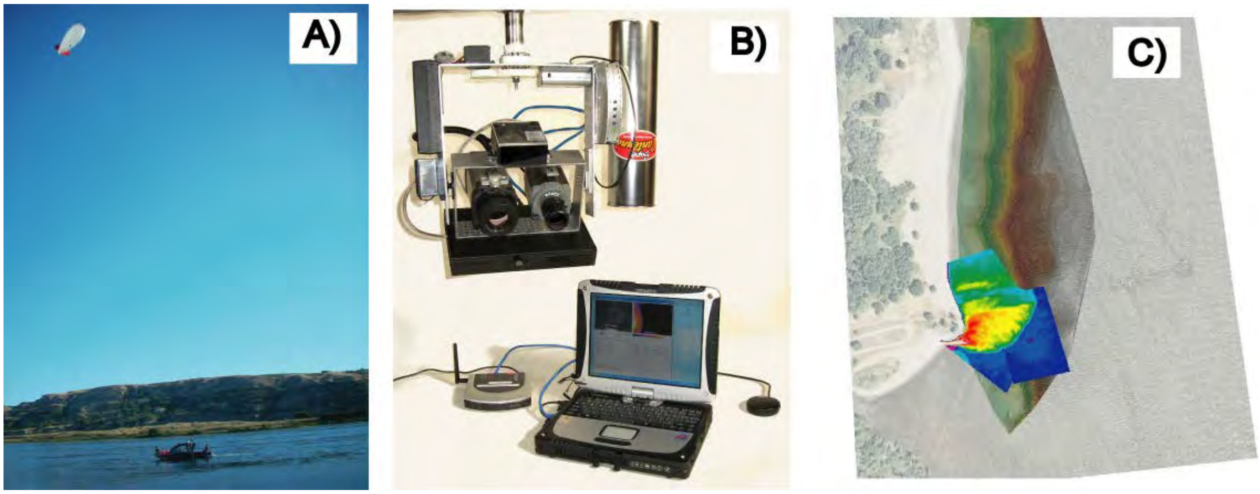

Figure 26-4
Integrated remote sensing of mixing zones. A) Balloon remote sensing platform deployment from a survey boat. B) Details of the remote sensing platform and ground station laptop ZoneView application using a wireless network. C) Geo-rectified aerial IR images with boat survey ADCP bathymetry data is used for CORMIX data input schematization.

To augment our aerial platform for monitoring point source mixing, we have integrated several additional boat-mounted sonar sensors: (i) a 1200 kHz Acoustic Doppler Current Profiler (ADCP) to collect detailed ambient velocity profiles, (ii) a 60 kHz depth sounder for bathymetry readings, and (iii) a Dual Frequency Identification Sonar (DIDSON) acoustic camera to assess physical outfall condition and mixing zone dilution modeling. All boat survey data is tagged with Differential GPS coordinates for sub-meter accuracy of latitude and longitude position. Figure 26-4C shows the integration of site bathymetry from ADCP survey and aerial IR plume data. Site bathymetry is crucial to ambient schematization for CORMIX data input specification [12].

Acoustic Camera Imaging for Assessment of Outfall Physical Condition

Physical condition of the outfall structure can influence mixing zone behavior. Diffuser structures may be damaged due to boat anchors or flooding; ports may be blocked or buried due to sedimentation. Sometimes, the "as built" configuration of a diffuser may differ from the design plans. When simulating mixing zone behavior with models such as CORMIX, the physical condition of the outfall can influence flow classification and dilution prediction. For these reasons, outfall physical inspection is often required for detailed mixing modeling and analysis.

Outfall inspection is commonly conducted by a scuba diver with a hand-held video camera. Turbidity is often so high that divers must in essence perform hand inspection. Divers may have little knowledge of multiport diffuser design so reporting of physical condition can be less than optimal. High turbidity conditions often produce poor quality video. Video images are not typically geo-referenced so it is difficult to assess physical condition spatially along the diffuser line.

Because of limitations in conventional underwater video imaging, we have evaluated and determined that the DIDSON acoustic camera can produce high quality images of outfall condition. DIDSON is a high-definition imaging sonar and gives near video quality images for inspection and identification of objects underwater. It is a surrogate for optical systems in turbid water. We deploy the DIDSON from our survey boat on a pole-mount as shown in Figure 26-5A. The camera connects to an onboard laptop computer for real time acoustic video imaging tagged with GPS coordinates and camera position.

Figure 26-5
Deployment of the acoustic camera. The camera is submerged during operation. Port condition and geometry data from the acoustic camera is used for CorHyd diffuser hydraulic analysis and CORMIX mixing zone prediction.

An example of a DIDSON image of a multiport diffuser in a highly turbid river appears in Figure 26-5B. In this case, the condition, operation, and orientation of individual diffuser nozzles were confirmed for a large multiport diffuser. Information from the DIDSON physical condition assessment can be used for data input for subsequent CorHyd simulations and CORMIX model validation, e.g. CorHyd simulations can provide details on diffuser line source performance helpful in CORMIX data specification for source characteristics such as port vertical angle θ_0.

Conclusions

We have developed technology and demonstrated deployment of a lightweight aerial remote sensing platform to collect geo-referenced water quality monitoring data within mixing zones. Our CORMIX model allows us to predict plume trajectory and plan field data acquisition campaigns. Field survey data collected by our sensors is broadcast via a wireless network to coordinate and facilitate data collection among the survey crew. We have integrated boat mounted sensors to collect site velocimetry, bathymetry, temperature, and outfall physical condition to augment our aerial remote sensing data for mixing zone regulatory management. Temperature measurements from aerial IR images correlate strongly with boat mounted temperature sensors. The sensor data collected is used for CORMIX data specification and mixing zone model validation.

When the boat-mounted instruments are deployed in conjunction with our balloon aerial remote sensing platform, the ZoneView application gives the boat survey crew an aerial perspective to monitor boat sensor location in relation to the discharge plume to facilitate monitoring. This real time aerial view allows us to identify critical monitoring locations for data collection within the mixing zone, as illustrated in Figure 26-6. Important mixing zone behavior such as the physical dilution, upstream density currents, plume boundaries, shoreline interaction, discharge canal leaks, and subsequent downstream mixing can be monitored in “real time”. This gives the boat crew detailed information on where to seek or obtain additional detailed data for subsequent modeling and analysis.

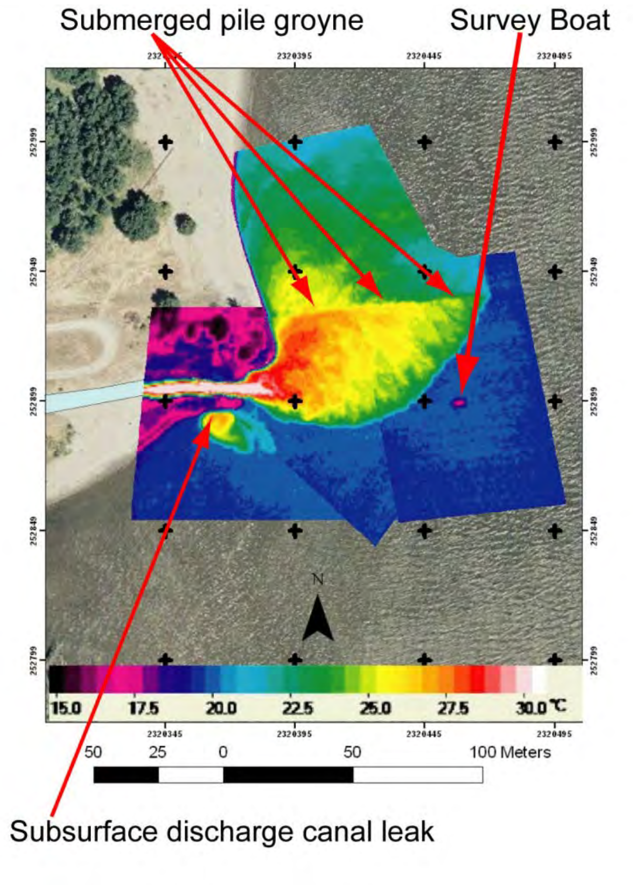

Figure 26-6
Details of the aerial IR image are available to the field survey boat crew in real time. This feedback allows boat crews to optimize collection location of field data collection for subsequent mixing zone analysis and CORMIX model validation.

The mixing zone dilution data provided by the aerial sensors provide high quality spatial relationships which would be difficult to discern with traditional mixing zone thermistor or dye studies. For example the subsurface discharge canal leak shown in Figure 26-6 was not apparent through visible inspection. This leak would be extremely difficult to identify with a synoptic dye measurement; however it is readily apparent with IR images. In addition, real time measurements provided by the aerial sensors can provide transitory spatial mixing zone data in unsteady environments, e.g. mixing zone properties during tidal reversal episodes which would be difficult (if not impossible) to capture with synoptic measurements.

We have found that the DIDSON acoustic camera resolves sufficient detail about diffuser condition to assist in assessment of diffuser condition and performance, e.g. port orientation, leaks, exit flow, and missing risers are clearly visible in the video images in shallow (< 10 m) riverine environments. We continue to develop methodologies to link physical assessment of diffuser condition with CORMIX simulation models.

In summary, this paper demonstrates integration of hydrodynamic modeling and remote sensing for mixing zone water quality management. CORMIX modeling is employed to plan the field data collection campaign. Data collected in the field campaign is then also used to perform CORMIX model validation. We demonstrate how multiple sensors can be integrated with mathematical modeling to perform outfall mixing zone studies for regulatory compliance monitoring and mixing zone model validation.

Acknowledgments

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A

WORKSHOP AGENDA

Agenda

The Third Thermal Ecology and Regulation Workshop
October 11-12, 2011
Great River Energy, 12300 Elm Creek Boulevard, Maple Grove, MN

Tuesday October 11th, 2011

Time	Topic	Presenter
7:00 a.m.	Continental Breakfast	
	I: Introductions and Workshop Overview	
8:00 a.m.	Welcome and Introductions	*Bob Goldstein, EPRI* *Mary Jo Roth, Great River Energy*
8:25 a.m.	Are We Still in "Hot Water" over Thermal Issues at Power Plants?	*Chuck Coutant, ORNL (retired), Keynote Speaker*
	II: Perspectives on Thermal Discharges	*Moderator: Rob Reash, AEP*
8:45 a.m.	Recent Developments in Power Plant Thermal Discharge Regulations, Thermal Effects, and Stressors	*Christine Lew, Tetra Tech*
9:05 a.m.	Outline of Regulations and Research Activities Regarding Thermal (Once-through Cooling System of Power Plants) Issues in Japan	*Mich Kiyono, Marine Ecology Research Institute*
9:25 a.m.	Everything Old is New Again: A Review of 316(a) Developments from a Legal Perspective	*Kristy Bulleit, Hunton & Williams*
9:45 a.m.	Discussion	*All*
10:05 a.m.	Morning Break	
	III: Water Quality, Thermal Standards and Protection of Aquatic Life	*Moderator: John Thiel, Dairyland Power Cooperative*
10:20 a.m.	Regulatory Perspective of US EPA Region 5 on Thermal Conditions in NPDES Permits	*Sean Ramach, EPA Region 5*
10:40 a.m.	Balanced Indigenous Populations?	*Jim McLaren, ASA Analysis & Communication*
11:00 a.m.	A Review of the Thermal Literature, with an Emphasis on Thermally Sensitive Species	*Greg Seegert, EA Engineering, Science, and Technology*
11:20 a.m.	Use of Benthic Invertebrate Thermal Traits to Evaluate Stream Classifications	*Steve Canton, GEI Consultants*
11:40 a.m.	Discussion	*All*
12:00 p.m.	Lunch	
	IV: Thermal Response Characterization	*Moderator: Chuck Coutant, ORNL (retired)*
1:00 p.m.	Macroinvertebrate Responses in a Laboratory Simulation of Thermal Effluents from Power Plants	*John Jackson, Stroud Water Research Center*
1:20 p.m.	Modeling Macroinvertebrate Response to Elevated Thermal Fields	*Bill Garrett, Alabama Power*
1:40 p.m.	Heat Shock Proteins: What are They, and do They Have a Role in Assessing Thermal Tolerance?	*Rob Reash, AEP*
2:00 p.m.	The Influence of Cold Shock and Reduced Ration on the Impingement Susceptibility of Gizzard Shad and Threadfin Shad	*Brooks Fost, Penn State University*
2:20 p.m.	Afternoon Break	

2:40 p.m.	Bioenergetics-based Fish Habitat Suitability along a Thermal Gradient	*David Coulter, Purdue University*
3:00 p.m.	Development of Thermal Criteria for Native Freshwater Mussels Based on Physiological and Reproductive Traits	*Alissa Ganser, University of Wisconsin*
3:20 p.m.	Enhanced Ecological Relevance in Laboratory Tests to Determine Thermal Tolerance of Juvenile Freshwater Mussels in Sediment	*Jennifer Archambault, North Carolina State University*
3:40 p.m.	Discussion	
	V: Poster Presentations & Facility Tours (Concurrent)	*Moderator: Bill Mills, Tetra Tech*
4:00 p.m.	Introductions by each poster presenter (2 min each)	*Various*
4:15 p.m.	Introduction to Tours	*Erik Silvola, Great River Energy*
4:20 p.m.	Poster Presenters: • Bill Mills (Tetra Tech) - Forecasting Inlet Water Temperatures for Open Cycle Power Plants and Power Curtailment to Meet Thermal Permit Standards • Greg Howick (Burns & McDonnell Engineering) - Evaluation of Reasonable Potential to Exceed Wisconsin's New Temperature Criteria Using Cormix Modeling • Greg Howick (Burns & McDonnell Engineering) - Plan for Section 316(a) Variance Renewal Studies for Power Plants in Kentucky • Willy Eldridge (Stroud Water Research Center) - Effect of Rate of Change During Diel Temperature Fluctuations on Growth, Acute and Chronic Stress, and Pathology of Multiple Warm Water Fish Species • Mary Terra (ASA Analysis & Communication) - Hydroacoustic Surveys for Thermal Plume Effects • Mark Mattson (Normandeau Associates) - Atlantic Salmon Smolt Downstream Migration past Merrimack Station's Thermal Plume • Joel Detty (Normandeau Associates) - A Low Cost Method of Evaluating Thermal Discharge Compliance using Detailed Field Measurements and Mass-Balance Scaling • Craig Swanson (Applied Science Associates) - Monitoring and Modeling the Thermal Plume from the Indian Point Energy Center in the Hudson River	*Various*
4:20 p.m.	Facility Tours: Half-hour tours departing every 10 min in groups of 25	*All*
5:20 p.m.	Adjourn	

Wednesday October 12th, 2011

Time	Topic	Presenter
7:00 a.m.	Continental Breakfast	
	VI: Case Studies	*Moderator: Chantell Johnson, Tri-State*
8:00 a.m.	Recent Experience with Thermal Compliance at the TVA Browns Ferry Nuclear Plant	*Paul Hopping, TVA*
8:20 a.m.	Monitoring and Modeling the Thermal Plume from the Indian Point Energy Center in the Hudson River	*Craig Swanson, Applied Science Associates*
8:40 a.m.	San Miguel River Case Study: Incorporating Elements of the CWA 316(a) to Develop Site-Specific Temperature Standards for a High Elevation, Low Summer Flow River in Colorado	*Chantell Johnson, Tri-State*
9:00 a.m.	Lay Reservoir Seicheing and Its Impacts on Thermal Discharges from the E.C. Gaston Plant	*Paul Craig, Dynamic Solutions*
9:20 a.m.	Mount Hope Bay, Brayton Point Station and the Decline of Fish Stocks	*Phil Colarusso, EPA Region 1*
9:40 a.m.	Morning Break	
9:55 a.m.	Freshwater Mussel Monitoring and Thermal Variance	*Heidi Dunn, Ecological Specialists*
10:15 a.m.	Assessment of Effects of Interaction of Pumped Storage Station Operations and Thermal Plume on Migration of American Shad (alosa sapidissima) in the Lower Susquehanna River	*Kimberly Long, Exelon Power*
10:35 a.m.	Lessons learned from long-term monitoring of the thermal discharge at Diablo Canyon Power Plant in California with implications for global climate change predictions.	*Chris Ehrler, Tenera Environmental*
10:55 a.m.	Discussion	*All*
	VII: Emerging Issues and Technologies	*Moderator: Bill Garrett, Alabama Power*
11:15 a.m.	Cost and Performance Consequences of Closed-cycle Retrofit	*John Maulbetsch, Maulbetsch Consulting*
11:35 a.m.	Application of Thermal Imagery to Optimization of Cooling Lake Performance	*Al Garrett, Savannah River National Laboratory*
11:55 a.m.	Lunch	
12:55 p.m.	Estimating Forced Evaporation from Surface Water	*Tim Diehl, USGS*
1:15 p.m.	A Review of EPA Clean Water Act §316(b) Regulations and their Potential Impact on Thermal Discharges and §316(a) Assessments	*Doug Dixon, EPRI*
1:35 p.m.	Beneficial Uses of Excess Heat	*John Veil, Veil Environmental*
1:55 p.m.	Advantages and Challenges of Thermal Discharge Modeling in Rivers Using Three Dimensional Hydrodynamic and Temperature Models	*Xing Fang, Auburn University*
2:15 p.m.	Integrated Site Scale Remote Sensing and Hydrodynamic Modeling for Regulatory Management of Thermal Plumes	*Robert Doneker, MixZon*
2:35 p.m.	Discussion	*All*
	Workshop Closure	*Moderator: Bob Goldstein, EPRI*
2:55 p.m.	Identification and summarization of issues	*All*
3:15 p.m.	Adjourn	

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