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# Proceedings: Second Thermal Ecology and Regulation Workshop

October 2 – 3, 2007

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# REPORT SUMMARY

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

## Background

In October 2007, more than 100 people met at the headquarters of Tri-State Generation and Transmission Association in Westminster, Colorado, 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 once-through 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

## 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 eight 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, recent advances in cooling technologies, and the interplay between Sections 316(a) and 316(b).

## Results

This document presents the proceedings from the Second Thermal Ecology and Regulation Workshop. Each of the presenters was asked to prepare a paper on his presentation. In total, 27 papers were received and are contained in this EPRI report. Copies of the presentations can be obtained from EPRI's eTherm website at http://www.epri.com/etherm.

## EPRI Perspective

Although the Clean Water Act has not changed in 35 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 change, 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 old and new thermal-discharge-related research and regulatory topics that excite the imagination and call out for creative scientific, technical, and policy solutions. The workshop was a follow-up to the first EPRI-sponsored workshop on Section 316(a) issues held in Columbus, Ohio, in 2003 (EPRI Topical Report 1008476).

## Keywords

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

# ACKNOWLEDGMENTS

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EPRI appreciates the hospitality of Tri-State Generation and Transmission Association in hosting the workshop at its headquarters in Westminster, CO., and the leadership of Chantell Johnson, Tri-State, in planning and handling many of the logistics.

EPRI further appreciates the members of the Workshop Steering Committee for their key role in organizing the technical program and recruiting speakers. Steering Committee members were: Chuck Coutant, ORNL (retired); Doug Dixon, EPRI; Raymond Harrell, Duke Energy; Chantell Johnson, Tri-State Generation; Ron Lewis, Duke Energy; David Michaud-WE Energies; Bill Mills, Tetra Tech; and Rob Reash, American Electric Power.

Although not an official member of the Steering Committee, Christine Lew played a key role in making the whole endeavor work and put together the Proceedings.

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# INTRODUCTION

In October 2007, over 100 people met at Tri-State Generation and Transmission Association Headquarters in Westminster, Colorado (Table 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**
**Tri-State Transmission and Generation Association Headquarters in Westminster, Colorado**

"Even if the Clean Water Act has not changed in 35 years, the world has and continues to do so," states Dr. Robert Goldstein, Senior Technical Executive at EPRI. "Water issues, such as thermal discharge, impingement and entrainment, Total Maximum Daily Loads, effluent guidelines, water availability and climate change, are converging. We have come together as a concerned community of power plant employees, regulators, consultants, researchers, professors and students to consider a mixture of old and new topics that excite the imagination and call out for creative scientific, technical and policy solutions." This workshop is a follow-up to the first EPRI-sponsored workshop on 316(a) issues in 2003 in Columbus Ohio, which had over 120 attendees. This most recent workshop provided an update on the regulations, research, and case studies in this area.

During the course of this two-day workshop, the group heard over 25 presentations on 316(a) and related topics, including legal and regulatory perspectives, development of water quality and thermal standards, thermal response characterization, thermal modeling, recent advances in cooling technologies, and the interplay between 316(a) and 316(b). The keynote speaker, Chuck Coutant, provided an overview of the history of the past 60 years of trying to set temperature criteria and standards to protect aquatic life. Dr. Coutant pointed out that, while regulatory efforts to control potential adverse effects from thermal discharges have been ongoing since the mid 1960's, there is no consistent framework by which states develop and implement protective temperature water quality criteria.

The Industrial Branch Chief of the Water Permits Division of the Environmental Protection Agency (EPA), Deborah Nagle, provided EPA's perspective on thermal discharge variances. She discussed the specific requirements of an applicant in requesting a 316(a) variance, and indicated that from EPA's perspective, the permitting authorities are not implementing 316(a) in a consistent and correct fashion. To help with this problem, next year EPA expects to update their 316(a) technical guidance document, originally drafted in 1977. "The 1977 316(a) guidance manual has served us well for 30 years, but certainly is due for updating," said Chuck Coutant. "The basic structure of using retrospective (no prior harm) and predictive (thermal requirements data for organisms) approaches for demonstrating a balanced community is strong, but the guidance needs to include a number of subsequent administrative and judicial decisions, such as including managed, non-indigenous fish species and not expecting a return to pristine conditions. Also, several indices of community health have been developed since 1977 that are very useful for evaluating the balance of aquatic communities, which is the crux of Section 316(a)."

While the EPA is working on updating their guidance, several States are putting forth an effort to revise long-outdated water temperature standards. Presentations from Erich Emery, Ohio River Valley Water Sanitation Commission (ORSANCO), Lareina Wall of GEI Consultants (Colorado), and Mike Wenholz of Wisconsin Department of Natural Resources discussed the status of updates to thermal standards in those states.

One of the major topics at the workshop was an update on the scientific research in thermal response characterization. Rob Reash, of American Electric Power, discussed the key issues associated with laboratory versus field tolerances for fish. Tamara Pandolfo, of North Carolina State University, presented her research on freshwater mussel sensitivity to a range of water temperatures and how the presence of a secondary toxicant can cause mussels to be more sensitive to temperature stress. Telemetry and other state-of-the-art tools for evaluating impacts of thermal discharges on fish were presented by Tim Brush of Normandeau Associates.

One-third of the presentations focused on recent, site-specific case studies. Terry Cheek of Geosyntec Consultants and Bill Evans of Georgia Power Company described the circumstances driving Georgia Power Company's decision to retrofit cooling towers on three plants to prevent fish kills under extreme conditions, and the implications for the viability of the 316(a) regulatory option. David Lee of We Energies shared the 316(a) demonstration process, including thermal plume modeling, used for the Oak Creek Expansion Project's Wisconsin Pollutant Discharge Elimination System (WPDES) permit application.

The conference took on an international flair as representatives from France, The Netherlands, and New Zealand provided insight into their countries' perspectives. Yves Souchon from Cemagref, a public research institute in France focusing on land management issues, and Cecile Delattre from Electricite de France (EDF), presented a summary of the thermal discharge regulations in France and some results of biological monitoring at power plant sites. Maarten Bruijs from KEMA, described a field study on the influence on fish behavior of higher water temperatures in the cooling water discharge from Claus Power Plant in the Netherlands. Jacques Boubee from the National Institute of Water and Atmospheric Research (NIWA) provided a summary of New Zealand's electricity generation and environmental regulations and the challenges faced in meeting these regulations at Huntly Power Station.

The workshop included a poster session where 8 posters were presented. The group of workshop attendees listened to each poster presenter summarize his or her poster for several minutes before breaking into a more informal setting where the posters were discussed on a one-on-one or small group basis. In his poster, Greg Seegert of EA Engineering presented the use of field data to support or refute laboratory-derived thermal tolerance values. Mark Hess of Ocean Imaging presented the utilization of aerial thermal imaging in a regional water quality monitoring program. The poster by John Young of ASA Analysis and Communication showed what types of information could be developed and presented to regulatory agencies in support of a site-specific numeric standard for rate of temperature change. Other poster topics included forced evaporation from once-through cooling systems, a summary of EPRI's eTherm website, the use of temporary cooling towers to comply with thermal discharge regulations, thermal discharge regulations in the Netherlands and thermal modeling.

One theme that ran through many presentations was climate change. Yves Souchon and Cecile Delattre discussed recent climate events in Europe, such as the heat wave of 2003, that have introduced new questions to be addressed in France's environmental policy. In Deborah Nagle's talk on the EPA perspective, she presented the challenges facing 316(a) regulations, including an increase in prolonged dry and wet conditions and an overall increase in ambient temperatures of waterbodies.

The workshop closed with several presentations on emerging issues and future research needs. E. Eric Adams of the Massachusetts Institute of Technology discussed advances in thermal plume modeling. Judson White and John Waddill of Dominion Resources Inc. discussed the decision to install a hybrid cooling tower at a new unit at the North Anna nuclear power facility and its anticipated performance. Tim Hogan of Alden Research Laboratory discussed how co-locating power plants with desalination and LNG facilities can create a win-win situation for both facilities, with the power plant discharge providing needed water to the desalination plant or LNG facility and the sharing of research, construction, permitting and monitoring can reduce costs for both facilities.

The workshop was organized by a steering committee consisting of Chuck Coutant (Retired), Doug Dixon (EPRI), Robert Goldstein (EPRI), Raymond Harrell (Duke Energy), Chantell Johnson (Tri-State Generation and Transmission Association, Inc.), Christine Lew (Tetra Tech), Ron Lewis (Duke Energy), Dave Michaud (We Energies), Bill Mills (Tetra Tech), and Rob Reash (American Electric Power).

This document presents the proceedings from the Second Thermal Ecology and Regulation Workshop. Each of the 36 presenters was asked to prepare a paper on their presentation. In total, 27 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.

# 2

# SIXTY YEARS OF TRYING TO SET TEMPERATURE CRITERIA AND STANDARDS TO PROTECT AQUATIC LIFE

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Charles C. Coutant
Oak Ridge National Laboratory (retired) and Private Consultant

## Introduction

It is a privilege and a pleasure to present this keynote for the Second Workshop on Thermal Ecology and Regulation. Protection of aquatic life from hazardous extremes of temperature and markedly unnatural temperature changes has been a topic of regulatory concern since the 1950s. The history of efforts to regulate temperature has been one of changing perspectives and unresolved needs. I believe a brief account of this history will set the stage for the Workshop's presentations and discussion.

Why understand the history of temperature regulation? There are several reasons pertinent to our current status.

Several states, stakeholders, and the U.S. Environmental Protection Agency (EPA) are currently revisiting temperature criteria and standards. Many state temperature standards have not changed since the 1970s and deserve updating. As these standards and the biological criteria behind them are re-evaluated, much of the "institutional knowledge" for their establishment has been lost.

Power plant issues are returning to thermal effects [Clean Water Act Section 316(a)] after several years of intense focus on water intake issues of entrainment and impingement [Section 316(b)]. Thermal power plants and their heated cooling-water discharges have been the focus of much of the concern for temperature regulation.

Temperature change comes from more than power plants, however. Consider climate change, land use changes, warm irrigation return flows, flow regulation from reservoirs, and other industrial cooling. All of these sources of temperature change are being integrated at the watershed level under Total Maximum Daily Load (TMDL) analyses.

New thermal-effects research has been conducted and published in the years since many criteria and standards were last scrutinized. We need to incorporate new knowledge of the biological and ecological effects of temperature and temperature changes obtained from this research and analysis. We need to know what relevant data we have on hand for setting criteria and standards. Perhaps equally important, we need to understand what important data we have yet to obtain so that needed work can be carried out without undue repetition.

And finally, the history of setting criteria and standards is important because those who don't remember it are bound to repeat it. We need to build on the past, not repeat the same trials and errors.

## Perplexing Regulatory-Related Questions

Re-evaluation of temperature criteria and standards is often stimulated by one or more perplexing questions related to specific regulations. It has long been acknowledged that there should be a scientific basis for criteria and standards, but often the basis is unclear or unsubstantiated. For example, what is the scientific basis for a specific numerical rate-of-change temperature standard to protect aquatic life (Pennsylvania allows a maximum rate of 2°F per hour; other states have different numbers)? What is the scientific basis for a standard for maximum temperature rise over ambient (Colorado's is 3°C), and how does one quantitatively define "ambient" in this context? I have assembled a list of some of these questions, in no particular order and certainly not comprehensive, in Appendix A. They are real questions derived from my efforts to assist various parties with re-evaluations of temperature regulations. These questions should make us think, not only about the regulatory process but also about its scientific underpinnings.

## Definitions

If nothing else is clear from looking at the history of water quality regulation, it is the semantic confusion between the terms "criterion" (plural criteria) and "standard" at all levels. The terms were (and often still are) used interchangeably. These terms were clearly defined by the National Technical Advisory Committee on Water Quality Criteria for the federal agency responsible for water pollution control, then (1968) the Federal Water Pollution Control Administration (FWPCA) [1]. The following definitions were considered appropriate and have remained essentially unchanged since then. Simply keeping the distinctions in mind avoids a great deal of confusion for both scientists and regulators.

- Criterion — a scientific requirement on which a decision or judgment may be based concerning the suitability of water quality to support a designated use.
- Standard — a plan that is established by governmental authority as a program for water pollution prevention and abatement.

In other words, the criteria are the scientific facts and concepts underlying the legal standard. Both criteria and standards are to be based on designated uses for water bodies (which may be so specific as to designate which species of fish are desired there). For example, the criterion for long-term upper maximum temperatures of a particular water body may be the temperature that preserves 75% of optimal growth for fish species A, whereas the legal standard adopted for attaining that criterion in that water body may be a simple 90°F (32.2°C) maximum temperature at any time or place.

## Criteria History

In this section, I briefly discuss my selections for significant and influential milestones along the journey toward national temperature criteria and standards. They begin with regional efforts in the mid 1950s and lead to the truly national perspectives of the 1970s and 1980s, which continue to be in effect today.

**Ohio River Valley Sanitation Commission (ORSANCO; 1956).** One of the earliest published temperature criteria for aquatic life was prepared in 1956 by the Aquatic Life Advisory Committee of ORSANCO. The ORSANCO effort was described in a summary by EPA [2]. These criteria were based on thermal conditions believed necessary to maintain well-rounded fish populations and sustain production of a harvestable fish crop in the Ohio River. They were simple upper limits: 34°C (93°F) any time or place; 23°C (73°F) in December-April; no rise in streams suitable for trout. These criteria were based on the perceived thermal requirements of species present in the Ohio River vicinity. There was no mention of an allowable temperature increment or rate of change. This regional effort was especially influential because the country's major water pollution control laboratory was located in Cincinnati.

**ORSANCO 1967.** An allowable temperature increment first appeared in 1967. In 1967, the ORSANCO Aquatic Life Advisory Committee modified its recommendations in several ways, including the first published instances of an incremental temperature criterion and a daily average [2]. To the previous instantaneous temperature limitation of 93°F was added a daily average of 90°F (32.2°C). During transition months of March, April, October, and November, the temperature could be changed gradually but not more than 7°F (3.9°C). To maintain trout habitats, stream temperatures should not exceed 55°F (12.8°C) October-May and 68°F (20°C) June-September. Although viewed as criteria based on science, the two ORSANCO documents really recommended temperature standards for the Ohio River ecosystem, which would be acted upon by states or other entities.

**1968 Water Quality Criteria ("Green Book").** The notion that temperature could be regulated nationally by a temperature increment above ambient temperature of a water body was formalized in the federal government's "Green Book" [1]. In the mid 1960s, the Secretary of the U.S. Department of the Interior appointed a National Technical Advisory Committee on Water Quality Criteria (NTAC) to serve the FWPCA. This committee, composed of recognized experts in water quality matters, was charged with summarizing the quality requirements of water for various uses, including fish and other aquatic life. Water quality included temperature as well as chemical constituents. The use of water for cooling electrical generating stations was specifically called out as influencing water temperature. The Committee's report was published in spring 1968, and because of the color of its cover it became known colloquially as the "Green Book" on water quality criteria.

An important contribution of the NTAC was resolution of the semantic problem of "standards" versus "criteria" in water quality matters, discussed above. The NTAC also noted that standards adopted by the states should "include water use classifications, criteria necessary to support these uses, and a plan for implementation and enforcement." They also noted that the terms "criteria" and "requirements" are sometimes used interchangeably. As a whole, the NTAC viewed criteria as scientifically defensible information, although application of this definition through the document was spotty.

The Fresh Water subcommittee of the NTAC defined the temperature issue thusly: "In arriving at suitable temperature criteria, the problem is to estimate how far the natural temperature may be exceeded without adverse effects." After noting that aquatic populations respond to gradual seasonal temperature changes and many other variables, the Committee acknowledged that no single temperature requirement can be applied to the whole of the U.S. or even to a single state, and that the requirements (criteria) "must be closely related to each body of water and its population." The committee concluded that: "To do this a temperature increment based on the natural water temperature is more appropriate than an unvarying number." A cautionary note was added: "Using an increment requires, however, that we have information on the natural temperature conditions of the water in question, and the size of the increment that can be tolerated by the desired species."

The maximum increments recommended for fresh water were 5°F (2.8°C) for warm-water stream species, 3°F (1.7°C) for warm-water species in lakes and reservoirs, 0°F for cold-water inland streams or lake hypolimnia containing trout and salmon, 5°F for cold water streams without trout or salmon, and 3°F for cold-water lakes and reservoirs without trout or salmon. All increments were to be applied based on the monthly average of daily maximum temperatures for the expected minimum daily flow for that month. The "Green book" contained no literature references supporting these numerical recommendations. There was one concession to the alternative view of species- and life-stage-specific thermal requirements in the form of a short table giving provisional maximum temperatures recommended as compatible with the well-being of various species of fish and their associated biota (also without documentation). In addition, the committee stated that "a seasonal cycle must be retained, the changes in temperature must be gradual and the temperature reached must not be so high or so low as to damage or alter the composition of the desired population."

Additional cautionary remarks were provided by FWPCA Commissioner Joe G. Moore in his letter of transmittal of the report to the Secretary of the Interior. He said that while the report was the most comprehensive such document to date, "…the Committee members and I wish to emphasize that this report is not sufficiently conclusive or inclusive to serve as the only guide to determining water quality criteria or requirements. … The work of the Committee illuminates the fact that the unknowns still far exceed the knowns in water quality requirements—even to the experts. Therefore, requirements should be applied with the best of judgments." The Commissioner also noted that the Committee sometimes tended to make recommendations that were less directed at water quality requirements and more toward policy (i.e., standards), such as would be the province of regulatory agency policy makers.

A number of evident deficiencies in the NTAC report, including the Committee's recommendation of specific increments as the temperature criteria (more like standards) without documentation of the scientific basis, led to a request for further evaluation of water quality requirements with emphasis on more scientifically justifiable, quantitative approaches. Further development of water quality criteria was referred in 1971 to the National Academies of Science and Engineering by the FWPCA's successor agency, the EPA.

**ORSANCO 1970.** Despite the NTAC Green Book, the FWPCA stressed the importance of absolute temperature limits based on biological requirements of affected species as preferable to an incremental temperature in its evaluation of ORSANCO's 1967 recommendations. Nonetheless, ORSANCO reinterpreted the NTAC recommendation as a limit on *added heat*, the first time this concept appeared [2]. It proposed a formula for an allowable heat-discharge rate (BTU/sec), but added: "in no case shall the aggregate heat-discharge rate be of such magnitude as will result in a calculated increase in river temperature of more than 5 degrees F." The 5°F limit tended to be more stringent than the calculated allowable heat-discharge rate, so it became the defacto criterion, even though it had no documented scientific basis.

**Water Quality Criteria 1972 ("Blue Book").** In 1971, at the request of the EPA, the National Academy of Sciences and National Academy of Engineering undertook a revision of the 1968 NTAC report. Freshwater Aquatic Life and Wildlife was one of six panels organized according to various aspects of water quality by the Committee on Water Quality of the Environmental Studies Board. The report was submitted for publication in August 1972 (thus the date in the title) and published by EPA in March 1973 [3]. As stated in the preface, the 1972 report was "vastly more than a revision of the NTAC report" in that it included new subjects and an "expansion of the information base…through new data from recent research activities and greater capabilities of information processing, storage, and retrieval…." In short, it was based on scientific data presented through appendices and literature citations. As with the "Green Book," the cover color of the Academies' report immediately assigned it the moniker of the "Blue Book."

The Academies' report explicitly rejected the NTAC's recommendation of an allowable temperature change as a scientifically valid temperature criterion. The introduction to the chapter on Heat and Temperature noted that aquatic organisms have varying temperature tolerances and optimum temperatures, and that natural temperatures of surface waters of the U.S. vary greatly as a function of latitude, altitude, season, time of day, duration of flow, depth, and many other variables. Even a single water body does not have uniform or consistent thermal characteristics. Therefore, the report stated that: "Criteria for making recommendations for water temperature to protect desirable aquatic life cannot be simply a maximum allowed change from 'natural temperatures.' This is principally because a change of even one degree from an ambient temperature has varying significance for an organism, depending upon where the ambient level lies within the tolerance range." The report also observed "historic temperature records or, alternatively, the existing ambient temperature prior to any thermal alterations by man are not always reliable indicators of desirable conditions for aquatic populations." Because human developments can both raise temperatures (e.g., power plants) or lower them (e.g., large reservoirs), the report considered "ambient" and "natural" to be exceedingly difficult to define. The report did accept the premise of the NTAC report that seasonal cycles needed to be maintained with gradual spring and fall changes (accommodating species-and site-specific spawning requirements, which were summarized as specific temperature ranges) and large unnatural day-to-day fluctuations should be avoided. The report concluded that: "Criteria for temperature should consider both the multiple thermal requirements of aquatic species and requirements for balanced communities." The report then provided amply documented scientific information on the thermal requirements of aquatic organisms, largely fish, with examples of how this information can be used to set water temperature standards and conduct analyses of potential thermal effects on aquatic life. I was the principal author of the Heat and Temperature chapter of the Academies' report, and I have published several articles supporting the approach in that report [e.g., 4, 5].

Despite the alternative paradigm presented by the Academies' Committee, the chapter on Heat and Temperature of its report did not specifically address the NTAC's stated desire to know "the size of the increment that can be tolerated by the desired species." It appeared evident to the Committee that if a specific temperature requirement of a species or life stage were known (e.g., X°C was lethal after 96 hours) then the difference between that temperature and the initial holding temperature (acclimation) would be the tolerated increment. It was clear from the data presented by the Committee that the tolerable increment varied widely depending on the initial starting temperature and the particular endpoint temperature. It was not a constant 5°F or 3°F as recommended by the NTAC in its "Green Book," but was usually much more than that except at temperatures approaching a species' tolerance limit. Data were presented in the Academies' report for acclimation temperatures and several endpoints for which the variable tolerable increment could be calculated.

**EPA Quality Criteria for Water (1976) and Brungs and Jones (1977).** The EPA rejected the incremental temperature approach in companion reports that adopted and amplified the Academies' Blue Book report. In 1976, the EPA Office of Water, Regulations and Standards published the first edition of "Quality Criteria for Water," colloquially known as the "Red Book," including a brief summary of temperature criteria [6]. In May 1977, EPA Office of Research and Development published "Temperature Criteria for Freshwater Fish: Protocol and Procedures" as a guide to implementing the National Academies' recommendations and its Quality Criteria for Water [2]. That report included additional species-specific data summaries beyond the Academies' report for a number of fish species.

**EPA and Nuclear Regulatory Commission (NRC) Interagency 316(a) Guidance (1977).** Section 316(a) of the Clean Water Act of 1972 provided for a variance from water temperature standards through detailed, site-specific analyses of a thermal discharge and its receiving aquatic community. Both EPA and the NRC had some responsibility for thermal discharges, EPA through the discharge permit system and NRC through licensing of nuclear power plants. Section 316(a) established the criterion of protection and propagation of a balanced indigenous community of aquatic organisms. An interagency team, of which I was a member, developed a guidance manual for implementing Section 316(a) [7]. The guidance stated that the community criterion could be met by demonstrations using predictions based on temperature requirements for Representative Important Species (especially for proposed discharges) and/or field studies of existing discharges that showed "no appreciable harm." The predictive approach essentially embodied the Academies' criteria methodology using species' thermal requirements. The retrospective approach fostered use of community-based indices, such as for diversity and integrity, as appropriate criteria. In practice, most 316(a) demonstrations for existing discharges have used a combination of the predictive and retrospective approaches. Site-specific variance demonstrations under Section 316(a) have largely supplanted direct application of the more broadly applicable water temperature standards at most power plants. The 1977 guidance manual is still the applicable guidance, although paradoxically, it never was made permanent guidance and is still in "draft." Other papers in this workshop expand on Section 316(a) implementation (Nagle, Jinks).

**EPA Guidelines for Criteria (1985).** Although not specific for temperature, this document provided general guidelines for developing water quality criteria [8]. It is important for the notion that not everything in an aquatic community needs to be assured protection. The EPA formally suggested that 95% of aquatic life be protected. It also considered field data to have priority over predictions from laboratory data.

**EPA Quality Criteria for Water (1986).** Lest there be any doubt that EPA favored the National Academies' approach of specific temperatures for aquatic life tolerances and other requirements over an approach using incremental temperature criteria above ambient, the 1986 revision of Quality Criteria for Water ("Gold Book") firmly restated its position [9]. That position remains unchanged to the present time.

## Now?

What is the situation now?

Institutional memory is fading. Many, if not most, of those involved with developing temperature criteria and standards in the 1970s, including development of the guidance manual for 316(a) demonstrations, are gone from the profession. Some, like me, are retired but still active. Others have retired to other pursuits or have passed away. Valuable knowledge is being lost. We have not effectively trained successors.

We have issues about data diversity and quality. Information on temperature requirements is gleaned from the scientific literature, which represents diverse measurement techniques, prior holding conditions, end points, and species. There is no standardization and little quality control for these studies other than general peer review (often by reviewers who themselves are not versed in thermal biology). Numerous agencies are conducting largely redundant reviews of the available thermal-effects literature to develop reliable data banks for species in their state or other location. At a minimum, these review efforts should be coordinated.

There is a divergence of study methods rather than standardization. Standardized laboratory bioassays with specific test organisms are the norm for defining tolerance and no-effect levels for other pollutants. These standardized approaches have evolved as short-cut means to develop reliable criteria for use in standards setting, separate from research on the particular pollutant. Temperature-effects studies, in contrast, have evolved toward more and more diverse research with little attention to standardized assay approaches. Data being developed, therefore, have little defined relationship to the results of other studies. We need new research on temperature effects, but we also need simple, reliable, standardized bioassays.

Old state standards remain, despite lack of scientific justification in many cases. Some numerical standards, developed from long-lost biological criteria, remain on the books unchanged. Many are the product of the early Green Book recommendations, many of which have been discredited. In some cases, we know clearly that the numbers are not scientifically justified. For example, a review I conducted with John Young (see later paper) showed that there is no evidence in the literature that supports a uniform limit of 2°F per hour rate of temperature change, such as is found in the Pennsylvania state standards [10].

Incremental approaches to temperature regulations (i.e., across-the-board allowable degrees above ambient) are reappearing, despite this approach having been discredited decades ago for logical scientific reasons. Physical scientists have made considerable progress toward defining "ambient" through historical records and modeling, but the relevance for uniform rise-above-ambient standards is lacking. Abundant evidence is available to show that species perform well at different degrees of departure from different ambient temperatures, with large margins for change at initial temperatures far from tolerance limits and little margin for change at temperatures near upper or lower tolerance limits. We should avoid repeating bad history if at all possible.

We have many sticky implementation issues, as exemplified by the list in Appendix A, which can be addressed with targeted research. One such issue, for example, is whether thermally stressed but not debilitated organisms can recover during non-stressful periods. Quantitative experiments by Mark Bevelhimer (see later paper) have shown that fish can intersperse recovery between periodic stress events, and that accumulation of recovery can be quantified in the same manner as accumulation of stress. This is especially relevant for streams in which daily high temperatures may exceed the nominal "lethal" temperature for a fish species for a few hours each afternoon but much cooler temperatures at night are well below stressful levels. An upper temperature limit applied at any time and any place is therefore not scientifically justified (assuming the experiments showing recovery pass muster through repeated testing). Equally pertinent is the issue of actual temperature exposures of fish in the field in comparison to temperatures monitored for thermal compliance. Fish seek physiologically advantageous temperatures (thermal refuges) under natural conditions of temperature extremes, and may not experience the temperatures that are attributed to them. In fact, thermal partitioning of summer habitats is a normal feature for many fish (11). In their world of seasonally changing temperatures in a spatially diverse thermal environment, a single temperature monitoring point for regulatory purposes would be meaningless for such a species. We need research targeted at these issues.

New syntheses of thermal-effects information are probably justified. The synthesis of the National Academies' Blue Book and the paradigm of species-specific (and life-stage-specific) thermal requirements it fostered is 30+ years old. Although thermal-effects research tailed off somewhat in the 1980s as concerns over thermal discharges from power stations lessened, both laboratory studies and field studies continued, particularly for 316(a) demonstrations. Studies under 316(a) and related monitoring have accumulated decades of data on species' sustainability under temperature changes in many water bodies. We should mine the scientific and regulatory literature for more than just additional thermal requirements data (such as incipient lethal temperatures), but also for new concepts that will foster true thermal habitat and aquatic life protection.

## Conclusions

There has been a long history of developing science-based temperature criteria and standards. This history has been an evolution of thinking with some dead ends and some fruitful approaches. Not all of the fruitful approaches have made it into state temperature standards, many of which need revision (and some of the dead ends have remained in place). Some current trends suggest that the history is being ignored, with the risk that those who ignore it may repeat it. This could have unhappy consequences for both aquatic resources and for those who depend on them. We cannot continue to lose knowledgeable people who are needed to further refine thermal criteria and standards at both the national and state/local levels. Targeted research is needed to resolve many regulation-related issues, but this should be balanced by more standardized methods and assurance of data quality. And finally, new syntheses of thermal-effects information are probably justified to extend (or possibly replace) the scientific paradigms of the past 30+ years related to temperature criteria and standards. I hope this workshop and its published proceedings, with a broad range of topics and case studies, will stimulate these new syntheses.

## Acknowledgments

This paper is based, in part, on my presentation and subsequent discussion with colleagues at a thermal effects symposium at the 137th Annual Meeting of the American Fisheries Society in San Francisco, September 2-6, 2007.

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## Appendix

### Regulatory-Related Thermal-Effects Questions

1. What is the scientific basis for a rate-of-change temperature standard to protect aquatic life? (e.g., Pennsylvania's maximum of 2°F change per hour)
2. What is the scientific basis for a maximum allowable rise over ambient temperature? (e.g., Colorado's maximum of 3°C over ambient)
3. If ambient temperature is included in a standard, how should it be determined? Statistically for a site over a historical period? Some place nearby where temperature is measured simultaneously with the regulated site?
4. Should cold tolerance be included in thermal standards as well as high-temperature tolerance, since most documented thermal fish kills are actually cold kills?
5. What species of fish and invertebrates have sufficient data for reliable chronic and acute temperature limits?
6. Is an acute thermal limit (e.g., incipient lethal temperature and resistance time data) also protective of thermal shock? Are they different?
7. Should data from only one study for a species be accepted as a basis for determining an acute or chronic limit, or should there be several studies?
8. Should differing results from several independent studies of the same species be averaged? Take the lowest value? How do you handle a range of values? (e.g., differing reported values for optimum growth temperature or preferred temperature)
9. Should we continue to mine research studies on thermal effects (usually not done for purposes of developing thermal criteria for use in standards setting) or develop standard bioassay tests like used for other pollutants and have certified testing labs develop the numbers?
10. What are the relative merits of several types of assays for both chronic (e.g., growth optimum, preferred temperatures) and acute (incipient lethal, CTM, more recent gradual-rise experiments) thermal limits for species and life stages?
11. Since the results of some standardized tests differ markedly in the endpoints (e.g., CTM and UILT) is there some mathematical relationship to relate the two so both could be useful?
12. Are thermal guilds well enough established to serve as general guides for thermal limits without needing data for every species (e.g., cold-water, cool-water, and warm-water or similar breakdowns)?

13. When there are several species in each category with data, should you select the most sensitive species or life stage to set the standard? Or should some statistical level be chosen, such as the 5% level (protective of 95% of the species)?
14. Should use designations for application of standards have a seasonal aspect, since cold-water fish often occupy habitats in winter that are warm-water habitats in summer?
15. Although maintaining normal seasonal patterns of temperature for fish life cycles is a common criterion, how do we handle streams that are composed primarily of effluent from municipal water treatment plants (e.g., Des Plaines River in Illinois, many streams in the arid West), irrigation returns (also many western streams), or reservoir releases that are often not typically seasonal (relatively warm in winter and cold in summer compared to natural patterns)?
16. Are community-based criteria as used in 316(a) guidance sufficiently protective, recognizing that a balanced community can exist in many different forms, some of which would not protect valued species?
17. What is the value of field data in selecting thermal criteria (e.g., preferred or avoided temperatures in the field as a measure for chronic criteria)? Should field and laboratory data be considered together in establishing a criterion or should field data be used only as verification of the (presumably) more rigorous laboratory data?
18. What level of minimal rigor should be expected of studies used to establish thermal criteria (e.g., must give acclimation temperature, test protocols, controls, replicates, etc.)?
19. Recognizing that most natural environments have temperatures that fluctuate on a daily cycle (often widely), what is the effect of such fluctuations on various criteria such as growth or thermal tolerance? What should be selected as the acclimation temperature from such fluctuating environments?
20. How should spawning temperature requirements be developed for use in standards? Is it important to ensure that spawning occurs at the traditional times or is shift in timing because of altered temperatures biologically acceptable (so long as suitable spawning conditions are provided at some point seasonally)?
21. Strategically, is it better to have stringent regional (state or river basin) thermal standards that are based on rigorous interpretation of criteria and laboratory data (which may place many water bodies in violation and prompt many variance requests) or standards that are designed to meet and preserve current desirable field conditions and fish populations?
22. What is the functional relationship between use designations, thermal standards, 303(d) listings, and thermal TMDLs? They are often handled very separately in states. For example, it is most reasonable to have thermal standards that protect the designated uses (e.g., desired fish species), but formal use designations are sometimes set totally apart from (and by different regulatory bodies) than thermal standards. Listings may use thermal standards that are not applicable to the river reach in question.

# 3

# THERMAL CRITERIA & STANDARDS - THE SECTION 316(a) PARADIGM

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## Introduction

Section 316(a) of the Clean Water Act provides an alternative to water quality or technology based standards for establishing thermal discharge limits. This paper provides a practitioner's overview of the values, concepts, practices and assumptions emerging from 316(a) assessments over the last three decades.

The statute itself provides little insight into how Section 316(a) should be implemented from a technical or regulatory perspective. Most of the concepts and practices intrinsic to 316(a) assessments are based on a series of guidance documents and administrative rulings published primarily during the 1970s, as well as on professional judgments and practices used in conducting 316(a) assessments for specific thermal discharges.

The 1972 Water Quality Criteria provided the first comprehensive attempt to develop thermal criteria using scientific data on species-specific thermal requirements [1]. That document illustrated a number basic conceptual approaches for predicting biothermal response temperatures that were incorporated into subsequent 316(a) Demonstrations. These procedures were formally adopted and summarized by USEPA in the 1976 and 1986 Quality Criteria for Water [2, 3].

In 1974, USEPA issued a draft of the first technical guidance specific to 316(a) [4]. This guidance document presented approaches and information needs for various types of 316(a) demonstrations, as well as guidance on mixing zone requirements for thermal discharges. Subsequently, the Interagency 316(a) Technical Guidance Manual expanded on the approaches for 316(a) assessment and provided criteria for assessing compliance with the 316(a) standard [5]. The USEPA 316(a) regulations, first published in 1979 [6], and several administrative decisions have provided additional information on the interpretation of various aspects of the statute and the standards for compliance.

Ecological risk assessment (ERA) guidance is perhaps the most recent source of guidance applicable to 316(a) assessment. ERA is a process for evaluating the likelihood that ecological effects may occur as a result of exposure to one or more stressors [7]. The ERA guidelines provide a logical framework for future assessments of the risk of adverse environmental impacts from cooling water withdrawals, since they represent current scientific thinking and approaches.

In fact, USEPA's ERA guidelines have much in common with the technical approaches recently used for 316(a) assessments. Common features includes a tiered approach, differentiation between ecological effects and the adversity of those effects, inclusion of both prospective and retrospective evaluations, and use of multiple lines of evidence or a weight of evidence approach to decision-making. As discussed below, the compliance criteria from the 316(a) Interagency Guidance Manual fit quite readily into the ERA framework for assessing ecological risk.

## The Section 316(a) Standard

The standard of protection under Section 316(a) is that the thermal discharge must assure the protection and propagation of a balanced indigenous community (BIC). On the plus side, this standard elevates the basis for permitting decisions to the highest level of ecological relevance. However, it replaces simple numerical criteria with an impact/risk assessment approach for determining compliance. As a result, 316(a) determinations often involve extensive site and waterbody specific data collection, impact assessment, and professional judgment. Successfully demonstrating that this standard is met entitles the facility to a variance from otherwise applicable thermal limitations. Section 316(a) variances have supplanted limits based on water quality criteria at many, if not most, power plants in the United States.

The statute does not define what constitutes a "balanced indigenous community", what degree of "protection" is required, or what level of assurance is needed. To obtain further definition of these terms, risk assessors and decision makers have looked to the foundation documents previously discussed.

USEPA's 316(a) regulations describe a "balanced" indigenous community as one that is typically characterized by diversity, the capacity to sustain itself through cyclic seasonal changes, and the presence of necessary food chain species. That is, the structure, function and cyclical patterns typical of the waterbody's aquatic community should be maintained in the presence of the thermal discharge. The regulations also state that the BIC should not be simplified in structure or function and should not be dominated by pollution-tolerant species, for example species tolerant of high temperatures or low dissolved oxygen.[1] USEPA's preamble to the proposed rules indicates that an "indigenous" community may contain species not historically native to the waterbody, if they are present because of major irreversible modifications to the system or were deliberately introduced in wildlife management programs.[2]

The words "protection and propagation" have typically not been interpreted to mean protection from all thermal effects. The principal question addressed in 316(a) determinations has been the ecological relevance of effects from the thermal discharge. For example, one administrative decision stated that, "every thermal discharge will have some impact on the biological community of the receiving waterbody", so that "the issue if the magnitude of the impact and its significance in terms of the short-term and long-term stability and productivity of the biological community affected."[3] The protection objective has generally been to assure the sustainability of

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[1] 40 C.F.R., 125.73(a)

[2] 39 Fed.Reg. 11,435 (28 March 1974)

[3] Boston Edison Company (Pilgrim Station Units 1 and 2), NPDES Permit Determination No. MA0025135 (Decision of the Regional Administrator, 11 March 1977)

an indigenous community and protect its beneficial uses. In the terminology of USEPA's 316(a) guidance, this objective is prevention of "appreciable harm". USEPA's 316(a) technical guidance provided a number of indicators of appreciable harm, as follows:

- Substantial increase in abundance or distribution of any nuisance species or heat tolerant community not representative of the highest community development achievable in receiving waters of comparable quality.
- Substantial decrease of formerly indigenous[4] species, other than nuisance species.
- Changes in community structure to resemble a simpler successional stage than is natural for the locality and season in question.
- Unaesthetic appearance, odor, or taste of the waters.
- Elimination of an established or potential economic or recreational use of the waters.
- Reduction of the successful completion of life cycles of indigenous species, including those of migratory species.
- Substantial reduction of community heterogeneity or trophic structure.

These criteria, along with others provided by USEPA 316(a) and ERA guidance as discussed below, have formed the basic criteria for evaluating the ecological significance of thermal effects and compliance with the 316(a) standard. Clearly, these criteria focus the determination on population and community impacts, not physiological and behavioral responses. Still, the exact nature and magnitude of population or community-level changes representing "substantial" or "unnatural" impacts on the BIC are undefined and may sometimes require significant consensus-building efforts.

Demonstrating that a balanced indigenous community exists requires a site-specific evaluation of the waterbody and the aquatic community. As is usual in risk assessment, uncertainties are present and expert judgment plays an important role in 316(a) compliance determinations. The standard of proof in 316(a) compliance determinations has been one of "reasonable assurance" based on the "best information reasonably available". Studies should therefore be well designed and as thorough as practicable.

## Assessment Methodology

USEPA 316(a) regulations and guidance defined three types of 316(a) Demonstrations, each distinguished by the nature of the information used to assess compliance with the 316(a) standard. A Type I Demonstration would focus on the assessment of prior appreciable harm from operation of an existing facility. A Type II Demonstration would contain a predictive assessment of protection of species selected to be representative of the BIC. USEPA was less specific in its definition of the Type III Demonstration, except to say that it would allow the applicant and regulator to use all additional relevant information and approaches and allow those sites with a

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[4] The original meaning of this somewhat nonsensical term "formerly indigenous" may have been "formerly abundant indigenous species.

low potential for impacting the BIC to reduce the complexity of their studies and assessments. In any case, the most effective approach is usually to use all relevant information and conduct both prospective (i.e., predictive) and retrospective assessments of ecological risk from the thermal discharge. The overview of the 316(a) assessment process that follows would be typical of such a comprehensive assessment. One should recognize, however, that prior assessments have varied in approach, sometimes using only some of the steps discussed.

## Information Needs

Studies and data required to conduct the 316(a) assessment support three major tasks:

1. Evaluating thermal exposure to components[5] of the BIC from the thermal discharge;

2. Evaluating thermal responses of BIC components from exposure to the thermal plume; and

3. Evaluating community vulnerability to, and/or evidence of prior appreciable harm from, effects of the thermal discharge.

Evaluating thermal exposure of the BIC requires information to characterize the spatial and temporal distributions of thermal plume temperatures and the time and space distributions of community components and/or representative species in relation to the plume. Hydrothermal field surveys provide a direct characterization of the thermal plume, but only for the specific set of station operations (i.e., thermal load, CWS flow) and hydrological and meteorological conditions existing during the surveys. To represent plume temperature elevations (ΔTs) for the full range of station operations and waterbody conditions, hydrothermal models usually must also be used in conjunction with the field data, the latter being used to calibrate and verify the predictive performance of the model. A number of well-reviewed and documented hydrothermal models are now available to estimate the time varying distributions of plume temperatures in three dimensions. While applying currently available models to site specific conditions often requires a significant commitment of time and dollars, doing so provides a much better understanding of plume dynamics and community exposure than was previously possible. Estimates of seasonal ambient or background waterbody temperatures in the waterbody region near the Station are also needed. Ambient temperatures are used to determine the acclimation states of the organisms potentially exposed to the thermal plume and to calculate total temperatures resulting from ΔT distributions in the thermal discharge plume.

Of course, exposure of the BIC components depends not only on temperature distributions in the thermal plume, but also on interaction of the indigenous community with the plume. Therefore, the 316(a) assessment requires information on the spatial and temporal distributions of community components in the waterbody. Such information is often acquired from field surveys designed and conducted specifically for the 316(a) Demonstration, as well as from literature sources and databases maintained by natural resource agencies. Impingement and entrainment

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[5] Community components evaluated may include both biotic categories or trophic levels (e.g., phytoplankton, submerged aquatic vegetation, zooplankton, shellfish, fish, etc.) and species selected to represent the community (representative important species or RIS).

(I&E) characterization studies conducted as part of Section 316(b) compliance determinations may also provide useful information on species occurrence in the vicinity of the Station. Although the latter studies reflect only the occurrence of species vulnerable to entrainment and impingement, they can provide detailed information on temporal changes in abundance since I&E sampling is usually frequent (e.g., weekly or biweekly).

The response of BIC components to the thermal plume are evaluated using thermal response data, most often those obtained in laboratory studies. Response temperatures determined in the laboratory using incipient lethal temperature or critical thermal maximum methodology are most often used to assess mortality and exclusion effects because such data are widely available. ILT's and CTM's measure responses to rapid changes in temperature, so their use tends to be conservatively protective since in reality organisms can acclimate and adapt physiologically and genetically to changed temperature regimes, recover from short-term thermal stress and utilize lower temperature areas of the waterbody as refuge from stressful temperatures when necessary [8, 9, 10]. Laboratory-determined response temperatures used to assess behavior and performance criteria have included Upper Avoidance Temperatures and the upper limits of the Optimum Temperature Range for Growth, Spawning, and Normal Egg Hatch.

Ultimately, the 316(a) assessment must determine the potential for effects from the thermal discharge to harm the BIC appreciably. This can be done prospectively by evaluating the vulnerability of representative important species (RIS) populations and community components to thermal effects on individuals and/or by looking for signs of prior harm to the BIC from the thermal discharge. Assessing population and community vulnerability may require detailed characterizations of the biotic community including the distribution of habitat types, identification of critical life-cycle functions occurring in the vicinity of the discharge, temporal & spatial distributions of indigenous populations, and life history information for important species representative of the BIC. Assessing the existence of prior appreciable harm may require data on the status of the community in the vicinity of the station and/or the waterbody as a whole, including species composition, indices of abundance and diversity, or multimetric bioassessment indices. One fundamental risk assessment issue where consensus among stakeholders is sometimes difficult to reach is defining the appropriate scale or extent of the indigenous community or waterbody segment to be protected. A second is agreement on the nature and magnitude of changes that are acceptable. For example, are localized shifts to a marine community more typical of warmer waters acceptable if the community remains diverse and productive and there is no reduction of beneficial uses?

## Steps in the Assessment Process

A useful and commonly used process to help address uncertainty in the 316(a) determination is to use multiple lines of evidence. In 316(a) assessment, this has tended to be a sequential analysis rather than a true weight of evidence approach (Figure 3-1).

For example, step 1 may consist of an evaluation of community vulnerability to the thermal plume. This evaluation typically focuses on the extent of contact of biotic categories or species populations with the thermal plume, as well as the life history characteristics that determine vulnerability of the populations to adverse impacts (e.g., reproductive potential, habitat utilization, relative thermal tolerance). Community components or populations with low potential for impact are identified in this step. The remainder of the assessment is then focused on portions of the community at highest risk. This step is also used to evaluate whether the thermal discharge occupies habitat or life cycle functions which are critical to the survival of indigenous populations. Spawning and nursery habitat and migratory pathways are examples of critical habitat/function zones. At this stage of the assessment, species life history information is assembled and integrated for use in the predictive RIS evaluation.

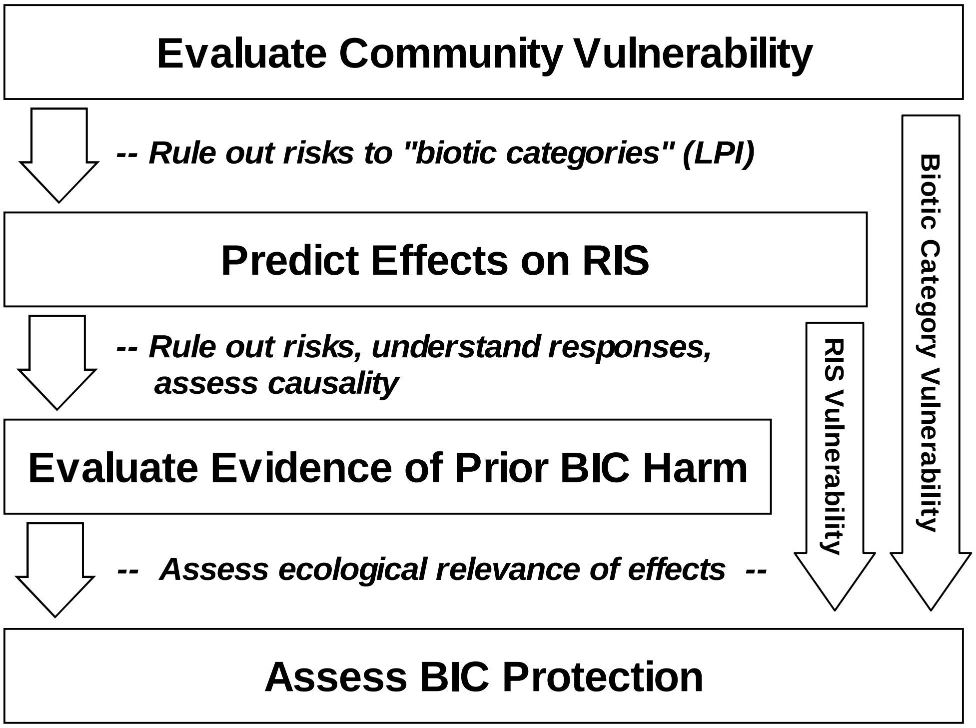
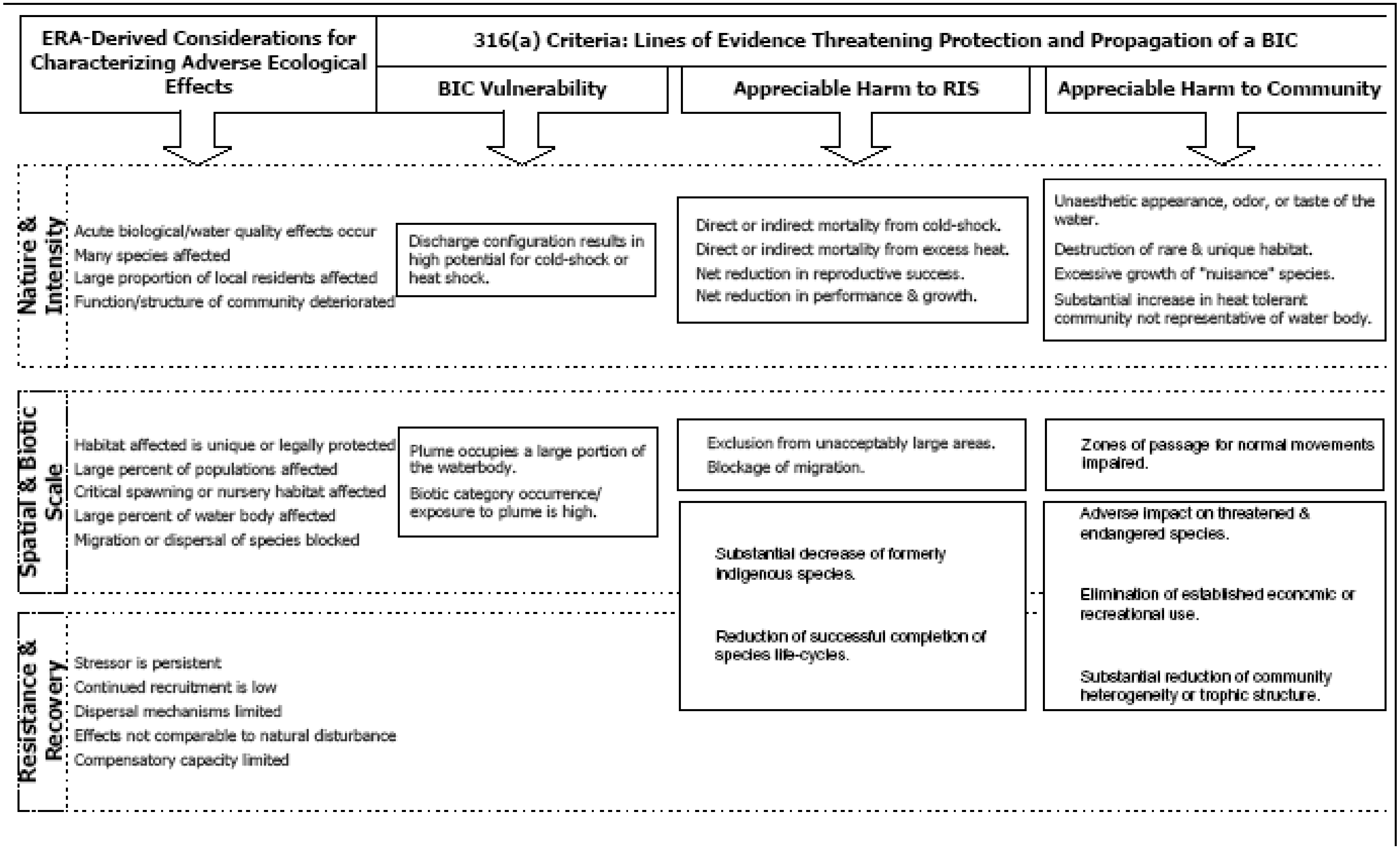


**Figure 3-1**
**Steps in the Biothermal Assessment Process**

A more detailed predictive evaluation of species selected to represent the ‘at risk’ categories (the RIS in 316a parlance) is then conducted to examine exposure-response relationships and assess the nature and likelihood of thermal effects.

For existing discharges, a retrospective evaluation is also conducted using field data to identify whether changes in the community have occurred that may be attributable to the thermal discharge.

Finally, all lines of evidence are synthesized and the levels of risk to the protection and propagation of the BIC is assessed using the criteria for appreciable harm. Examination of these criteria indicates that they are congruent with the general factors described in ERA guidance for assessing the ecological significance of effects (Figure 3-2). Risks to the protection and propagation of the BIC are communicated in what the 316(a) guidance refers to as the “Master Rationale”.



| | ERA-Derived Considerations for Characterizing Adverse Ecological Effects | 316(a) Criteria: Lines of Evidence Threatening Protection and Propagation of a BIC | | |
|---|---|---|---|---|
| | | BIC Vulnerability | Appreciable Harm to RIS | Appreciable Harm to Community |
| Nature & Intensity | Acute biological/water quality effects occur<br>Many species affected<br>Large proportion of local residents affected<br>Function/structure of community deteriorated | Discharge configuration results in high potential for cold-shock or heat shock. | Direct or indirect mortality from cold-shock.<br>Direct or indirect mortality from excess heat.<br>Net reduction in reproductive success.<br>Net reduction in performance & growth. | Unaesthetic appearance, odor, or taste of the water.<br>Destruction of rare & unique habitat.<br>Excessive growth of "nuisance" species.<br>Substantial increase in heat tolerant community not representative of water body. |
| Spatial & Biotic Scale | Habitat affected is unique or legally protected<br>Large percent of populations affected<br>Critical spawning or nursery habitat affected<br>Large percent of water body affected<br>Migration or dispersal of species blocked | Plume occupies a large portion of the waterbody.<br>Biotic category occurrence/ exposure to plume is high. | Exclusion from unacceptably large areas.<br>Blockage of migration.<br>Substantial decrease of formerly indigenous species.<br>Reduction of successful completion of species life-cycles. | Zones of passage for normal movements impaired.<br>Adverse impact on threatened & endangered species.<br>Elimination of established economic or recreational use.<br>Substantial reduction of community heterogeneity or trophic structure. |
| Resistance & Recovery | Stressor is persistent<br>Continued recruitment is low<br>Dispersal mechanisms limited<br>Effects not comparable to natural disturbance<br>Compensatory capacity limited | | | |

**Figure 3-2**
**Assessment Criteria Derived from 316(a) and ERA Guidance**

## Prospective Assessments

The conceptual model for predictive 316(a) evaluations, including the evaluation of vulnerability of the waterbody community to the thermal discharge and evaluation of thermal effects on the RIS is represented in Figure 3-3.

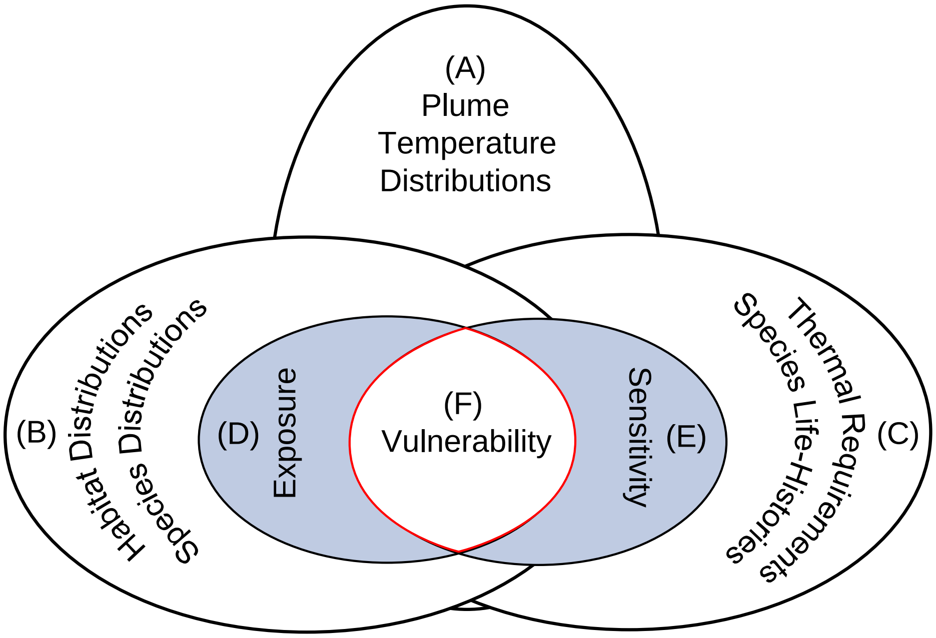


**Figure 3-3**
**Conceptual Model for 316(a) Prospective Biothermal Evaluations**

The vulnerability (F) of biotic categories and representative populations to the thermal plume is determined by the probability, nature (e.g., mortality, effects on growth or reproduction), and magnitude of effects (e.g., % of habitat or population affected). Vulnerability is a subset of the interaction of thermal exposure of community components (D) and their sensitivity to that exposure (E). Exposure and sensitivity themselves are subsets of the interaction of plume temperature distributions (A), spatial and temporal distributions of organisms (B), and their thermal requirements and species life-histories (C). The challenge to risk assessors is to synthesize all relevant information and effectively communicate levels of risk resulting from the intersection of these sets of risk factors.

## Evaluations of Community Vulnerability

The vulnerability of community components to effects of the thermal discharge provides is evaluated both to identify the overall level of risk posed by the design and location of the thermal discharge and to distinguish community components at low risk from those requiring more detailed assessment at the population level. For purposes of the evaluation, "vulnerability" typically means the potential for exposure from the plume and/or the resistance to impacts from such exposure. The evaluation typically considers the potential for the design and location of the thermal discharge to impact critical function zones or resource areas such as migratory paths, spawning and nursery areas, or areas of high productivity or providing forage and shelter critical to the community. In addition, the vulnerability of principal community components or “biotic categories” to the thermal plume is evaluated. Six biotic categories are usually addressed following USEPA 316(a) guidance: phytoplankton, zooplankton (including meroplankton), habitat formers, shellfish/macroinvertebrates, fish, and vertebrate wildlife. The 316(a) guidance also provides indicators of low potential impact for use in this screening process [5].

## Predictive Evaluations of Thermal Effects on RIS

As recommended by USEPA 316(a) guidance, RIS predictive evaluations assess the risk that RIS may suffer appreciable harm from any of six categories of thermal effects: mortality from excess heat, mortality from cold shock, exclusion from unacceptably large areas, blockage of migration, reduced growth, or reduced reproductive success (Table 3-1).

**Table 3-1**
**Thermal Effect Categories and Response Temperature Parameters Frequently Used in the Predictive RIS Evaluation**

| Thermal Effect Category | Response Temperature Parameter(s) |
|---|---|
| Mortality from excess heat | Upper incipient lethal temperature (UILT - minutes) |
| Mortality from cold shock | Lower incipient lethal temperature (LILT - 24hr+) |
| Habitat exclusion | UILT - 96hr+ or Upper avoidance temperature (UAT) |
| Blockage of migration | UILT - 96hr+ or Upper avoidance temperature (UAT) |
| Reduced growth | Upper end of optimum temperature range for growth or Mean weekly average temperature limit (MWAT) |
| Reduced reproductive success | Upper end of spawning temperature range; Upper optimum temperature for normal hatch; Ultimate upper incipient lethal temperature (UUILT) for larvae & juveniles |

RIS (generally 5-15 species) are selected for evaluation from those biotic categories found to be at highest risk in the BIC vulnerability evaluation. Most 316(a) assessments have focused on fish and shellfish/macroinvertebrates, but at some sites RIS from the habitat former category (e.g., kelp beds, eel grass beds) have also been important. In general, the phytoplankton, zooplankton (excluding meroplankton) and other vertebrate wildlife categories are not represented in the RIS evaluation, primarily because early 316(a) studies have shown them to be much less vulnerable to adverse thermal impacts.

The prospective RIS evaluation examines whether the thermal discharge is likely to cause the effects listed in Table 3-1 and, if so, whether the magnitude of such affects represents a significant risk to the protection and propagation of the BIC. The evaluation is fundamentally simple in that it involves comparing plume temperature fields to RIS response temperatures, but complicated in practice because a variety of factors affecting exposure and response need to be appropriately considered. Such factors include the thermal acclimation state at the time of plume exposure, variations in temperature tolerance among life stages, temperature and duration of exposure in a spatially dynamic plume, seasonal variations in abundance in the discharge vicinity, habitat preferences affecting temperature exposure (e.g., shoals vs channel, benthic vs pelagic), and the ability of mobile organisms to regulate their time and temperature exposures. Since data are not available to quantify the effect of all the important variables, simplifying assumptions are typically necessary in assessing thermal risks.

For example, because aquatic organisms adapt physiologically to their thermal environment, their temperature thresholds for the lethality and avoidance parameters shown in Table 3-1 will vary with the temperature of acclimation preceding plume exposure. It is therefore important for the analysis to account for the acclimation state of the organisms and its affect on response temperatures. However, even independent of the influence of the thermal discharge, an organism's history of temperature exposure may vary seasonally as well as with position in the waterbody and time of day, particularly in waterbodies temperate regions. Moreover, the time-varying temperatures elevations in the far-field portions of the thermal plume also influence the thermal environment and acclimation state of organisms. Assessments typically simplify the incorporation of acclimation state into the analysis by ignoring small-scale spatial differences in ambient temperatures and conservatively assuming that there is no acclimation to far-field plume temperatures.

Examples of methods used to predict the occurrence of thermal effects by comparing exposure and response temperatures have been provided elsewhere [8, 11]. The magnitude or scale of any predicted thermal plume effects may be characterized by the waterbody volume, river cross-sectional area, bottom area, or shoreline length exceeding a response temperature threshold. One of the major challenges in prospective RIS assessment is to make necessary simplifying assumptions that provide a reasonably protective, yet realistic, evaluation of potential effects on the BIC from the thermal discharge. Where possible uncertainties should be characterized. For example, the variation in the potential to block the spawning migration of anadromous herring (blueback herring, alewife, American shad) was assessed at Mercer Generating Station on the Delaware River estuary. Frequency distributions of the percent of river cross-section occupied by plume temperatures exceeding avoidance temperatures for the RIS were estimated based on seasonal changes in plume dimensions and seasonal and interannual variations in ambient temperature (Figure 3-4) [12].

## Retrospective Evaluations

When appropriate field data are available or can be obtained, the retrospective evaluation is perhaps the most important of the 316(a) assessment methods since it provides real-world information on changes potentially caused by the thermal plume. This is especially important given the data limitations, need for simplifying assumption, and protectively conservative nature of laboratory thermal tolerance data for predicting thermal responses in the field.

The nature of the retrospective assessment depends on the data available and study design. Species composition, indices of abundance and diversity, and biocriteria measures such as the index of biotic integrity (IBI) may be compared: 1) in plume-exposed versus control areas, 2) in plume-exposed areas or the water body as a whole before versus after plant operation, 3) or in both ways (e.g., before-after-control-impact or BACI analysis). Indices of long-term trends in population abundance also provide useful indicators, where available.

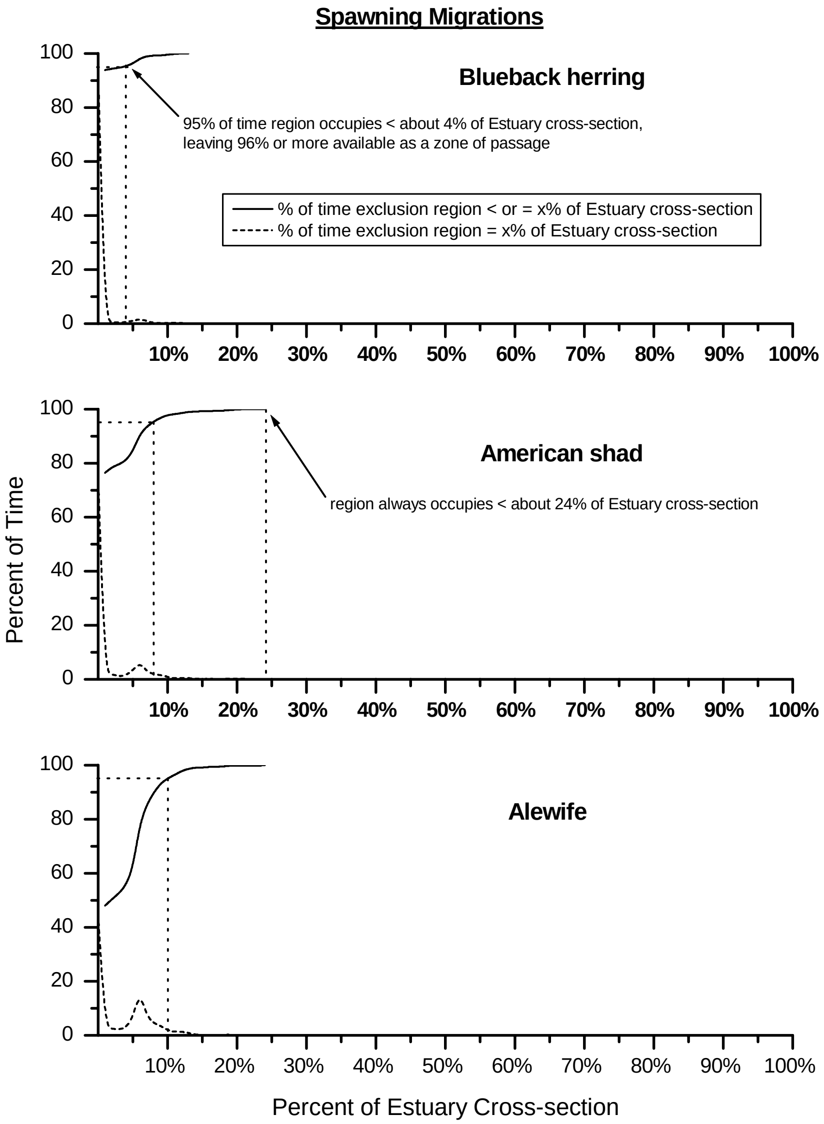


**Figure 3-4**
**Frequency Distribution of the Percent of River Cross-Section Occupied by Plume Temperatures Exceeding Avoidance Temperatures of Alewife, American Shad and Blueback Herring Adults During their Spring Spawning Migration Past Mercer Generating Station**

## Interface of 316(a) and Thermal Water Quality Criteria

For regulatory compliance purposes, 316(a) variances are often linked to the concept of mixing zones. A thermal mixing zone is a designated area of the waterbody where temperatures, or temperature changes, are not required to meet thermal water quality criteria. In general, mixing zones should be defined so as not to impair the integrity of the waterbody as a whole or cause lethality to organisms passing through the mixing zone [13]. A facility obtaining a 316(a) variance may have an allowable area or volume for the thermal mixing zone incorporated into the facility's SPDES permit. The granting of a variance means the plume has been found to protect the integrity of the waterbody as a whole, as embodied in the 316(a) standard of protection and propagation of the balanced indigenous community. Therefore, the thermal mixing zone can encompass the spatial extent of the plume and its size is often delineated by the plume isotherm equal to the temperature elevation allowed by existing water quality criteria.

Some states have also incorporated various aspects of the 316(a) decision criteria directly into numerical or narrative thermal water quality or mixing zone criteria. Examples include limits on the maximum cross-section or width of the waterbody occupied by the thermal plume, preservation of natural seasonal cycles in water temperature, no growth of nuisance organisms, and protection from acute lethality for organisms entering the mixing zone. Although the 1972 and 1976 Water Quality Criteria guidance documents provided example methodologies for establishing WQ Criteria based on scientifically credible thermal response data, existing state numerical criteria for temperature are generally not scientifically well-founded.

## A Few Thoughts on Research Needs

Although 316(a) assessment practices now has over a 30-year history, the need for much more extensive data, improved assessment methods, and better understanding of the thermal responses of aquatic organisms remains. A few of these needs are that:

- Beneficial effects of thermal discharges, such as on recreational fishing, have usually been addressed only anecdotally in 316a. Better documentation of benefits observed at sites around the nation would be especially useful.
- Few if any 316a assessments have explicitly addressed the effect of global warming on the compliance determination. Indeed how to do so in any meaningful way is an especially complex issue since relatively small changes in mean temperature may affect the character of the indigenous community itself.
- Evaluation of biothermal responses could be improved with new data that are more representative of natural exposure durations and variations than are ILTs and CTMs. New laboratory methods such as the Acclimated Chronic Exposure (ACE), summaries of field observations of inhabited temperatures, and attempts to develop thermal stress response models have moved in this direction in recent years.
- Biothermal response data are still unavailable for a large portion of the species, life stages, and thermal response categories required to comprehensively assess impacts at many waterbody locations. Collected of additional laboratory and field data on targeted species and life stages is needed.
- Finally, additional information and new approaches are needed to improve the assessment of indirect thermal effects such as the potential for synergistic effects of heat on the toxicity of other pollutants.

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# 4

# LESSONS FROM RECENT REGULATORY DECISIONS ON THERMAL DISCHARGE LIMITS FOR POWER PLANTS

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## Introduction

In August 2007, according to press reports, one unit of a three-unit nuclear reactor in northern Alabama had to shut down, on a day when power demand for the system set a record, because the average temperature of the Tennessee River exceeded 90 degrees. *E&E Publishing*, Aug. 17, 2007. This sort of event focuses the mind on heated discharges from power plants.

This paper will sift out the lessons that can be learned from recent regulatory decisions on thermal discharges from electric generating plants. The paper takes an approach different from the one usually taken in a forum like this, in that we rely on legal literature rather than scientific. As lawyers, we are limited to the literature of our trade, which consists of written decisions by courts or administrative law judges, like EPA's Environmental Appeals Board.

We make no apology for this, because scientists and engineers need to take notice of what the courts and administrative law judges are saying. Many scientific studies of heated water are driven by a legal standard, often a non-quantitative description in some statute or regulation. For example, biologists tasked with studying the thermal effluent from a power plant into a river or estuary may have as their goal proving that, despite the heated discharge, there will be a "balanced, indigenous population of shellfish, fish, and wildlife." Their job will be to use the data they collect to prove the verbal standard is met. Typically this requires a good deal of thought when designing the study. Ideally, as we say later in the paper, it also involves winning the agreement of the regulatory agency on the design of the study.

In this field words are almost as important as numbers. The word "any," for example, can be of overwhelming importance when used by Congress, which is presumed by courts to parse the dictionary with the intensity of a medieval cleric. See Mirant Kendall Response to Comments at F9, *citing New York v. EPA*, 443 F.3d 880 (D.C. Cir. 2006); *NRDC v. EPA*, 489 F.3d 1250, 2007 U.S. App. LEXIS 13388 *16-17 (D.C. Cir. 2007).

The problem of identifying "lessons learned" is difficult because, when it comes to thermal requirements for industrial cooling water, there are so many requirements from which to choose and they often interlock in complicated ways. Here, we will focus on the most prominent provisions and most recent lessons learned.

## Best Available Technology and the § 316(a) Variance

The Clean Water Act's basic technology-based requirement is that the power plant discharging heated water must install the "best available technology economically achievable." To identify this technology, the permit writer is to consider certain "factors," namely "the age of equipment and facilities involved, the process employed, the engineering aspects of the application of various types of control techniques, process changes, the cost of achieving such effluent reduction, non-water quality environmental impact (including energy requirements), and such other factors as [EPA] deems appropriate." Clean Water Act § 304(b)(2)(B).

Once the technology-based BAT limit is determined, it is possible to substitute a less stringent requirement under § 316(a) of the Clean Water Act. Here the standard is that the alternative effluent limitation "assure the protection and propagation of a balanced, indigenous population of shellfish, fish, and wildlife" in and on the body of water into which the discharge is made (colloquially known as the "BIP").

In the beginning EPA did attempt to require cooling towers at what were, for the time, newer facilities (*i.e.*, steam electric plants brought into service on or after December 31, 1973 or, for plants generating 500 MW or more, December 31, 1973). Those 1974 regulations were overturned by the Fourth Circuit, which found that EPA has failed to a court because EPA had failed to determine whether the rule, in light of its costs, would result in reasonable effluent reduction levels. *Appalachian Power Co. v. Train*, 545 F.2d 1351 (4th Cir. 1976). Notably, the court considered the environmental benefits of the rule to be a factor that EPA ought to consider in deciding whether the costs were "reasonable" (although it also made clear that those benefits need not be reduced to monetary terms).

Since that time, thermal requirements in permits for electric generating plants have been decided site-by-site. Typically, permit writers do not establish those site-specific limits on a technology basis, although CWA 402 authorizes establishment of case-by-case "best professional judgment" BAT requirements in the absence of uniform national guidelines. Recognizing (wisely, we think) that the existence of the § 316(a) variance provision effectively makes in-stream conditions the fulcrum of any final limitation, permit writers most often begin by developing limits designed to implement water quality standards (which we discuss below), then consider any request for a § 316(a) variance from that water quality-based limit.

But that is not always the case, as the recent case involving the Brayton Point Station on Mount Hope Bay in Massachusetts illustrates. There, the NPDES permit writer (EPA Region I) first determined that retrofitting closed-cycle cooling constituted BAT for the facility and imposed thermal limits reflecting that determination. Interestingly, the Massachusetts Department of Environmental Protection, also played a significant role in NPDES permit development, prepared a memorandum indicating that EPA had assured the Commonwealth that it did not see this determination as a precedent for other facilities in the region. On appeal to the EPA Environmental Appeals Board ("EAB"), that memo was excluded from the record on procedural grounds.

Of course, that is not the end of the story (or the lesson). The permittee had submitted a § 316(a) demonstration and requested an alternative limit. EPA agreed that the BAT limit was more stringent than necessary to protect the "BIP." On the other hand, it found that the permittee's proposed alternative was not stringent enough. Therefore, EPA arrived at its own alternative limit, which in effect required retrofitting closed-cycle cooling.

On review by the EAB, the Board hinted that it thought EPA need not have established an alternative limit where it determined that the permittee's proposed alternative was insufficiently stringent. Because that was not the case at hand, however, it went on to review the alternative standard. In the course of that review, it held that (1) EPA's establishment of a limit based on a variance did not moot any underlying issues concerning the establishment of the BAT limit, but (2) EPA was not obliged to set an alternative standard that reflects the least restrictive standard necessary to assure protection and propagation of the BIP. In re Dominion Energy Brayton Point, LLC, NPDES 07-01, 13 EAD __ (Jan. 3, 2007).

Although the permittee appealed the EAB ruling to the United States Court of Appeals for the Fourth Circuit, the case settled prior to briefing. Thus, a more definitive resolution of these issues by a decision-maker outside the confines of EPA will await some future case.

## State Water Quality Standards and the § 316(a) Variance

Even if the BAT requirement for a plant is not cooling towers, in-stream water quality standards may require more than BAT. Many state water quality standards contain numeric standards for heat or temperature, often a maximum in-stream temperature (with or without some designated excursion frequency); some form of limit on the extent to which "ambient" temperatures can be changed (typically referred to a "delta T"; and occasionally a period average of some type.

Other attributes of the state standards, such as a mixing zone or anti-degradation policy, also may come into play. Mixing zones policies may impose spatial limits for the mixing zone as well as numeric criteria establishing limits on temperatures in and/or at the edge of the mixing zone. State anti-degradation policies have to follow EPA regulation 40 C.F.R. 131.12, which says that existing in-stream uses have to be protected everywhere and existing water "quality" in high-quality waters has to be maintained unless lowering water quality is necessary to accommodate "important economic or social development." Both types of provisions arose during the Kendall Station permit proceeding.

If the § 316(a) BIP standard is met, though, it should be an adequate answer to these arguments, because a § 316(a) variance overrides water quality-based permit limits as well as technology-based ones. Indeed, EPA regulations establishing minimum requirements for state anti-degradation policies specifically provides that anti-degradation policies and implementation for situations involving thermal discharges must be consistent with § 316(a). Although advocates for closed-cycle cooling will occasionally argue that a 316(a) variance is only for technology-based standards, not water quality standards, but there is no longer any reason to listen to this claim. As EPA Region 1 said in the Mirant Kendall case, EPA "adheres to its position the § 316(a) authorizes variances from state water quality standards for heat." Response to Comments at F10. Unless EPA reverses itself on the law or some court overrules it, § 316(a) trumps other thermal requirements.

## TMDLs for Heat (and the BIP Standard)

One way of implementing water quality standards is with a total maximum daily load ("TMDL"). TMDLs must be prepared for all waters listed as impaired under CWA § 303(d); preparation of a TMDL involves calculating the total load of the pollutant in question that can be assimilated by the segment. EPA's regulations then require that that load be allocated among the contributors, including land use authorities. Section 303(d) establishes special listing and TMDL requirements for thermal loads, however. Section 303(d)(1)(B) requires states to identify those waters for which controls on thermal discharges are not stringent enough to assure protection and propagation of a balanced, indigenous population of fish, shellfish, and wildlife. Similarly,§ 303(d)(1)(D) requires states to "estimate" the total daily maximum thermal load required to assure protection of a balanced, indigenous population of fish, shellfish and wildlife. That estimate must take into account normal water temperatures, flow rates, seasonal variations, existing sources of heat input, the dissipative capacity of the waterbody, and a margin of safety to account for uncertainty.

Although the statute clearly applies the BIP standard for listing and TMDL decisions related to heat, EPA suggested in a draft watershed rule in 2003 that the water quality standard should be used instead, where the standards are exceeded due to both point and nonpoint sources of heat. The rule was never finalized. In guidance documents for listing waterbodies as impaired in 2004 and 2006 EPA again seemed to say that TMDLs for heat should aim at the water quality standards rather than the BIP standard. Although none of these has the force of law, they raise troubling questions and the potential for inconsistent treatment of different sources -- inconsistencies for which there is no plausible statutory basis.

As a practical matter, where no § 316(a) determination has been made, states typically will assume that exceedance of numeric water quality criteria is causing impairment of the BIP. An example is a temperature TMDL developed for the Walla Walla Basin in Oregon in 2005. The Oregon streams got warmer because trees that had shaded the water had been removed. Also, disturbance of vegetation and stream straightening had caused erosion of the bank, wider channels, and more solar heating. Low flows were also a factor, resulting from irrigation diversion and bed loss.

Oregon water quality standards account for high natural temperatures. They provide that where the natural thermal potential of the waterbody exceeds the biologically based criteria in the standards, the "natural thermal potential temperatures supersede the biologically-based criteria, and are deemed to be the applicable temperature criteria for that water body."

The Oregon Department of Environmental Quality prepared a TMDL and management plan for heat. DEQ identified vegetation heights and stable channel widths that would provide "more natural" heating. The agency also estimated potential increased stream flow. Meeting the TMDL allocations, the DEQ said, would require reductions in heating associated with agriculture, forestry, and transportation corridors. This would mean restoring streamside areas so that banks were stable and vegetated. Where feasible, floodplains, sinuosity, and channel complexity should be restored to more natural conditions.

## The § 316(a) Variance

As noted, both technology-based and water quality standards-based permit limits can be overridden by a § 316(a) variance. To get the variance you must demonstrate that alternative limits on heat will protect the propagation of a "balanced, indigenous community of fish, shellfish and wildlife." "Population" means "community" (see 40 C.F.R. 125.71(c)). EPA has defined "balanced indigenous population" (community) in 40 C.F.R. 125.71(c). EPA has promulgated regulations implementing § 316(b), although they are fairly general. Besides those regulations, permit writes and permittees continue to apply EPA's 1977 draft guidance document, *Interagency 316(a) Technical Guidance Manual* (Draft May 1, 1977).

Recent experience suggests that the difficulty of the task – showing that there will be a balanced indigenous community despite the hot water from the power plant – will depend on whether there are well-publicized concerns about the fish in the waterbody and whether the species are popular and charismatic. At Brayton Point, for example, the permittee's job was difficult because "the case involves an important estuarine ecosystem – Mount Hope Bay – whose fisheries have shown huge decreases in productivity over the past two decades, a decline that began to become manifest around the time that the facility's withdrawals from and discharges into the Bay appreciably increased." 2006 EPA App. LEXIS 9, slip op. at 8.

In the Brayton Point permit proceeding, EPA Region 1 argued that the statute and regulations "do not dictate an exact methodology or exactly what type of information must be used" to make a 316(a) determination. *In re Dominion Energy Brayton Point, L.L.C.*, Brayton Point Station, NPDES 03-12, 2006 EPA App. LEXIS 9, 107 (EPA App. Bd. 2006). The Region used an "area-impacted" approach that it said EPA had long supported.

Critical temperatures were evaluated for 26 species of finfish and later keyed to the critical temperatures for the most sensitive species, the winter flounder. *Id.* 107. Region 1 developed summer and winter critical threshold temperatures for both the benthic and pelagic layers. The Region selected a discharge from the power plant that would "ensure that no more than 10% of the bay exceeds 24°C for more than five days per month." *Id.* 116. Starting with this criterion, the Region back-calculated a summer thermal discharge limit of 0.14 tBTU per month. A similar approach was used for winter. *Id.* 117. Region 1 did not claim that this alternate standard was the least restrictive that could be applied while still assuring protection and propagation of a BIP, and EPA's EAB said it was not required to. Rather, according to the EAB, the statute requires only that EPA provide support sufficient to show that the alternative limit it set is stringent enough to protect the BIP. The EAB did not attempt to square this holding with Congress's desire, apparent on the face of § 316(a), to avoid discharge limits more stringent than "necessary" to assure protection and propagation of the BIP. Moreover, because EPA amended its administrative appeal procedures in 2000 to delete any provision for an adjudicatory hearing, there is now little meaningful opportunity to test the technical basis for the Agency's judgments. This is not necessarily the case for state-issued permits, because many states continue to provide for adjudicatory proceedings.

In the Mirant Kendall permit proceeding, EPA Region 1 used § 316(a) to set in-stream maximum temperatures *lower* than state water quality criteria required. Massachusetts water quality standards set a maximum in-stream temperature of 83°F. Critical river temperature permit limits range from 61°F in early spring for yellow perch up to 81° and 83°F in summer for river herring.

Also, river temperatures in the zone cannot increase more than 5°F above upstream ambient river temperatures during a 24-hour averaging period (http://www.epa.gov/region1/npdes/mirantkendall/). The state recommended a temperature no higher than 90°F in the mixing zone. For the Mirant Kendall permit, though, EPA Region 1 set temperature limits in a "Zone of Passage and Habitat" (ZPH) lower than 83°F, the highest temperature allowed under the state's water quality standards.

EPA denied that the limits were "more strict" than the water quality criteria. EPA explained that "these temperatures are designed to assure that some portion of the lower Basin in the area of the discharge provides suitable habitat to support the [Balanced Indigenous Population] and provide a Zone of Passage and Habitat, after having ceded a portion of that area to temperatures in the Zone of Dilution that will exceed both the temperature criterion in the State's [water quality standards] and the temperatures EPA has determined are required to support all life stages of the BIP." Mirant Kendall Response to Comments at F11. Because EPA had no modeling results it regarded as acceptable, it relied on real-time in-stream monitoring. The in-stream limits lower than 83°F were, according to EPA, necessary to protect the "balanced indigenous population" in the Zone of Passage and Habitat. EPA also argued that at most these below-WQS limits implemented the narrative requirement that site-specific temperature limits should protect "normal species diversity, successful migration, reproductive functions, or growth of aquatic organisms." Mirant Kendall Response to Comments at F12. EPA apparently was unswayed by extensive field studies indicating that increased thermal loads and in-stream temperatures have not been associated with reduced abundance of the representative species on which EPA's analysis focused

The Kendall Station thermal limits are now the subject of an appeal to the EAB. Thus, it remains to be seen whether they will survive review. Of course, the permit writer typically enjoys great deference, and EPA's appellate procedures no longer provides any meaningful opportunity to question the Agency's judgment. Nevertheless the existence in the record of significant field data that appear to contradict EPA's literature-based thermal limits could make a difference in that case.

## What About Species Other Than Fish?

The petitioner argued in *In re Aurora Energy, L.L.C.* (Chena River Power Plant), 2004 EPA App. LEXIS 30 (Environmental Appeals Board September 14, 2004), that Region 10 had not adequately addressed the adverse impact on wintertime surface ice recreation (cross-country skiing, ice skating, dog mushing, snow mobiling). Region 10 responded that the State of Alaska had not expressly established water quality standards to protect winter [surface-ice] recreational issues and that therefore EPA had no obligation to exhaustively analyze the impact of the discharge on winter recreation, much less include permit limits that would protect such uses. Because the petitioner had failed to address Region 10's responses, the Appeals Board denied review of the issue.

The Petitioner argued that the discharge would cause unstable and unsafe ice conditions downstream and ice fog resulting in hazardous driving conditions. *Id.* *49. Several people had broken through the thin ice and at least one had drowned, according to petitioner. In its brief, Region 10 argued that the Clean Water Act did not protect against drowning. Section 316(a), the Region said, is not an appropriate mechanism to address such safety concerns.

The Appeals Board agreed with the Region, citing *In re Pub. Serv. Co. of N.H.*, 1 E.A.D. 455, 458 (EPA Adm'r 1978), to the effect that EPA's sole function was to determine whether the proposed thermal discharge would assure the protection and propagation of a balanced indigenous population. He said "I have not considered, nor may I consider, … whether [the project] is desirable from an overall environmental perspective." *Aurora*, *53 n. 44.

The petitioner in *Aurora Energy* invoked ducks as well as humans, arguing that the introduction of ducks into a winter ecosystem automatically disqualified the permittee from getting a 316(a) variance. *Id.* *40. In essence, the petitioner argued that the year-round presence of a species that is otherwise only seasonal is not allowed by 316(a). EPA Region 10 responded, however, that the guidance document states that the [indigenous] community may include species not historically native to an area but whose value is esthetic. Several commenters had said that the wintertime presence of ducks was an esthetic pleasure to them. *Id.* *42 n. 37. Because the petitioner had failed to address Region 10's responses, the Administrator declined to review this issue.

## Conclusion

This is no compendium of the thermal issues past and present. Rather, it aims simply to examine several of the most recent developments, in hopes of illustrating some of the complexities often involved in thermal decision-making.

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# NARRATIVE TEMPERATURE STANDARDS IN COLORADO: WHY THEY REMAINED

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## Recent History of Colorado Temperature Standards

Until recently, Colorado temperature standards for the protection of aquatic life were both simplistic and ambiguous. Standards were set at a single temperature value specific to either cold or warm water aquatic life use (ALU) designations, which encompass a wide range of aquatic habitats including streams, lakes, and reservoirs, over a wide elevational and latitudinal range. The cold and warm water ALU standards were 20˚C and 30˚C, respectively (CDPHE/WQCC 2000). No specific averaging period or statement of whether these standards were based on average or "not to exceed" conditions were provided in those earlier regulations. However, the standards did include a narrative footnote at that time, which had been in place since the 1980s:

- Temperature shall maintain a normal pattern of diurnal and seasonal fluctuations with no abrupt changes and shall have no increase in temperature of a magnitude, rate, and duration deemed deleterious to the resident aquatic life. Generally, a maximum 3 degrees Celsius increase over a minimum of a four-hour period, lasting for 12 hours maximum, is deemed acceptable for discharges fluctuating in volume or temperature.

The standards had been in place for over 25 years until interested stakeholders (e.g., utilities, non-governmental organizations [NGOs], etc.) began asking questions regarding implementation and compliance issues. In part, as a result of these questions, limited information was added to the standards during a review of listing procedures for impaired waterbodies in the early 2000s (i.e., the 303[d] list assessment protocols). Based on preliminary discussions as part of the statewide review of the "Basic Standards and Methodologies for Surface Water" (Regulation No. 31), the Colorado Water Quality Control Commission (WQCC) adopted a policy for the 303[d] assessment protocols stating that to measure instream compliance with the temperature standards, the appropriate statistics are weekly average temperature (WAT) values that are not to exceed 20°C in cold water segments and 30°C in warm water segments. This language was not added to the standards in the tables, though.

In preparation for the 2005 Basic Standards triennial review, a stakeholder group called the Temperature Workgroup (TWG) was formed in summer 2004 to discuss how temperature standards could be updated and/or revised. The TWG was comprised of members of various governmental agencies, including the WQCC, Colorado Water Quality Control Division (WQCD), U.S. EPA Region VIII, and Colorado Division of Wildlife (CDOW). In addition, NGOs such as Trout Unlimited, and other stakeholders representing the municipal wastewater, water supply, energy, mining, and agriculture sectors were involved.

It was generally agreed in the TWG that the specific underlying basis for the existing temperature standards was vague, stemming from historic pre-1980 EPA guidance. It was not possible to either determine if these standards protect the ALU or attempt to adjust the broad values to reflect site conditions as there was no species-specific information available. In addition, there was no written guidance to support effective enforcement.

## Colorado Challenges

In discussing updates to the temperature standards, the stakeholders noted many unique attributes to Colorado waters that make generalized state-wide temperature standards difficult to use. For example, Colorado is topographically extremely diverse. Thus, waters that begin as high gradient, alpine, cold water ecosystems flow downstream to become low gradient, plains streams and warm water ecosystems.

Managing temperature standards is fairly straightforward at the clearly defined cold and warm end of this gradient. However, the "transition zones" in the foothills as the streams leave the mountains and begin to flow onto the high plains can support seasonal use of both cold and warm water species, thus negating simple application of either the cold or warm temperature standard. Furthermore, there is an abundance of natural lakes and man-made reservoirs throughout this elevational gradient that vary in size and depth, further complicating use of simple temperature standards.

A further complication is with the existing aquatic life use classifications. Currently, Colorado has two primary aquatic life classifications, Cold and Warm. There are also two sub-categories of Class 1 and Class 2 waters available, but these sub-categories do not specifically relate to temperature. Cold/warm water species can seasonally utilize the same reach, as transition zones are not constants. This fact, combined with the structure of stream segmentation in Colorado water quality regulations, greatly complicates both classification of a segment as well as defining its accompanying temperature standard.

## Reevaluation of Temperature Standards in Colorado

### *2004 Through June 2005*

In Colorado, the water quality regulations for various river basins, as well as the state-wide Basic Standards, are reviewed and updated on a 5-year cycle. This is functionally the triennial review process of the Clean Water Act as applied in Colorado. As noted earlier, in preparation for the 2005 Basic Standards Triennial Hearing before the WQCC, the WQCD initiated discussion of temperature (and other) standards in the summer of 2004.

The TWG discussed various issues regarding the current standards and data needs for revising or updating those standards. As a basis for updating standards, the WQCD released a draft database in December 2004 that contained a wide variety of species-specific temperature tolerance data, including field and laboratory derived optima, avoidance, preference, critical thermal maxima (CTM), and upper incipient lethal temperatures (UILT).

This database was reviewed and expanded by GEI Consultants on behalf of a group of stakeholders that included utilities, mining, and energy sectors. Similar to the WQCD December version, this expanded database was all-inclusive (field and lab studies, optima, preference, avoidance, CTM, and UILT data). This updated database formed the basis for the original proposal by the WQCD in late January 2005 to establish temperature standards representing "cold," "cool," and "warm" water fisheries.

As part of the hearing process, a variety of alternate proposals were submitted by the WQCD, the collective stakeholder group, and individual stakeholders from April through May 2005 in anticipation of the June 2005 Basic Standards hearing before the WQCC.

### *June 2005 Through January 2007*

Despite the best efforts of all the parties, agreement was not achieved during the Basic Standards hearing in June 2005. The WQCC rescheduled another hearing for January 2007 and initiated a schedule to meet that deadline. It was recognized by the parties that one obstacle that contributed to the wide variety of proposals was the lack of more standardized guidance on how to develop new temperature standards. In an effort to standardize methods, the WQCD organized a Technical Advisory Committee (TAC) comprised of experts in the field to provide methods for temperature criteria development. This was termed the Policy 2006-1 document.

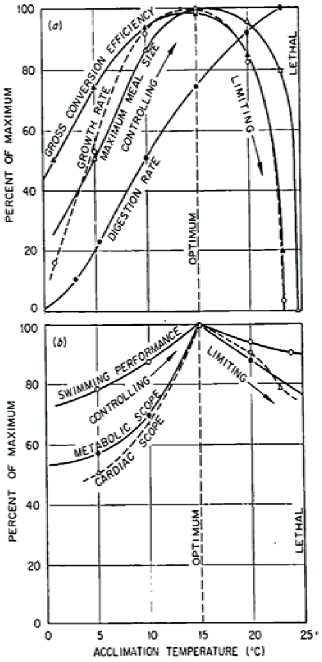


**Figure 5-1**
**Sockeye Salmon Example (Coutant 1977, Adapted from Brett 1971)**

Questions addressed by the TAC included issues related to:

**Appropriate thermal thresholds**

- Acute and/or chronic
- Species-specific

- Appropriate measurement endpoints
- Optimal and/or preference based

**Use of laboratory derived vs. field data**

- How should field data be used, if at all?
- How does use of laboratory temperature studies compare to laboratory studies for toxics criteria?

**Acceptable level of risk?**

- How can mixed fisheries that have species with different temperature tolerances be protected?
- Is use of EPA 5th percentile approach applied to toxic chemicals applicable to temperature criteria?

The TAC completed their work in late fall of 2005 and produced a draft Policy statement. Following review and comment by various Stakeholders, the final Policy 2006-1 was adopted by the WQCC in April 2006.

With methods/protocols for reviewing temperature tolerance data now in place, the WQCD conducted a new review of temperature data, beginning with the temperature database from January 2005 and adding new data, removing duplicate data from use of literature summaries, and including new data published since 2005.

Meanwhile, the TWG was reinstated in summer 2006 to discuss potential revisions to the earlier proposals and any new topics. New WQCD proposals, stakeholder reviews, and alternate proposals were developed over the fall, including proposals for numeric standards for aquatic life uses and proposals for non-numeric (narrative) issues.

## Final Numeric Temperature Standards

The final updated Colorado temperature standards were adopted in the January 2007 hearing and included numeric values for cold and warm aquatic life uses – the “cool” classification originally proposed in 2005 was no longer being considered since Colorado doesn’t have a “cool” aquatic life use classification. The adopted standards had values specific to habitat types (i.e., tiered temperature standards), as well as a narrative footnote to address non-numeric issues. Numeric standards generated relatively strong agreement amongst the parties as review of the database indicated lethal thermal effects and optimum temperatures were well defined for many species, especially game species.

**Cold Water Numeric Criteria:** The cold water criteria were based on those cold water species with appropriate laboratory-derived thermal tolerance data including arctic grayling, brook trout, brown trout, cutthroat trout, rainbow trout, mottled sculpin, longnose sucker, and sockeye salmon. Lake trout and mountain whitefish are also present in Colorado, but insufficient thermal data were available to consider them in numeric criteria development. The cold water fish species were grouped into two communities:

- Rivers and Streams
- Lakes and Reservoirs

Other potential groupings were investigated during the process leading up to the hearing, including categorizing by east or west slope of the Rocky Mountains. These various groupings, however, provided no significant difference in criteria values and were not used.

For the Rivers and Streams fish community, the 5th percentile approach resulted in calculated standards not fully protective of cutthroat trout (the most temperature sensitive species). Since cutthroat trout are an ecologically important species in cold-water communities, and are the only native trout species in Colorado, the cold summer criterion was lowered to 17ºC to ensure full protection of that species. A second "non-sensitive" cold water tier was also created with a standard of 18.2ºC to protect brown trout and rainbow trout waters.

The Lakes and Reservoir community was also split into default and "large" lakes/reservoirs, with the "non-large" default group having the default numeric cold standards and the large lakes/reservoirs having the non-sensitive temperature standards – reflecting the management strategies used by CDOW for these differing waters.

Winter numeric standards were also adopted representing values protective of spawning by trout. These values were the same for both tiers (9ºC chronic, 13ºC acute) as there was no measurable difference in protective temperature values for this. The two tiers did differ in the months these values applied, though – Oct-May for the sensitive tier and Nov-Mar for the non-sensitive tier.

**Warm Water Numeric Criteria:** The warm water numeric criteria were also developed using fish species for which laboratory-based temperature data were available. As with the cold water numeric criteria, several fish community groupings were considered. The default Rivers and Streams criteria are based on temperature data for a wide variety of warm water fish species, including the Arkansas darter; bigmouth; golden, red, spottail, and sand shiners; black, brown, and yellow bullhead; bluegill; pumpkinseed; orange spotted and green sunfish; boneytail; channel catfish; fathead and plains minnows; hornyhead and roundtail chubs; longnose, speckled, and southern redbelly dace; plains killifish; plains topminnow; smallmouth bass; and western mosquitofish. The species present in Colorado warm water streams and lakes were also noted even if no thermal tolerance data were found. The warm water fish species were also grouped into two communities:

- Rivers and Streams
- Lakes and Reservoirs.

Three additional tiers of sensitive warm water species were also created to protect warm water species with similar thermal requirements or geographic distribution. Data suggest these species are more sensitive to temperature relative to the other warm water fish. If these species had been included with the other warm-water species, the resulting criteria could have been over-protective for waters where these thermally sensitive species are not found and not expected to be found.

Where thermally sensitive species occur, or are expected to occur, the most protective applicable criteria are used. The groupings are as follows:

- Warm-water sensitive group ***a*** - is the most thermally sensitive and includes the common shiner, Johnny darter, and orangethroat darter. The common shiner and Johnny darter specifically occupy the eastern slope transition zone. The orangethroat darter occurs only in the Republican River Basin.

- Warm-water sensitive group ***b*** - includes only the razorback sucker that occurs on the west slope.
- Warm-water sensitive group ***c*** - includes the brook stickleback, central stoneroller, creek chub, longnose dace, Northern redbelly dace, finescale dace, and white sucker.

The default warm-water standard applies in segments that do not have, and are not expected to have, any of these thermally sensitive species indicated above. The Lakes and Reservoir warm water community has different temperature standards from these three tiers – again, reflecting the management strategies used by CDOW for these waters with recreational fisheries frequently maintained by stocking of non-native game fish.

Winter standards were also established for the warm water use based on one-half the summer temperature standards. Unlike the cold use winter standards that are meant to protect spawning cues, the method to set winter values for the warm-classified waters was set to ensure "seasonality" and restrict spawning cues.

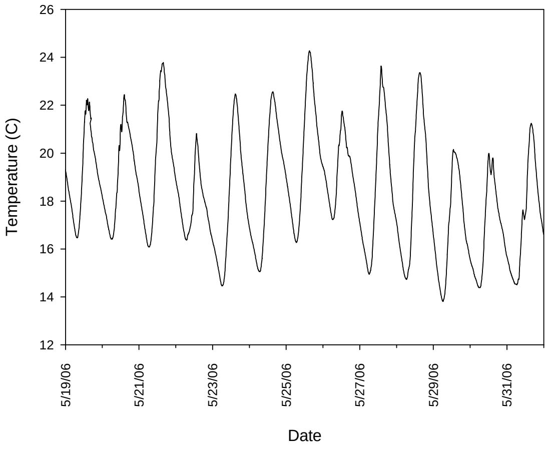
## Numeric vs. Narrative Criteria

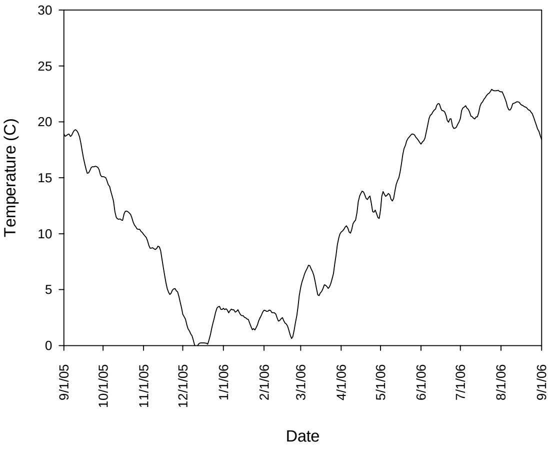
The adoption of temperature standards with "tiers" within the two broad cold and warm use classifications provides considerable flexibility for implementation. However, a number of issues were difficult to quantify in such a manner that would allow derivation of numeric standards. These issues included diel and seasonal variability, spatial diversity, and abrupt change in temperature. Review of the literature suggests responses to these types of temperature issues can be very species and site-specific. Attempts to develop numerical standards for these issues could result in challenging policy decisions. In the end, it was decided that narrative standards for these issues would offer the best outcome. This decision resulted in a footnote to the temperature numeric standards which stated:

- Temperature shall maintain a normal pattern of diel and seasonal fluctuations and spatial diversity with no abrupt changes and shall have no increase in temperature of a magnitude, rate, and duration deleterious to the resident aquatic life.

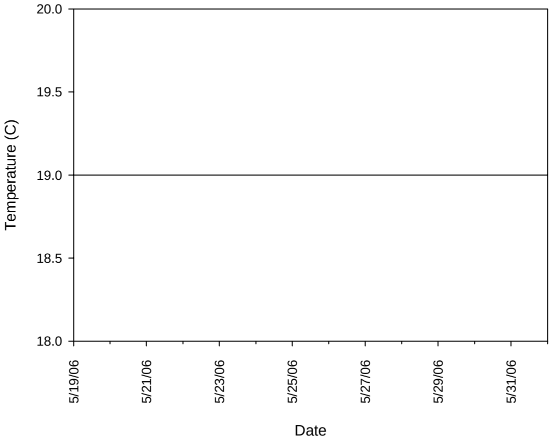
## Diel and Seasonal Variability

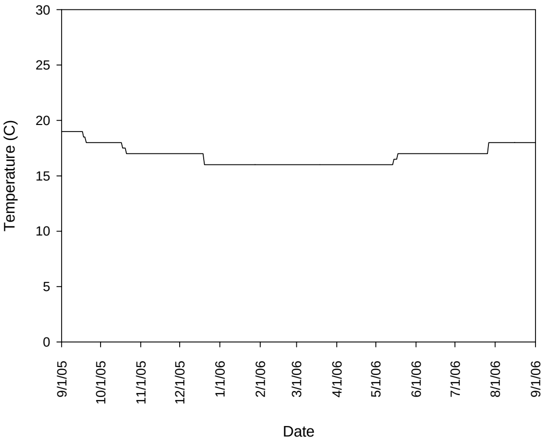
Some degree of variability is expected with temperature in streams and lakes. The magnitude of expected change would vary with parameters such as altitude, channel shading, habitat diversity, flow, tributary input, and effluent dependent or effluent-dominated status.





Daily and seasonal variability would be expected to look like the figures above – night time temperatures should be cooler than daytime and summer should be warmer than winter. Less desirable temperature regimes would be like the figures below, with no temperature variation during the day and little change over seasons.





Earlier proposals included the idea of a minimum diel flux for cold and warm water segments. However, that became unworkable as the proposals, based largely on measured diel changes in streams at varying elevations, were too variable.

**Normal Pattern of Summertime Diel Fluctuation:** Interpretation of this narrative provision emphasizes the importance of diel fluctuation specifically in summer. Aquatic life in Colorado relies on nighttime cooling during the summer to allow for physiological recovery from daily afternoon high temperatures. However, given the potential for site-specific conditions to affect this, a single value to protect summertime diel fluctuation was not adopted by the Commission, instead relying upon the narrative statement.

**Winter Criteria to Protect Reproductive Functions and Normal Pattern of Seasonal Fluctuation:** The “normal pattern of seasonal fluctuation” in the narrative standard is thought to protect thermal cues necessary for aquatic life cycles, especially spawning in cold water fish. While this provision is still included in the narrative, Colorado did adopt “winter season” numeric temperature standards. As noted earlier, for cold water fish, this value was based on the spawning requirements of trout. For warm water fish, the value was set at one-half of the appropriate warm water numeric standard to provide some degree of seasonal temperature variation and restrict seasonal spawning cues. The default winter season for cold water is October to May, and for warm water it is December to February.

## Spatial Diversity

Initial discussions of the TWG raised the issue of spatial diversity and there was general agreement that this can be an important component of temperature for fish, especially in streams. Natural aquatic ecosystems have a range of temperatures available to organisms in microhabitats. This array of microhabitats makes it possible for a broader range of organisms and life-cycles to flourish in the aquatic system. However, it became quickly clear that it would be impossible to set numeric limits for different habitat types and the different fish found within a reach.

If expected temperature spatial diversity does not exist, the TWG concluded that it would not likely be a National Pollutant Discharge (NPDES) permit issue. Rather, this would more appropriately be addressed by habitat improvements, discharge release designs, and other physical modifications. Keeping spatial diversity as a narrative encourages temperature monitoring of different habitat types to ensure appropriate refugia exists.

## No Abrupt Change

The restriction of "no abrupt change" has been part of the narrative temperature standard in Colorado for a long time, as noted earlier. Abrupt change is more commonly known as thermal shock, and this restriction limits the rate of temperature change over a brief time period. While this is thought to be necessary to protect aquatic life from rapid changes resulting in lethal temperatures, the actual tolerable change will vary with species and acclimation temperature. For example, a fish acclimated at relatively low temperatures can handle a greater abrupt change in temperature than those acclimated at higher temperatures.

Multiple approaches were explored when initially attempting to develop numeric standards for "no abrupt change," including review of field and laboratory data. For the field studies, various parties used instream temperature data from sites throughout the state to determine a 'natural' maximum rate of change on a daily basis. However, the preponderance of data were for mountain streams and not representative of other waters. While these data were descriptive of diurnal rates of change, there was no comparison to fish response, begging the question: Does any change beyond "natural" constitute harm? This is important because standards are intended to protect against harm – not to maintain natural conditions.

As part of the discussions regarding "abrupt change" or thermal shock, the TWG evaluated the relationships between acclimation temperature and UILT data. It was noted that a strong relationship between the acclimation temperature and subsequent UILT value exists for both cold and warm water fish species. It is possible that such relationships could be used to develop a mathematical method for establishing a range of values for thermal shock, based on ambient temperature.

To provide a level of protection, this allowable temperature change that resulted in mortality (i.e., UILT data) would be divided by a safety factor of 2. For the purposes of evaluation, the acclimation temperature would be equal to the upstream ambient temperature. While an interesting approach, in the end this method of calculating allowable "abrupt change" was not accepted by the TWG. There was uncertainty whether this would be protective.

In fact, there was considerable discussion whether a numeric for "abrupt change" was really necessary. Many believed protection from "abrupt change" is built into the seasonal acute numeric standard. Specifically, UILT data are used to derive daily maximum criteria, and during UILT testing, researchers acclimate fish to a given temperature and *immediately* transfer the fish to the test temperature. In other words, the methods used to derive UILT data provide the worst case scenario for "abrupt change" or "thermal shock."

With the lack of agreement for a numeric value or regression approach to thermal shock, the narrative ensures site-specific considerations in permits through evaluation of the potential for abrupt change based on operations; i.e., is heat added?

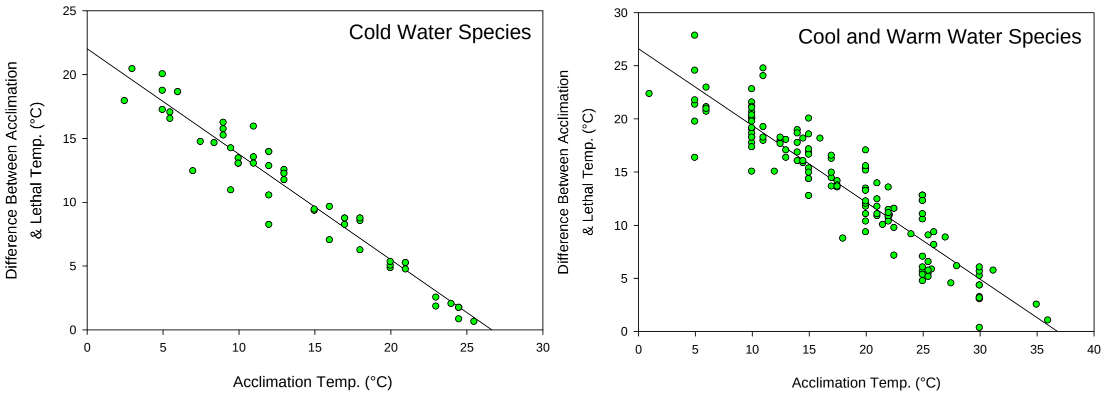


**Figure 5-2**
**Relationships Between Acclimation Temperature and UILT Data For Cold Water Fish (Left) and Cool/Warm Water Fish (Right)**

## No Magnitude, Rate, and Duration Deleterious to Aquatic Life

This closing phrase in the narrative footnote is basically a catch-all phrase that could allow the WQCD to evaluate whether site-specific conditions warrant additional effluent limits or attention for a particular discharge, if necessary. The downfall to this specific narrative text is that considerable site-specific data would be required to make this determination, including deployment of numerous thermographs and collection of accompanying biological data in order to collect information that would allow quantification of 1) magnitude, 2) rate, 3) duration, and, most importantly, 4) data showing the actual deleterious effects on aquatic life.

## Summary

Numeric temperature standards provide reasonable protection of fish communities based on a sizeable database of laboratory-derived thermal tolerance data. However, they are still single numbers and may not provide the full range of protection. Narratives allow a site-specific evaluation of compliance for each permit by considering 1) discharger operations, 2) is heat added to effluent or are they discharging at ambient temperatures, 3) reasonable potential analysis, and 4) documentation of resident fisheries.

Narratives do place additional responsibility on permit writers. But, they are a useful tool to protect the ecological integrity of the system without application of questionable numeric values which may not be specifically relevant to all sites.

## References

1. Colorado Department of Public Health and Environment-Water Quality Control Commission. 2000. Regulation No. 31. *The Basic Standards and Methodologies for Surface Water (5 CCR 1002-31)*. Denver, CO. AMENDED: August 15, 2000; EFFECTIVE: December 22, 2000.

2. Colorado Department of Public Health and Environment-Water Quality Control Commission. 2007. Regulation No. 31. *The Basic Standards and Methodologies for Surface Water (5 CCR 1002-31)*. Denver, CO. AMENDED: February 12, 2007; EFFECTIVE: July 1, 2007.

# 6

# TOWARDS SCIENTIFICALLY-BASED IMPLEMENTATION OF THE EUROPEAN WATER FRAMEWORK DIRECTIVE (WFD, 2000) WITH REGARD TO FISH COMMUNITIES; THERMAL FLUCTUATIONS AND THEIR IMPLICATIONS FOR POWER PLANT THERMAL RELEASES

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## Abstract

The main objective of the Water Framework Directive (WFD) is to reach a “good ecological status” in all rivers and watersheds by 2015. The health of fish communities is considered to be one of the main environmental indicators to evaluate the status of a river. Lessons have been learned from the impacts of the 2003 heat wave, and a working group in “hydrobiology and temperature” has been created in France. One of the goals is the exploitation of long-term data (> 20 years) from biological monitoring programs set up in the vicinity of all French nuclear power stations. An initial meta-analysis assessing the effect of climate change on stream organisms was presented in 2005. The fish communities in French rivers, subject to various anthropogenic pressures, globally showed long-term changes that have paralleled the progressive rise in water temperature (+0.5 to +1.6 °C over the last ten years), consistent with the predicted effects of climate warming. This study provides evidence that the effects of climate change should not be ignored when analyzing long-term changes in community structures, even in highly disturbed sites. The authors also propose the questions and components for establishing a new research agenda, to make optimum use of the knowledge gained in the 70s and to build up new knowledge.

## Introduction

The completion at the end of the Sixties of France’s major hydropower installations prompted EDF to focus almost exclusively on building thermal power plants to meet the country’s growing demand for electric power. This was a period in which studies on the biological effects of thermal releases were widespread [1]. They enabled better assessment of the potential impact of releases of heated water, and gave rise to regulatory guidelines. Moreover, systematic monitoring was set up on all streams equipped with nuclear installations. This made it possible to measure physico-chemical and biological variables and to identify any shifts in terms of the flora and fauna present.

After a rapid overview of the characteristics of the French nuclear capacity, we shall present the regulations now in effect and the monitoring undertaken.

We have access to synthesized data for periods sometimes exceeding 25 years for various sites. In this paper, we present a summary of the main trends found to be linked to yearly thermal characteristics, their relationship to the climate and any local effects found related to the characteristics of the release and diffusion of the thermal plume.

The heat wave that hit Europe in 2003 resulted in record temperatures and caused disruptions in the operation of certain plants, where the authorized thermal threshold is set by regulations in terms of a maximum temperature not to be exceeded. During that period, it was occasionally necessary to reduce power production activity.

This paper briefly reports on the biological impacts observed at that time.

In view of converging simulations of projected climate change, which predict increasingly frequent crisis situations, and with the entry into effect of the new European Water Framework Directive [2]), the need is once again being felt for studies in the field of thermo-ecology. Beginning with the central questions that arise in this regard, we propose various research paths which could well be explored in the future.

## Overview of the Characteristics of the French Nuclear Capacity

Since its beginnings in 1973, the French nuclear pool has now grown to 58 production units on 19 sites. More than 80% of all energy needs in France are covered by nuclear power; the remainder comes from hydropower and, to a lesser degree, conventional fossil-fired plants.

Of these 19 nuclear plants, 5 are on the seacoast and 14 on rivers (Figure 6-1).

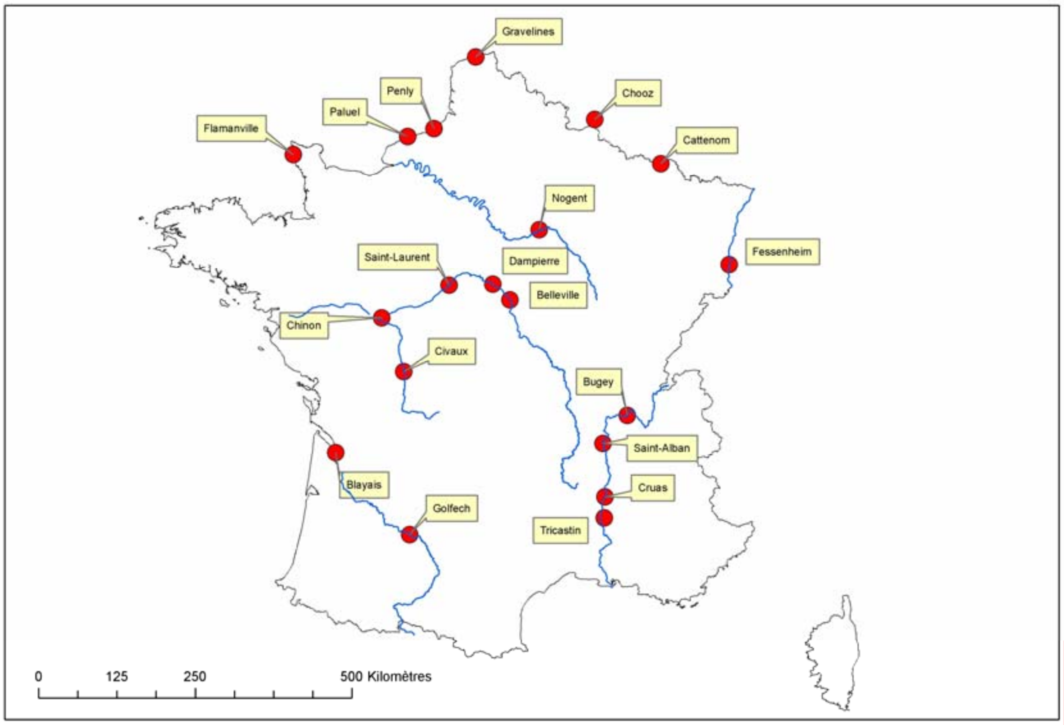

**Figure 6-1**
**Map of the Nuclear Power Stations in France**

Two types of cooling systems are used: the “open” or once-through system and the closed loop system. Open systems require large amounts of cooling water. A 12°C rise in temperature at the condenser requires discharge of around 50 $m^3/s$ for a 1300-MW unit, and only large rivers like the Rhine and the Rhone (Table 6-1) and the seacoast can accommodate sites with from 2 to 6 open-system units. By fitting the systems with cooling towers (on rivers such as the Seine, the Loire and the Garonne, Table 6-1), it is, however, possible to significantly reduce the requirements for water, down to 2 $m^3/s$ per 1300-MW nuclear unit. Subsequent warming is then on the order of a few tenths of a degree.

**Table 6-1**
**Characteristics of the 4 Major French Rivers**

| River | Length (km) | Discharge (at Mouth) ($m^3/s$) | Nuclear Power Plants | Type of Cooling Circuit |
|---|---|---|---|---|
| Seine | 780 | 520 | Nogent | closed |
| Loire | 1010 | 850 | Belleville, Dampierre, St Laurent, Chinon | closed |
| Rhone | 810 | 1720 | Bugey, St Alban, Cruas, Tricastin | Open and closed |
| Garonne | 575 | 700 | Golfech | closed |

## Current Regulations and Trends

The European directive now governing the quality of fish-bearing streams sets the thermal thresholds given in Table 6-2. That 1978 directive will remain in effect until 2013, at which time it will be abrogated.

**Table 6-2**
**Mandatory Thermal Thresholds (that can be Exceeded 2% of the Time) Stipulated in the European Directive on the Quality of Fish-Bearing Streams**

| Thermal Requirement | Salmonid Waters* | Cyprinid Waters** |
|---|---|---|
| Maximum temperature at the boundary of the mixing zone | 21.5°C | 28°C |
| Maximum temperature during the breeding period of cold water species | 10°C | 10°C |
| Maximum temperature rise at the boundary of the mixing zone | + 1.5°C | + 3°C |
| *rapid and colder waters; generally small streams in mountain areas<br>**larger and slower rivers with relatively high summer temperatures | | |

In France, each power plant has a decree governing water uptake and release which imposes constraints such as the maximum temperature of the water released from the installation, and seasonal adaptation of the thresholds for warming and the maximum temperature in the river downstream of the release (Table 6-3). These thresholds, whose scientific basis merits re-examination, are sometimes critical for industrial operation in years with a high frequency of heat episodes.

**Table 6-3**
**Thermal Thresholds for the Nuclear Power Plants on the Loire and the Rhone**

| **River** | **Loire** | **Rhône** | | | |
|---|---|---|---|---|---|
| **Power station** | **all 5 sites** | **Bugey** | **St Alban** | **Cruas** | **Tricastin** |
| **T max in the discharge** | no | **30°C**<br>**34°C** summer* | no | no | **30°C**<br>**34°C** summer* |
| **T max calculated in the downstream flow** | no | **24°C**<br>**26°C** summer**<br>(280 periods of 3 hours)<br>**27°C** if heatwave | **28°C** | no | **25°C**<br>**27°C** summer*<br>(20 days)<br>**29°C** if heatwave |
| ΔT | **+1 °C**<br>**+1.5 °C**<br>if < 15°C | **+7.5°C**<br>**+5.5°C** summer*<br>**+3°C** if heatwave and < 26°C<br>**+1°C** if heatwave and < 27°C | **+4°C** if < 22°C<br>**0°C** if > 28°C<br>**+3°C** summer** | **+1°C** if < 27°C<br>**28-Tupstr.** if 27-28°C<br>**0°C if** > 28°C | **+7°C**<br>**+3°C** if heatwave |

(*) summer = 01/07-15/09
(**) summer = 01/06-30/09

## Monitoring

Fish, plant and macroinvertebrate populations and the water quality (N and P concentrations) in their environment continue to be monitored upstream, at the discharge point and downstream, two or four times a year. Temperature, oxygen concentration, pH and conductivity are measured continuously (See [3], Tab. 2 p 108, for details).

## Main Trends Observed

### *General Effects*

The 25-year time series of fish inventories collected for EDF around 7 nuclear power plants on the Seine, the Loire and the Rhone were analyzed [4]. The objective was to study the relationship between the structure of the fish assemblages and temperatures during reproduction period (April to June). Spring is a key period in the response of organisms to climate change. In the northern hemisphere, it has warmed up significantly in the last 20 years, and very often corresponds to sensitive phases in the life cycle of the organisms.
The main conclusions of the study are as follows:

- A global increase in fish abundance due to the impact of warm springs on recruitment for most cyprinids,
- A global increase in specific richness, which can be attributed to migration of species from downstream zones who progressively find, in these warmer areas, favorable conditions for their ecological needs,
- A drop in diversity and evenness, reflecting domination of the stocks by a smaller number of species,
- An increase in the percentage of southern, thermophilic species, at the expense of northern, psychrophilic species,
- Global trends which are correlated with the mean temperature for reproduction (April to June),
- Temporal shifts in assemblages which are very similar upstream and downstream of the plants, supporting the hypothesis of general climate forcing.

This study shows that climatic factors can no longer be ignored when analyzing changes in the structure of communities in major rivers over the last 20 years, without running the risk of incorrectly attributing the changes solely to other types of anthropic disturbance of the environment. It also indicates that, in order to distinguish the effects of the different factors on the organisms, more targeted studies are needed on the scale of individual sites.

Recent studies conducted on the Rhone have also enabled estimating the impact of temperature on aquatic ecosystems. The long-term (25 years) hydroecological monitoring data from 4 nuclear plants on the Rhone have been subjected to statistical analysis. The principal conclusions of these studies are as follows [30]:

- All the biological compartments studied (macroinvertebrates and fish) show a longitudinal gradient, with a marked differentiation between the upper Rhone (Bugey) and the lower Rhone (St Alban, Cruas, Tricastin);

- There is a clear temporal shift in the time chronologies, with a rising proportion of species from warmer, slow-running water, at the expense of those from cold, swift-running water;
- There appears no significant difference between the upstream and downstream assemblages at the sites with the exception of areas with unmixed thermal releases. These changes are markedly more noticeable in the downstream sites near Bugey than at those on the lower Rhone, where the shift is less evident;
- The changes observed in macroinvertebrate and fish stocks can first be attributed to the effects of climate change.

### Local Effects

Let us take the example of Bugey, where the warm water release (+ 10°C) produces a thermal plume on the right bank of the Rhone, whose temperature drops around 1°C per km [6]. There is a qualitative effect on the fish: some species like the stream bleak, *Alburnoides bipunctatus*, bleak, *Alburnus alburnus* and, to a lesser degree, the black bullhead, *Ameiurus melas*, bream, *Abramis brama* and telestes, *Leuciscus souffia*, which are captured in greater numbers on the impacted sites. Conversely, the chub, *Leuciscus cephalus* and gudgeon, *Gobio gobio* are captured more at the non-impacted sites. There is, however, great variability between seasons and between sites. Throughout the monitoring period (1979-2004), the relative percentages of contribution to the total biomass of 6 species, dace, *Leuciscus leuciscus*, chub, barbel, *Barbus barbus,* nase, *Chondrostoma nasus*, pike, *Esox lucius* and brown trout, *Salmo trutta,* are, depending on the year, from 81 to 98% of the biomass for the upstream reference stations, and only between 40 and 71% since 2001 at the impacted sites. There may therefore be an exacerbation of this effect on the right bank influenced by the hot plume over time.

## The European Heat Wave of 2003

In the face of exceptional climatic conditions in August 2003, Electricité de France was obliged to ask for an easing of French regulations. In response to this request, dT +3°C for open circuits and +1°C for closed circuits were permitted. However, the French Ministry of Ecology required that research be carried out in partnership with energy producers to study the effects on aquatic life.

Consequently a Working Group (WG) on “Hydrobiology and Temperature” was created in 2004 with the French Ministry of Ecology, Cemagref, universities, hydrobiology consultants and Electricité de France. The main objective is to determine the impact on aquatic life of a rise in temperature, and to define reference values for the new European Water Framework Directive (WFD).

The WFD was implemented in France in 2004. Its main objective is to reach a good ecological status in all rivers and watersheds by 2015. The indicators used to assess the ecological status of French rivers are fish, macroinvertebrate and diatoma communities.

The first decision of the Hydrobiology and Temperature WG was to analyze existing biological data (20 years) from monitoring programs carried out in the vicinity of all nuclear power stations.

A hydroecological assessment of the effects of the 2003 heat wave was made at the annual hydroecology seminar of 2004 [7]. The analysis of migrators was based on counts obtained from the long-standing monitoring at fish-ladders at Golfech (Garonne) since 1987, at Tuilières (Dordogne) since 1989 and at Vichy (Allier) since 1997. In 2003, the observations showed that a stop in upstream migration corresponded to periods when three thermal thresholds were exceeded in terms of the daily mean (daily maxima were 1 to 2 degrees higher): 24°C for the marine lamprey, 25°C for the Atlantic salmon and the large shad, and 27°C for the European eel. Those stops in migration correspond to salmon mortality in the Loire and along the Garonne-Dordogne axis [8].

## Questions and Paths for Research

The recommended research strategy would be based on 5 complementary fields of investigation, of increasing complexity, as summarized in Table 6-4 (1st line):

1. Updating existing knowledge of the thermal preferences and tolerances of aquatic species,
2. Field research on the behavior of fish species in the presence of thermal contrasts (behavioral ecology),
3. Further study of the relationships in geographical distribution of aquatic species by means of targeted exploitation of large-scale monitoring data, paying particular attention to measured or modeled water temperature data,
4. Continuation and in-depth exploitation of long-term time series, attempting to identify the physical/thermal/chemical-to-biology relationships,
5. Further research on the metabolism of aquatic ecosystems, paying particular attention to the bacteria, alga and benthic compartments at the base of trophic levels. We must also consider the influence of temperature on the sensitivity of aquatic organisms to infectious diseases and parasites, and to their tolerance to more or less toxic xenobiotics.

**Table 6-4**
**Proposed Paths for Research into Thermal-Biological Relationships**

| Ecological variables | Preferences<br>Tolerances<br>Species or guild | Behavior<br>(realized niche)<br>Species or guild | Distribution<br>Species or guild | Trends/forcing<br>Populations and communities | Metabolism<br>Organism (bacteria, algae, etc.) |
|---|---|---|---|---|---|
| Localization<br>(number of sites) | Laboratory<br>Literature | *In situ*<br>(X) | *In situ*<br>(XXX)<br>(monitoring) | *In situ*<br>(X)<br>(LT monitoring) | *In situ* |
| Nature of the thermal variables | T min, T max, dT<br>f (T Acclim.) | T max, dT spatialized | T min, T max, dT | Thermal regime = f (Q, space) | Thermal regime |
| Nature of the research | Compiling<br>Updating<br>Complements to work in the 70s | Radiotracking<br>Measurements<br>Hydraulic/thermal modeling | Coupled analyses:<br>Temperature<br>Pres./abs. of species<br>Diachronic analyses | Trend analyses<br>Forcing by variables (V): T, physical, chemical, biological | Functional analysis |
| Management tools | Thermal sensitivity thresholds | Thermal refuges or “barriers” | Geographical thermal thresholds<br>Distribution models<br>References frames | Thermal regimes and thresholds<br>Predictive models (d biol. = f (d,V) | Thermal thresholds<br>Functional models |

The questions to be resolved in each of these areas, together with the research that could be envisaged, are discussed below.

## Preferences and Tolerance Thresholds of the Aquatic Species, Considered Separately or Grouped Into Guilds

If we posit a tolerance threshold of 26°C for the brown trout, we must specify which temperature this is (lethal temperature -LT50- i hours after acclimation of j hours to y T°C), whether this temperature has significance in relation to survival of the species *in situ* and, lastly, whether there are phenotypical or genetic differences in tolerance to temperature. This example leads us to formulate three questions:

- What do we know about the extreme temperatures tolerated under laboratory conditions (*ex situ*) by the aquatic organisms?
- What is the significance of the experimental temperatures in ecological terms of survival of the populations *in situ*?

- Can we consider that the thermal thresholds apply generally to the species or that we should make distinctions either in accordance with early thermal impregnation of the population or in accordance with genetic differences?

### *Question 1.1*

To avoid a number of ambiguities that might affect regulations on a national or European level, we need to stabilize and share the knowledge that has been acquired on the tolerance thresholds of aquatic organisms.

This effort should first involve a clarification of the vocabulary used for specific, standardized laboratory conditions. This could be based, for example, on the syntheses of Coutant [9], Alabaster and Lloyd [10], Lutterschmidt and Hutchinson [11] or Beitinger and Bennett [12], Beitinger et al. [13]. One would then choose the most pertinent and most frequently available threshold values.

Furthermore, given that much of this research dates from the Seventies, it needs to be made available and compiled on an international level. It would be advisable to return to the source articles, including those in non-digitized grey or early literature, since syntheses such as those of Küttel [14] or Truslé and Quignard [15] may be useful but are sometimes imprecise.

Generally speaking, this knowledge of the autoecology of species is still crucial to our understanding of the changes observed in communities, despite the recurrent difficulty of extracting explanatory parameters which are often covariant and confused.

In this discussion, we have focused on fish, but it would be advisable also to consider data which may be less widespread, on benthic macroinvertebrates.

### *Question 1.2*

We read, for example, that the temperature really “experienced” in the field may range between 1° and 4°C below the laboratory values for the lethal temperature [16, 17]. This point should be examined alongside the preceding question since the bibliography explored may also contain this type of information, particularly regarding temperatures for reproduction, incubation and growth.

This question should also be handled in connection with path 3, thermal distribution of species.

### *Question 1.3*

A recent study [18] on zebrafish, *Danio rerio* (fish with a short lifespan) shows that an intrinsic plasticity allows this species to withstand higher temperatures in the adult phase if it is exposed in the juvenile phase to high temperatures, and to a certain daily amplitude. Differences have been found in tolerance to maximum temperatures among different salmonid populations [19]. However, no difference has been found in thermal behavior among genetically different populations of 2-year-old muskellunge [20].

This is therefore a question which is not fully answered in the literature and which needs further examination, at least a synthesis of existing data, to identify promising paths for future research.

### *Behavior of Aquatic Organisms in Contrasted Thermal Environments; Notions of Refuge*

We know that water temperature is not homogeneous at all points in a stream. The variations are linked to river morphology, such as the existence of annexes or water depths creating vertical stratification, to a confluence with affluents, to more or less shaded banks or to the existence of alluvial aquifer inputs. Releases of cooling water can also create thermal differences between two river banks if they have been designed for gradual longitudinal mixing: the Rhone at Bugey is a good illustration of this (see above).

### *Question 2*

How do fish behave over time in environments with such spatial thermal differences? What are the interrelationships between temperature, flow rate and morphology? Do fish seek and easily find refuges? If so, where? Is this a phenomenon that concerns the majority of the aquatic communities?

If displacement is necessary for fish, do they retain the capacity to return to habitats which are temporarily inhospitable or do they subsequently avoid these areas?

Are there configurations which create thermal barriers and, if so, at what threshold and for what values of discharge/habitat/temperature?

### *Paths for Research*

The existence of cold refuges in streams with heavy aquifer loads has been confirmed by the appropriate field measurement techniques complemented by aerial photographs (thermal infrared and color videography [21]). Salmonids appear to make very efficient use of these contrasts [22] and to take refuge in colder environments when necessary, providing their displacement is not hampered by obstacles (cross-river weirs, differences in level difficult to overcome between the main and annex channels).

Little work has been done to date on non-salmonid species: the radiotracking of smallmouth bass, *Micropterus dolomieu*, has shown that this species actively avoids warm zones and does not return to them if there is simultaneous chemical pollution in the release [23]. In a thermal release basin in Holland, artificially introduced fish behaved erratically [24]: it would be difficult to draw general conclusions from this as to the status of communities in the receiving water body.

This is therefore a question that merits considerable exploration.

The sites where such contrasts are sharp are the most promising for this type of study: this is the case, for example, of the Rhone at Bugey. The question should be examined by characterizing both temperature and habitat, on the understanding that these variables are discharge-dependent. This approach is similar to implementation on the scale of a single site of the microhabitat method (hydraulic model coupled with a habitat preference model [25]), with the addition of the thermal dimension. The choice of the type of model will depend on the objectives: if one is investigating behavioral thermo-regulation (the search for refuges), it is necessary to track fish in an appropriate matter and localize them spatially in a thermal environment and a habitat, which presupposes a suitable analytical tool, i.e. a hydro-thermal model.

Related questions arise for amphibiotic migrators and studies seeking to determine their preferred migration paths, together with the existence of any thermal barriers and temporary refuge zones should be encouraged.

### *The Role of Temperature in the Spatial Distribution of Species*

Fish distribution models (Huet's [26] longitudinal zoning patterns, Verneaux's biocenotypes [27], the "Indice Poisson France" [28], or the European FAME index [29]) all include relationships linked to temperature and to altitudinal and longitudinal contrasts, underscoring the preponderant role played by this variable.

### *Question 3*

This question relates to the realized niche of the species. Are there definite limits at which species are excluded? What are the thermal thresholds or regimes with which these are associated?

What are the relationships between these field values and the experimental values touched on in path 1?

### *Paths for Research*

Considerable work has been done as indexes have been built, consisting in establishing the relationships between air temperature, the most easily measured data, and water temperature, and then spatializing this relationship; for the French IPR index, the temperatures for January and July were retained [28].

In the future, it will be necessary to obtain better coverage of the networks in place (large-scale data), effectively measuring the temperature so as to better allow for climate changes already observed or predicted. This will make it possible to improve measurement of change, better study the notion of thermal regime and its influence on organisms, and even fine-tune temperature models. It will also provide a means of efficient measurement of any changes in flora and fauna, so that conclusions can be drawn as to regulatory guidelines.

There would also be the possibility of seeking to test the metrics of the indexes that best respond to temperature.

Moreover, lessons could be learned from temporal comparisons (diachronic studies) on streams where quality data coupling temperature and biology are available, or could feasibly be updated and completed. The hypothesis is to test whether the disappearance of any species between two sufficiently distinct time series can be attributed to thermal factors.

### *Trends in Population Change, Metrics, Determinants, Functional Significance, Change Prediction*

This is work that has already been successfully begun by analyzing both structural change in fish and invertebrate communities [30, 4], and the juvenile fraction of some species (chub, bleak, roach, *Rutilus rutilus*; [31, 32]). Some of this literature points up trends in structural change correlated with the general warming of water. The possible relationship between spring precocity and successful recruitment of some cyprinids has also been explored [33].

### Question 4

Several questions remain concerning the combined dynamic influence of temperature and discharge factors, to which – for certain sites – habitat should be added. With respect to abiotic factors, what are the critical thresholds or the series of events found to accompany marked biotic changes? In biological terms, what are the metrics which indicate a change in the trend for population structures? What does this mean in terms of the dynamics of the hydrosystem? Are some theories concerning changing strategies of species being confirmed (e.g. less investment in reproduction, a shortening of the life cycle)? What are the temporal variability and reversibility of the phenomena observed? Is it possible to combine modeling of this abiotic and biotic dynamic using predictive models? What “values”, expressed in regulatory terms as “ecological status or potential” in the WFD, are associated with the population structures observed?

### Paths for Research

Time series are of central importance.

Monitoring over long periods of up to 30 years in the vicinity of French nuclear power plants has given us valuable data which is extremely rare in the world today. In the United States, there is a comparable series on the Ohio [34], with a difference in fishing protocol that leaves only fifteen years’ data exploitable. Given the climatic changes to be expected and the evolution in many factors which can influence biological responses, this monitoring must be continued and, if possible, complemented with certain variables such as more systematic measurement of habitats, or of spatial distribution of temperatures, but also more extensive sampling of deep waters that that are not accessible to electrofishing by fish nets. This would also present the advantage of trapping large individuals so that it would be possible to characterize parameters of growth and even of health of the individuals.

### Data Processing

Existing time series must be inventoried, including data on fish ladders, to evaluate further possibilities for data exploitation. Further data processing could target new geographical series, new groups of flora or fauna, specific species (e.g. the dace, which has exhibited marked changes), or informative life phases like fish juveniles.

It would be advisable to look more systematically for disruptions linked to high temperatures, along the lines of studies begun by Cemagref (B. Villeneuve, pers. com.), working with quantile regressions [35] and taking more data to continue the work carried out at the time of the 10th anniversary of Bugey operations [6]. Seegert et al. have proposed treating the Ohio series in a similar way with loess regressions and focusing on the metrics of biological indices like the richness or proportion of guilds [34].

Generally speaking, more thorough and systematic exploitation of monitoring data every 5 years would have the benefit of ensuring that data are more efficiently saved and validated and of maintaining the scientific focus on long time series.

### Model Building

Keeping in mind the benefit of modeling for the exploitation of monitoring data provided by the national instream flow study unit [36], we propose considering the building of ad hoc models capable of combining the dynamics of abiotic factors and biotic responses on the level of a community. One possible path would be to explore and adapt promising Swiss data on a trout population using Bayesian statistical networks (Fischnetz project, [37, 38]). This type of model, once validated, can be used for predictive studies to compare several different remedial scenarios.

### *Metabolism of Hydrosystems and Temperature*

Recent work on climate change shows that the disruptions observed in upper trophic levels stem from sudden changes in dynamics in relation to lower levels (phenomena of match/mismatch, pointed up in lakes or in the marine environment for salmon nurseries [39]).

### *Question 5*

What is the situation in streams, where trophic levels interact differently? What is the link between temperature and principal basic functions like metabolizing of organic matter and assimilation of nutrients? How do the bacterial and algal compartments react?

Do we find thermal thresholds consistent with the limit values tolerated by the upper trophic echelons?

Paths for Research (B. Montuelle, Cemagref, pers. com.):

- Thermal effect on microbial processes generating greenhouse gases (CO2, CH4, N2O); in principle, the importance of aquatic organisms in this respect should be less than that of land-based ecosystems, industry and animal breeding;
- Thermal effect on the proliferation of pathogenic bacteria: either more warmth for more tropical organisms or less freezing with less elimination of thermophilic bacteria. This investigation should be extended to viruses which may also be temperature-sensitive;
- Thermal effect on vectors for bacteria and pathogenic viruses (mosquitoes, parasites, etc.), sometimes concomitant with reductions in the lotic nature of the environment (fewer stagnating areas).

On this subject of general dynamics, it might be considered that methods attempting to model production of the different trophic levels would be structuring and helpful.

We shall not discuss here any potential risk linked to a temperature-related increase in vulnerability of organisms to chemical substances [40]; this is an issue which should certainly not be neglected.

### *Application of Research to Future Regulations*

Regulations are changing and we need to be prepared to provide needed information, attempting to keep the debate as objective as possible by offering meaningful data and well integrated concepts. The generic question is whether or not we can identify changing trends, explain the causes and, if possible, predict them. On the subject of threshold temperatures, our overall monitoring has not been sufficiently specific to provide a satisfactory answer. Finally there arises the question of the “value” associated with the metrics, which is to say the degree of respect of the WFD (plants, invertebrates, fish).

### Paths for Research

Generally speaking, pursuing each of these paths should provide us with elements for a **true sensitivity analysis for each site**: this would include relating (1) the aquatic communities present on site, (2) knowledge of their thermal profiles and their habitat requirements, (3) their sensitivity to the values of the thermal variables on site and (4) the physics and thermics of the site (spatial and temporal distribution, cartography) (Figure 6-2). Our discussion would then be much better informed in terms of threshold values, periods and duration of imposition, discharge/temperature regimes, but also the degree of impact (existence or absence of thermal barriers, small or large impacted area, zones or periods of a return to colder temperatures).

For large streams, the data obtained will be valuable for testing the sensitivity of the metrics associated with definitions of good status or good potential, in the sense understood in the WFD. Continued monitoring will guarantee that future changes in reference frames will be well grounded.

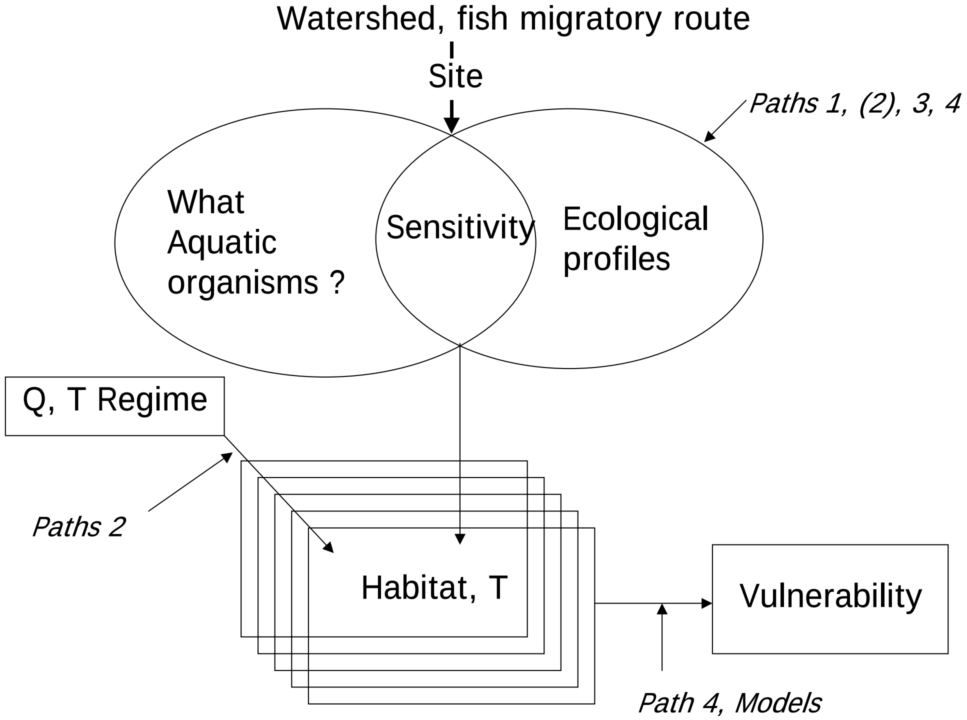

**Figure 6-2**
**The Components of A Vulnerability Assessment For Each Site**

*The site is part of a watershed and is located on a path where there may be migratory fish. Its sampled or probable (modeled) aquatic assemblages are determined. The ecological profiles of its components are described. The first correlation gives us the sensitivity of the community at different thermal levels. The hydrological and thermal regimes are established and correlated with the physical geometry of the site to give a temporal representation of the habitats and the thermal environments. Comparing these two steps provides an initial analysis of the vulnerability of the site, covering the most sensitive individuals in the community, the period of imposition of a level of vulnerability, and its spatial importance. The paths for research proposed in this text are shown in bold, pointing to their expected contribution.*

## Conclusion

The establishment with the WFD of a new European regulatory framework and its implementation in the member states raises once again the question of authorizations for thermal releases, much in the news in the Seventies. We must credit the plant operators and inspectors of that time with the foresight to set up monitoring outside each nuclear site.

The resulting data is of great help today in understanding the changes observed in flora and fauna, and attempting to link these both to general factors typical of the host rivers and to more local impacts from the industrial installations. Analysis of these long-term time series, unfortunately rare in the world today, teaches us much about the effects of climate forcing, particularly with respect to the recent impacts of generalized warming of the waters by some 1°C as an annual mean, over the last decade. To anticipate future changes and more adequately predict the repercussions of new regulations, it will be necessary to develop new and more targeted research programs examining the behavioral aspects of the organisms *in situ* and the overall metabolism of hydrosystems. The use of this new knowledge, combined with earlier knowledge of the thermal profiles of the species concerned - which needs to be synthesized - should involve models coupling physical data on the sites (thermal regime and spatial distribution of temperatures, hydrological regime and spatial distribution of habitats) with data on the biological behavior of aquatic organisms. Setting up a coherent method for analyzing the ecological sensitivity of the sites will ensure respect of the real spirit of the WFD: avoid threatening existing conditions and attempt to improve them wherever possible.

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# 7

# DEVELOPMENT OF PROPOSED THERMAL WATER QUALITY RULES IN WISCONSIN

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## Introduction

With time, and for various reasons, rules need to be revised. Such is the case with Wisconsin's rules for regulating thermal discharges to surface water. Wisconsin's thermal rules have been under revision for a significant amount of time. An advisory committee made up of a diverse group of professionals has been the primary vehicle for making the revisions. The author is chair of this advisory committee. The primary goal of the advisory committee is to produce a water quality-based thermal rule package that is environmentally protective, scientifically defensible, and reasonably implementable. Much effort has been made by the advisory committee members, as well as others, to assure this goal is met.

The purpose of this paper is to provide a summary of the thermal surface water quality rules revisions being proposed by the Wisconsin Department of Natural Resources (WDNR). The paper will discuss some details regarding the nature and development of the water quality-based thermal standards, as well as how these standards are proposed to be applied to and implemented by point source discharges of heat. A brief history of why WDNR is revising its thermal rules and an overview of the general goals of the rules revisions effort are included to provide context.

It is important to note that Wisconsin's thermal rules revisions process remains ongoing at this time. Thus all details in this paper regarding the rule revisions are to be considered "draft". The draft rules are expected to go out for public hearing and comment in early 2008, and the final rules are expected to be promulgated mid 2008.

## Brief History

A common question is, "Why is Wisconsin revising its thermal rules"? This is not surprising since most states are not doing so, and are continuing to use some variation of the long-since adopted federal values and/or approach. To better understand Wisconsin's proposed revisions, it is important to understand why the revisions are being made.

The State of Wisconsin established thermal standards for water quality in 1974 as part of its delegated responsibility of implementing the Federal Water Pollution Control Act Amendments of 1972 (i.e. the Clean Water Act or Public Law 92-500). These standards took effect in 1975, and stated that "he maximum temperature rise at the edge of the mixing zone above the existing natural temperature shall not exceed 5° F for streams and 3° F for lakes." Further, "the temperature shall not exceed 89° F for warm water fish." These standards were included in Chapter NR 102 of Wisconsin's Administrative Code. Additional thermal standard language, primarily narrative in nature, is also included in Chapter NR 102.

However, following the filing of two lawsuits in 1975, the Wisconsin Supreme Court in 1979 ruled that the thermal standards established by the WDNR were unconstitutional, and thus invalid [1]. The basis for the Court's ruling was that the application of the standards was not based on water quality parameters or conditions and thus should not be considered water quality-based. The court believed instead, that the application of the standards was categorically-based. Although other states were using (and continue to use) standards similar to what Wisconsin had established, since Wisconsin's statutes allow State standards to be more stringent than federal guidelines only when they are water quality-based, the Court ruled that Wisconsin's thermal standards were unconstitutional and invalid.

Following the State Supreme Court ruling in 1979, the WDNR was unable to apply the established thermal standards in Wisconsin Pollution Discharge Elimination System (WPDES) permits. Instead the WDNR applied a maximum end-of-pipe discharge temperature of 120°F, based on protection of incidental human contact, in most permits for dischargers of heated effluent. This approach was challenged in 1991 when the U.S. Environmental Protection Agency (EPA) Region 5 objected to two steam electric utility permits submitted by WDNR on the basis that they did not include thermal limits.

Since the U.S. EPA Region 5 would not approve the two permits unless the thermal issues were addressed, an agreement was reached that the thermal standards of Chapter NR 102 needed to be revised. The resulting revised rule was to include scientifically sound and water quality-based standards that were protective of the biological, chemical, and physical components of receiving waters. Additionally, the revised rule was to enable enforceable water quality-based effluent limitations for thermal discharges. A U.S. EPA grant was used to support the thermal rule revision effort.

As a result, an advisory committee (AC) was formed in 1994. The AC met approximately 18 times between November 1994 and August of 1997, making significant progress in meeting the revision objectives noted above. The AC's work resulted in a draft proposed rule package which included significant revisions to both Chapter NR 102 and Chapter NR 106 (dealing with application of water quality standards to point source discharges) of Wisconsin's Administrative Code. The draft rule package went out for public hearing, review, and comment in the autumn of 1998. Many comments were received by WDNR into 1999.

Despite the progress that had been made, finalization of the thermal rules revisions was halted in 1999 due to external opposition, followed by internal WDNR issues related to Department-wide reorganization, retirement, and staff reassignments. The thermal rules revisions effort remained in hiatus until May 2001, when the author was hired and assigned the task of finalizing the rules revisions. The AC was reconvened (some members the same as the original, some new) and met 15 times between October 2001 and July 2004. A WDNR internal work group worked on making significant thermal standards revisions for the majority of 2002, and presented the results of its work as a proposal for the AC to consider. Overall, the focus of the renewed effort was to make final revisions to the thermal rules, using the 1998 proposed draft rules as a starting point. Comments received in 1998 and 1999 have been considered.

After another approximately two year hiatus, the AC met twice in 2007. Based on comments from the AC, internal staff, and U.S. EPA Region 5 staff a new draft rule package has been completed and is expected to go out for public hearing and comment in early 2008. The final rules are expected to be promulgated mid 2008.

## General Rules Revisions Goals

The AC has operated under four primary principles in revising Wisconsin's thermal rules. The four primary operating principles are that the revised rules must be:

- Water Quality-Based
- Environmentally Protective
- Legally & Scientifically Defensible
- Reasonable in Its Application

To address the primary argument of the Wisconsin Supreme Court, the first principle is that the resulting rules must be water quality-based. Several things have been done to assure the revised rules will be considered water quality-based, and include the following:

- The thermal standards are developed for each particular water body use or classification in Wisconsin (i.e. cold water, warm water, Great Lakes, specific rivers, etc.).
- All data included in criteria development is based only on species known to exist in Wisconsin.
- Acute criteria are based on ambient temperature, rather than a static value (e.g. 89°F).
- Data from three different sub-lethal endpoints are included.
- Sub-lethal criteria are based on the month that a given endpoint is known to exist in Wisconsin.

Second, the rule must be environmentally protective. This is being accomplished by including numerous and varied laboratory-derived and field observed biological effects data, as well as considering the comments of appropriate fisheries biologists and others. Third, the rule must be legally and scientifically defensible. The two primary ways that this principle is being accomplished is by following WDNR legal counsel and U.S. EPA Clean Water Act review and using an extensive amount of detailed data. Additionally, this has been accomplished by having a rationale for each decision made. Fourth, the rule must be reasonable in its application. The objective here is to assure that those who will be required to implement the rule can do so with a reasonable amount of effort and/or impact, and that the rule is not overly burdensome. Similar to this is what could be considered a fifth operating principle of the AC - that the rule revisions and the final rule should pass the “common sense” test. This “test” has been considered often throughout the rules revision process, and has helped the AC develop a much sounder rule that incorporates the four primary principles. The “common sense” test helps the AC to consider how to adjust good-intentioned initial revisions based on good data that just don't “fit” a given scenario, into much more relevant and reasonable proposals.

## Summary of the Proposed Rules Revisions

Some of the more significant details of the thermal rules revisions currently being proposed by WDNR are highlighted in this section. The purpose is to provide a glimpse of the types of revisions being proposed, as well as an idea of the types of issues that have been worked through to consider these revisions. Consider how the proposed revisions are meeting the goals and principles discussed in the previous section. Without question the most current proposed revisions are much more detailed, comprehensive, and water quality-based than the original 1998 draft rule. Please remember that all things listed in this section are the current state of our work, but are to be considered draft until final rules are promulgated.

### *Overview*

The thermal rules revisions occur in primarily two existing rules. The surface water quality standards exist within Chapter NR 102 of Wisconsin Administrative Code. The proposed revisions include ambient temperatures and acute and sub-lethal water quality criteria within a newly created subchapter, and a public health and welfare criterion. The rules within NR 102 have broad application, and can be implemented within or in concert with other rules. The implementation rules for point source discharges to surface water exist within Chapter NR 106 of Wisconsin Administrative Code. The proposed revisions include procedures to determine when water quality-based effluent limitations (WQBELs) are necessary, procedures to calculate WQBELs, special provisions for publicly owned treatment works and privately owned domestic sewage treatment works, and provisions for general permits within a newly created subchapter. The rules within NR 106 have specific application, and outline how water quality standards in NR 102 are implemented by point source dischargers. Additionally, it is proposed to move the procedures for implementing alternative effluent limitations for temperature (Wisconsin's rules for implementing s. 316(a) of the federal Clean Water Act) from its own Chapter to a newly created subchapter within NR 106.

### *Chapter NR 102*

The two primary components of Chapter NR 102 that are being proposed for revision are the water quality criteria and the ambient (background) temperatures. Details of proposed revisions pertaining to each are presented below.

As mentioned above, the previous water quality standards for temperature in Wisconsin were based on the maximum temperature rise at the edge of the mixing zone above the existing natural temperature not exceeding 5°F for streams and 3°F for lakes, as well as the temperature not exceeding 89°F for warm water fish. Further, the code stated that "there shall be no artificial increases in temperature where natural trout reproduction is to be protected." In a significant diversion from the former approach, monthly acute and sub-lethal water quality criteria have been developed. All criteria are based on fish data as the original AC found 1) fish data to be protective of other species and 2) insufficient data existed on thermal impacts to other aquatic organisms. In all, data and information from 721 references, representing the years 1874-2007, have been used and cited pertaining to the development of the proposed standards. The vast majority of the references are from peer-reviewed publications or agency reports, etc., while a small number are from personal communications or other sources.

Acute criteria are based on 360 Upper Incipient Lethal Temperature (UILT) - acclimation temperature data pairs, as described by Fry et al [2] and McCauley [3], and will be applied as a daily maximum. Using the UILT-acclimation temperature data in concert with regression and analysis of covariance statistical analyses has enabled the development of acute criteria that work on a "sliding scale" with ambient temperature, thus eliminating the use of static number criteria (such as 89° F). This sliding scale considers the receiving water's ability to assimilate heat (more when water temperatures are cooler and less when water temperatures are warmer). Separate criteria have been developed for each water body use or classification by considering only data from fish that exist in each given water body classification for developing that classification's criteria.

The sub-lethal criteria are based on three different life stages-gametogenesis, spawning, and growth. Twelve data points were used to develop criteria to protect gametogenesis, 444 data points were used to develop maximum spawning temperature criteria, and 124 data points were used to develop maximum no growth temperature criteria. A matrix considering water body use or classification (and the fish that exist in each) and the months each life stage occurs in Wisconsin, in combination with a polynomial regression, was used to develop a single sub-lethal criterion for each month. The sub-lethal criteria are to be applied as a seven-day average.

Unlike for other pollutants, both acute and sub-lethal criteria will be applied at the edge of a mixing zone. An acute mixing zone is allowed because heat is a non-conservative pollutant that dissipates. The acute and sub-lethal criteria are applied at the edge of the same mixing zone to streamline and simplify the application of the criteria. This is possible since the acute criteria are applied as daily maximums and the sub-lethal criteria are applied as seven-day averages. Yet the two criteria are applied simultaneously.

Ambient temperatures were developed using data from as many stations in Wisconsin between October 1987 and December 2002 as possible. The time range allowed capture of data from relatively warm, cold, and average temperature years. Approximately 4070 monthly average temperature values were used to develop ambient temperatures for all waters including the Wisconsin portions of the Mississippi River, except for the Great Lakes. Data sources included U.S. Geological Survey (USGS) Wisconsin Water Year Books, other USGS data, DNR Wisconsin River data, and Fox River data from the Green Bay Metropolitan Sewerage District (which keeps water quality data for many locations in the lower Fox River and lower Green Bay). This data is derived from continuous 15-minute temperature readings. Approximately 938 monthly average temperature values were used to develop ambient temperatures for Great Lakes waters of Wisconsin. Sources of the Great Lakes data were intakes at numerous water treatment facilities along Lake Michigan and Lake Superior. This data is derived from daily temperature readings. All data are organized into appropriate water body uses or classifications by month. Final ambient temperatures are geometric means of all monthly averages for a given month and water body use or classification. In all, monthly ambient temperatures were developed for 17 specific waterbody use classifications.

It is important to note again that significant effort went into assuring the proposed thermal water quality standards are Wisconsin-specific.

Figure 7-1 displays an example of the monthly ambient temperatures and acute and sub-lethal water quality criteria for large warm waters. The “sliding scale” is seen in the figure by noting the difference between the acute criterion and the ambient temperature from winter months (where the waterbody has the greatest ability to assimilate heat) to summer months (where the waterbody has the least ability to assimilate heat).

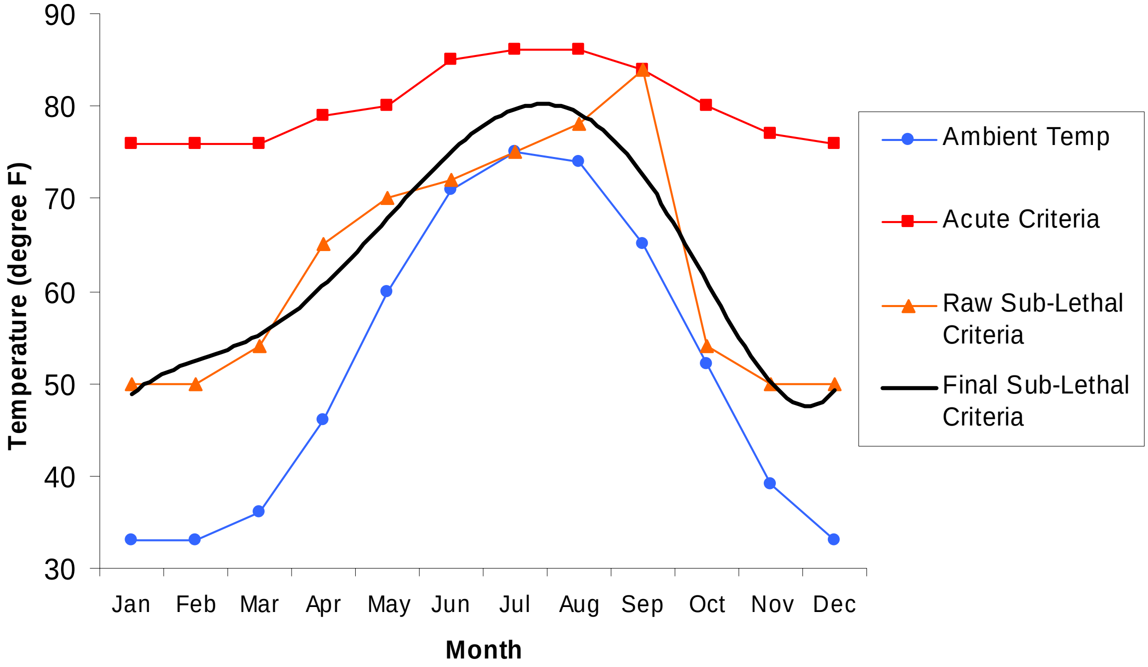

**Figure 7-1**
**Display of Monthly Ambient Temperatures and Acute and Sub-Lethal Water Quality Criteria – Large Warm Water Example**

A public health and welfare criterion of 120 F is proposed to protect humans from scalding. The criterion is to be applied in all surface waters. The criterion is based on information gathered from 9 sources related to recommendations and regulations for public bathing, hot tubs, and hot water plumbing.

Heated discharges to wetlands are to be regulated on a case-by-case basis under a separate rule relating specifically to wetlands – Chapter NR 103.

## *Chapter NR 106*

The primary components of Chapter NR 106 that are being proposed for revision are the procedures to determine when WQBELs are necessary (reasonable potential analysis), procedures to calculate WQBELs, special provisions for publicly owned treatment works (POTWs) and privately owned domestic sewage treatment works (PODSTWs), and provisions for general permits. Details of proposed revisions pertaining to each are presented below.

The primary component of Chapter NR 106 proposed for revision is the limit calculation procedure, including the reasonable potential analysis. A modification of the mass balance equation for toxics has been developed for use in calculating limits for temperature. The equation integrates the appropriate water quality criterion, ambient temperature, effluent flow, and mixing zone considerations (stream flow and fraction of effluent from the receiving stream for flowing waters, and mixing zone area and an empirical factor for lakes) to calculate an end-of-the-pipe temperature limit that assures the water quality criterion will be met at the edge of the mixing zone. The same equation is used to calculate both the acute and sub-lethal limitations; the difference is that each uses the appropriate water quality criteria – acute or sub-lethal, respectively.

In addition to the calculated WQBEL, a “cap” limit is applied. The cap limit is water use or classification-specific and is based on the highest acute values listed in NR 102 for each water use or classification. The purpose of the cap limit is to prevent acute mixing zones from being too large. Thus, the cap limit is not applied in situations when the stream flow rate:effluent flow rate ratio is equal to or greater than 100:1, as the acute mixing zone would not be assumed to be too large under these conditions.

The lower value of the calculated WQBEL (acute or sub-lethal) or cap limit is what is applied as a permit limit.

The reasonable potential analysis is used to determine whether or not there is a reasonable potential for a monthly acute or sub-lethal limit to be exceeded considering worst-case scenarios. An acute limitation for temperature shall be established in a permit for each month in which the representative daily maximum effluent temperature for that month exceeds the lower of the acute WQBEL or cap limit. A sub-lethal limitation for temperature shall be established in a permit for each month in which the highest representative weekly average effluent temperature for that month exceeds the lower of the sub-lethal WQBEL or cap limit. The weekly average effluent temperature is the arithmetic mean of all daily maximum effluent temperatures over a calendar week (Sunday – Saturday). “Representative” effluent temperatures are those known or expected to occur on any day under normal operating conditions.

Figure 7-2 displays a graphic example of the reasonable potential analysis for a power plant on a large warm water river. In this case, acute WQBELs would be required for four months (June, July, August, and September) because the representative daily maximum effluent temperature for those months exceeds the cap limit (which is lower than the calculated acute limits). Additionally, sub-lethal WQBELs would be required for eleven months (all but December) because the highest representative weekly average effluent temperature for those months exceeds the sub-lethal WQBEL (which is lower than the cap limit).

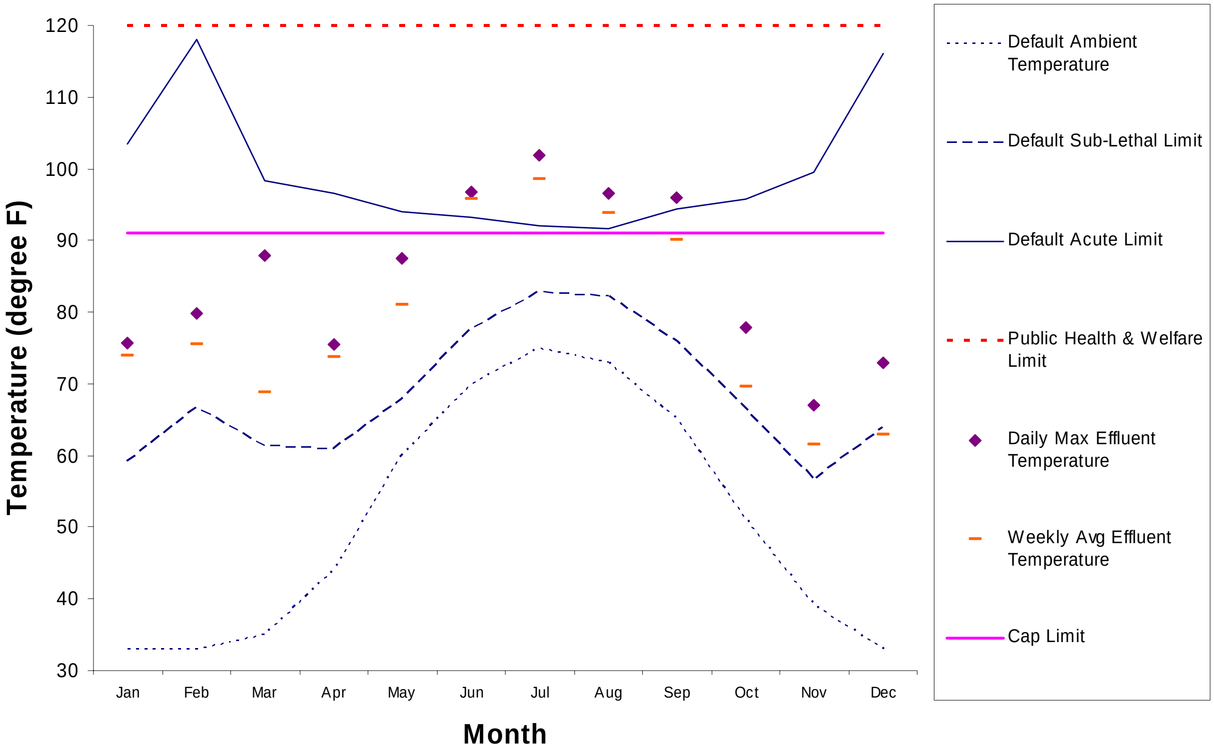

**Figure 7-2**
**Display of the Reasonable Potential Analysis – Large Warm Water Example**

Figure 7-3 is a continuation from Figure 7-2 and displays a graphic example of the calculated monthly acute and sub-lethal water quality-based effluent limits and representative effluent temperature data for a power plant on a large warm water river. Compliance can be observed by comparing the appropriate representative effluent temperatures with the acute and sub-lethal limits. In this case, the discharge is out of compliance with acute limits to varying degrees per month (June – September) and is out of compliance with sub-lethal limits at least once per month for each month (January – November).

A special variance provision is proposed for POTWs and PODSTWs since they are not generally in control of the temperature of their influent, which is controlled by the surrounding/contributing community the facility services.

General permits may be granted under the proposed rule, provided they meet a number of conditions, including having effluent flow rates less than 50,000 gallons per day, having a stream flow rate: effluent flow rate ratio greater than 5:1, the effluent does not discharge into a wetland or outstanding or exceptional resource water, the discharge does not contain biocides or other harmful pollutants, the discharge does not cause unsafe ice conditions in winter, and the temperature of the effluent meets a water use classification-specific maximum temperature limit.

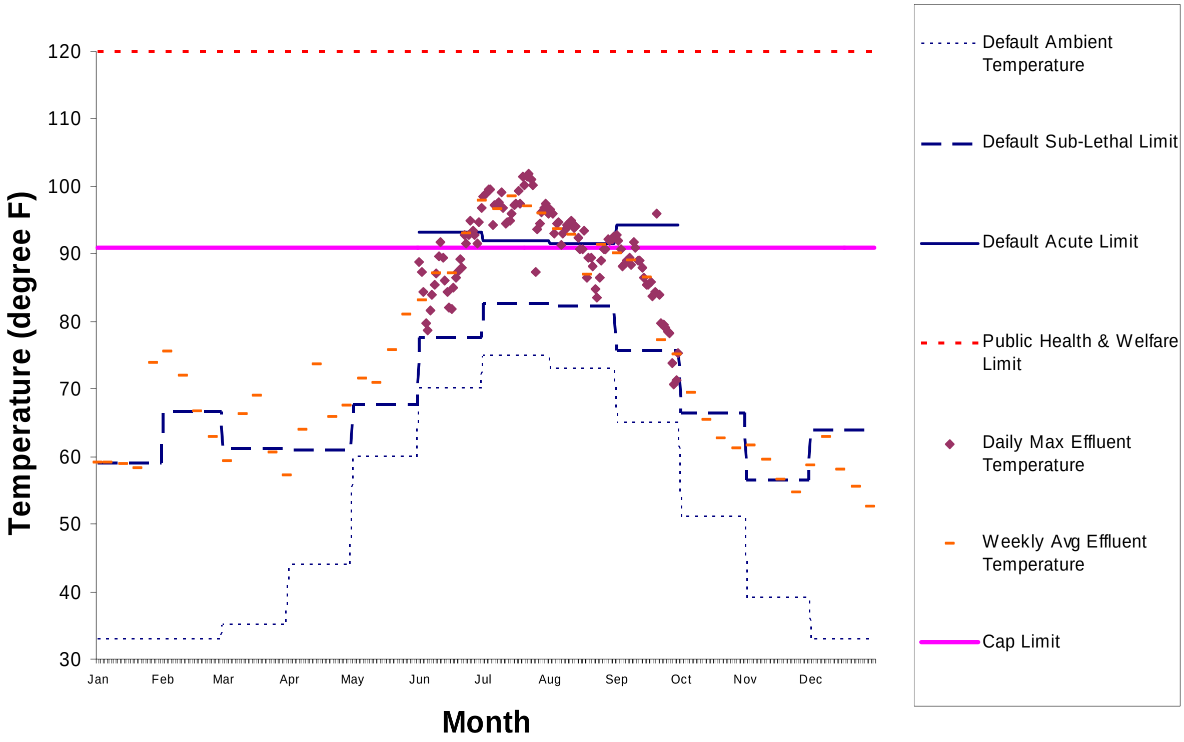

**Figure 7-3**
**Display of Monthly Acute and Sub-Lethal Limits and Representative Effluent Temperatures – Large Warm Water Example**

## *Site-Specific Options*

The details of Chapter NR 102 and Chapter NR 106 provided above describe the development of the default regulations in the rules. Despite making significant effort to produce defaults that are specific to given water body uses or classifications, the WDNR realizes that some discharge site conditions may significantly vary from the rule defaults. Thus, a variety of options have been proposed in the rules to provide site-specificity, including:

- Development of site-specific ambient temperatures
- Development of site -specific water quality criteria
- Use of WQBEL equivalents and models to calculate limits
- Real-time data collection and permitting
- Variable effluent flow permitting
- Storm sewer and effluent channel heat loss-based limits
- Consideration of multiple discharge scenarios
- Development of cold shock criteria and limits
- Development of rate of temperature change criteria and limits
- Alternative effluent limits (316(a) variance)

These site-specific options provide reasonable flexibility for both permittees and WDNR.

## Resources

The proposed rules may have some potential impact to a wide variety of dischargers, but on a very site and season-specific basis. In an effort to help individual dischargers better understand the proposed rules and evaluate the potential impacts of the proposed rules to their sites, several resources have been prepared and made available. These resources include a Technical Support Document [4] that provides significant detail regarding the proposed rules and how the different components (ambient temperatures, acute and sub-lethal water quality criteria, WQBEL equation, etc.) were developed, a limit calculation spreadsheet that calculates and graphically displays the reasonable potential analysis and WQBELs when site-specific data is entered, and an Answers to Common Questions document (which is a precursor to an Implementation Guide that will be completed once the rules are promulgated). WDNR has found these resources to be valuable to both internal staff and external stakeholders.

## Concluding Remarks

This paper summarizes a significant amount of effort and negotiation over many years. The general process used to integrate stakeholder input within the AC with internal requirements in developing the proposed rules has been discussed elsewhere [5]. Considering the process used when reviewing this paper will provide a more complete picture of the overall level of effort that can go into a rule revision effort. It is the author's hope that this paper will be useful to those who are or will be making revisions to thermal water quality rules.

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# 8

# CHALLENGES WITH MODERNIZING A TEMPERATURE CRITERIA DERIVATION METHODOLOGY: THE FISH TEMPERATURE MODELING SYSTEM

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## Introduction

Temperature criteria are one of the few parameters that have been consistently included since the first post-1972 Federal Water Pollution Control Act state water quality standards (WQS) were adopted in the early 1970s. The technical basis for these early temperature criteria were largely based on available national compendia such as that produced by the National Academy of Sciences [1]. The temperature criteria of the majority of the U.S. states are based on the recommended criteria of the NAS study [2]. However, some states have "modernized" their temperature criteria using approaches that were developed since the 1972 Federal Water Pollution Control Act (FWPCA) amendments that also generated a heightened interest in thermal criteria and impacts via Section 316(a). One such example is the Fish Temperature Modeling System (FTMS) that was developed by Ohio EPA [3] in support of the adoption of river and basin specific temperature criteria in the 1978 Ohio WQS. ORSANCO followed by adopting temperature criteria for the mainstem of the Ohio River in 1984 using the FTMS of Ohio EPA.

In 2003 ORSANCO commissioned a study to review and update the original Ohio EPA FTMS [2]. This included an examination of other methodologies for developing temperature criteria and an update to the thermal effects literature database on which the FTMS relies. The resulting report updated the FTMS and used it to develop different temperature criteria options for three segments of the Ohio River based on realistic variations in the baseline FTMS input variables. A consensus was reached by the ORSANCO sponsored panel that the FTMS was a valid method for deriving temperature criteria. The Illinois EPA followed this effort in 2007 by proposing temperature criteria for the lower Des Plaines River and the Chicago Area Waterway system based on a subsequent study that also employed the FTMS methodology using the updated literature database [4].

While the specific thermal effects database has been updated, the baseline input variables and assumptions of the FTMS methodology have not changed substantially since 1978. As such the temperature criteria options that it produces are based on lethal endpoints even though non-lethal endpoints are stored and considered in the methodology. U.S. EPA has continued to support making further refinements to this methodology. In addition, questions and issues raised by the ORSANCO process and at recent symposia (this conference included) provide an important focus for conducting further research and determining potential refinements to the FTMS.

## Fish Temperature Modeling System (FTMS)

The FTMS is based on the original Ohio EPA methodology [3] that uses data from the thermal effects literature to create a thermal effects database primarily for freshwater fish. This data was then used within a procedure that calculates four behavioral and physiological thresholds for a list of fish species (RAS) that are intended to represent the fish assemblage of a particular water body or class of water bodies. The temperature criteria derivation process was later incorporated within the FTMS that is part of the Ohio ECOS data management system. The FTMS was originally developed as a mainframe routine, but was later converted to FoxPro as part of the Ohio ECOS data management system. MBI developed a more portable routine as part of the ORSANCO project [2].

The primary input variables to the Fish Temperature Model are four thermal parameters for each representative fish species; a physiological optimum temperature, a maximum weekly average temperature for growth, an upper avoidance temperature, and an upper incipient lethal temperature. These are derived from a literature based thermal effects database that presently includes temperate climate fish species of eastern North America [2].

### Thermal Parameters

The four primary thermal input variables are used in the Fish Temperature Model to determine the summer (June 16 – September 15) average and daily maximum temperature criteria. However, in developing these baseline input variables, data for up to seven thermal parameters were compiled first. General concepts of thermal responsiveness (e.g., acclimation) were also considered and are described in more detail elsewhere [5]. Of the seven thermal parameters that were inventoried for each fish species, the upper incipient lethal temperature (UILT), the critical thermal maximum (CTM), and the acclimated chronic exposure (ACE) are considered lethal endpoints and the remaining four (optimum, final preferendum, growth, and upper avoidance) are considered sublethal endpoints. At the time the original Ohio EPA [3] methodology was developed, the rapid transfer method (from which the UILT is derived) was viewed as providing "a firmer basis for physiological response than does the slow heating method on which the CTM is based" [5]. Each of the seven thermal parameters are defined as follows:

**Upper Incipient Lethal Temperature** – at a given acclimation temperature this is the maximum temperature beyond which an organism cannot survive for an indefinite period of time;

**Critical Thermal Maximum** – the temperature at which a test organism experiences equilibrium loss resulting from a steady and *rapid* increase in temperature (approximately 0.5-1.0°C/hr.);

**Acclimated Chronic Exposure** – the maximum temperature beyond which an organism cannot survive for an indefinite period of time based on *slowly* increasing the test temperature (0.5-1.0°C/day) [6];

**Optimum** – the temperature at which an organism can most efficiently perform a specific physiological or ecological function;

**Final Preferendum** – the temperature at which a fish population will ultimately congregate regardless of previous thermal experience [7];

**Upper Avoidance Temperature** – a sharply defined upper temperature at which an organism that a given acclimation temperature will avoid [8];

**MWAT for Growth** – the mean weekly average temperature (MWAT) for acceptable growth [9].

These data are recorded by species and include notes and comments about the type of test (lab, field), endpoint derived (UILT, CTM, etc.), duration, and results by acclimation temperature whenever applicable. The original database compiled by Ohio EPA [3] was recently updated to include studies published since 1978 [2]. The thermal effects database is maintained by MBI and includes mostly temperate climate fish species (cold and warmwater) of eastern North America. Some macroinvertebrate data was also recorded for comparison purposes. New tax a groups (e.g., freshwater mussels) could be added as these data become available.

## Thermal Input Variables

The FTMS uses four thermal input parameters that include: 1) the optimum or final preferendum; 2) the mean weekly average temperature (MWAT) for growth; 3) the upper avoidance temperature; and, 4) the upper incipient lethal temperature (UILT) at an acclimation temperature that is representative of the ambient thermal regime. Thermal parameters compiled from various literature sources for 125 freshwater fish species and 6 hybrids are presently included in the primary database for the FTMS [2]. Any of the four FTMS input parameters that are missing in this database are estimated by calculating relationships between the seven thermal parameters that were gleaned from the literature for all species. This included calculating the differences between the; 1) optimum and UAT, 2) optimum and UILT, 3) optimum and critical thermal maximum (CTM), 4) UAT and UILT, 5) UAT and CTM, and 6) UILT and CTM [3]. Extrapolated values are then derived and used in a stepwise procedure as follows:

1. Based on the species sub-family or family relationships (e.g., golden redhorse, “round-bodied” Catostomidae; longnose gar, Lepisosteidae); or
2. based on the next closest family if information for a parameter did not exist within the species family; or,
3. based on the average of all families.

The four primary thermal parameters are stored by species and accessed by the FTMS when that species is designated during the initial RAS selection step of the routine.

## Representative Aquatic Species (RAS)

The derivation of temperature criteria is also dependent on the development of a list of representative fish species, which is the primary input variable for the model. Representative species constitute a *subset* of the assemblage for which sufficient thermal tolerance data is available to derive temperature criteria options. Species regarded as being tolerant to intermediately tolerant to a wide variety of environmental impacts are well represented in these databases, which is similar to other water quality criteria databases. As such, there will likely be species members in the potential assemblage that are not represented in the RAS that are more sensitive to the parameter that is being considered. While the intent of the RAS approach is to represent the entirety of the potential assemblage, it is inherently limited by the extant tolerance databases. As such, the FTMS output will propagate a degree of uncertainty, which can be considered in the eventual derivation and application of the temperature criteria by the custodial entity.

In developing a list of representative fish species for a particular water body or area, the following criteria for membership were used:

1. species that represent the full range of response and sensitivity to environmental stressors;
2. species that are commercially and/or recreationally important;
3. species that are representative of the different trophic levels;
4. rare, threatened, endangered, and special status species;
5. species that are numerically abundant or prominent in the system;
6. potential nuisance species; and,
7. species that are indicative of the ecological and physiological requirements of representative species that lack thermal data.

In addition to these conceptual guidelines, the historical occurrence of fish species in a particular water body is also considered.

### *Temperature Criteria Derivation Process*

The FTMS calculates a set of average and daily maximum summer temperature criteria via an analytical process similar to that first described by Bush et al. [10]. Thermal parameters compiled from various literature sources for 125 freshwater fish species and 6 hybrids are presently included in the primary database for the FTMS [2]. This represents a substantial increase in the number of species that were included in the original Ohio EPA [3] methodology. These include the seven thermal parameters described previously. The four primary FTMS thermal tolerance input variables (optimum, mean weekly average for growth, upper avoidance, and upper incipient lethal temperature) are then selected from this database as the primary thermal tolerance input variables in the FTMS. Alternative thermal tolerance values for a particular RAS can be substituted and the FTMS results can be maintained as alternate outputs to be used for determining the effect of any species-specific differences on the derivation of summer season thresholds.

The tolerance values in the updated thermal effects database [2] are used in the derivation of the summer average and maxima for a specific waterbody. The procedure is simply one of listing each representative species under each of the four primary thermal parameters adjacent to the whole Fahrenheit temperature when it is exceeded. The cumulative effect of increasing temperature is readily apparent as each species thermal criteria are exceeded. The FTMS produces a table of temperatures at which 100%, 90%, 75% and 50% of the representative fish species for the four thermal thresholds occur. This output shows what proportion of the representative assemblage is protected at a given temperature.

In addition to the four primary thermal tolerance thresholds that are the primary input variables in the FTMS, a calculated value termed the long-term survival temperature is included as a calculated value. This threshold is calculated from the short-term survival (i.e., the UILT) as the UILT minus 2°C. In terms of the recommended process for deriving summer season average and maximum temperature criteria, the long-term survival represents the average and the short-term survival represents the daily maximum [2, 3].

The following guidelines are recommended to derive summer average and maximum temperature criteria.

Averages should be consistent with:

- 100% long-term survival of all representative fish species;
- growth of commercially or recreationally important fish species;
- growth of at least 50% of the non-game fish species;
- 100% long-term survival of all endangered fish species; and
- the observed historical ambient temperature record.

Daily maxima should be consistent with:

- 100% short-term survival of all representative fish species; and
- the observed historical ambient temperature record.

The long and short-term survival thresholds are the first choice for deriving the summer season average and daily maximum criteria options. The other criteria listed above can also be used to modify those criteria if there is a management need to do so. For example, a custodial agency may wish to ensure that growth is protected in certain water bodies thus growth of commercially or recreationally important species may be used to derive the summer season average in lieu of the long-term survival threshold. This is also the point at which the observed historical ambient temperature regime can be considered. It is a practical consideration because of the baseline concern about setting temperature criteria that will be exceeded by natural conditions, which could become an issue when the consequences of those exceedences trigger other management and regulatory responses that are out of proportion to the environmental reality of a particular situation. Temperature is one of the parameters that will always carry some risk of "natural exceedences", but these should be rare from a practical standpoint. The historical temperature record must be complete and representative of ambient conditions. Datasets that are comprised of continuous measurements or multiple grab samples that represent daily fluxes and which span multiple years are the most desirable for this task. Modeled temperature may be useful in places where ambient temperature measurements are not representative of natural conditions.

Non-summer season temperature criteria are derived primarily from the historical temperature record and are intended to provide for the natural seasonal temperature regime. While species-specific thermal tolerance values applicable to these seasons are not part of the FTMS at present, such data may be considered and can include requirements for growth, gametogeneisis, and spawning. However, an inherent assumption of maintaining the natural seasonal thermal regime is that these functions will be protected as a result [2, 3].

## Case Study Application of the FTMS

Yoder and Emery [11] previously described the design and content of the FTMS for the 1984 Ohio River temperature criteria in the first EPRI thermal ecology symposium proceedings. While the general methodology has not changed since that time, the available input variables have as a result of the 2006 [2] update. These changes included an expansion of the number of fish species with thermal data and a better description and understanding of the RAS process. Each was shown to significantly affect the FTMS outcomes and temperature criteria options that were produced. Since the ORSANCO sponsored work, the FTMS was applied to the lower Des Plaines River in Illinois. This case example includes additional considerations based on a use attainability analysis (UAA) that was conducted to determine the attainable designated uses that should apply to a managed and altered river [4]. Hence this example provides the additional issued associated with the evaluation of and applicability of designated uses.

### *Lower Des Plaines River Case Study*

MBI was requested by U.S. EPA, Region V and the Illinois EPA to develop temperature criteria options for the Lower Des Plaines River in northeastern Illinois. The need to review and possibly revise the existing temperature criteria was a result of a use attainability analysis (UAA) conducted for the Brandon and Dresden navigation pools of the mainstem [4]. MBI produced temperature criteria options for three different use designation scenarios based on possible outcomes of the UAA process [12]. The derivation of seasonal temperature criteria options for each of the designated uses considered in the UAA process included summer season average and maximum values based on the output of the FTMS. Non-summer season criteria options were based mostly on consistency with the historical ambient temperature record, which was based on analyses of long-term temperature monitoring data in the Lower Des Plaines R. and Chicago Area Waterway System (CAWS) outside the direct influence of artificial sources of heat. A thermal modeling study was also used given the challenges with defining “ambient” in this system.

#### Project Background and Purpose

The Brandon and Dresden navigation pools of the lower Des Plaines River were the subject of a use attainability analysis (UAA) completed in 2006 [4]. The purpose of the UAA was to evaluate the efficacy of the existing Illinois Secondary Contact/ Indigenous Aquatic Life use designation and the potential for upgrading to the General Use designation or some intermediate designation that reflects the modified habitats of these navigation pools and impoundments. Thus, it was a major goal of this project to develop options for temperature criteria that more closely reflect the potential biological assemblages that are representative of the possible designated use outcomes of the UAA process [4].

The temperature criteria options produced by the FTMS are the result of decisions and assumptions about the key input variables, two of which are the lists of representative aquatic species (RAS) and the statistical endpoints derived from the ambient temperature database. RAS lists were varied in accordance with three distinct use designations [4]. Ambient temperature data collected in the Lower Des Plaines R. and the Chicago Area Waterway System (CAWS) was analyzed and statistical thresholds were developed for use in deriving non-summer season criteria. The results of a thermal modeling study of the lower Des Plaines River [13] were also used to estimate the ambient temperature regime because of uncertainties about the representativeness of the ambient temperature monitoring locations. Table 8-1 and Table 8-2 provide FTMS summer season outputs for a combination of different RAS options for the General Use, a modified use, and the Secondary Contact/Indigenous Aquatic Life use. The differences between each option are the primarily the result of different RAS lists.

### General Use

The general use RAS list for the lower Des Plaines River included 49 fish species [4]. More than 90 fish species have been recorded in or adjacent to this area, but only 49 had thermal effects data. Two additional subsets of the General Use RAS list – one adding yellow perch, walleye, and sauger and another removing stonecat madtom from the original RAS list. These changes were made to determine the sensitivity of the FTMS output to adding and removing key RAS and to address questions about the data upon which the stonecat madtom thermal tolerance inputs were derived. The results are summarized in Table 8-1 and the long term and short term survival thresholds that protect 100% of the RAS represent summer average and maximum criteria options for the period June 16 – September 15. For the updated General Use RAS list a summer period average temperature of 80.6°F (27.0°C) and a daily maximum of 84.2°F (29.0°C) will protect for the long term survival of 100% of the RAS. The period average of 27.0°C exceeded the upper avoidance temperature of one RAS (stonecat madtom) by 1.3°C. Thirteen (13) RAS are considered to be either commercially or recreationally important - the 27.0°C period average exceeds the growth temperature for one of these species (northern pike) by 1.7°C. No Illinois rare, threatened, or endangered species are among the species included in any of the RAS lists. The revised criteria based on the updated RAS list (compared to the 2004 original draft list) are 0.5°C lower. We also tested the influence of species additions by adding yellow perch, sauger, and walleye. While these species were not included by the review of historical distribution data and occurred in very low numbers in the 1994-2002 databases, each occurs in the Kankakee River or the CAWS and they could possibly occur in the Lower Des Plaines R. as water quality conditions improve in the future. The inclusion of these species did not change the model outputs, thus the aforementioned criteria should be protective of these species. However, the growth criteria of sauger and walleye are exceeded by the period average of 27.0°C by 0.1°C and 0.8°C, respectively. Stonecat madtom was the most thermally sensitive species in the updated RAS list. Removing this species changed the period average to 29.5°C and the daily maximum to 31.5°C. This option exceeded the UAT of fifteen (15) RAS and the growth criterion of four (4) recreational and commercially important species.

**Table 8-1**
**Summer Season Temperatures °F (°C)that are Protective of the FTMS Thermal Tolerance Endpoints for 100%, 90%, 75%, and 50% of the Representative Aquatic Species (RAS) for the Lower Des Plaines River Applicable to the General Use Designation**

| **General Use Option 1[1]** | **Proportion of RAS “Protected”** | | | |
|---|---|---|---|---|
| ***Thermal Tolerance Endpoints*** | **100%** | **90%** | **75%** | **50%** |
| Optimum | 67.4 (19.7) | 72.7 (22.6) | 81.1 (27.3) | 82.8 (28.2) |
| MWAT for Growth | 74.8 (23.8) | 79.1 (26.2) | 79.1 (26.2) | 86.7 (30.4) |
| Upper Avoidance (UAT) | 78.3 (25.7) | 84.7 (29.3) | 87.3 (30.7) | 88.9 (31.6) |
| Long-term Survival (UILT – 2°C) | 88.9 (31.6) | 86.9 (30.5) | 88.7 (31.5) | 90.9 (32.7) |
| Short-term Survival (UILT) | 84.2 (29.0) | 90.5 (32.5) | 92.3 (33.5) | 94.5 (34.7) |

| **General Use Option 2[2]** | **Proportion of RAS “Protected”** | | | |
|---|---|---|---|---|
| ***Thermal Tolerance Endpoints*** | **100%** | **90%** | **75%** | **50%** |
| Optimum | 67.4 (19.7) | 72.7 (22.6) | 78.3 (25.7) | 82.6 (28.1) |
| MWAT for Growth | 74.8 (23.8) | 78.8 (26.0) | 82.8 (28.2) | 86.5 (30.3) |
| Upper Avoidance (UAT) | 78.3 (25.7) | 85.1 (29.5) | 86.9 (30.5) | 88.9 (31.6) |
| Long-term Survival (UILT – 2°C) | 80.6 (27.0) | 86.9 (30.5) | 88.3 (31.3) | 90.9 (32.7) |
| Short-term Survival (UILT) | 84.2 (29.0) | 90.5 (32.5) | 91.9 (33.3) | 94.5 (34.7) |

| **General Use Option 3[3]** | **Proportion of RAS “Protected”** | | | |
|---|---|---|---|---|
| ***Thermal Tolerance Endpoints*** | **100%** | **90%** | **75%** | **50%** |
| Optimum | 67.4 (19.7) | 72.9 (22.7) | 78.8 (26.0) | 82.6 (28.1) |
| MWAT for Growth | 75.4 (24.1) | 79.2 (26.2) | 82.9 (28.3) | 86.5 (30.3) |
| Upper Avoidance (UAT) | 83.3 (28.5) | 85.5 (29.7) | 87.1 (30.6) | 88.9 (31.6) |
| Long-term Survival (UILT – 2°C) | 85.1 (29.5) | 87.3 (30.7) | 88.5 (31.4) | 90.9 (32.7) |
| Short-term Survival (UILT) | 88.7 (31.5) | 90.9 (32.7) | 92.1 (33.4) | 94.5 (34.7) |

## Modified Use

Twenty-seven (27) fish species were considered representative of the intent of a theorized Modified Use, which reflects the habitat modifications caused by impoundments formed by low head dams. The deletion of 22 species from the General Use list reflects the biological consequences of the inundation of run and riffle habitats by the resulting impoundment. Two

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[1] All RAS used by Yoder and Rankin [4] are included.

[2] Yellow perch, sauger, and walleye added to RAS.

[3] Stonecat madtom removed from RAS.

variants were developed for this designated use option; one including silver redhorse and the other excluding this species. Of the redhorse species that are potential inhabitants of the Lower Des Plaines River system, silver redhorse would likely tolerate impounded conditions. To calculate the temperature criteria, golden redhorse was used as the RAS surrogate since the thermal tolerance data are presently insufficient for silver redhorse [1, 2]. The results including golden redhorse (as a surrogate for silver redhorse) are a period average temperature of 85.1°F (29.5°C) and a daily maximum of 88.7°F (31.5°C) to protect 100% of the modified habitat RAS during the summer period (Table 8-2). The period average of 85.1°F (29.5°C) exceeds the upper avoidance temperature for three Modified Use RAS and the MWAT for growth for two recreationally important RAS. If silver redhorse are excluded, there is no effect on the period average or maximum. Fifteen (15) of the 27 RAS are considered to be either commercially or recreationally important [4]. No rare, threatened, or endangered species are among the RAS for this use option.

### Secondary Contact/Indigenous Aquatic Life

Eight (8) species were selected as being representative of the intent of this designated use option. We regarded this use as being minimally protective of aquatic life and aimed at the prevention of "nuisance conditions" such as acute toxicity and anoxia. The RAS are regarded as being highly tolerant to most forms of anthropogenic impacts including thermal pollution. The results indicate that an average temperature of 30.4°C and a daily maximum of 32.4°C will protect 100% of the RAS during the summer period. The period average of 30.4°C does not exceed the upper avoidance temperature of any RAS or growth temperature of any recreationally or commercially important RAS for this designated use option.

### Seasonal Temperature Criteria Options

Seasonal average and daily maximum temperature criteria for the General Use RAS1 are provided as an example of deriving and displaying a seasonal temperature criteria option (Table 8-3). The derivation of the summer period (June 16 – September 15) average and maximum criteria were just described. Non-summer season criteria are derived to maintain seasonal norms and cycles of increasing and decreasing temperatures [2, 3]. Important physiological functions such as gametogeneisis, spawning, and growth should be assured since these are products of each species long term adaptation to natural climatic and regional influences of which temperature is one of the fundamentally controlling factors. Thermal tolerance data for these physiological endpoints is comparatively limited being available for only a few RAS and their exceedence within a particular time period does not necessarily imply the same consequences as do the summer season thresholds.

**Table 8-2**
**Summer Season Temperatures °F (°C) that are Protective of the FTMS Thermal Tolerance Endpoints for 100%, 90%, 75%, and 50% of the Representative Aquatic Species (RAS) for the Lower Des Plaines River Applicable to a Modified Use and the Secondary Contact/Indigenous Aquatic Life (SC/IA) use Designation**

| **Modified Use Option 1**[4] | **Proportion of RAS "Protected"** | | | |
|---|---|---|---|---|
| ***Thermal Tolerance Endpoints*** | **100%** | **90%** | **75%** | **50%** |
| Optimum | 71.2 (21.8) | 75.4 (24.1) | 81.3 (27.4) | 82.6 (28.1) |
| MWAT for Growth | 77.5 (25.3) | 81.0 (27.2) | 85.8 (29.9) | 86.7 (30.4) |
| Upper Avoidance (UAT) | 83.7 (28.7) | 84.9 (29.4) | 87.1 (30.6) | 88.9 (31.6) |
| Long-term Survival (UILT – 2°C) | 85.1 (29.5) | 86.5 (30.3) | 89.1 (31.7) | 91.4 (33.0) |
| Short-term Survival (UILT) | 88.7 (31.5) | 90.1 (32.3) | 92.7 (33.7) | 95.0 (35.0) |

| **Modified Use Option 2**[5] | **Proportion of RAS "Protected"** | | | |
|---|---|---|---|---|
| ***Thermal Tolerance Endpoints*** | **100%** | **90%** | **75%** | **50%** |
| Optimum | 71.2 (21.8) | 75.0 (23.9) | 81.5 (27.5) | 82.8 (28.2) |
| MWAT for Growth | 77.5 (25.3) | 80.6 (27.0) | 85.8 (29.9) | 86.9 (30.5) |
| Upper Avoidance (UAT) | 83.7 (28.7) | 85.6 (29.8) | 87.4 (30.8) | 89.1 (31.7) |
| Long-term Survival (UILT – 2°C) | 85.1 (29.5) | 86.5 (30.3) | 89.8 (32.1) | 91.4 (33.0) |
| Short-term Survival (UILT) | 88.7 (31.5) | 90.1 (32.3) | 93.4 (34.1) | 95.0 (35.0) |

| **SC/IA Use Option** | **Proportion of RAS "Protected"** | | | |
|---|---|---|---|---|
| ***Thermal Tolerance Endpoints*** | **100%** | **90%** | **75%** | **50%** |
| Optimum | 81.0 (27.2) | 81.1 (27.3) | 82.4 (28.0) | 84.1 (29.0) |
| MWAT for Growth | 85.3 (29.6) | 85.4 (29.7) | 86.7 (30.4) | 87.7 (31.0) |
| Upper Avoidance (UAT) | 87.8 (31.0) | 87.8 (31.0) | 88.0 (31.1) | 91.9 (33.3) |
| Long-term Survival (UILT – 2°C) | 88.3 (31.3) | 88.6 (31.4) | 90.5 (32.5) | 93.0 (33.9) |
| Short-term Survival (UILT) | 91.9 (33.3) | 92.2 (33.4) | 94.2 (34.5) | 96.6 (35.9) |

Seasonal ambient temperature data was analyzed from eight locations in the Lower Des Plaines River and the CAWS for the period 1998 through 2004 in an attempt to characterize the normal ambient regime. Monthly and semi-monthly arithmetic mean, geometric mean, median, 98th, 95th, 90th, 75th, and 5th percentile values were calculated based on daily recordings by the Metropolitan Water Reclamation District of Great Chicago (MWRD). Also included in these analyses were the daily maximum temperatures that occurred once, twice, and three times in each monthly, bi-monthly, or seasonal period and the interquartile ranges of 1.5 and 2.5 times beyond the 75th

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[4] includes golden redhorse as RAS for silver redhorse

[5] excludes golden redhorse.

percentile (non-parametric analogs of standard error and standard deviation, respectively). The monitoring location at Route 83 in the Cal Sag channel was used as a "background" location in Table 8-3. This site is located upstream from the lower Des Plaines River segment of interest and it is not directly impacted by heat load discharges. The monitoring site in the Chicago Sanitary and Shipping Channel at Rt. 83 are also listed in Table 8-3 (in parentheses) and these represent thermally altered results.

**Table 8-3**
**Seasonal Average and Daily Maximum Temperature Criteria (°F) for the Illinois General Use RAS 1 Option. Summer Season Temperatures Measured at the Rt. 83 Cal Sag Monitoring Location Appear in Brackets and are Based On The Geometric Mean and the 98th Percentile Values [4]. Non-Summer Season Temperatures in the Chicago Sanitary and Shipping Channel at Rt. 83 are in Parentheses and Represent a Thermally Enriched Location**

| Month - Inclusive Dates | Monthly/Bimonthly Average | Daily Maximum | Criteria Rationale |
|---|---|---|---|
| January 1-31 | 38.4 (49.5) | 46.6 (54.8) | Consistent with seasonal temperature measured at the Route 83 (Cal Sag) monitoring location. |
| February 1-29 | 41.7 (51.1) | 51.7 (56.9) | |
| March 1-31 | 47.0 (54.8) | 57.3 (62.4) | |
| April 1-15 | 54.0 (59.2) | 59.9 (63.2) | Consistent with observed spawning occurrences and temperatures for all representative fish species in March, April, May, and early June. |
| April 16-30 | 57.3 (58.8) | 67.7 (65.0) | |
| May 1-15 | 63.7 (65.8) | 71.6 (75.3) | |
| May 16-31 | 65.1 (68.4) | 71.2 (74.0) | |
| June 1-15 | 69.8 (70.9) | 77.8 (77.3) | |
| June 16-30 | 80.6 [74.8] | 84.2 [79.8] | Average and maximum provide for short and long-term survival of 100% of representative fish species; one minor exceedence of ambient temp. at the Route 83 (Cal Sag) location. |
| July 1-31 | 80.6 [79.0] | 84.2 [84.7] | |
| August 1-31 | 80.6 [78.4] | 84.2 [83.8] | |
| September 1-15 | 80.6 [76.2] | 84.2 [81.5] | |
| September 16-30 | 69.9 (74.4) | 75.7 (81.0) | Consistent with seasonal temperature measured at the Route 83 (Cal Sag) monitoring location. |
| October 1-15 | 63.7 (69.8) | 71.2 (76.0) | |
| October 16-31 | 59.8 (66.9) | 68.0 (75.0) | |
| November 1-30 | 53.0 (61.3) | 63.6 (70.7) | |
| December 1-31 | 43.4 (53.9) | 56.9 (63.5) | |

The geometric mean was used as the monthly and semi-monthly average and the 98th percentile as the daily maximum. Other statistical thresholds could be used. The 75th percentile has been used as the average since it takes in account the occurrence of warmer temperatures during warmer years. None of the values in Table 8-3 exceeded the spawning criteria for any of the RAS options [4] and all except one value in July were below the summer average (1.6-5.8°F) and maximum (0.4-4.4°F) tolerance values for the RAS option represented in Table 8-3. The

Route 83 location on the Chicago Sanitary and Ship Canal exhibited higher ambient temperatures, presumably the result of enrichment by thermal discharges, thus reflecting higher seasonal temperatures that would exceed the thermal tolerances of the RAS. Other monitoring locations that were analyzed [4] exhibited more pronounced evidence of thermal enrichment, thus these were rejected as being representative of "background" ambient conditions.

The determination of temperatures that are representative of ambient or "background" conditions for the upper Des Plaines River was complicated by the physically and thermally altered characteristics of the lower Des Plaines River and the Chicago Area Waterway System.

An alternative to relying on a representative monitoring location to serve as a data source for determining this benchmark, the outputs of predictive modeling [13] can also be used for this purpose. It is important to understand here that our primary purpose is to determine a representative background temperature, not to determine the acceptability of different thermal loading scenarios. The available thermal modeling study [13] included simulations of the upper Des Plaines River temperature in the absence of thermal enrichment by electric generating station discharges. The study simulated a summer season maximum temperature at the current downstream boundary of the General Use designation (I-55 bridge) of 82-83°F *with no thermal sources, i.e.,* the conditions that could be expected in the absence of thermal enrichment by electric generating station discharges. The maximum 75th percentile values were 75-76°F, which is also consistent with the analysis of the Cal-Sag Rt. 83 ambient temperature monitoring location. The non-summer season simulations were also consistent with the ambient values at this location, thus the ambient temperature data from that location should adequately represent background or ambient conditions for this river. While the lower Des Plaines River and Chicago Area Waterway System represent a complex mix of natural and human influenced hydrologic and thermal alterations, we are focused here primarily on the determination of representative background conditions as a baseline for evaluating the seasonal temperature criteria options that are reasonably available to the Illinois EPA.

As such, these analyses provided Illinois EPA, as the custodial agency, options for proposing new seasonal temperature criteria applicable to the lower Des Plaines R. and in consideration of the use designation decisions emanating from the UAA process. The availability and portability of the FTMS model also affords Illinois EPA the option of selecting different input variables than what were employed in the original study of temperature criteria options [4].

## Discussion: Issues and Challenges in Improving the Development and Application of Temperature Criteria

Coutant (this symposium) posed a list of 22 regulatory related thermal-effects questions. This paper attempts to address either directly or indirectly 13 of these questions in addition to other issues that have recently been raised about the FTMS. These are consolidated and re-phrased below in an attempt to more clearly set the stage for further EPA sponsored research as follows:

- How is ambient temperature determined and what role does it have in setting seasonal temperature criteria? What role do seasonal ambient temperature regimes play and are these sufficient for protecting and assuring biological functions? How is this determined for thermally or otherwise altered water bodies?

One of the most difficult issues in setting fixed temperature criteria is the consideration of "normal" ambient thermal regimes and "natural" exceedences of fixed criteria. It is possible and perhaps likely that thermal thresholds for key RAS will be exceeded on occasion by natural background temperatures, thus raising the dilemma of criteria exceedences and their potential consequences. Such exceedences are of particular concern where they are frequent enough to result in the designation of an impaired designated use via the TMDL process. However, as with other "naturally occurring" physical and chemical constituents, exceedences are inevitable and may not necessarily result in a biologically impaired use [14, 15]. Conversely, setting criteria too high to avoid the regulatory inconveniences of such exceedences can also have potentially adverse biological consequences. These issues must be considered together when deriving and applying ambient temperature criteria.

Some have proposed that exceedences be dealt with directly in a state's WQS via statements and conditions about the allowable frequency, duration, and magnitude of exceedences. Some states (including Illinois EPA) already include such provisions in their WQS. However, most states do not, instead dealing with the issue as part of a regulatory or management application of the temperature criteria. Ohio EPA, for example, incorporates such considerations on a permit-by-permit basis specifically as heat load management requirements for once-through cooling discharges at electric generating stations. An advantage of this practice is that it allows the criteria to be applied in accordance with the dynamics of the receiving water and the management issue at hand. Temperature is a widely applicable parameter and the criteria must serve a broader set of management issues other than thermal loads from electric generating stations.

- What thermal effects data are available for which aquatic species and what is the basis for determining data sufficiency? Is one study sufficient or should multiple studies be available per species? How are multiple data from different studies used in the FTMS? Given that existing data emanate from studies composed of different methods should the methodology be standardized? What level of rigor should studies include before they are included in a database?

The recent update to the FTMS database [2] added a substantial number of new studies and species to the original database of Ohio EPA [3]. However, the studies that were included do represent a diverse range of methods and what might seem to be data sufficiency. Our initial "admission requirement" was that the study be published either in a peer reviewed venue or in a reputable compendium. So called "grey literature" was used provided that the sources and methods could be verified. As a result we structured the database with the understanding that a particular piece of data could be included or excluded at the point of FTMS application.

The state of the extant thermal tolerance literature is such that a diversity of different studies exist and the opportunity to "standardize" test procedures and therefore what data becomes available has long since passed. While new studies could be conducted under more controlled protocols that scenario seems unrealistic at this point in time. To better illustrate the preceding point about diversity, the thermal effects database that was compiled for the ORSANCO study [2] included two different types of field studies, nine distinct types of laboratory designs, and 56 different types of experimental endpoints (e.g., type of test, duration, endpoint measured).

The answer to the question of "how many studies are needed" is also tempered by the realities of the extant thermal tolerance literature. As has already been pointed out species that are tolerant to intermediately tolerant of a wide range of environmental stressors are "well represented" in the FTMS database [2], while species that are highly intolerant and sensitive are much less represented and then by single studies if at all. This is also true of parameters and stressors other than temperature. It raises the all important issue of how representative of the most sensitive species is a procedure that excludes entire tolerance guilds for the sake of meeting what may be an arbitrary criterion of the number of tests that are available. While care needs to be taken with the inclusion of any study in the thermal effects database, the inclusion of the sensitive guilds of the species response spectrum must also be given at least equal weight. We would further suggest that critics of the inclusionary approach step forward to provide the additional studies that would fill this critical gap.

- What are the relative merits and/or disadvantages of existing chronic and acute end-points? Can endpoints from different methods be equated?

Here again the majority of the extant information is based on studies that are regarded as not being directly translatable to one of the four primary FTMS parameters (e.g., CTM as a lethal endpoint) or do not represent the state of the most recent science (e.g., ACE). More recently experimental procedures that incorporate fluctuating temperatures (Bevelhimer, this symposium) are providing an improved understanding of more realistic exposure and response scenarios. Unfortunately, there are simply insufficient studies available for these relatively recent advances to significantly influence the present version of the FTMS.

The diversity of available acute and chronic endpoints necessitates "equating" categorically similar endpoints in attempt to standardize their application via the FTMS. A case in point is the CTM, the most commonly available lethal endpoint, which needs to be "transformed" via the use of a 2°C safety factor in order to have a reasonably representative and protective lethal effect endpoint. In addition, the four parameters of the FTMS that would ideally be available as measured values for all RAS simply are simply not available for all species. This necessitated the development of an extrapolation procedure [3] the result of which seems to yield reasonably valid estimated values [2]. Once again, the critics of this process need to step up and deliver better experimental values for these missing parameters.

- Should temperature criteria be based on the most sensitive outputs of the FTMS, i.e., inclusion of 100% of the RAS? Are RAS representative of the entire assemblage and how should these relate to direct assessments of biological assemblages?

The aforementioned "top heavy" representation by tolerant and intermediately tolerant species in the extant thermal tolerance database [2] strongly argues for protecting for the most sensitive RAS. Some point to the U.S. EPA national water quality criteria methodology [15] as a reason to not protect at the 100% level for all RAS. A major weakness in that argument is the U.S. EPA databases are more broadly representative of the entire aquatic fauna including data not only for fish, but macroinvertebrates, plankton, plants, etc. The FTMS database is comprised almost entirely of fish alone and this is partly because of the long held concept that fish are the most thermally sensitive aquatic assemblage [5]. While that may argue for a similar approach to U.S. EPA [15], we also believe that the RAS concept itself argues for the most sensitive approach. It should be kept in mind that because of the under-representation of the sensitive and highly tolerant response guilds in the thermal effects database that any of these RAS must "carry" a significantly greater proportion of the assemblage that is not directly included as RAS.

- What is the relationship between designated uses, temperature criteria, and the development of water quality based requirements via TMDLs? What other water quality management functions do temperature criteria need to support?

Designated uses are the fundamental "first half" of a water quality standard. Ideally the designated use establishes the ecological specificity of what the application of the attendant water quality criteria are designed to protect and maintain. They also function as critical restoration goals for waters that are polluted to levels below Clean Water Act minimums. Thus temperature criteria should be set much the same as other parameters in keeping with the goal of the designated use narrative. Unfortunately, many state WQS presently lack sufficient specificity and dimension in terms of their designated uses and hence their water quality criteria. Such was the case with the lower Des Plaines River case example where an intermediate use was used ahead of its formal adoption by the state [4, 12]. In 2005, U.S. EPA [16] developed guidance and methods for deriving and adopting tiered aquatic life uses (TALUs) and the accompanying technical concepts and processes to support their development and implementation. One such technical underpinning is the biological condition gradient (BCG; Davies and Jackson [17]) that also has promise for improving the delineation of RAS and better defining their ecological roles. One vulnerability of the present RAS criteria is that they could become "relativeized" based on human induced changes via the intentional and unintentional introduction of alien or non-indigenous species. It also includes the use of direct biological assessments by employing numeric biocriteria as the operational measure of the attainment or non-attainment of TALUs. TALUs also include a focus on all relevant water quality management issues such as TMDLs in addition to the more "common" programs like NPDES permits.

With the recent national focus on TMDLs, water quality management has inherently expanded to include a focus on all environmental stressors beyond those included in the management of industrial and municipal point sources. As such WQS will need to be versatile enough to properly respond to all environmental issues both those that are well understood and those that are just emerging. Thermal impacts beyond those exerted by once-through cooling water discharges must be addressable by modern WQS. The question remains if EPA and the states will indeed pursue this modernization.

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# 9

# LABORATORY VS. FIELD THERMAL TOLERANCES: A REVIEW AND MECHANISMS EXPLAINING THERMAL TOLERANCE PLASTICITY

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## Introduction

The concept that a given ectothermic species does not have an inherent, invariable "fixed" tolerance to external temperature (or other limiting conditions such as hypoxia) is not only an accepted biological maxim, but has been demonstrated empirically for several decades. During a thermal effects workshop held in 1968, a prominent regulatory biologist observed:

- Much of the confusion that exists today concerning thermal requirements for aquatic life results from indecision as to the goals we hope to attain. For too long we have sought some "magic number" which, if met, would protect all aquatic life.
- Clear-thinking scientists and engineers have known for some time that the many species of fish and other aquatic animals vary greatly in individual tolerances or sensitivities. [1]

Indeed, any quantitative measure of population response (e.g., survival of a laboratory population to varying levels of a contaminant) is based on the *collective* responses of individuals. Central tendency estimates (e.g., average or median values) are used to quantify a population response, since biological variability among individuals is inherent and is often based on genotypic plasticity.

Among distinct populations of an ectothermic species, variability in thermal response may be significant. "Thermal response" is hereby defined as a lethal or sublethal biological response that is induced by some change in the ambient temperature regime. Because both external and internal temperature drives many metabolic, physiological, and behavioral processes in these organisms [2], critical life history attributes such as early life history survival, somatic growth, and reproduction must be protected against extreme temperature regimes. Regulatory controls on anthropogenic thermal inputs (e.g., rate of temperature change, total heat loading, maximum instream temperatures) are thus necessary to ensure the long-term maintenance of both sensitive and tolerant aquatic fauna.

Numeric regulatory thermal thresholds are typically developed by evaluating the response of aquatic populations in laboratory tests. There are distinct technical advantages of quantifying biological responses using these controlled tests. Relative to *in-situ* determinations of population temperature response, laboratory tests: 1) are generally not cost-prohibitive; 2) ensure against the introduction of confounding variables; 3) enable measurement of discreet, quantifiable biological responses; and 4) can ensure high statistical power through optimization of study design. Despite these advantages, it is well recognized that laboratory-based thermal thresholds may not be directly applicable to field populations exposed to stochastic temperature changes and other environmental factors. A recent example [2] compared statewide temperature criteria, measured stream temperature, and salmonid composition and age-structure at site-specific locations in several watersheds in Idaho. The evaluation indicated that sensitive salmonid life stages were present (in a high percentage of cases) where the applicable temperature criterion was exceeded. Such contradictory (yet common) observations can be problematic for resource agencies, who must assume that laboratory-derived criteria have relevance to biological responses in the field.

The purpose of this paper is to review the evidence of thermal tolerance variability (plasticity) within a species (or closely related species) with emphasis on fish. The availability of thermal tolerance data for fish (especially freshwater types) is extensive. Thermal tolerance plasticity is evaluated by two means: 1) differences between field-measured and laboratory-based thermal tolerances; and 2) differences among field populations. Moreover, the underlying ecological gradients and mechanisms explaining intraspecific thermal tolerance plasticity are discussed. While definitive underlying biological causes of thermal tolerance plasticity among populations are difficult to discern due to uncertainty in discriminating between genetic and epigenetic factors, an example of a carefully designed field investigation is provided and discussed.

## Thermal Tolerance Plasticity Among Field and Laboratory Populations

Selected publications on thermal sensitivities between field and laboratory populations were obtained to demonstrate the range of thermal tolerance comparability. A study evaluating the presence and abundance of brook trout (*Salvelinus fontinalis*) and brown trout (*Salmo trutta*) populations in several Wisconsin and Michigan streams, relative to a time series of measured stream temperatures, was conducted to determine estimates of thermal tolerances [3]. Mean, maximum, and temperature range tolerance values were calculated based on presence or absence of the two species. These values, subsequently, were compared to laboratory-based estimates of upper incipient lethal temperatures. The authors found that trout in Michigan and Wisconsin streams tolerated short-term exposure (≤ 7 days) to maximum temperatures that were higher than laboratory-based 7-day ultimate upper lethal temperature (UILT) values. Moreover, the researchers found that the field-derived thermal tolerances for both trout species were very similar, in contrast to interspecific differences in thermal tolerance documented in previous laboratory and field studies.

In a related study, the presence and abundance of Bonneville cutthroat trout (*Oncorhynchus clarki utah*) in Wyoming streams, along with concomitant measured water temperatures, were compared with 7-day UILT estimates using fish tested in the laboratory [4]. Based on laboratory measures, the authors hypothesized that the cutthroat trout would avoid or suffer mortality in stream temperatures at or near 24.2°C. Field observations, however, indicated that fish suffered no adverse effects at stream temperatures as high as 27°C.

In a novel study, field-derived "realized thermal niches" of several fish and amphibian species – based on numerous electrofishing surveys in Oregon watersheds – were evaluated and compared to laboratory-derived growth and UILT thermal endpoints [5]. Two important results were observed. First, geographic differences in field-derived thermal niche values were evident for some species; for example, the upper thermal limit for rainbow trout (*Oncorhynchus mykiss*) was 22.4°C in the Blue Mountains ecoregion and 16.9°C in the Cascades ecoregion. These results- and results for other fish and amphibian species - indicate the thermal plasticity of ectotherms among watersheds in a fairly limited zoogeographic area. Regarding comparison of field-derived thermal niche boundaries to laboratory-determined endpoints, the authors found that the "central thermal niche values" (hypothesized to represent optimum growth temperatures) were similar to upper (maximum) growth temperatures from laboratory studies. In contrast, field-derived "upper thermal niche values" were consistently lower than experimentally-derived UILT values for rainbow trout, cutthroat trout, and coho salmon (*Oncorhynchus kisutch*).

A comprehensive review of field and laboratory tolerances to temperature, salinity, and dissolved oxygen for several cyprinodontid fishes was compiled [6]. Records for the presence of these fish at varying temperature, salinity, and oxygen conditions were reported by various authors using non-standardized field procedures, and were sometimes anecdotal. A comparison of species-specific temperature *ranges* (highest temperature found in field study minus lowest temperature found in field study) versus laboratory-determined range values indicated that, in general, the range of temperatures and salinities reported for various cyprinodontid species in field settings were less extensive relative to ranges for laboratory-challenged populations. In interpreting reasons for this observation, the author states that laboratory studies tend to extend the level of a stressor at magnitudes that are typically not encountered by field populations:

- The range of salinities normally inhabited by individuals of a species is generally more limited than the ranges of physiological limits found following extensive laboratory acclimations.
- Most individuals of these species rarely or never encounter a range of salinities in nature as wide as those to which they are subjected in laboratory studies.
- It is unlikely that individuals of any of these species can fulfill all of their normal functions over the full range of salinities tolerated in laboratory acclimations

The presence of several fish species in field surveys conducted in California (using contemporaneous temperature measurements) was compared to laboratory-determined upper and lower thermal tolerance endpoints [8]. The evaluation indicated a general concordance between upper temperatures a fish species was collected at, and its corresponding laboratory-based upper tolerance value. Laboratory-based lower thermal limits, however, were often higher than coolest temperatures recorded when a certain species was present.

The principal conclusions that appear from evaluating the representative literature on laboratory versus field temperature tolerances in fish are:

- Any observed differences in thermal sensitivities between field and laboratory populations are highly species-specific; thus, universal conclusions that field populations are more tolerant to challenging laboratory thermal exposures cannot be made. Collectively, the literature does seem to indicate that field-based tolerances and/or avoidance temperatures (which are elucidated by varying means) are often less limiting than laboratory-based upper temperature endpoints.

- Methodological differences in elucidating thermal tolerances between field and laboratory populations are significant, and these differences can confound the validity of interpretations. As a general rule, differing thermal histories will result in observed differences in thermal sensitivities, among populations of a given species. Reliable empirical data on a species' thermal exposure history in the field is problematic, however, due to technical limitations (e.g., remote tracking) and stochastic temporal patterns of environmental variables.
- Inconsistent thermal endpoints; it is extremely rare to observe fish mortality – or moribund conditions – in field settings. In the field, fish tend to avoid limiting temperatures and seek cooler refugia. Sublethal endpoints such as avoidance or preferred temperature are more easily transferable when comparing field and laboratory population responses.

## Field-Based Estimates of Temperature Tolerance

As a means to compensate for biases in laboratory-derived thermal tolerances, some researchers have proposed using field collection data to derive thresholds such as avoidance temperature and/or upper tolerance level. The Fish Temperature Database Matching System (FTDMS) was one of the first proposed methods to assimilate field temperature regime data for a large number of fish species [8]. This procedure is akin to elucidating sublethal temperature endpoints (preferred or avoidance temperature) that are derived from 316(a)-type intensive field studies near once-through cooled power plants. The authors acknowledge that the principal FTDMS-based endpoint (maximum mean weekly temperature) is typically lower than laboratory-determined lethal temperatures, where these are available. Due to factors discussed earlier, this finding is not unexpected. Recent examples of field-based temperature preference/thresholds for individual species [3, 4, 5] reflect the variability of how paired *in situ* fish presence/temperature can be analyzed.

A clear benefit from using field-based thermal preference/avoidance/upper threshold information is that fishery managers can implement management strategies for those waterbodies that meet the thermal regime of a particular species. In one case, linkages between regional variation in stream temperature regimes and fish community structure (lower peninsula of Michigan) were used to classify streams into coldwater, coolwater, and warmwater faunal designations [9]. The realized thermal niche width (boundary of tolerated water temperatures based on *in situ* measurements) of several species was calculated, and the average niche width for coldwater-designated species was 10.3°C. The authors suggested that the extensive database on thermal niche width and temperature fluctuation tolerance could be used as a valuable baseline for understanding effects caused by regional climate change.

Concerning the process by which temperature water quality criteria are developed, establishing a method that captures the strengths of both laboratory and field-derived presence is desirable. A robust database on waterbody-specific presence and abundance data for individual species, allowing the calculation of basic statistical parameters (e.g., 50th, 90th, and 99th percentile values) would seem to be more biologically meaningful than laboratory-based determinations of upper thermal tolerance and resistance. Such a database would be relevant to actual *in situ* response if species-specific data were obtained during a wide range of hydrothermal conditions.

Table 9-1 provides an example of measured field temperatures that selected upper Ohio River fish species were collected at during 1991 – 2004, as part of the Ohio River Ecological Research Program (source: EA Engineering, Science and Technology). Information in the table is taken from results of over 1,000 electrofishing samples collected during drought (low flow), normal, and high river flow conditions. Such a summary could be used by regulatory agencies to "ground truth" laboratory-based temperature criteria by providing a range (instead of a discrete value) of acceptable exposure temperatures.

## Axes of Intraspecific Thermal Plasticity

The literature contains many examples of a single fish species (or two closely-related species) having elastic thermal tolerances. Of interest is what ecological axes, or gradients, are associated with thermal plasticity within a species. Simply put, what are the environmental factors that are associated with thermal tolerance plasticity within a species?

Within adjacent stream systems, tolerance to temperature and other physicochemical factors among closely-related cyprinid and darter species was shown to vary with stream zonation [11]. A minnow species collected from intermittent headwater areas (*Phoxinus oreas*) was more tolerant to low dissolved oxygen, higher temperature, and acidic pH compared to three other minnow species collected from mainstream locations in an adjacent larger stream system; likewise, individuals of fantail darter (*Etheostoma flabellare*) collected from intermittent headwater sites had a higher short-term survival in hypoxic conditions compared to darters collected from more hydrologically-stable mainstream sites.

Laboratory-derived critical thermal maximum (CTM) values of orangethroat darters (*Etheostoma spectablie*) collected from four separate watersheds within the Red River drainage (Oklahoma) varied significantly [12]. The key ecological difference among the sites where individuals from the four populations were collected was habitat zonation, specifically the variability of water temperature and flow conditions.

Because temperature and dissolved oxygen saturation are interacting variables regarding how well a species can maintain metabolic function, the co-adaptation of genotypic shifts (or phenotypic traits) may occur in ectothermic aquatic organisms. Co-adaptation of upper temperature tolerance and enhanced survival in low oxygen conditions was noted for several minnow species from Oklahoma and Arkansas streams, collected in either harsh prairie stream habitats or clear upland streams [13].

**Table 9-1**
**Summary Statistics of Temperatures (°C) for Selected Upper Ohio River Fish Species That Have Been Collected During the Ohio River Ecological Research Program, 1991 – 2004. CPE Rank Indicates Comparative Relative Abundance (Catch Per Unit Effort) Between Species**

| Species | Temperature Statistics (from 1,036 of the 1,126 Electrofishing Samples) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **CPE Rank** | **Mean** | **Max.** | **95th %ile** | **90th %ile** | **90th %ile** | **75th %ile** | **Median** | **Min.** | **Inter-Quartile Range (25-75%)** |
| Gizzard Shad | 1 | 24.8 | 38.4 | 30.6 | 29.6 | 29.6 | 28.0 | 25.0 | 13.8 | 6.0 |
| Emerald Shiner | 2 | 24.9 | 38.4 | 30.6 | 29.5 | 29.5 | 28.0 | 25.1 | 12.0 | 5.8 |
| Freshwater Drum | 3 | 24.7 | 37.4 | 30.4 | 29.4 | 29.4 | 28.0 | 25.0 | 12.0 | 6.0 |
| Channel/Mimic Shiner | 4 | 24.7 | 35.7 | 30.0 | 29.2 | 29.2 | 28.0 | 25.0 | 14.9 | 5.7 |
| Smallmouth Bass | 5 | 24.7 | 38.4 | 30.5 | 29.5 | 29.5 | 28.0 | 24.9 | 12.0 | 6.0 |
| Bluegill | 6 | 24.9 | 35.7 | 30.5 | 29.5 | 29.5 | 28.0 | 25.0 | 13.8 | 5.8 |
| Morone Sp. | 7 | 24.6 | 37.4 | 30.0 | 29.2 | 29.2 | 28.0 | 24.8 | 12.0 | 6.0 |
| Sauger | 8 | 24.4 | 37.4 | 30.0 | 29.0 | 29.0 | 27.2 | 24.7 | 12.0 | 5.2 |
| Smallmouth Buffalo | 9 | 24.7 | 37.4 | 30.1 | 29.4 | 29.4 | 28.0 | 25.0 | 12.0 | 6.0 |
| Golden Redhorse | 10 | 24.4 | 37.4 | 29.8 | 29.0 | 29.0 | 27.2 | 24.6 | 12.0 | 5.2 |
| Channel Catfish | 11 | 24.4 | 38.4 | 30.0 | 29.0 | 29.0 | 27.0 | 24.4 | 12.0 | 5.0 |
| Silver Chub | 12 | 24.2 | 32.3 | 29.7 | 29.0 | 29.0 | 27.0 | 24.4 | 12.0 | 5.0 |
| Spotted Bass | 13 | 24.8 | 38.4 | 30.3 | 29.4 | 29.4 | 28.0 | 25.0 | 13.9 | 6.0 |
| Skipjack Herring | 14 | 24.9 | 35.1 | 30.9 | 29.5 | 29.5 | 28.0 | 25.1 | 17.3 | 6.3 |
| Logperch | 15 | 25.1 | 37.4 | 30.3 | 29.3 | 29.3 | 28.0 | 25.0 | 13.8 | 5.5 |
| Common Carp | 16 | 24.4 | 38.4 | 30.0 | 29.0 | 29.0 | 27.9 | 24.6 | 12.0 | 5.9 |
| Smallmouth Redhorse | 17 | 24.3 | 37.4 | 29.9 | 28.8 | 28.8 | 27.0 | 24.4 | 12.0 | 5.0 |
| Flathead Catfish | 18 | 25.2 | 38.4 | 30.6 | 29.6 | 29.6 | 28.0 | 25.2 | 14.0 | 5.5 |
| Spottail Shiner | 19 | 25.0 | 31.8 | 30.4 | 29.9 | 29.9 | 28.3 | 26.0 | 15.1 | 7.3 |
| Silver Redhorse | 20 | 24.2 | 32.0 | 29.0 | 28.5 | 28.5 | 27.0 | 24.1 | 12.0 | 5.0 |
| Largemouth Bass | 21 | 24.8 | 38.4 | 30.6 | 29.6 | 29.6 | 28.0 | 24.9 | 13.8 | 6.0 |
| Longnose Gar | 22 | 25.9 | 37.4 | 30.9 | 30.0 | 30.0 | 28.6 | 26.2 | 15.8 | 5.1 |
| Quillback | 23 | 24.4 | 37.4 | 30.8 | 29.0 | 29.0 | 27.6 | 24.0 | 14.9 | 5.8 |
| Bluntnose Minnow | 24 | 25.3 | 38.4 | 30.8 | 29.6 | 29.6 | 28.7 | 26.0 | 15.0 | 5.9 |
| River Carpsucker | 25 | 25.0 | 37.4 | 29.8 | 29.1 | 29.1 | 28.0 | 25.1 | 14.0 | 5.3 |
| Black Redhorse | 26 | 24.1 | 31.6 | 30.1 | 29.0 | 29.0 | 27.8 | 23.8 | 13.8 | 6.0 |

Among a given species, temperature preferences or thresholds may differ among populations in geographically proximal watersheds. Figure 9-1 indicates temperature selectivity (defined as the temperature width at which a given population is observed at in 85% of total observations when a temperature gradient is provided) for 14 populations of red shiner (*Notropis lutrensis*) collected from streams in Kansas, Oklahoma, and Texas [13]. Regional differences in temperature selectivity are suggested in the figure; the Kansas, Oklahoma, and Texas populations are depicted in bars 1-4 (from top), 5-7, and 8-14, respectively.

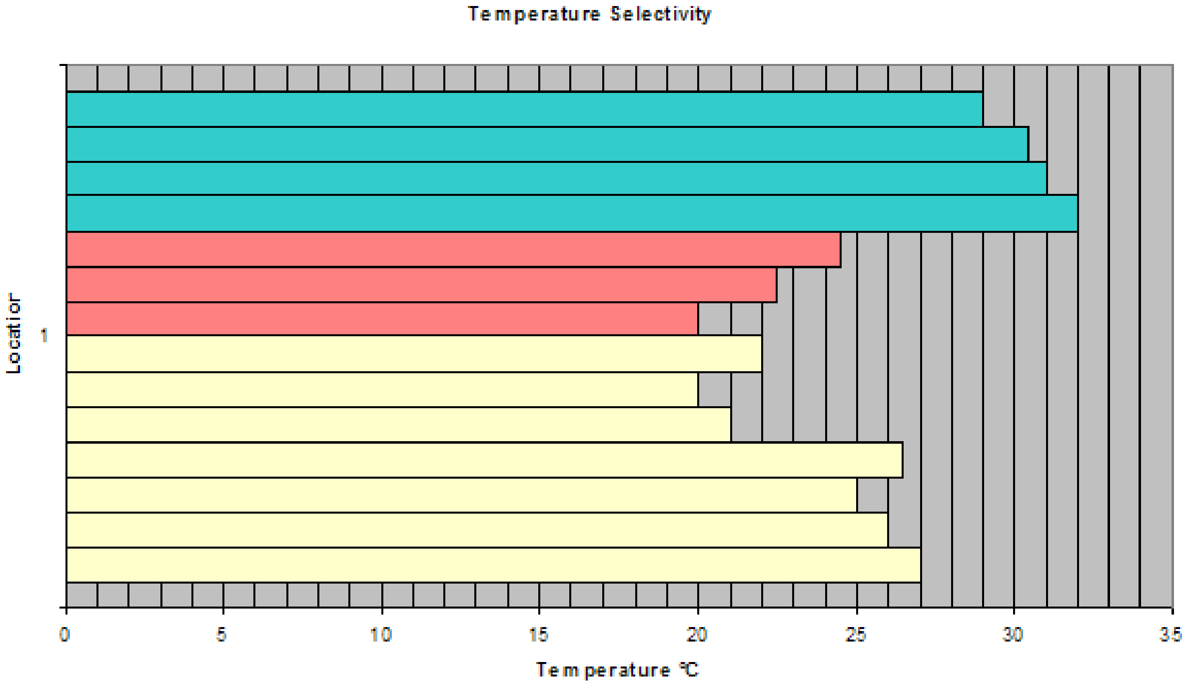

**Figure 9-1**
**Temperature Selectivity Measurements of Red Shiner (*Notropis Lutrensis*) Populations Collected from Streams in Kansas, Oklahoma, and Texas. Individuals from each Population (Horizontal Bars) Were Exposed to Temperature Selection Gradients in the Laboratory. From Matthews 1987 [13]**

Latitudinal differences in thermal thresholds, among a given species, have been observed for wide-ranging cyprinodontids such as banded killifish (*Fundulus diaphanus*) and the mummichog (*Fundulus heteroclitus*) [7]. Individuals of white perch (*Morone americanus*) collected from estuarine waters in New Jersey, Maryland, and North Carolina were evaluated for thermal preference in the laboratory [14]. Even though the ambient temperature at the collecting localities differed little (25 ± 2C°), statistical differences in preferred temperature differed among the three populations. Individuals collected off the North Carolina coast had a temperature preference of 32.4°C whereas fish from New Jersey had a preferred temperature of 29.6°C. Upper critical and chronic thermal maxima values were determined for two largemouth bass subspecies (*Micropterus salmoides salmoides and Micropterus s. floridanus*) – and both reciprocal $F_1$ hybrids - originating from Wisconsin and Florida, respectively [15]. Parent bass from the northern stock had a significantly lowered CTM and chronic thermal maximum compared to the other test populations.

In some cases latitudinal or other geographic origins have not been observed to be a significant determinant in the thermal tolerances of a given species. Individuals of largemouth bass (*Micropterus salmoides salmoides*), originating from hatcheries or lakes from Wisconsin and Tennessee, were tested for survival, reproductive success, and growth when exposed to elevated thermal regimes within a range of acclimation temperatures [16]. The authors found that individuals from neither the northern or southern stock were consistently more or less thermally tolerant, indicating low thermal plasticity for the subspecies tested. Juvenile walleye (*Sander vitreum*) collected from a fish hatchery in Iowa, and in Mississippi, were tested for critical thermal maximum determinations in the laboratory at an acclimation temperature of 23.0°C [17]. The author found no significant difference in CTM values between the two populations.

Contrasting thermal regimes, even among populations of fish in relatively proximal geographic areas, have been shown to spur genetic or acclimatization potential shifts resulting in significantly different tolerances to physicochemical conditions. Populations of Amargosa pupfish (*Cyprinodon nevadensis*), residing in salt pools having either constant (isothermal) or seasonally varying temperature regimes, were shown to have significantly different upper thermal tolerances [18].

These examples illustrate how local conditions can confer the adaptation of certain physiological and/or behavorial traits in populations. These adaptations may be genetic (higher frequencies of alleles favoring increased survival and/or reproduction) or acclimatization-based. Clearly, the direction and magnitude of adaptive changes (genetic or epigenetic) in a given population is influenced by a number of variables, however two factors seem to be the most influential: 1) the inherent genetic “blueprint” of individuals (dictating the relative degree of eurythermy or stenothermy), and the length of time (or generation time) that a population is exposed to a certain thermal regime. Thus, the common observation that certain stenothermal (or sensitive) fish are present in waters affected by thermal discharges would not be unexpected as long as *in situ* populations were not exposed to temperature gradients that prevented some kind of physiological acclimation.

## Mechanisms of Intraspecific Thermal Plasticity

In general, differences in thermal tolerance, avoidance, or preferred temperatures among populations of a given species are either genetic (shift in allele frequency) or epigenetic (change in cellular function without a change in genetic material) in causation. Presumably, both mechanisms can operate on a given population at any given time. It should be noted that field populations of ectotherms are constantly undergoing seasonal acclimation, the rate and direction of the acclimation being dependent on the external temperature regime. Thus, both genetic and epigenetic-caused shifts in thermal tolerances must be viewed within a continuum.

The potential for genetic-based shifts in thermal tolerance is largely dependent on demographic and biological characteristics of a population. Factor such as longevity, age at maturation, fecundity, population size, and demographic barriers to genetic mixing with other populations influence a given population’s predisposition, and potential, for shifts in alleles that confer enhanced survival at altered temperature regimes. Moreover, the determination of potential genetic shifts requires a careful study design. Direct measurements of loci or polymorphic frequencies are typically needed to provide empirical evidence of allelic shifts. The genetic basis of phenotypic traits can also be inferred by carefully designed reproductive studies (crossing studies or comparing thermal tolerances of $F_1$ populations). Species having multiple reproductive cycles in a relatively short period of time are ideal for these kinds of studies.

An elegant study of the importance of genetic factors in dictating shifts in thermal tolerance was conducted using mosquitofish (*Gambusia holbrooki*) collected from a power plant cooling lake and a reference pond [19]. Fish inhabiting the cooling lake suffered occasional mortality when water temperatures ranged between 40 - 50°C; surviving fish had moved to a portion of the lake where a cool inlet stream (water temperatures between 35 - 39°C) enters. Thus, the dynamics of temperature regime in the lake could exert considerable pressure on the selection of genotypes that conferred enhanced survival at temperatures greater than 40°C. The authors evaluated the upper thermal tolerance of mosquitofish (collected from the cooling lake and a reference pond) by determination of CTM. In addition, the degree of genetic heterozygosity (seven allozyme loci evaluated) was assessed to determine evidence of genetic differences between the two populations.

Fish from the cooling lake (Pond C) were shown to have significantly greater CTM values relative to fish from the reference pond; two measures of impending mortality (orientation loss and righting response) were used in the CTM trials (Figure 9-2). Next, the authors exposed fish from both populations to an acute thermal stress and then compared genetic heterozygosity among those fish that survived the trials. The authors found that mosquitofish from Pond C had significantly greater genetic heterozygosity compared to control fish. Moreover, in fish from Pond C there was significantly greater genetic heterozygosity in fish that had survived the acute thermal stress, relative to fish that died; thus, there was a genetic basis explaining why some mosquitofish survived the acute stress while others suffered mortality.

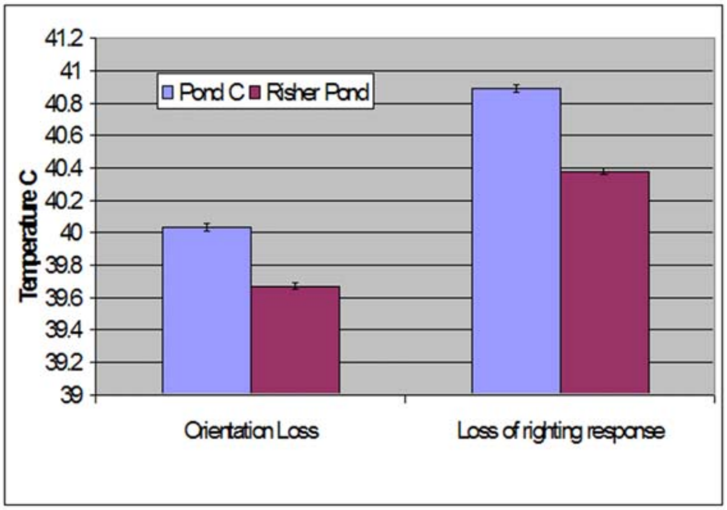

**Figure 9-2**
**Comparison of Critical Thermal Maximum Parameters (Orientation Loss and Loss of Righting Response) in Mosquitofish Inhabiting a Thermally-Stressed Cooling Lake (Pond C) and a Reference Pond Having an Ambient Thermal Regime (Risher Pond). From Meffe et al. [19]**

The authors also documented changes in life history characteristics (fecundity, age at maturation, etc.) among the two populations, indicating how thermal history shapes the plasticity of key population-level parameters [20, 21].

## Summary

There is ample evidence in the technical literature indicating that, among species or closely-related species, the preferred or upper thermal tolerance temperature is variable, and this plasticity can be significant in some cases. Field investigations of thermal niche width in ectothermic vertebrates provide insightful information concerning the factors that seemingly cause intraspecific variability: habitat selection, watershed distribution, climatic factors, temperature and flow regimes, etc. The elucidation of field-based thermal tolerances (or boundaries) can be effectively coupled with laboratory-based tolerance data to derive realistic and relevant water temperature criteria. While it is generally accepted that a species can adapt to local conditions (as temperature regime changes) either through physiological acclimatization, genetic selection, or both, actual documentation of these biological mechanisms is difficult. The reality of thermal tolerance plasticity, which is variable between species, is an important factor in predicting the magnitude of adverse effects potentially caused by global climate change. As hydrothermal regimes change in a particular region, there will be an "adaptation race" among species in a community. The rate of adaptation between species (and major faunal groups) is sure to be asynchronous; potential food web cascade effects could result that may be more influential in changing the structure and function of communities than a single environmental variable (thermal regime).

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# 10

# SENSITIVITY OF EARLY LIFE STAGES OF FRESHWATER MUSSELS TO A RANGE OF COMMON AND EXTREME WATER TEMPERATURES

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## Introduction

Freshwater mussels are long-lived, benthic aquatic organisms. They are one of the most rapidly declining faunal groups in North America. In fact, nearly 70% of North America's 300 freshwater mussel species are extinct or vulnerable to extinction [1, 2].

Mussels have a unique life history and reproductive strategy that makes them susceptible to both chemical and non-chemical stressors [3]. The reproductive cycle begins during the spawning season when mature males release sperm into the water. Females take up the sperm as they siphon water, and their eggs are fertilized and transferred to the gills where they develop inside a brood pouch called the marsupium. The fertilized eggs become the larval life stage known as glochidia. Glochidia can be released within a few weeks or held in the brood chamber for months, depending on the mussel species. Once released, glochidia develop as obligate parasites on the gills or fins of host fish. When glochidia have successfully infested a host fish, they remain attached for a variable amount of time, depending on the species and water temperature. During this time the glochidia develop a heart, gills, digestive system, and muscular foot to become juvenile mussels. The juvenile mussels drop from the fish and fall to the stream substrate where they continue to develop into benthic dwelling adults. This is a very complex life cycle, with multiple opportunities for a stressor to have an adverse effect.

Though the mussel's life cycle makes it susceptible to disruptions, large data gaps exist regarding the effects of both chemical and non-chemical stressors, such as temperature, on freshwater mussels. Heated effluent and rising environmental temperatures may pose a previously unexplored risk to sensitive mussel species.

## Experimental Design and Methods

The purpose of this study was to determine the temperature tolerances of selected freshwater mussel species. To accomplish this, the two early life stages, glochidia and juveniles, of three species of freshwater mussels were exposed to a range of common and extreme water temperatures. Temperature tests were also conducted in the presence of a secondary stressor, copper, to determine any additional effect on the mussels' temperature tolerances. Each test was conducted at three acclimation temperatures: 17ºC, 22ºC, and 27ºC, and each acclimation temperature had five corresponding experimental temperatures in 3ºC increasing increments (Figure 10-1). A 20ºC control was assessed alongside each test.

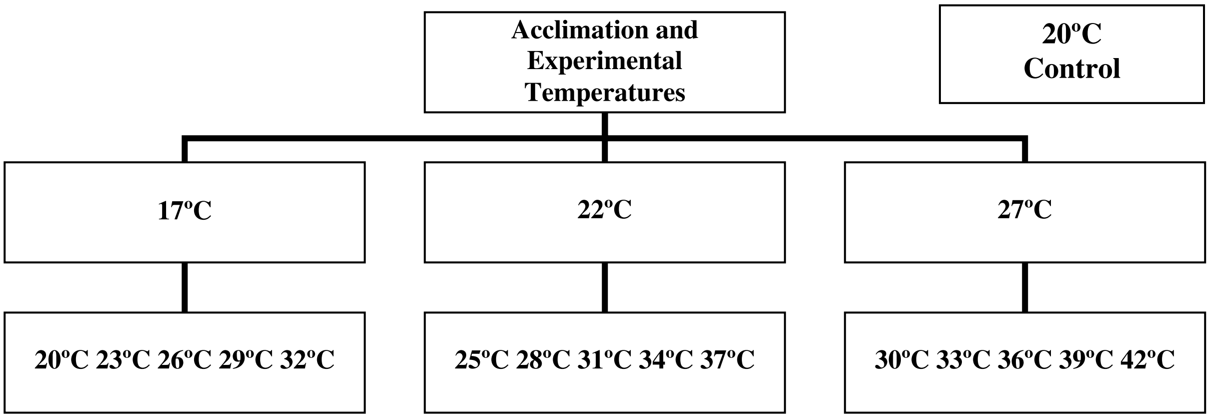

**Figure 10-1**
**Experimental Design: Acclimation and Experimental Temperature Scheme**

The three species used in this study were fatmucket (*Lampsilis siliquoidea*), pink heelsplitter (*Potamilus alatus*), and black sandshell (*Ligumia recta*). These species were chosen because of their wide geographic distribution, particularly in the central United States, and because they encompass a variety of life history strategies and habitats. All test organisms were transported from a propagation facility at Missouri State University in insulated coolers with temperature loggers to record any temperature variation during shipping.

Upon arrival at the laboratory, glochidia were assessed for initial viability, and determined to be 90% or greater to initiate the experiment, in accordance with American Society for Testing and Materials (ASTM) protocols [4]. The glochidia were then acclimated to the test acclimation temperature by adjusting their temperature by no more than 1ºC per hour, with a 2 hour acclimation period once the target test acclimation temperature was reached. After this period, viability was assessed a second time and glochidia were dispensed to test chambers. Tests were 24 hour non-aerated static experiments conducted according to ASTM guidelines for glochidia, and viability (survival) was assessed at 24 hours by the addition of a saturated sodium chloride solution. The viability endpoint was assessed visually by glochidia shell closure via microscope and digital photographic software. Tests were conducted for temperature and temperature plus the addition of copper as a secondary toxicant. For glochidia, the target copper concentration was 25 µg/L. This copper concentration was chosen based on published copper toxicity data for glochidia of several mussel species [5, 6].

The same three species were then used to conduct juvenile tests. Upon arrival at the laboratory, viability of juveniles was determined to be 90% or greater in order to initiate testing; mussels were then acclimated to the test acclimation temperature by adjusting their temperature by no more than 2.5ºC per day, with at least a 24 hour acclimation period once the target acclimation temperature was attained. After this period, viability was assessed a second time and organisms were distributed to test chambers. These were 96 hour non-aerated static renewal tests, with 100% water renewal at 48 hours, conducted according to ASTM guidelines. Juvenile mussel viability (survival) was assessed visually using a dissecting microscope to detect foot movement outside of the shell, foot movement within the shell, or the presence of a heart beat. Tests were conducted for temperature and temperature plus the addition of copper. The target copper concentration was decreased to 10 µg/L for this life stage.

Quality assurance and control were maintained by conducting all tests according to the Standard Guide for Conducting Laboratory Toxicity Tests with Freshwater Mussels [4]. All tests were conducted in light and temperature controlled environmental chambers, and National Institute of Standards and Technology (NIST) certified thermometers were used for daily temperature monitoring. Test temperatures had a maximum of 2ºC departure from the target temperature, with only 3.0% of samples exceeding a 1ºC departure (n=328). Water quality conditions, including alkalinity, hardness, conductivity, pH, and dissolved oxygen, were monitored at the start of each test and again at the 48 hour time point. For all tests, alkalinity ranged from 92 to 110 mg $CaCO_3$/L with a mean of 101.9 mg $CaCO_3$/L, hardness ranged from 146 to 162 mg $CaCO_3$/L with a mean of 153.2 mg $CaCO_3$/L, conductivity ranged from 476 to 730 µs/cm with a mean of 574 µs/cm, pH ranged from 6.51 to 9.00 with a mean of 8.31, and dissolved oxygen ranged from 61.5% to 119.5% saturation with a mean of 82.0%. Copper concentrations were verified according to Standard Methods [7] using Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES). The measured copper exposure concentrations for glochidia averaged 134.4% of the target concentration of 25 µg/L, with a mean concentration of 33.6 µg/L (n= 26; range= 32.1 to 35.7 µg/L). Copper exposure concentrations for juveniles averaged 108% of the target concentration of 10 µg/L, with a mean concentration of 10.8 µg/L (n= 57; range= 7.4 to 13.7 µg/L).

## Results and Discussion

### *Glochidia*

For the glochidia at the 17°C acclimation temperature (Figure 10-2), there were no major responses due to temperature alone. However, viability decreased for fatmucket and pink heelsplitter when copper was combined with the temperature treatment. Black sandshell was most sensitive to copper with total mortality at most temperatures, thus copper/temperature interactions for glochidia of that species were unable to be determined.

For glochidia at the 22°C acclimation temperature (Figure 10-3), pink heelsplitter was the most sensitive with viability starting to decrease at 25°C. Black sandshell started to decline at about 28°C and fatmucket was the most thermally tolerant with a decline in viability beginning at 34°C. Pink heelsplitter and fatmucket had similar copper responses with decreasing viability with each increase in temperature until around 31°C.

For glochidia at the 27°C acclimation temperature (Figure 10-4), there was a clear difference in species responses. Fatmucket was the most thermally tolerant with a decline in viability starting at 33ºC, black sandshell viability decreased at 30°C, and pink heelsplitter again appeared to be most sensitive with a substantial decrease in viability at the acclimation temperature. This corresponded with data from the 22°C acclimation test in which pink heelsplitter viability began to decrease at 25°C. In the copper treatment, fatmucket showed decreased viability with temperature responses at 27°C compared to 33ºC without copper. In contrast, temperature alone may be the causative agent of decreased viability in pink heelsplitter.

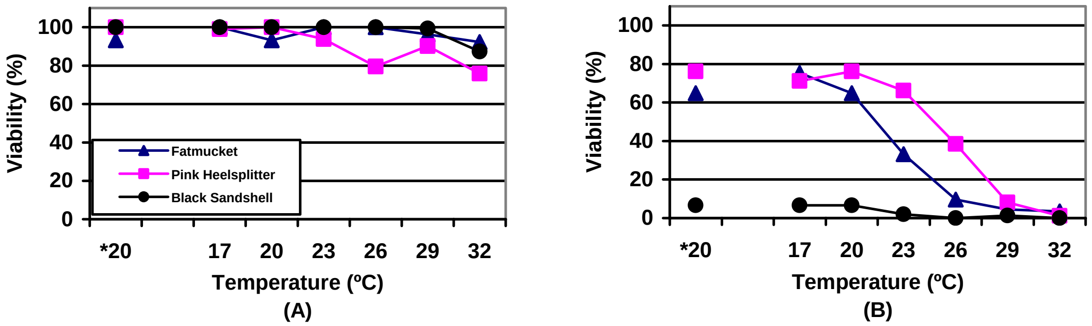

**Figure 10-2**
**Glochidia at 17°C Acclimation Temperature: Results from Temperature Treatment only (A), and Results from Temperature Plus Copper Treatment (B) are shown. *20 Corresponds to 20°C Control Viability**

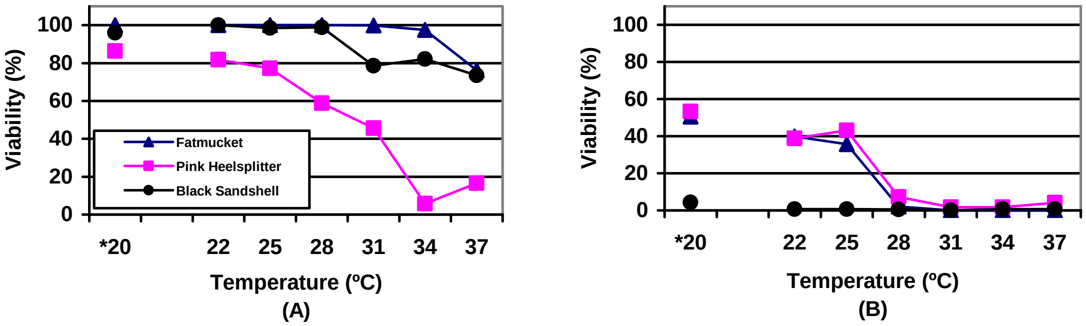

**Figure 10-3**
**Glochidia at 22°C Acclimation: Results from Temperature Treatment only (A), and Results from Temperature Plus Copper Treatment (B) are shown. *20 Corresponds to 20°C Control Viability**

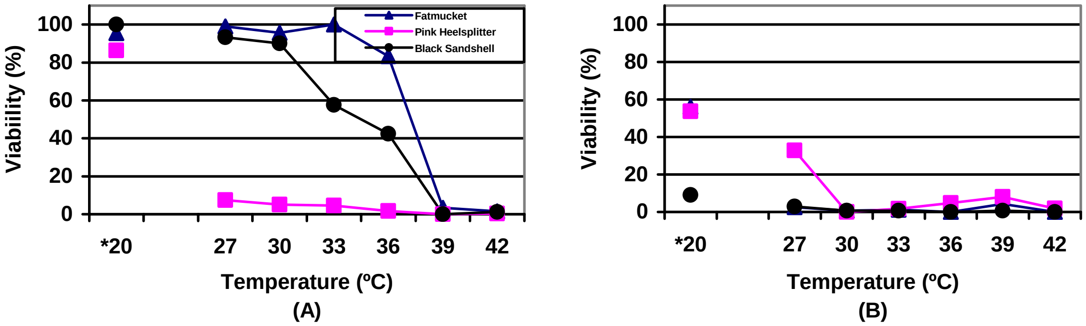

**Figure 10-4**
**Glochidia at 27°C Acclimation: Results from Temperature Treatment only (A), and Results from Temperature Plus Copper Treatment (B) are shown. *20 Corresponds to 20°C Control Viability**

### Juvenile

Each of the three species of juvenile mussels at the 17°C acclimation temperature (Figure 10-5) had similar responses with no apparent temperature driven mortalities. Copper treatment also caused no obvious decreases in viability at those temperatures.

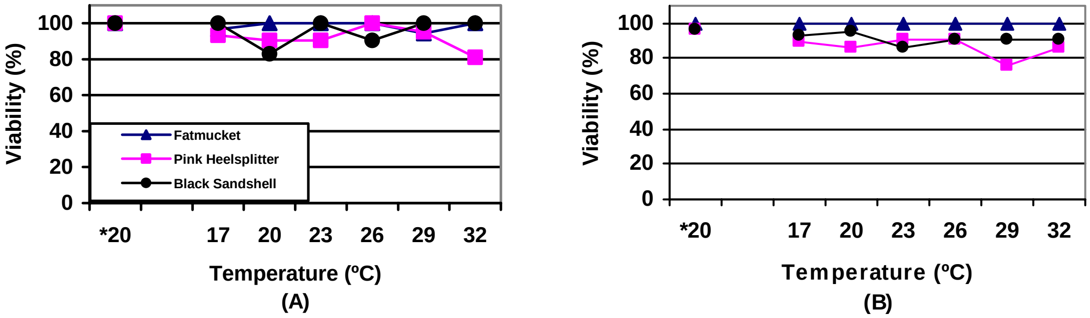

**Figure 10-5**
**Juveniles at 17ºC Acclimation: results from temperature treatment only (A), and results from temperature plus copper treatment (B) are shown. *20 corresponds to 20ºC control viability.**

For juveniles at the 22ºC acclimation temperature (Figure 10-6), fatmucket and pink heelsplitter began to decline in viability at 34ºC, but black sandshell began an earlier and more gradual decline starting at the acclimation temperature, then had a sharper decline at 31ºC. All species had total or near total mortality at 37ºC. Copper appeared to lower thermal tolerance at this acclimation temperature for pink heelsplitter, which began to decline in viability at 28ºC compared to 34ºC without copper. Fatmucket and black sandshell had no additional copper-related response.

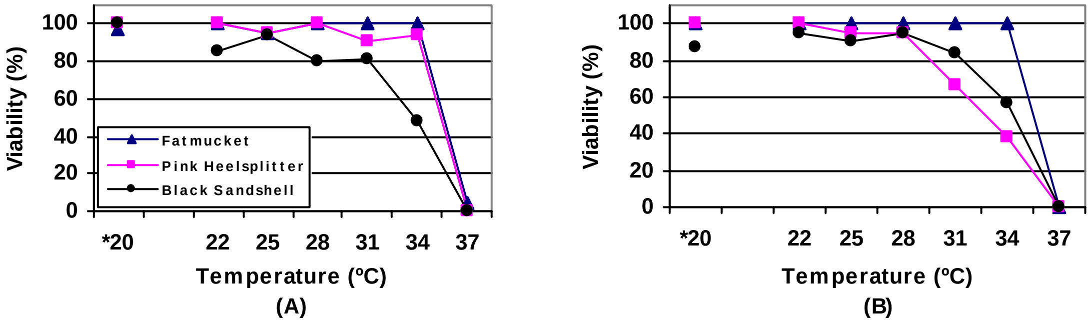

**Figure 10-6**
**Juveniles at 22°C Acclimation: Results from Temperature Treatment only (A), and Results from Temperature Plus Copper Treatment (B) are shown. *20 Corresponds to 20°C Control Viability**

At the 27ºC acclimation temperature (Figure 10-7), juvenile fatmucket and pink heelsplitter had very similar responses, with declines in viability beginning at 33ºC. Black sandshell had a more gradual decline, which started at lower temperatures but reached a sharp decline at 33ºC. All three species had total mortality at 39ºC and 42ºC. Copper treatment at this acclimation temperature had an adverse effect on viability for fatmucket and pink heelsplitter; both species experienced total mortality at 36ºC whereas without copper, both species had some survival at that temperature. Copper also decreased the temperature at which black sandshell began its decline in viability, shifting from 33ºC without copper to 30ºC with copper, though the mortality was still more gradual than the other two species.

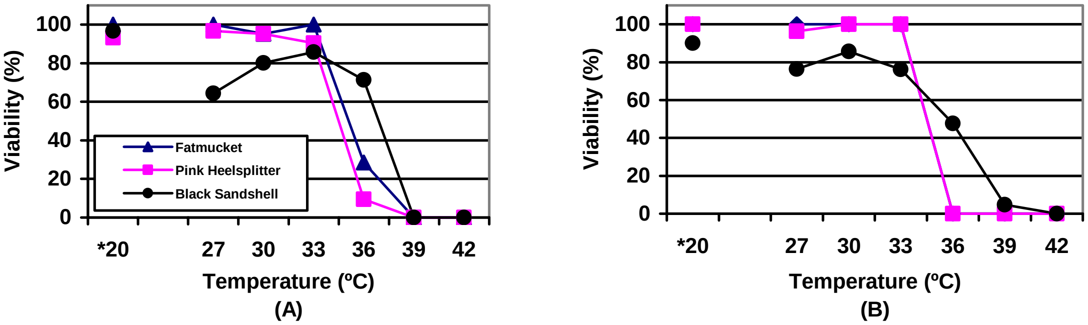

**Figure 10-7**
**Juveniles at 27°C Acclimation: Results from Temperature Treatment only (A), and Results from Temperature Plus Copper Treatment (B) are shown. *20 Corresponds to 20°C Control Viability**

The median effective temperature (ET50) was determined for all tests that had both partial and total mortalities (Table 10-1). An ET50 is the temperature at which 50% of the exposed population exhibited a predefined effect in the designated time period. For glochidia, the effect measured was viability, as indicated by shell closure with sodium chloride addition at 24 hours. For juveniles, the effect was viability, as indicated by the presence of a heart beat, foot movement within the shell, or foot movement outside of the shell at 96 hours.

**Table 10-1**
**ET50s and 95% Confidence Intervals for Glochidia (24h) and Juveniles (96h) at 22°C Acclimation and 27°C Acclimation. *ET50s Outside of Tested Temperature Treatment Range**

| | 22ºC Acclimation | | 27ºC Acclimation | |
|---|---|---|---|---|
| | Glochidia | Juvenile | Glochidia | Juvenile |
| Fatmucket | >37.0* | 35.5 (35.1 – 36.0) | 37.0 (35.4 - 38.6) | 35.1 (33.4 - 36.9) |
| Pink Heelsplitter | 29.1 (25.5 - 33.1) | 34.8 (33.1 - 36.5) | <27.0* | 34.6 (33.4 - 35.9) |
| Black Sandshell | >37.0* | 32.9 (29.6 - 36.6) | 33.2 (30.1 - 36.6) | 36.8 (34.1 - 39.8) |

Only ET50 data from the 22ºC and 27ºC acclimation temperatures were calculated because there were no significant mussel mortalities in the 17ºC acclimation temperature. Calculated glochidia ET50s ranged from 29.1ºC to 37.0ºC and juvenile ET50s ranged from 32.9ºC to 36.8ºC. Three ET50s were unable to be calculated because they fell outside of the tested temperature range, these are listed in the table as greater than or less than values. Based on the fact that all juvenile ET50s had overlapping 95% confidence intervals, there were no significant differences among species or acclimation temperatures for the juveniles. In contrast, for glochidia there was a significant difference between pink heelsplitter glochidia at 22ºC and fatmucket at 27ºC, but not between pink heelsplitter at 22ºC and black sandshell at 27ºC.

## Conclusions

Overall we determined that environmentally relevant temperatures can have an adverse effect on early life stages of freshwater mussels. ET50s were similar for species and acclimation temperature among juveniles, though additional tests are needed to draw conclusions about glochidia. Moreover, the presence of copper as a secondary toxicant caused mussels to be less tolerant of temperature stress. Interestingly, the increase in acclimation temperature did not seem to confer increased temperature tolerance. Viability decreased at similar temperatures with increasing acclimation temperature. This suggests that mussels which may be continuously or intermittently exposed to higher temperatures, such as in heated effluent, may not be more tolerant of these temperatures.

The results of this research showed that early life stages of freshwater mussels were sufficiently sensitive to warrant further testing, especially with additional species. This study also has direct implications for the understanding of the potential effects of heated effluents as well as global climate change on freshwater mussels. Following additional statistical analysis of species, life stage, and acclimation temperature comparisons from these tests, future studies will assess sublethal measurements of thermal stress such as heart rate and oxygen consumption, as well as assessment of environmental conditions in rivers and streams.

### *Acknowledgments*

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# 11

# STRESS AND RECOVERY IN FISH EXPOSED INTERMITTENTLY TO NEAR-LETHAL TEMPERATURES: A MODEL BASED ON LABORATORY RESULTS

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## Introduction

Although it is convenient to determine the thermal resistance of organisms at constant temperatures in the laboratory, such constant temperatures are rarely found in nature or near power station cooling systems. Thermal death at lethal temperatures, if it occurs at all, occurs under changing temperature conditions. At power stations, this could potentially occur in the piping of the condenser cooling circuit downstream of the condenser or in the zone of mixing at the outfall. One would like predictability of lethal effects for any pattern of changing temperatures, and particularly whether brief exposures to a series of potentially lethal temperatures will actually cause death. For this, one needs to know the relationship between the thermal resistance times for a species obtained at constant temperatures in controlled exposures and the time-course of accumulating lethality (or lack thereof) over the period of temperature changes. It is also important to know whether any ill effects of brief, sublethal heating to potentially lethal temperatures can be accumulated and affect later exposures.

In 2005 researchers at Oak Ridge National Laboratory began a study to better understand the thermal tolerance of fish exposed to dynamic temperature regimes like those present near the heated discharges of thermoelectric power plants. The general objectives of the study were:

- To complete laboratory experiments to better define the relationships between exposure magnitude and duration and thermal stress in fish and the role of recovery (or stress repair), and
- To incorporate laboratory results into a thermal stress model to simulate fish response to dynamic temperature regimes like those that might be experienced at power plant thermal discharges.

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[1] Oak Ridge National Laboratory is managed by UT-Battelle, LLC, for the U.S. Department of Energy under contract DE-AC05-00OR22725.

The results of the first two years of the study are available as an EPRI report [1]. This paper presents the results from the third year of the project. We first present the methods and results of the laboratory portion of the study followed by a description and results of the modeling exercise.

## Laboratory Study: Thermal Challenge Tests

We designed a set of laboratory studies to address several questions related to the effects of rate of temperature increase, acclimation, and intermittent exposure to high and low temperatures on thermal stress and stress-induced mortality in fish. We were particularly interested in how stress accumulates during exposure and how it might be alleviated during periods at intermittently low temperatures. These studies involved exposing fish to various temperature regimes and documenting at what time and temperature fish lost their ability to maintain equilibrium, which is normally a precursor to mortality if thermal conditions were to remain the same or continue to increase. These experiments varied in length from 30 minutes to 48 hours with most lasting a few hours or less.

The most common thermal tolerance tests reported in the literature are the Critical Thermal Methodology (CTM) and Incipient Lethal Temperature (ILT) methods. These are useful for predicting the effects of a sudden exposure to high temperature like that sometimes experienced by fish as they pass through a heated plume from a power plant discharge. However, this type of rapid exposure is not particularly representative of the fluctuating thermal conditions that are often experienced as a result of movement into and out of a heated discharge plume or fluctuations in the plume temperature as a result of temporal changes in operations and natural heating and cooling.

We designed a series of laboratory experiments for this study that borrowed methodology from several of these methods. We hope to better define the relationships between exposure magnitude and duration and thermal stress in fish and the role of recovery or stress repair during periods of exposure to cooler sub-stressful temperatures. Results from these experiments were used for calibration of a thermal stress model for rainbow trout (*Oncorhynchus mykiss*).

### *Methods*

#### Experimental Endpoint

Our general design included exposing fish individually or in small groups (of up to 10 individuals) to various thermal regimes at or above lethal temperatures. For each trial, fish were subjected to a predetermined thermal regime that would ultimately lead to loss of equilibrium (LOE). This is a standard procedure whose objective is to determine the point at which locomotor activity becomes disorganized and the animal loses its ability to escape from conditions that would lead to its death [2]. The time and temperature of LOE is the endpoint of interest. Using LOE instead of death as an endpoint is a common and preferred method in thermal challenge tests.

During each experiment, the observer monitored water temperature with a digital thermometer and recorded time and temperature regularly on a data sheet along with observations of fish behavior. Erratic behaviors that often preceded LOE included darting, drifting or coasting with fins still, listing to the side, and spinning or rolling over. LOE was considered when a fish remained on its side for more than 1 second, rolled completely over, or remained motionless while listing to one side for several seconds. Time and temperature at LOE were recorded for each fish. After LOE, fish were removed and placed in a recovery tank at the original acclimation temperature (15 or 20°C) and monitored for recovery. Once a fish was tested, it was not used in subsequent experiments and was released to the wild if fully recovered or otherwise euthanized.

We used the median value of temperature (or time at temperature) of LOE as the critical value for each trial. Median values are typically used in these types of studies because mean values are subject to being unduly skewed by outliers. At least 10 fish were used for each trial of different temperature regimes. Thermal regimes tested varied in rate of temperature increase, time held at a constant temperature, magnitude of constant temperature, and time and temperature of recovery periods. Some trials were replicated to establish repeatability for fish collected from the ponds at different times resulting in a slightly different thermal history.

## Experimental Setup

The experimental chamber consisted of a 45-L glass aquarium with two Cole-Parmer Polystat heaters. Fish (up to 10 at a time) were placed individually into the test chamber, then allowed to acclimate to the test chamber for 15 minutes. Fish were removed immediately with a small dipnet at loss of equilibrium (LOE), a precursor to death, without disturbance to other fish in the trial. The heating rate was determined by the number of heaters used (one or two) and the volume of water in the aquarium. Constant temperatures were achieved by setting the thermostat on the heater to the desired temperatures. Cooling was achieved by the controlled introduction of fresh water.

## Thermal Regimes Tested

We began our tests with fairly simple thermal regimes and progressed to more complex. The first thermal regime tested was a constant increase in temperature until LOE was observed (Figure 11-1). This test represents the typical CTM maximum (CTMax) evaluation. The rate of temperature increase in these studies typically varies from 0.07 to 0.35ºC per min.

The second type of experiments tested the effects of chronic exposures to constant sub-CTMax temperatures. We raised temperature to just below the CTMax and then held fish at that temperature until they lost equilibrium. The objective of these trials was to establish the level of thermal stress accumulation at a chronic high temperature exposure that was equivalent in response (i.e., LOE) to that observed in the acute exposures in the first series. Figure 11-2 shows the general thermal exposure scenario for these tests, conducted from 1-3ºC below the CTMax that was determined in the first set of experiments.

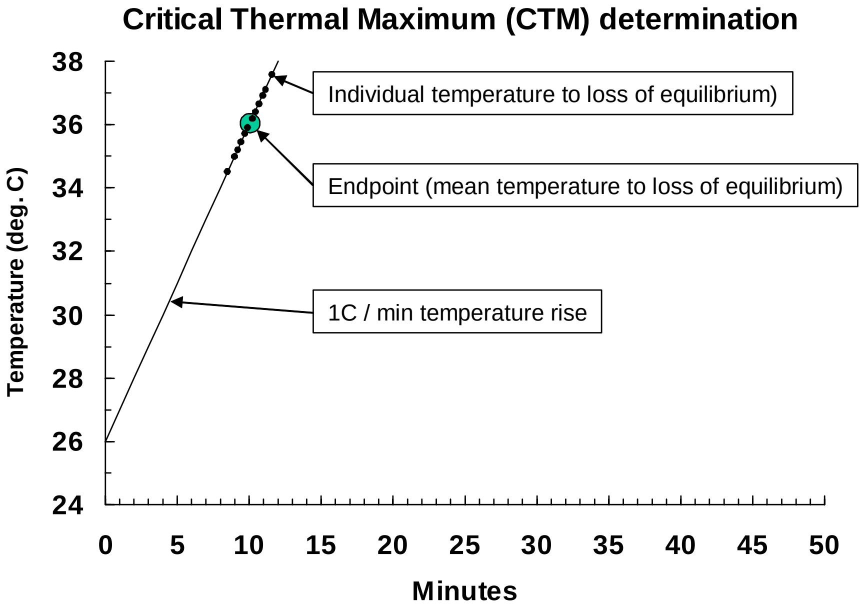

**Figure 11-1**
**Hypothetical Thermal Challenge Test with a Continuous Rise in Temperature until All Fish Exhibit Loss of Equilibrium**

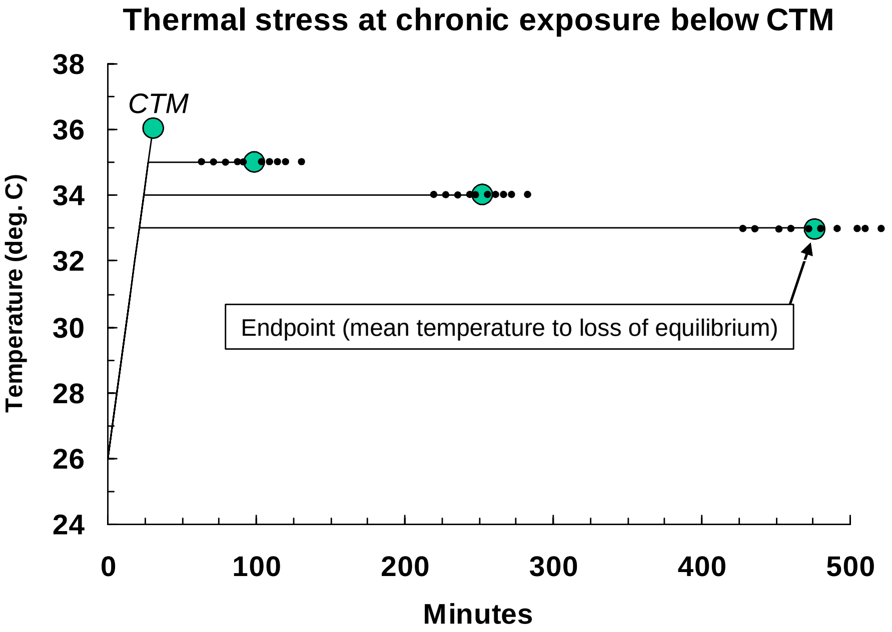

**Figure 11-2**
**Hypothetical Thermal Challenge Tests with Exposure to Three Constant Temperatures Just Below the Critical Thermal Maximum Temperature**

The third set of experiments was designed to test the effect of acclimation on thermal tolerance. Temperature was raised to a point below what was believed to be stressful and then held for different amounts of time before increasing temperature gradually until LOE was achieved Figure 11-3).

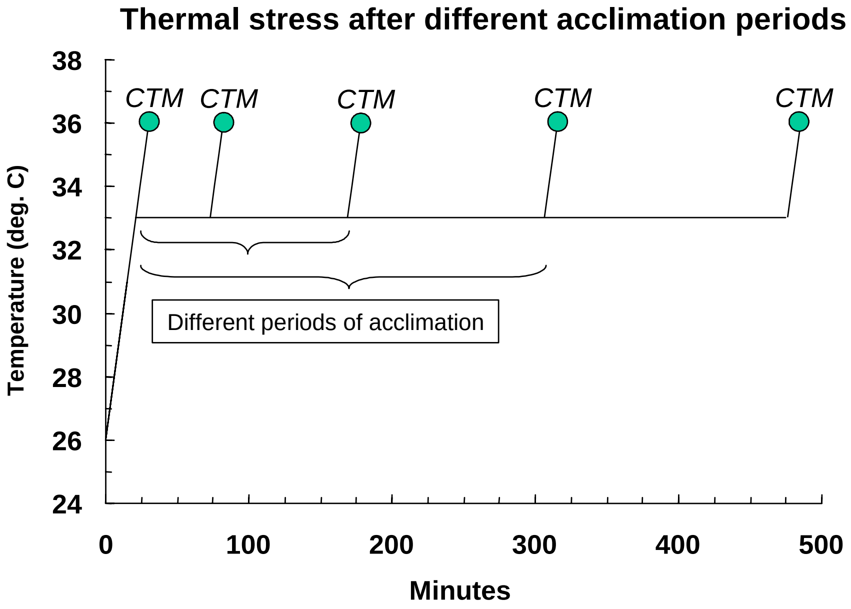

**Figure 11-3**
**Hypothetical Thermal Challenge Test after Different Periods of Acclimation to High Non-Stressful Temperature**

The last set of experiments tested the effects of exposure to a thermal regime that fluctuated between stressful and non-stressful temperatures before a rise that resulted in LOE (Figure 11-4). We hoped to learn from these experiments how thermal stress was accumulated and alleviated during intermittent exposure to near lethal temperatures.

## Test Species

Juvenile rainbow trout were obtained from Buffalo Springs state fish hatchery in east Tennessee. Upon return to the laboratory, trout were maintained in fiberglass tanks with continuous flow through and aeration. Trout were fed daily and maintained at either 15°C or 20°C for the duration of the experimental period except when being used in an experiment. Two size ranges of fish were used in experiments, 3.6-10.5 cm and 22-30 cm.

Different combinations of thermal regime, acclimation temperature, and fish size resulted in 26 different trials (Table 11-1).

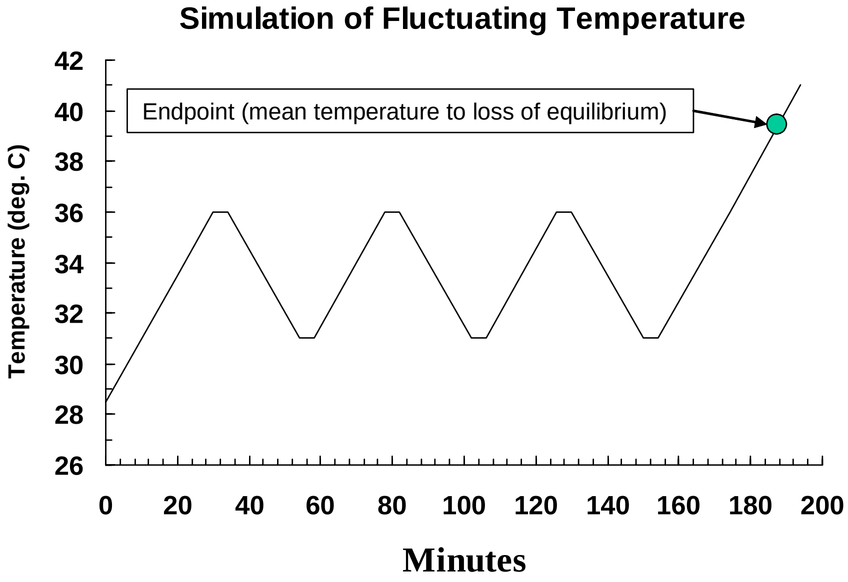

**Figure 11-4**
**Hypothetical Thermal Challenge Test of Daily Fluctuating Temperature**

## *Results and Discussion*

### Steady Rate of Increase

The results of the thermal exposure experiments are best described in figures that show the temperature regime, the time at which each individual was considered to have lost equilibrium, and the median time of LOE. The least complex experiments were those with a steady linear increase in temperature until LOE was observed. In trials 1, 14, and 18 we exposed trout to three rates of increase (0.35, 0.17 and 0.07°C/min) and found that slower rates of increase resulted in lower thermal tolerance (Figure 11-5). We also found that when trout were returned to cooler water after LOE, the rate of recovery (or survival) was highest for the fastest rate of increase and vice versa.

### Chronic Exposure to Constant Temperature

Trials 2 to 6 were similar to the basic CTMax trials except that heating was stopped at 1, 2, 2.5, 3 and 4°C below the CTMax and then temperature was held constant until LOE (Figure 11-6). As expected, LOE took longer to occur at the cooler temperature. These chronic exposure experiments are provided data to develop a relationship between duration of exposure at a temperatures and the accumulation of thermal stress. Survival of trout after return to cooler water was higher (100%) for those exposed for short durations at the highest temperatures than for those exposed to cooler temperatures but for longer durations prior to LOE.

**Table 11-1**
**Details of Thermal Challenge Tests with Rainbow Trout**

| Trial | Acclimation (°C) | Temperature regime (°C) |
|---|---|---|
| 1 | 15 | 0.35°/min increase |
| 2 | 15 | 0.35°/min increase then hold at 29.0° |
| 3 | 15 | 0.35°/min increase then hold at 28.2° |
| 4 | 15 | 0.35°/min increase then hold at 27.7° |
| 5 | 15 | 0.35°/min increase then hold at 27.2° |
| 6 | 15 | 0.35°/min increase then hold at 26.2° |
| 7 | 20 | 0.3°/min increase |
| 8 | 20 | 0.3°/min increase then hold at 29.3° |
| 9 | 20 | 0.3°/min increase then hold at 27.3° |
| 10 | 15 | 0.35°/min increase to 28.2°, cool to 20.2°, increase to LOE |
| 11 | 15 | 0.3°/min increase to 28.2°, cool to 20.2°, repeat 3X, then increase to LOE |
| 12 | 20 | 0.3°/min increase to 29.3°, cool to 21.3°, then increase to LOE |
| 13 | 20 | 0.3°/min increase to 29.3°, cool to 21.3°, repeat 3X, then increase to LOE |
| 14 | 15 | 0.17°/min increase |
| 15 | 15 | 0.15°/min increase then hold at 28.2° |
| 16 | 15 | 0.3°/min increase (large size) |
| 17 | 20 | 0.3°/min increase (large size) |
| 18 | 15 | 0.07°/min increase |
| 19 | 15 | 0.3°/min increase then hold at 27.2° (large size) |
| 20 | 15 | 0.3°/min increase then hold at 26.2° (large size) |
| 21 | 20 | 0.3°/min increase then hold at 28.0° (large size) |
| 22 | 15 | 0.35°/min increase |
| 23 | 15 | 0.3°/min inc to 25°, hold for 1 hr, then increase to LOE |
| 24 | 15 | 0.3°/min inc to 25°, hold for 6 hr, then increase to LOE |
| 25 | 15 | 0.3°/min inc to 25°, hold for 24 hr, then increase to LOE |
| 26 | 15 | 0.3°/min inc to 25°, hold for 48 hr, then increase to LOE |

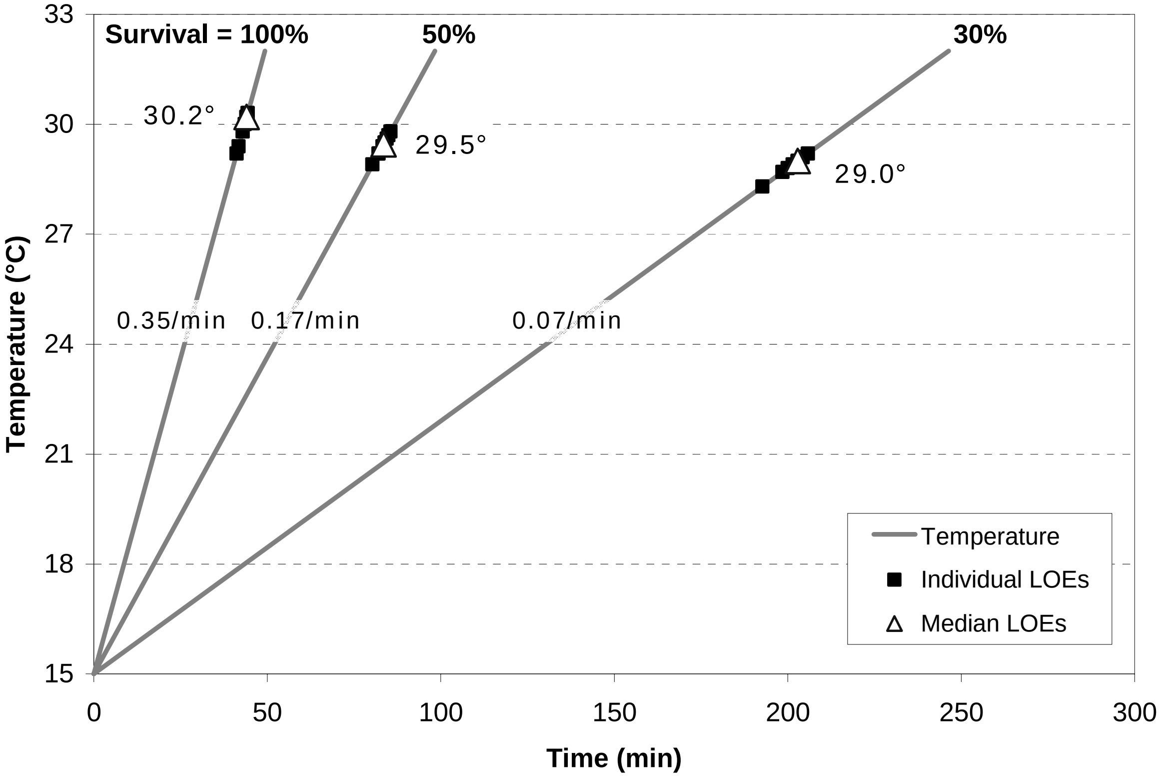

**Figure 11-5**
**Results of Thermal Challenge Tests of a Constant Rise in Temperature at Three Different Rates (0.35, 0.17 And 0.07°C/Min, Left To Right) until Loss of Equilibrium; Survival Rates after Return to Recovery Tank with Cooler Water**

## Acclimation

In these experiments we subjected trout to different durations of acclimation at an elevated temperature prior to subjecting them to the standard LOE test. Water temperature was raised at 0.3°C/min to 25°C and then held at that temperature for 0, 1, 6, 24, and 48 hr prior to being raised at 0.3°C/min until LOE of all fish. The results suggest that acclimation is clearly taking place over this short time (Figure 11-7). The temperature at which LOE occurred increased from 30.22°C with no additional acclimation to 31.0°C with 48 hr of acclimation.

We also repeated some experiments with fish acclimated for at least 2 weeks at 20°C instead of 15°C. For the baseline determination (0.3°C increase per minute) the CTMax for 20°C acclimated trout was 31.3°C, a degree higher than those acclimated at 15°C, which was 30.2°C. The mortification curves for the two acclimation temperatures were also about 1 degree apart (Figure 11-8). The difference we found as a result of different acclimation temperature compares favorably to those reported in other studies [3].

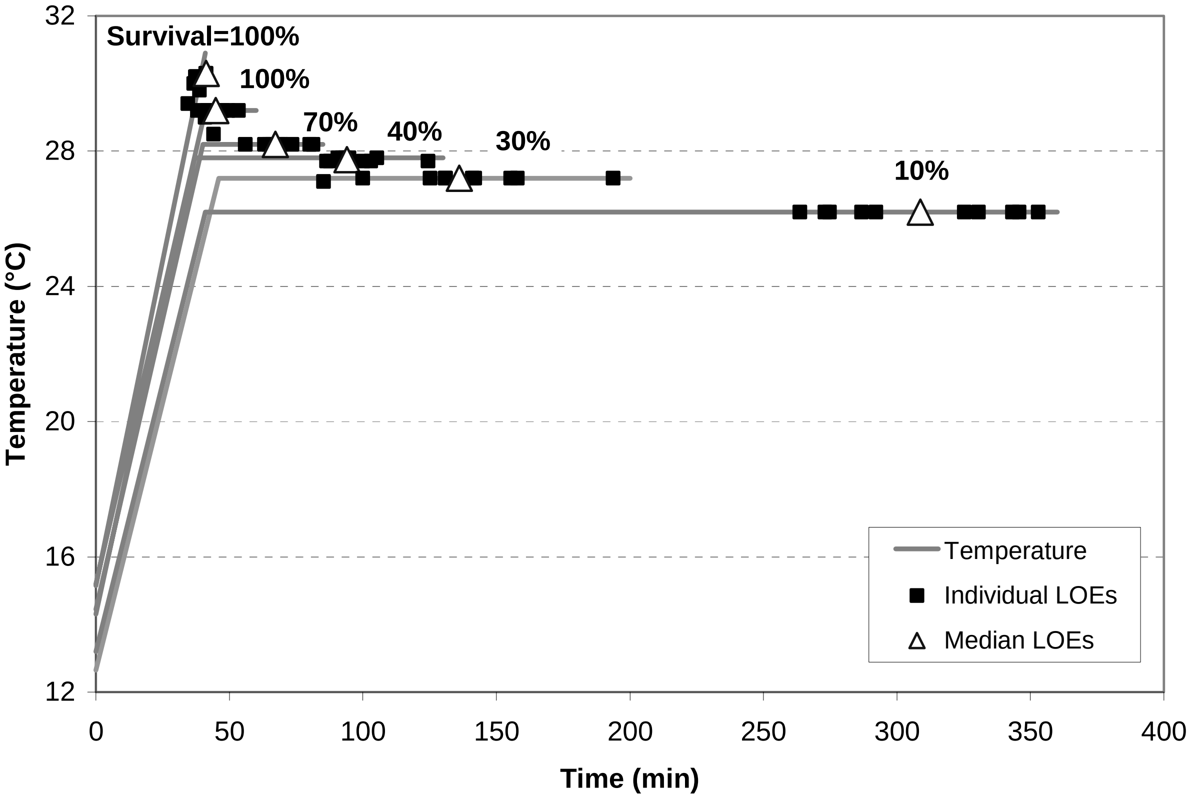

**Figure 11-6**
**Results of Thermal Challenge Test of Exposure to Constant Temperatures of 29.2, 28.2, 27.7, 27.2, And 26.2°C; Survival Rates after Return to Cooler Water**

## Fluctuating Temperature Regime

One objective of this study was to better understand the thermal stress response of fish exposed to intermittently high temperatures. As with different rates of temperature increase discussed above, exposure to fluctuating temperatures can result in several possible responses: 1) an accumulation of thermal stress which would result in apparent lower thermal tolerance, 2) acclimation to elevated temperature resulting in higher thermal tolerance, or 3) a combination of these effects. In addition, complete or partial recovery from stress might occur during the low temperature portion of the cycle which would alleviate the accrued thermal stress.

When we compared the effects of a single cycle of high and low temperature exposure to a multiple cycle and to the standard CTMax determination, we found almost no difference in the LOE temperature (Figure 11-9) for fish acclimated to 15°C. These results suggest that any stress accrued during the brief exposure above stressful temperatures (i.e., 25-28.5°C), seems to have been fully recovered. We found the same results for fish acclimated to 20°C except that the temperature of LOE was higher (Table 11-2).

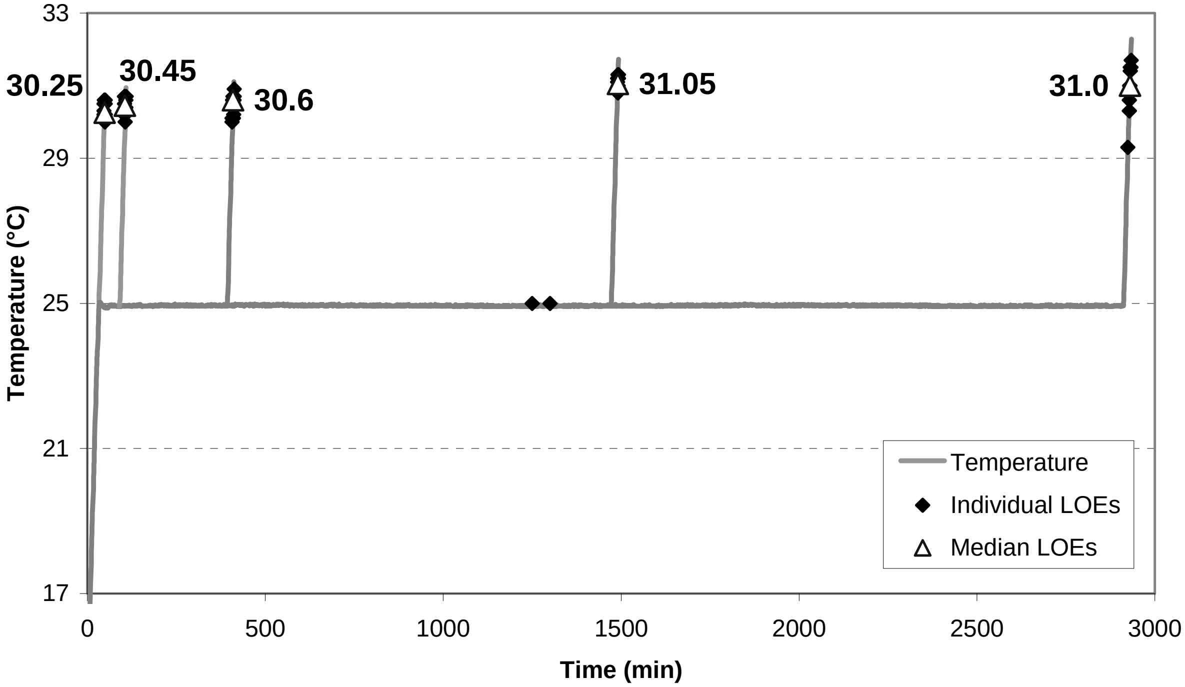

**Figure 11-7**
**Time and Temperature of Loss of Equilibrium (LOE) of Rainbow Trout Exposed to Five Acclimation Durations at 25°C Prior to Determination of LOE Temperature**

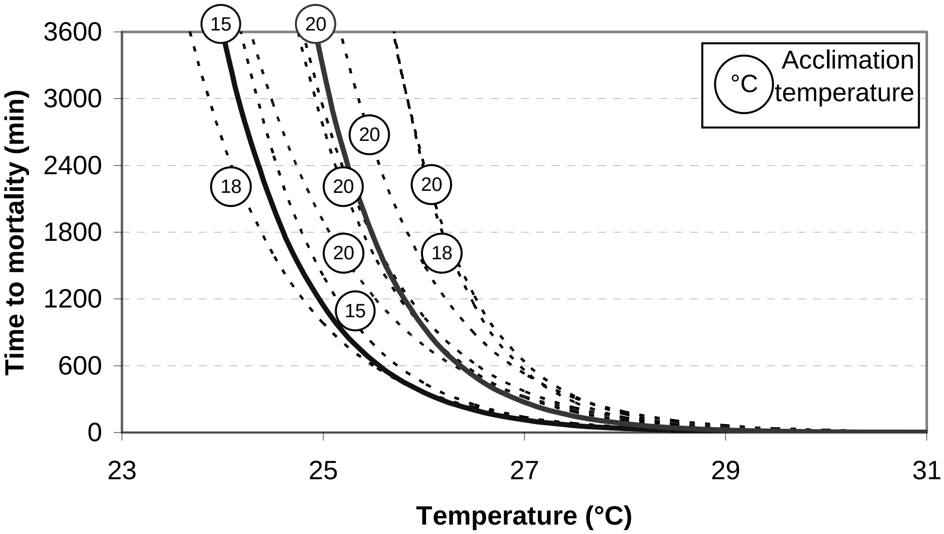

**Figure 11-8**
**Relationship Between Temperature and Time to LOE for Rainbow Trout at Two Acclimation Temperatures in This Study (15°C and 20°C, Solid Lines) and at Several Acclimation Temperatures from Other Studies [3] (Dashed Lines)**

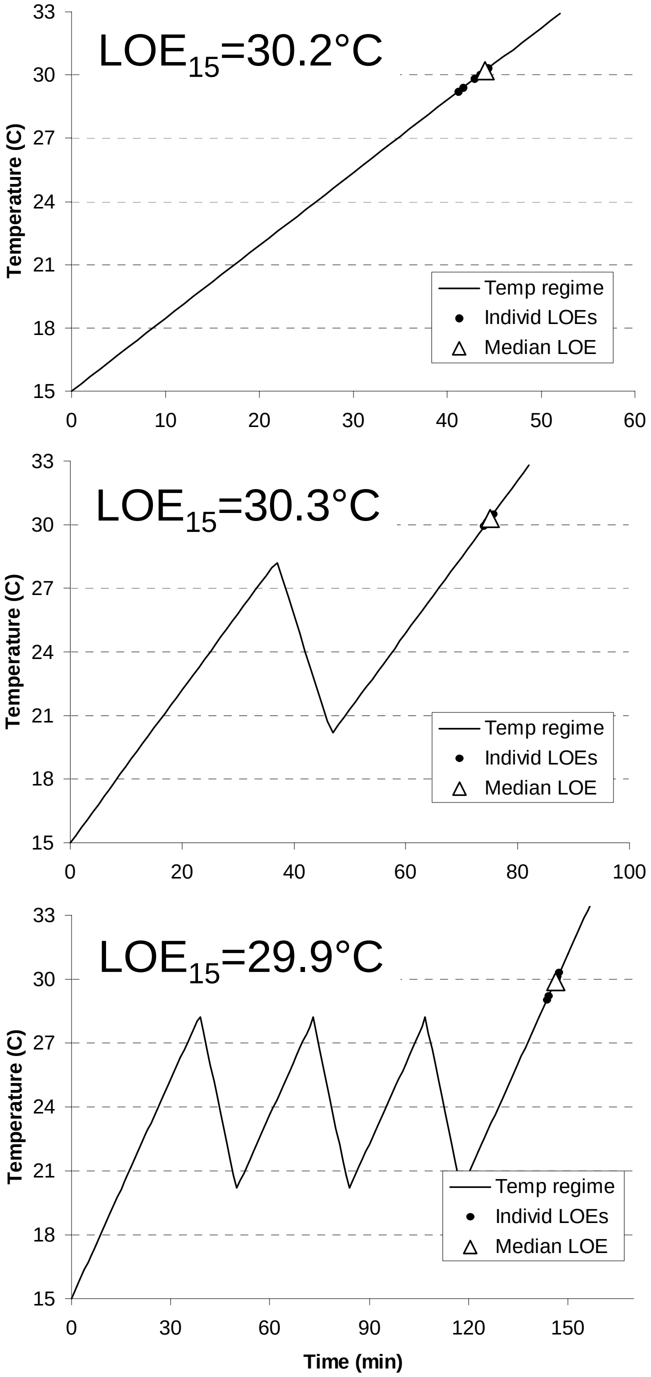

**Figure 11-9**
**Results of Thermal Challenge Test of Exposure to Fluctuating Temperature Regimes**

**Table 11-2**
**Median Temperature of Loss of Equilibrium during Treatments of Fluctuating Temperature**

| Treatment | 15°C Acclimation | 20°C Acclimation |
|---|---|---|
| Baseline CTMax | 30.2 | 31.3 |
| 1 fluctuation (20.2-28.2°C) | 30.3 | |
| (21.3-29.3°C) | | 31.5 |
| 3 fluctuations (20.2-28.2°C) | 29.9 | |
| (21.3-29.3°C) | | 31.5 |

## Lab Experiments Summary

We performed a series of thermal challenge experiments designed to gain a better understanding of various components of thermal stress accumulation. We began with the standard CTMax tests to test immediate effects of rapid increases in temperature. Testing then progressed to the effects of high constant temperatures and eventually thermal regimes with varying periods of recovery. We found that lowering temperature a few degrees for brief periods appeared to be enough to allow for recovery from the thermal stress accumulated during periods of high temperature exposure.

In experiments that tested different rates of temperature increase during a continual rise to eventual LOE, we found that slower rates of increase resulted in earlier LOE for rainbow trout. The earlier LOE at slower heating rates is somewhat counter intuitive as one might expect a more rapid change in temperature to be more damaging. However, we believe this occurs because fish experience thermal stress above some threshold temperature and a slower rate of increase means a longer exposure to temperatures above this threshold temperature.

In experiments where fish were allowed to acclimate for various lengths of time at a temperature slightly below the expected stress threshold, we found that the longer fish were allowed to acclimate the more tolerant they were of high temperatures and the higher the point of eventual LOE. These results are consistent with those found in our prior work with mosquitofish (*Gambusia affinis*) [1].

In experiments where fish were exposed to fluctuating temperatures, we found that fish experiencing hourly fluctuations of 8-9°C (with the upper limit within 1.5-2.5°C of the CTMax) had virtually the same point of LOE as did those fish that were raised directly to LOE. This result suggests that any stress accumulated during exposure at the high end of the cycle was alleviated during exposure to cooler conditions at the low end of the cycle.

The CTMax values we determined for rainbow trout are slightly higher than the 29.1 to 29.8°C for trout acclimated at 15 and 20°C reported by others [4]. This difference is likely due to differences in stock origin or recent thermal history prior to the relatively short acclimation period.

The recovery of fish after thermal exposure and LOE also produced interesting results. It is not unusual for thermally stressed fish to recover and survive [5]. We found that duration of exposure was more important than the temperature of exposure. Those fish exposed for long times at low (but stressful) temperatures had lower rates of ultimate survival than fish that lost equilibrium at higher temperatures but were only exposed for a short time.

## Thermal Stress Accumulation Model

The possible combinations of interesting and informative laboratory experiments that can be performed to address thermal stress are endless. However, by combining lab experimentation with simulation modeling, we can simulate an endless number of temperature regimes to investigate potential effects. We previously described a modeling framework that we developed to assess cumulative thermal damage (or stress) in fish when exposed to constant or fluctuating temperatures near lethal levels [1]. With this approach we assume that stress accumulation occurs when temperature exceeds some threshold at a rate dependent on the degree to which the threshold is exceeded. The model framework includes short-term and long-term acclimation and the rate of temperature increase as factors in determining what the threshold is and the rate at which thermal damage accrues. The model also includes a mechanism for repair (or recovery) when temperature drops below the threshold temperature as in systems where anthropogenic heat sources are intermittent or in unaffected systems with large natural daily variation. Results from our laboratory experiments were used to derive model parameters for rainbow trout. We then simulated thermal stress in rainbow trout when exposed to various fluctuating thermal regimes.

### Model Description

The direct thermal stress component of the model is similar to damage-repair models developed for ecotoxicology investigations [6, 7, 8]. Thermal stress accumulates when a fish is exposed to temperatures above some threshold temperature and stress is relieved or repaired when temperatures are below the threshold. The rate of thermal damage and repair are functions of the rate and magnitude of temperature change and are represented in the model by equations derived from laboratory experiments.

The model tabulates an index of thermal stress that corresponds to the amount of stress that results in LOE. The basic equation of the thermal stress model is:

$$accumulated\ stress(t) = previously\ accumulated\ stress(t - dt) + damage(dt) - repair(dt)$$

where *t* is the current time and dt is change in time (or the time step, which is one minute in this model). During each time step, either thermal damage or thermal repair occurs (but not both) which causes an increase or decrease in the accumulated thermal stress. The model accepts any type of thermal regime and tracks accumulated thermal stress through time.

## Thermal Damage

The relationship between temperature and time to LOE is best described as a regression equation of the form:

$$Log10(t) = a + b * T$$

where 't' is time (min) to LOE, 'a' is the intercept, 'b' is the slope, and 'T' is temperature (°C) [9]. This is illustrated in Figure 11-10 which is a variation (i.e., same data) of Figure 11-6.

The reciprocal of the time to LOE for any temperature is the "minute rate to LOE" which is analogous to the "minute-rate of mortification" as defined decades ago by F.E.J. Fry [10], although he was referring to death and our reference point is LOE. Using the relationship shown in Figure 11-11, the equation for minute rate to LOE becomes:

$$minute\ rate\ to\ LOE = 1/Log10(t) = 1/(10\text{^}(15.553 + 0.4998 * \mathrm{T}))$$

The model operates on 1-min time steps during which a minute-rate to LOE is calculated as a function of temperature (Figure 11-11) and accumulated. Theoretically, when the accumulated value reaches 1, LOE should occur. For example, from the equation above, time to LOE at 29ºC is 11 minutes. During each minute one eleventh (or 0.09) of total LOE occurs. For fish that experience dynamic temperature regimes, the minute-rate to LOE varies each time step with temperature.

The intercept coefficient 'a' is a convenient parameter for model calibration if needed. Increasing or decreasing 'a' slides the LOE rate curve along the temperature axis without changing the shape of the curve. This creates the effect illustrated previously in the plot of nine mortification curves for rainbow trout in Figure 11-8. We believe this is an easy way to adjust the model for different acclimation conditions or for application to other species where sufficient empirical evidence is not available to derive a species-specific curve.

## Repair

Repair from thermal stress occurs when temperature drops below the threshold. Whether the rate of repair is dependent on the magnitude below the threshold is uncertain. We suspect two possible repair scenarios – either the rate is fairly constant regardless of the temperature once below stressful levels, or repair increases with distance from the stress threshold probably peaking at some optimal temperature. At this time we know of no evidence that supports one scenario over the other since, and we know of no way to measure outright the amount of thermal stress either being accrued or alleviated. Therefore, in lieu of empirical data on the rate of stress repair, we assumed that the repair occurs at generally the same rate regardless of temperature once the fish is at a thermally 'safe distance' from the threshold temperature. We assumed that rate of recovery occurs slowly at first just below the threshold and then increases to a constant level one degree below the threshold. Based on what we generally know from other studies about recovery from thermal stress and other stress indicators (e.g., cortisol), we suspect that full recovery from a significant thermal stress occurs on the order of a several hours to a full day.

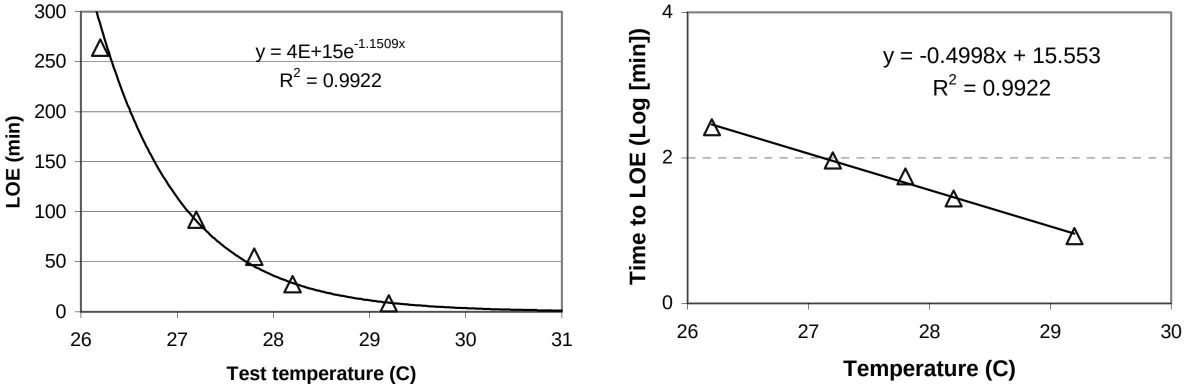

**Figure 11-10**
**Time to Loss of Equilibrium for Rainbow Trout at Five Temperatures (Original Data–Left Panel; Log-Transformed Data–Right Panel)**

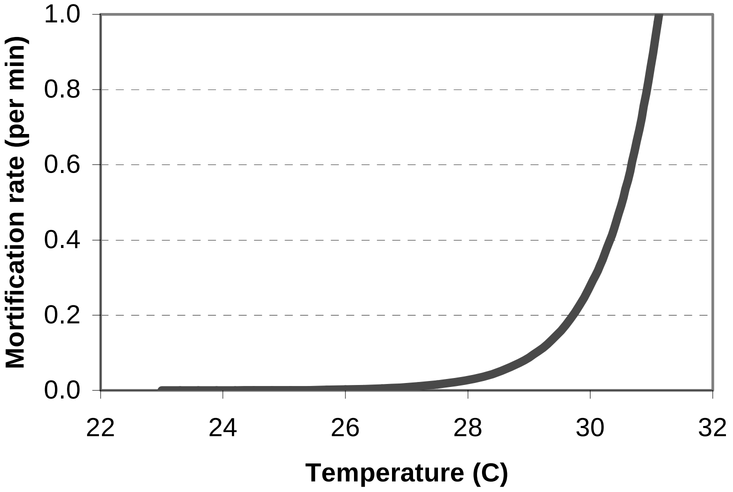

**Figure 11-11**
**Derived Relationship between Temperature and Per Minute Rate to LOE**

Based on our experiments with mosquitofish we concluded that the amount of thermal stress acquired in an hour took about the same time to alleviate. We found similar results with rainbow trout (see Figure 11-9) where complete recovery seemed to occur during durations of time at cooler temperatures that were similar to the duration of thermal exposure. Therefore, we chose a maximum repair rate of at least 1 unit per hour and a rate-of-repair relationship like that portrayed in Figure 11-12, which has been adjusted to correspond with the temperature we determined as the onset of thermal stress for rainbow trout.

Figure 11-13 combines the rate to LOE and repair into the same figure by including repair as negative thermal stress.

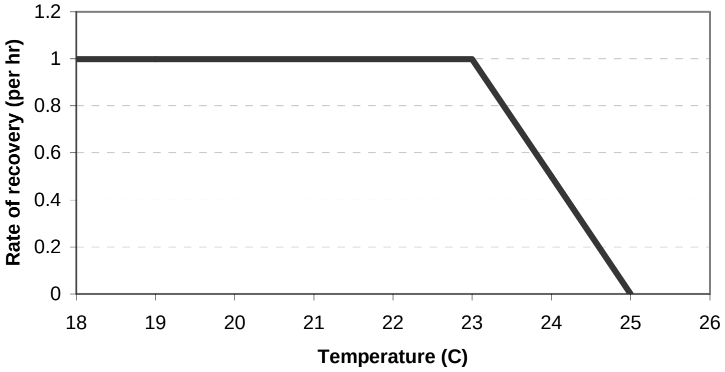

**Figure 11-12**
**Relationship between Temperature and Rate of Recovery Used in the Thermal Stress Model**

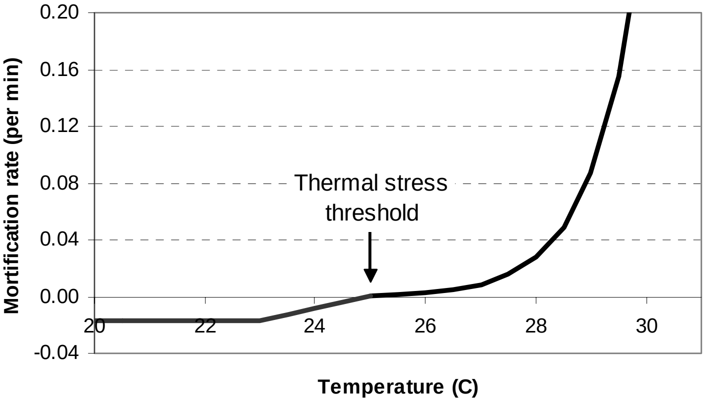

**Figure 11-13**
**Relationship between Temperature and Combined Rates of Mortification (Above Zero) and Recovery (Below Zero)**

## Acclimation

An important component of the model that we have incorporated is the inclusion of mechanisms to account for thermal acclimation. Our laboratory experiments with rainbow trout and previously with mosquitofish clearly showed that acclimation to warmer temperatures can occur fairly rapidly, such that LOE occurs at increasingly higher temperatures as acclimation time increases (Figure 11-14). In the model we accounted for acclimation by increasing the value of 'a' by an amount necessary to shift the mortification curve to the right along the temperature axis to meet the increase in LOE temperature as a result of increased acclimation.

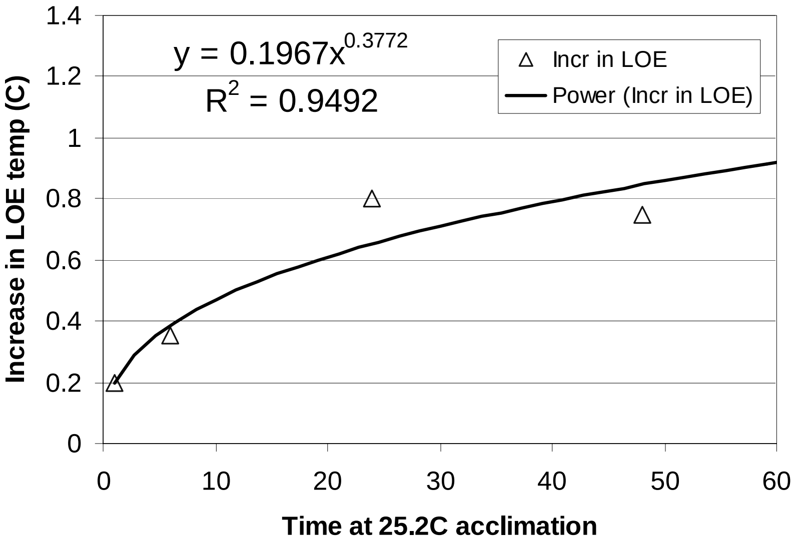

**Figure 11-14**
**Relationship between Acclimation Time at 25.2C and Increase in Thermal Tolerance**

### *Model Simulations*

The value of having a calibrated thermal stress model is the ability to use it to better understand the effects of various thermal regimes beyond which we are able to test in the laboratory. We simulated three sets of simulations where we varied either the daily range, mean, or maximum temperature. During the simulations, thermal stress index was tracked. An index score of 1 corresponds to the median LOE for a group of fish exposed to that scenario.

In the first set of simulations, we tested four fluctuating temperature regimes with mean temperatures of 21, 22, 23, 24°C and a daily range of 6°C each (Figure 11-15). Stress recovery occurred for the three lowest temperatures each day with the maximum daily stress index increasing with each mean temperature. For the simulation with a 24°C mean, there was no recovery and an index of 1 was exceeded the first day of the simulation.

In the second set of four simulations, each had the same mean temperature (23°C) and daily ranges of 2, 4, 6, and 8°C (Figure 11-16). Only in the simulation with a daily range of 6°C was recovery enough to prevent the stress index from increasing eventually to 1. Simulations with the smallest and largest fluctuations resulted in the most rapid rise in thermal stress.

In the third set of simulations, all four had the same maximum temperature (25°C) but with different daily ranges (8, 6, 4, and 2°C) and means (21, 22, 23, 24°C; Figure 11-17). The two simulations with the greatest ranges and lowest means exhibited enough stress recovery to maintain a level of stress below 1. The other two simulations either reached 1 or were trending upward toward 1 during the 7-day simulation.

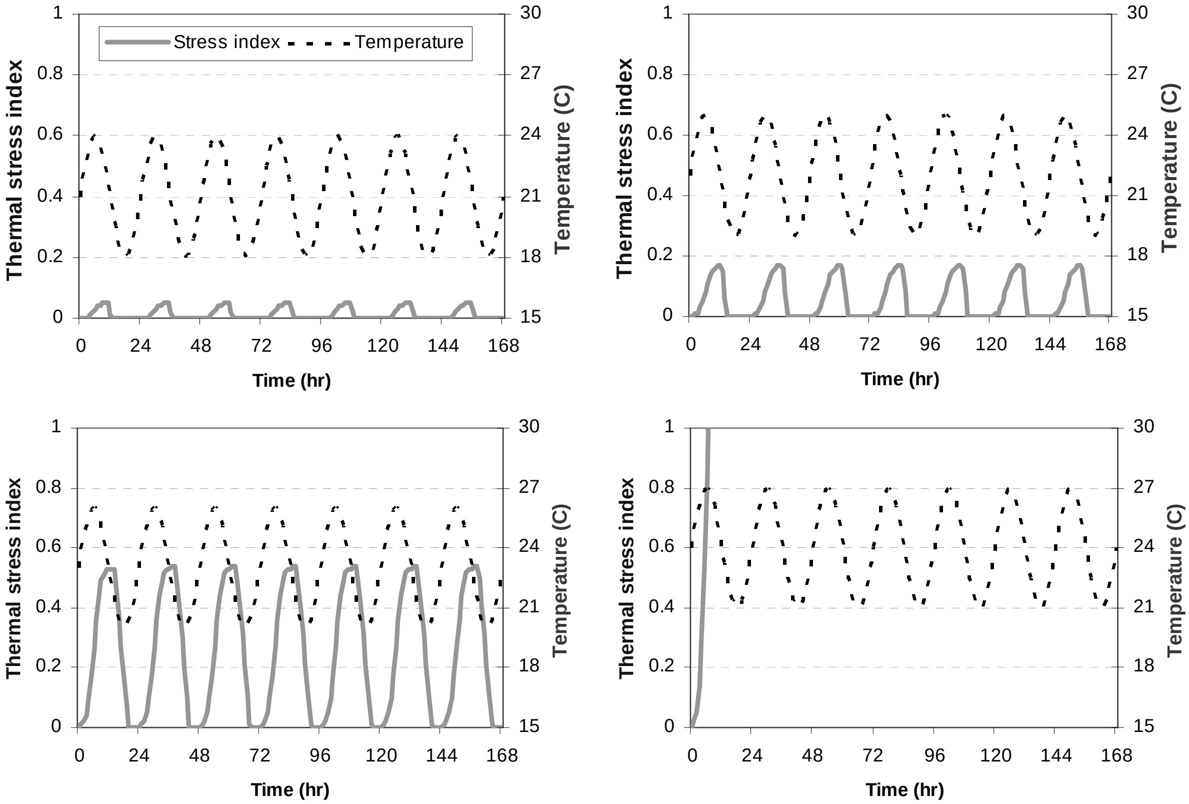

**Figure 11-15**
**Simulated Thermal Stress from Four Fluctuating Temperature Regimes with Different Daily Means but Equal Daily Range of Temperature**

## *Modeling Summary*

Based on data derived in laboratory experiments, we parameterized a thermal stress accumulation model for rainbow trout. By incorporating rainbow trout parameters in the thermal stress model we demonstrated that the model is easily applicable to other species. In addition the parameter adjustment used to account for acclimation at different temperatures for a single species can also be used to produce differences in thermal tolerance among species.

Our simulations of hypothetical fluctuating temperature regimes show how the model can be used to compare different environmental conditions. We found that fluctuating temperatures are not necessarily detrimental and can produce increased acclimation resulting in higher thermal tolerance. Information like this could be used to better understand potential effects and perhaps direct plant operations.

The model could also be used to retrospectively evaluate conditions during reported fish dieoffs to assess the contribution of thermal effects and as a tool for evaluating the protectiveness of various types of thermal standards, such as rate of change and delta T.

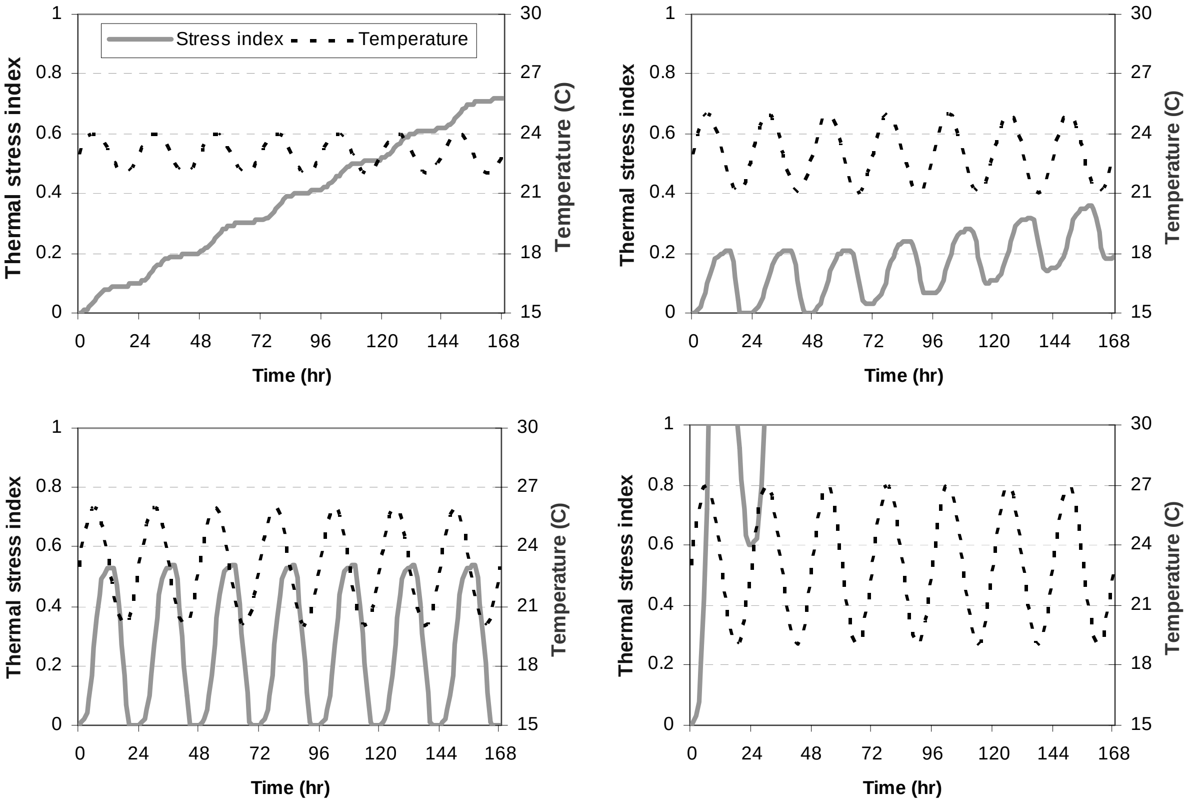

**Figure 11-16**
**Simulated Thermal Stress from Four Fluctuating Temperature Regimes with Equal Daily Means but Different Daily Ranges of Temperature**

## Summary

The overall objective of this study is to contribute technical information on biological effects of fluctuating temperatures that can be used by EPRI for recommendations to electricity generators on approaches to Clean Water Act Section 316(a) thermal discharge compliance. Our most recent experiments corroborated the findings from previous years such as:

- Laboratory results suggest brief forays near critical temperatures are not necessarily harmful and recovery can be 100% after return to tolerable temperatures. Therefore, thermal standards based on daily averages may be more useful than a single maximum value.
- The rainbow trout experiments corroborate our previous observation that recovery seems to occur over a relatively short period of time. Our results suggest that as little as 1 hr at a less than stressful temperature is enough for full recovery from conditions that caused LOE in the most thermally sensitive members of the test group. We also found that full recovery (i.e., survival) is much more likely to occur after brief exposures to the highest temperatures than to long exposures to lower temperatures.
- By incorporating rainbow trout parameters in the thermal stress model we demonstrated that the model is easily applicable to other species.

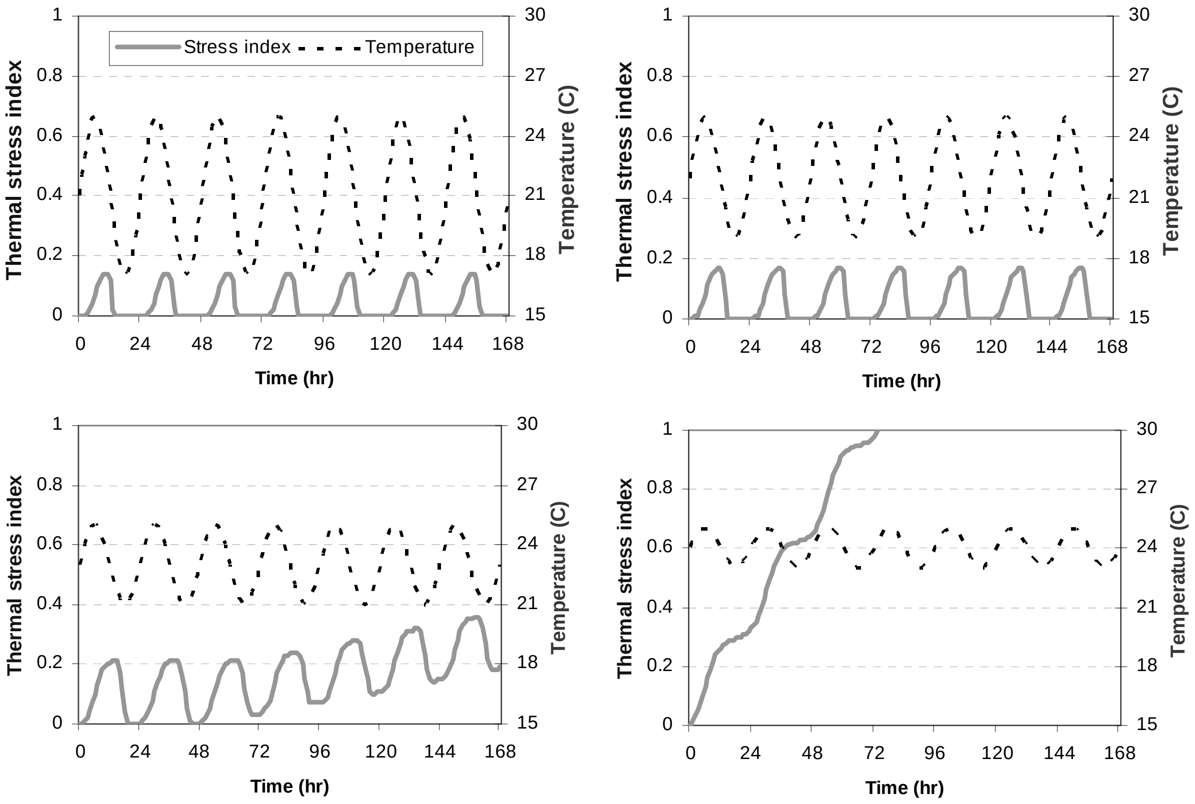

**Figure 11-17**
**Simulated Thermal Stress from Four Fluctuating Temperature Regimes with Equal Daily Maximums but Different Daily Ranges of Temperature**

Other key findings include:

- Compared to previous experiments with mosquitofish and black crappie (Pomoxis nigromaculatus), we found that for rainbow trout thermal stress occurs over a slightly broader range of temperatures. The difference in temperature that causes mortification in 1 min and that in 1 hr for rainbow trout is about 3.6ºC compared to 1.4ºC for mosquitofish. The difference in temperature between 1 hr and 1 day to mortification for rainbow trout is about 2.7ºC compared to 1ºC for mosquitofish. The high level of within population variability (usually at least 1ºC difference from most to least tolerant individuals in our experiments) further complicates this issue.
- Both laboratory experiments and modeling show that standards that incorporate only a single dimension of the thermal profile of a system (e.g., maximum temperature, rate of change, or increase over ambient) instead of multiple dimensions and period averages are likely to be over protective.

## Future Research Needs

For the modeling approach to be most useful, it needs to be easily applied to a variety of species. One way to do this would be to place species in guilds or on a continuum based on their thermal tolerance and then incorporate this organization into easy parameter selection in the model. We have demonstrated that change accounting for tolerance differences due to acclimation, size or species can be accomplished by adjusting only one or two parameters. It is our intent to eventually be able to use historical CTM and ILT values for other species available in the literature to derive parameters for the fluctuating temperature model without having to do additional laboratory testing for each species.

There is very little information in the published literature on recovery from thermal stress. This is a critical component to an understanding of how fish respond to fluctuating temperature regimes. More laboratory experiments are needed to investigate this, especially if metrics other than loss of equilibrium, such as performance measures, physiological responses, or expression of thermal stress proteins) can be used to measure stress and recovery.

Little is known about the actual thermal experience of fish that live in both spatially and temporally variable thermal environments in areas around heated effluents. In many cases, the temperature that is actually being experienced by fish is largely unknown. Do they use cool refuges in summer when temperatures throughout a larger area are often higher than preferred or optimal? Do they move about on a regular basis such that their exposure to excessively warm temperature is tempered by periods at cooler temperatures? These are old questions that have been explored before, but new telemetry technology could provide better answers. Tags are smaller allowing use in more varied sizes of fish. Enhanced memory allows data to be collected more frequently and archived if necessary for later downloading. Receiver systems are more sophisticated allowing for automatic and more frequent data collection. A telemetry study that tracked the thermal experience of individual fish near a thermal discharge over a several week period would provide valuable information on actual thermal exposure. This approach does have some serious obstacles to overcome, however. For example, fish that are large enough to be tagged with transmitters are also often very mobile and the number of fish that need to be tagged in order to get data from the few that don't leave the vicinity of a heated discharge could be cost-prohibitive.

Although the focus in this study is on critical levels of high temperature that might result in debilitation or death, there is also a concern about how high temperatures affect growth. In addition to protecting against lethal conditions, regulators are trying to maintain (or provide) temperatures that provide for normal growth. We agree that normal growth should be protected, but we believe there is often a misunderstanding about what normal growth is and what is needed to protect it. Our experience is that many folks don't appreciate that periods of no growth and even negative growth are normal and that criteria development needs to take into account growth over the course of the year and not at discreet times. Some seem to think they can and should provide optimal conditions at all times. This isn't necessarily beneficial or even possible to do. Such criteria should also consider the effects of temperature criteria based on "coolwater" fish needs on the growth and production of "warmwater" fish in the same system. Several of these issues can be addressed through bioenergetics modeling. In an analysis we did several years ago we found that warmer river temperatures as a result of hydro operations had little effect on net annual growth, even though summer growth was very low. Methods to easily evaluate the long-term growth effects of various thermal regimes is needed by regulators trying to protect for normal growth. In addition, it would be interesting to extend such an analysis to representative species of a fish community to see how selecting thermal criteria based on needs of those with lower thermal tolerance affects those with higher tolerance.

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# 12

# MODELING OF THERMAL IMPACTS ON BENTHIC ALGAE

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## Introduction

In many parts of the Great Lakes, excessive growth of the benthic filamentous green alga, *Cladophora* sp., has become a serious management problem in the past decade. Negative impacts associate with the algae include loss of lakeshore property values, economic losses in the tourism industry, potential human health problems, and fouling of water intakes [1, 2, 3]. For power plants that draw cooling water directly from the Great Lakes, the clogging of cooling systems has caused partial and complete plant shutdowns costing millions of dollars per year.

Excessive growth of *Cladophora* in the Great Lakes is not a new problem. High nutrient loads resulted in nuisance levels of *Cladophora* in at least some parts of all of the Great Lakes except Superior in the 1960s and 1970s [4, 5, 6]. Nutrient abatement programs implemented in the 1970s were generally successful in reducing the standing stock of *Cladophora* and other algae. These programs have remained in effect, and total phosphorus concentrations have continued to decline in most parts of the Great Lakes [7, 8]. Therefore, the recent resurgence of *Cladophora* is puzzling. Possible causes include an increase in water clarity, an increase in water temperatures, and changes in phosphorus cycling within the lakes that accelerate P supply to the nearshore zone [9, 10].

Temperature can have both a direct and indirect effect on *Cladophora* growth. Experiments in the lab and observations in the field have shown that *Cladophora* photosynthetic rates and growth rates are directly influenced by temperature. Minimum, maximum, and optimal temperatures for *Cladophora* photosynthesis and growth vary among studies. The minimum temperature requirement for *Cladophora* growth appears to be between 2 and 10°C [11, 12, 13]. Reported optimum temperatures for photosynthesis range from 13 to 24°C [13, 14], while optimum temperatures for growth (which represents the net change in biomass resulting from all gain and loss processes) range from 18 to 30°C, [13, 14, 15, 16, 17]. Reported maximum temperatures, above which there is no net growth, range from 25 to as high as 40°C [13, 15, 18]. Seasonal *Cladophora* biomass measurements in the Great Lakes often reveal a period of biomass loss in mid- to late summer, which has been attributed to metabolic imbalance resulting from higher respiration rates at higher temperatures [15, 19]. This mid-summer biomass minimum usually corresponds to water temperatures above 19°C, suggesting that the optimal growth temperature under natural conditions is well below 19°C.

Temperature may also indirectly influence *Cladophora* through its effect on nutrient cycling. In the Great Lakes *Cladophora* growth and biomass are strongly influenced by phosphorus availability [20, 21, 22]. Prior to the 1990s, dissolved P concentration in the nearshore zones of the Great Lakes were determined primarily by loading from rivers and proximity to river mouths [19]. However, following the invasion by the zebra mussel (*Dreissena polymorpha*), and its more recent congener the quagga mussel (*Dreissena bugensis*), there appears to have been a fundamental shift in nutrient cycling processes in the Great Lakes. Dreissenid mussels have the capacity to consume large quantities of suspended particulate material and excrete large amounts of nutrients, and it has been suggested that excretion of dissolved P by dreissenids may in part explain the recent resurgence of *Cladophora*, which grows on the same hard, nearshore substratum as dreissenids [10, 23, 24, 25]. Because dreissenids are poikilotherms, their metabolic processes, including nutrient excretion, will vary according to ambient temperature. Therefore, if dreissenids are an important source of dissolved P for *Cladophora*, temperature may indirectly influence *Cladophora* growth through its effect on mussel metabolism.

To assess the direct and indirect of temperature on *Cladophora* growth and biomass, we applied two simulation models – a *Cladophora* model that simulates *Cladophora* growth and biomass as a function of temperature, light and soluble reactive phosphorus (SRP) concentration, and a mussel model that describes P excretion by quagga mussels in relation to temperature, food supply and mussel size.

## Model Descriptions

The *Cladophora* model is a revision of an earlier model that was calibrated using data from an extensive set of laboratory experiments and calibrated with data for Lake Huron [21, 26]. Using daily data for water temperature, SRP concentration and vertical light extinction, and hourly data for surface irradiance, the model calculates daily changes in biomass resulting from the net difference between gross photosynthesis and respiration. These rates are determined as functions of *in situ* irradiance, temperature and *Cladophora* tissue P content, which in turn is a function of SRP concentration and growth rate. The model also accounts for sloughing and self-shading through a biomass negative feedback algorithm. We conducted lab experiments to determine whether the effects of temperature on *Cladophora* photosynthesis and respiration remained the same as those observed in previous studies [13]. In addition, we monitored *Cladophora* biomass, *Cladophora* tissue P content, water temperature, light, and SRP concentration at a 9-meter deep station in Lake Michigan, 4 km north of Milwaukee Harbor, at weekly intervals between May and October, 2006 to validate the *Cladophora* model. Initial model runs, using temperature, light and SRP data for the Lake Michigan station, resulted in simulated biomass values that were significantly less than measured values. Lab experiments indicated that the specific respiration rate (the proportion of gross photosynthesis that is respired) was almost always less than the default value of 0.44 day$^{-1}$ used in the original model. Therefore we adjusted this value to the mean measured in our experiments, which was 0.23 day$^{-1}$. When this revised parameter value was used in the model, there was good agreement between simulated and measured biomass values during the *Cladophora* growth period in the first half of the summer. Agreement was not as good in the second half of the summer, when sloughing occurred and *Cladophora* biomass decreased in the lake. This is due to the fact that sloughing mechanisms are not well understood, and therefore sloughing is poorly accounted for in the model. However, our primary objective was to determine how environmental conditions affect *Cladophora* growth during the early summer growth period, and summer biomass maximum, which is the variable of most interest to managers. Although the poor simulation of sloughing results in a temporal hysteresis between simulated and observed biomass, the simulated and observed maximum biomass values were very similar ($\leq$ 15% difference), indicating that the model has utility in determining the influence of temperature on maximum biomass.

The mussel model simulates SRP excretion by quagga mussels as a function of temperature, food supply (measured as particulate P concentration), and mussel size. The effects of temperature and food supply were determined in 2X2 factorial experiments in which quagga mussels were acclimated to temperatures ranging from 10 to 22°C and food concentrations of between 0 and 24 μg P $L^{-1}$. These ranges are similar to those typical of the Lake Michigan nearshore region during summer. The data from these experiments were fitted to a Michaelis-Menten type model:

$$R = \frac{V_{\max} S}{K_m + S} \qquad \textbf{Equation 12-1}$$

where $R$ = SRP excretion rate (μg P $\mathrm{mgDW}^{-1}$ $\mathrm{hr}^{-1}$)

$V_{max}$ = maximum SRP excretion rate

$K_m$ = half saturation constant (μg P $L^{-1}$)

$S$ = food concentration (μg P $L^{-1}$)

DW = dry weight of mussel soft tissue

At each experimental temperature, $R$ was measured over a range of $S$. This allowed for the determination of temperature-specific values of $V_{max}$ and $K_m$. Results are shown in Table 12-1.

**Table 12-1**
**Measured Values of Model Parameters $V_{max}$ and $K_m$ at Three Different Temperatures. Model Parameters were Determined for 20 mm Mussels Acclimated to a Temperature of 23°C and to Four Food Concentrations Ranging from 0 to 24 mg P $L^{-1}$. Exponential fits of the Parameter-Temperature Relationships Resulted in $r^2$ Values of 0.95 for $V_{max}$ and 0.99 for $K_m$**

| Temperature (°C) | Vmax (μg P $\mathrm{mgDW}^{-1}$ $\mathrm{hr}^{-1}$) | Km (μg P $L^{-1}$) |
|---|---|---|
| 10 | 0.0030 | 0.427 |
| 15 | 0.0045 | 0.854 |
| 22 | 0.019 | 2.44 |

The effect of mussel size on SRP excretion was measured in separate experiments in which the SRP excretion rates of mussels ranging from 11 to 30 mm in length were measured following acclimation to a fixed temperature (23°C) and food concentration (6.9 μg P $L^{-1}$). The resultant data revealed a strong curvilinear relationship:

$$R = 18.79L^{-2.37} \qquad \textbf{Equation 12-2}$$

where $L$ = mussel length (mm).

Using this equation, a size-correction factor can be determined, which represents the ratio of $R$ for a given size class to $R$ for the 20 mm size class:

$$M = 1207.8L^{-2.37} \qquad \textbf{Equation 12-3}$$

$R$ for any size class ($i$) is then determined as

$$R_i = RM_i$$ **Equation 12-4**

This approach assumes that the relative influence of size on *R* is constant at all temperatures and food concentrations. Although this assumption may not be completely valid, the effects of temperature and food concentration on the size-*R* relationship are likely small enough that they will result in minimal error relative to the direct influence of temperature on *R*.

## Model Results

To assess the direct influence of temperature on *Cladophora* growth and biomass, we conducted model simulations in which light and nutrient conditions were fixed and temperature was allowed to vary between 5°C and 30°C (see Figure 12-1 legend for simulation conditions). For each temperature the model was run for a time period sufficient to reach steady state (constant biomass), which was between 4 and 6 weeks. Model results indicate that maximum growth rate occurs at around 15°C (Figure 12-1). At temperatures lower than this, gross photosynthetic rate decreases with decreasing temperature. At higher temperatures, gross photosynthetic rate increases with temperature, but respiration rate increases at a proportionately greater rate, so that net production decreases with increasing temperature. Maximum biomass is reached at a slightly lower temperature than that of maximum growth rate. Biomass represents the balance between net growth rate and loss rate. The primary loss mechanism for *Cladophora* is sloughing. While the sloughing mechanism is still not well understood, the model simulates sloughing as a temperature dependent process, which is consistent with observations of *Cladophora* in the natural environment [19]. The lower temperature of the biomass maximum relative to that of the growth rate maximum is due to the fact that sloughing rate increases with temperature.

Data records from a temperature logger deployed at a depth of 9 m in Lake Michigan indicate that optimal growth temperatures are reached in early June (Figure 12-2). Between June and early August 2006, water temperature was highly variable, but the average was 13.7°C, indicating that conditions are near-optimal for much of this period. In August and early September, temperatures were almost always greater than 18°C. According to the model, growth rate and steady state biomass should be lower at these high temperatures (Figure 12-1), and this is supported by earlier observations of seasonal biomass trends in both Lake Huron [26] and Lake Erie [5].

In order to assess the mussel mediated temperature effect on *Cladophora*, it is necessary to determine the effect of mussel P excretion on nearshore SRP concentration, as it is this concentration that drives P uptake and growth of *Cladophora*. The availability of mussel-excreted SRP to mussels will be controlled by vertical diffusion rate and horizontal advection. Under low turbulence conditions, SRP excreted by mussels will accumulate near the benthos, where it is available for uptake by *Cladophora*. In contrast, high turbulence will result in rapid vertical diffusion, making excreted SRP less available for assimilation by *Cladophora*. The effect of horizontal long-shore advection will depend on the areal distribution of mussels and *Cladophora*. In very large patches, advection may not be important, because when advection is low *Cladophora* will assimilate SRP excreted by mussels in the immediate vicinity, and when it is high *Cladophora* will assimilate SRP excreted by mussels up-current. However, in small patches SRP-rich bottom water will be quickly replaced by SRP-poor ambient water when current speeds are high, and in this case SRP excretion by mussels will likely have little influence on *Cladophora* growth.

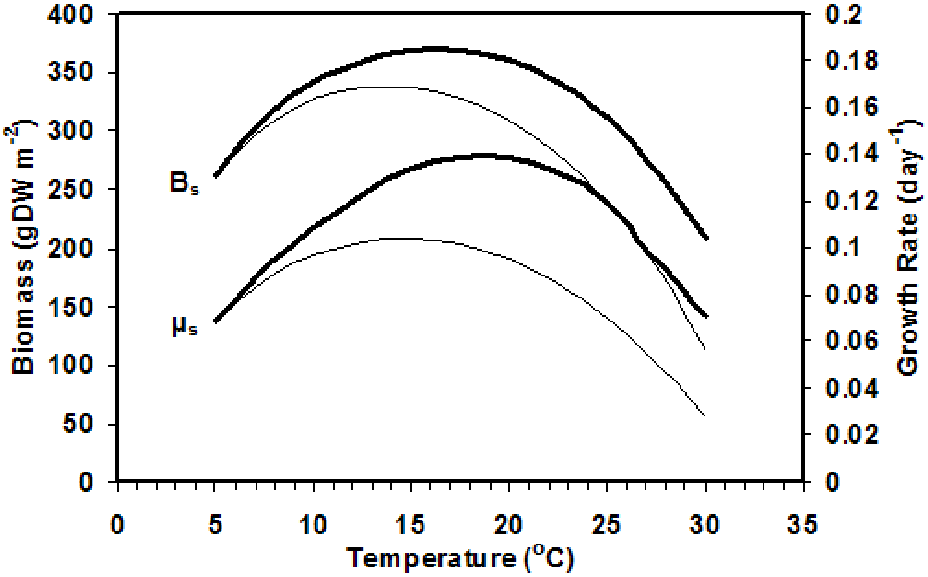

**Figure 12-1**
**Model Simulation Results Showing the Effect of Temperature on *Cladophora* Growth Rate. $B_s$ = Biomass at Steady State; $\mu_s$ = Growth Rate at Steady State. For the Simulation, Initial Biomass was Set at 50 gDW $m^{-2}$, initial *Cladophora* P Content was 0.09% DW, Surface Light was made Equal to Measurements made on June 30, 2006, the Light Extinction Coefficient was 0.25 $m^{-1}$ (typical of Lake Michigan Nearshore Conditions), SRP Concentration without Mussels was 0.86 $\mu$g $L^{-1}$, and Depth was 9 m. Mussel SRP Excretion was Assumed to be Negligible at 5°C**

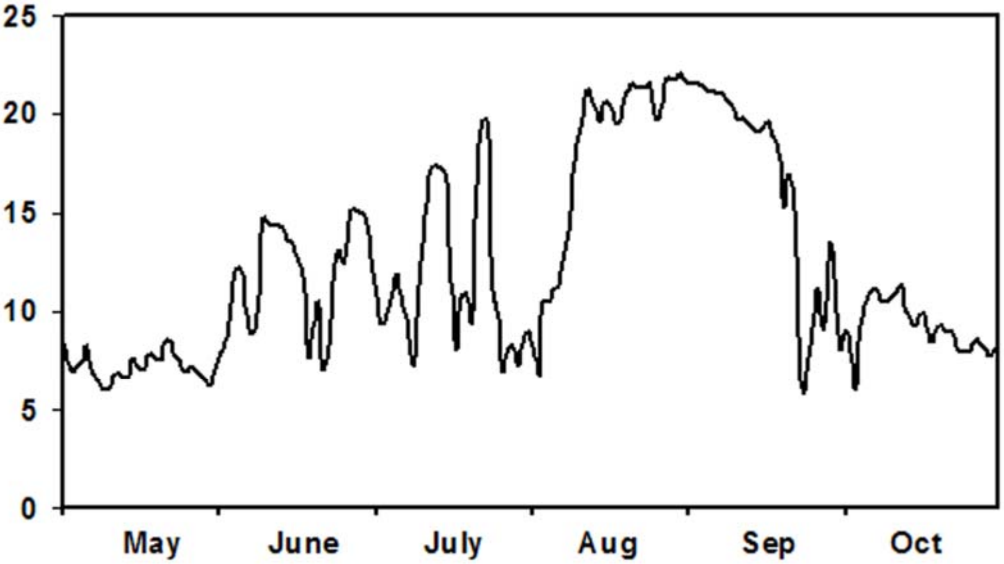

**Figure 12-2**
**Water Temperature at a Bottom Depth of 9 m from May to October 2006**

A conservative estimate of the impact of mussel SRP excretion on near-bottom SRP concentration can be made by assuming that excreted SRP is uniformly distributed through the water column, which will be the case when the water column is well mixed. We modeled nearshore SRP concentration and *Cladophora* growth under this condition, assuming that dilution of nearshore SRP was accomplished only through nearshore-offshore exchange. Under these assumptions, nearshore-offshore SRP flux can be determined as

$$F = D([SRP_N] - [SRP_O]) \qquad \textbf{Equation 12-5}$$

where $D$ is the exchange rate (day$^{-1}$), $[SRP_N]$ and $[SRP_O]$ are the nearshore and offshore SRP concentrations (μg L$^{-1}$), respectively, and the units of $F$ are μg L$^{-1}$ day$^{-1}$.

Few studies have quantified nearshore-offshore mixing rates in the Great Lakes, but exchange coefficients derived from water current measurements for Lake Michigan and Lake Ontario range from 0.019 to greater than 0.5 m$^2$ s$^{-1}$ [27, 28]. For a nearshore zone extending to a depth of 12 m with a bottom slope of 1:250, these exchange rates are equivalent to a $D$ of 0.1 to 2.6 day$^{-1}$. We used a value of 0.5 day$^{-1}$. This is close to the median value reported for cross-shore transport during a storm event in Lake Michigan [27]. This is likely a greater value than typically occurs during the *Cladophora* growing season, and therefore it will result in a conservative estimate of the impact of mussels on nearshore SRP concentration. Other assumptions used in the model were based on multi-year observations made at the *Cladophora* monitoring station: 1) The *Cladophora* / mussel patch is large enough that longshore transport results in no net gain or loss of SRP; 2) The SRP concentration of offshore water is 0.4 μg L$^{-1}$; 3) Mussel length is 14 mm, and density is 5,500 m$^{-2}$; 4) 70% of the lake bottom in the nearshore zone (0-12 m) is covered with mussels; 5) nearshore particulate P concentration is 7 μg L$^{-1}$.

The results of the simulation are shown in Figure 12-1. Under the above conditions, mussel excretion resulted in a nearshore SRP concentration of between 0.9 and 5.4 μg L$^{-1}$, depending on temperature. This in turn resulted in *Cladophora* growth rates up to 2.5 times greater than those without mussels, and biomass densities of up to 1.9 times greater. The supply of dissolved P from mussels also increased the optimum temperatures for growth and biomass. Without mussels, growth rate is maximal at around 15°C, but with mussels the growth rate peaks at 19-20°C. This is because the ratio of gross photosynthesis to respiration, which is an index of net growth rate, is influenced by both temperature and SRP concentration, and higher SRP concentrations result in higher growth rates that counter the effects of temperature on respiration.

These observations have implications for the effects of climate warming and thermal plumes on *Cladophora*. In the past three decades the mean summer (June-August) nearshore water temperatures in Lake Michigan have risen from around 8°C to around 12°C, probably due primarily to changes in lake hydrodynamics related to shifts in wind regime [29]. 12°C is near the optimal growth temperature for *Cladophora*, and therefore if SRP concentrations remain constant, further temperature increases will likely have a minimal influence on *Cladophora* growth and biomass. However if, as our mussel model suggests, SRP excretion rates will increase with further temperature increases, then *Cladophora* production and biomass can also be expected to increase. At low SRP concentrations, Lake Michigan nearshore temperatures would have been above the optimum for *Cladophora* growth for much of August and September in 2006. However because mussel SRP excretion was likely greater during these warm months, the negative effect of warm temperatures on *Cladophora* growth rate may have been minimized. Indeed, measurements of *Cladophora* biomass at the standard monitoring station in 2006 (not shown) indicate that biomass continued to increase until temperatures approached 18°C, suggesting that *Cladophora* may have benefited from higher mussel SRP excretion rates at these temperatures.

In the natural lake environment, *Cladophora* growth and biomass are not only influenced by temperature and nutrient concentrations. Light is a third controlling factor that interacts with temperature and nutrients to influence growth rates. To determine how temperature might affect *Cladophora* production in the natural environment, the *Cladophora* and mussel models were linked and provided with in situ data collected from Lake Michigan in 2006 to assess the effects of temperature on *Cladophora* production at two depths – 3 m and 9 m. Input data included *in situ* photosynthetically active radiation and water temperature measured at 30 minute intervals, and soluble reactive phosphorus concentrations measured at weekly intervals. Parameters for the mussel model, including nearshore-offshore exchange rate, were the same as described above. For each depth, the linked models were run under three temperature scenarios: measured 2006 temperatures, 2006 temperatures + 5°C, and 2006 temperatures + 10°C. Results are shown in Figure 12-3.

At the shallower depth of 3 m, cumulative *Cladophora* biomass increased with temperature. Over the May – October growing period, the biomass produced under the +10°C scenario was 30% greater than that produced under the 2006 temperature scenario. At the deeper depth of 9 m there was a different response. Productivity responded positively to a temperature increase in the spring, but negatively after early August, and over the entire growth period there was greater biomass production under the 2006 temperature scenario than under the +10°C scenario. This demonstrates the complexity of the *Cladophora*-temperature relationship. Not only does mussel SRP excretion modulate the *Cladophora*-temperature interaction; the response to temperature is also a function of light. At lower light intensity *Cladophora* has a slower P assimilation rate, and therefore it is less able to take advantage of SRP excreted by mussels. As a result, mussel P excretion has less of an influence on the *Cladophora*-temperature relationship, and *Cladophora* growth rate at 9 m is inhibited by the warm temperatures in late summer.

## Conclusion

The model results presented here assume that the interactive effects of temperature, nutrients and light on *Cladophora* growth in Lake Michigan are similar to those built into the original *Cladophora* model (Canale and Auer 1982a). The parameterization of the mussel model is based on recent measurements, but experimental temperatures did not exceed 22°C, and we have made assumptions about hydrodynamics processes that will influence the relationship between mussel P excretion and nearshore SRP concentration. Therefore these results should be seen as more qualitative than quantitative. However, despite the quantitative uncertainties, the main findings of this exercise remain valid. Any predictions of the effect of temperature on *Cladophora* cannot consider *Cladophora* temperature physiology alone, but must account for the interactive effects of temperature, nutrients and light. The optimal mussel SRP excretion temperature is much higher than the optimal *Cladophora* growth temperature. As a result, SRP availability to *Cladophora* increases with temperatures above 15°C. Net growth rate is a function of both temperature and SRP concentration. If temperature increases while [SRP] remains constant, maximum growth will be near 15°C. But if dreissenid mussels are present, SRP concentration can be expected to increase with temperatures above 15°C. As a result, the effective optimal growth temperature is increased. Our model simulation results in an optimum growth temperature of about 19°C. This is based on a mussel density of 5,500 $m^{-2}$, a bottom coverage of 70%, and a relatively high nearshore-offshore exchange coefficient of 0.5 $day^{-1}$. At greater mussel densities or lower nearshore-offshore exchange rates, the optimal growth temperature will be even greater than 19°C.

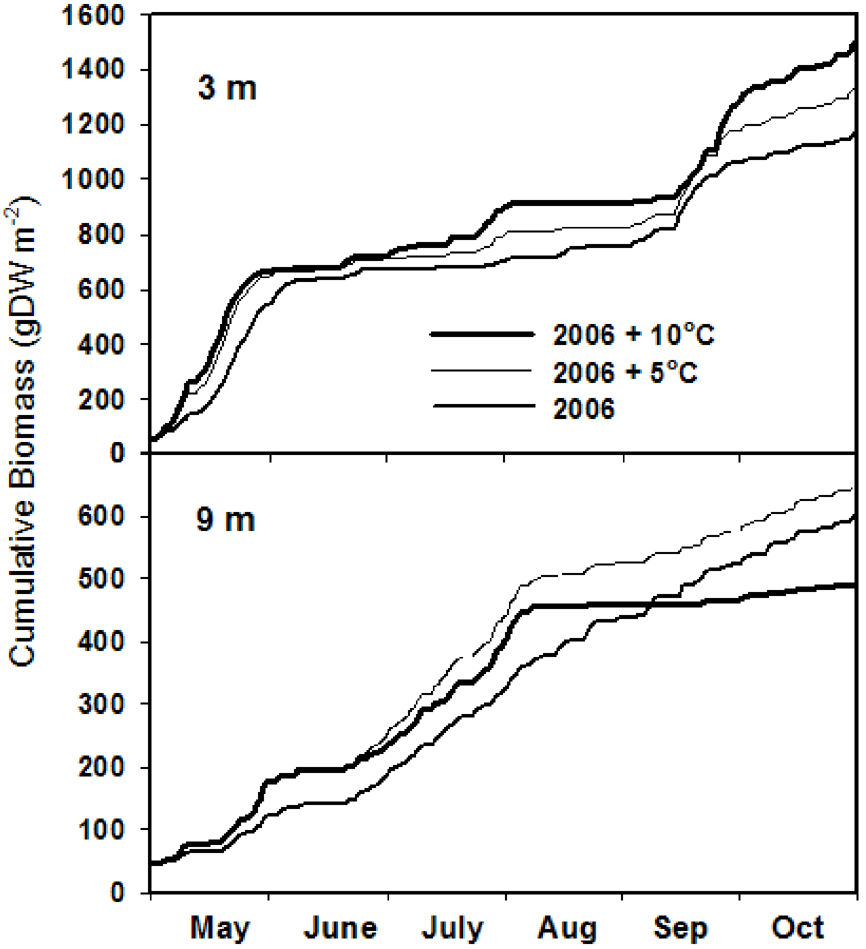

**Figure 12-3**
**Simulated Cumulative *Cladophora* Biomass at Depths of 3 m and 9 m under Three Temperature Scenarios. Measurements of *in situ* Irradiance, Temperature and SRP Concentration Made at the Standard Lake Michigan Nearshore Monitoring Station were used for Input to the Model**

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# 13

# TELEMETRY AND OTHER TOOLS FOR EVALUATING IMPACTS OF THERMAL DISCHARGES ON FISH

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## Introduction

There is a renewed focus on the potential impacts of thermal power plants on fish. This renewed focus is rooted in at least the following factors: legal challenges to how the Clean Water Act Section 316 has been enforced [1] that have resulted in recent requests and requirements for empirical study of those potential impacts; aspects of the Energy Policy Act of 2005, along with continually increasing energy demands that have resulted in serious planning for new nuclear power (and other types of) electric power generation; and perhaps, due to lack of success in many fish restoration programs [2]. In the decades since thermal discharge issues were first extensively studied, new sampling, monitoring, and analytical tools have been developed and many of the older tools have been substantially improved. Due in part to the regulatory environment for the hydropower sector of the industry, and due to the fact that in many systems developed for hydropower there are protected migratory species, much of the work in power plant impacts over the past 20 years or so has been in the hydropower arena. In fact many of the new tools and advancements have come about through hydropower plant environmental impact investigations. Because we have worked extensively in the hydropower arena with many of the tools included herein, we were invited to participate in this symposium to assure that key technical professionals who are more focused in the thermal plant generation aspect of the business were aware of at least some of the newer tools and advancements. The tools now available should allow us to better understand the interactions of fish with thermal discharges (and with respect to cooling water intake effects) and how fish can be, and in some cases are impacted.

Sophisticated modeling techniques and visualization software, various platforms and applications of telemetry techniques, simple and inexpensive temperature loggers, new and improved physiological tests, satellite thermal imagery, and instruments that measure flow velocity and vectors, and improved data analyses tools are now available to assist in the evaluation of the potential impacts of thermal discharges on fish. Ideally, some combination of the available tools is utilized because typically no single tool will provide sufficient data to address all the likely questions. As with any empirical evaluation, the tools selected depend in large part on the objective(s) and experimental design. As an example, to evaluate whether a thermal discharge (or multiple discharges in a river) affects the emigration of migratory fish, a combination of one or more telemetry techniques combined with temperature data could provide very useful information. The telemetry data would describe the travel routes used by fish that move downstream, potentially the ‘thermal history’ during their emigration, and potentially what the timing and even survival is to a downstream point of interest; temperature data from an array of thermistors (as a more simple approach) or a hydrothermal model (as a more sophisticated and flexible approach) would supply data to help evaluate whether fish avoid the plume, what thermal regime they experience, or how long they are exposed to it. Another example is using telemetry along with standard techniques for growth analyses to evaluate the use of a thermal plume area by resident fish and whether growth is affected by time spent in thermal areas. Telemetry based data on physiological variables can also be collected and evaluated with respect to presence in a thermal plume. Acoustic tags now allow for three dimensional positioning of tagged fish in a monitored volume. Coupling high resolution positional data with a GIS map or model output of thermal plume data can be very powerful in an assessment of the impacts of elevated water temperatures. Some of these tools are not new, however the capabilities and sophistication of many have been improved so that much more information can be obtained than was possible even ten years ago. In some cases, laboratory experiments may be preferable or necessary. Telemetry based pilot or coordinated studies can be used to parameterize laboratory experiments for such things as physiological assessments. Along with hardware improvements, software and analysis techniques have also been improved or refined. These are but a few applications of various tools and combinations of such that are available to investigators.

## Today’s Tool Box

This treatment is not exhaustive for the available tools or a thorough review for the tools that are presented. The intent is to provide an update, based largely on experience in other arenas such as hydropower project impacts assessment, of the tools now available for such research and monitoring efforts. This paper does not review the conventional fisheries and water quality/habitat assessment tools, but focuses on those that have been newly developed or improved since the previous extensive studies on thermal plants were conducted in the 1960s – 1980s. In most cases, the newer tools[1] require extensive training and experience to use effectively. Additional information can be found via the cited literature, via the cited websites below or internet searches, or by contacting the author.

## Fish Behavioral Related Data

### *Biotelemetry*

Various types of telemetry have been used for decades [e.g., 3, 4, 5]. In the early days of telemetry work, there were many limitations to what information could be collected. In general, juvenile fish could not be tagged because the tag package was too large. Some of the first attempts to radio tag juvenile American shad (*Alosa sapidissima*), a species that is extremely sensitive to handling, were conducted by Royer et al [6]. The large majority of telemetry data was also collected by manual tracking of fish via boat, vehicle, or airplane. Advancements in battery technology, electronic component miniaturization, and data storage capability have largely overcome these limitations.

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[1] The use of a company, brand, or specific model is not an endorsement of that item.

Telemetry techniques are very powerful at providing detailed data from individual fish. With respect to the assessment of power plant impacts, most radio telemetry studies focus on fixed monitoring stations positioned at strategic locations within the study area. We typically advocate for some level of manual tracking (usually by boat) to supplement the data collected as fish pass the fixed location monitors. Manual tracking data can be especially useful if tagged fish do not arrive at fixed monitoring stations in the anticipated time frame, or not at all, and if there are extensive reaches between fixed monitoring stations wherein more detailed information could be useful. Fixed monitoring locations typically consist of an antenna (aerial and/or underwater), a data logging radio receiver, and a power source. One attractive possibility with today's hardware and software is that in some locations, receivers can be set up to off load the data remotely via cellular phone, radio connection, or satellite link. This can provide a significant labor savings if monitoring sites are remotely located, geographically distant from one another, and/or there are many data-logging receivers in the study. Since the early thermal effluent studies were completed in the 1960s – early 1980s, some of the significant advances in radio telemetry techniques include:

- Data logging receivers
- Coded tags that allow for hundreds of tags on the same frequency. Prior to this development, tags were differentiated by the pulse pattern assigned to frequencies. Receivers could only monitor one frequency at a time, so scanning of frequencies was necessary for pulsed tags. This can result in missed detections in some cases. A limitation with coded tags to date is that when multiple fish with tags on the same frequency (but different codes) are essentially in the same location at the same time, a "collision" occurs. In essence, the multiple codes cannot be discerned by the receiver, so it logs the signals as noise. Experimental design can help to limit or eliminate tag collision issues.
- Miniaturization of tags. As examples, Lotek Wireless makes a NanoTag as small as 13.5 mm x 5.3 mm x 3 mm, with a weight of 0.37 g in air. Advanced Telemetry Systems provides one as small as 12 mm x 6 mm x 12 mm and 0.5 g.
- Multi-parameter tags. Today investigators can monitor thermal exposure history of fish [e.g., 7, 8], depth of fish [e.g., 9], physiological correlates of metabolism [e.g., 10, 11], dissolved oxygen concentration or saturation at the tagged fish's location [12], whether the fish is alive or dead [e.g., 13], velocity sensors [9].
- Three dimensional position of fish. A major advancement in recent years has been the development of three dimensional positioning systems of fish [e.g., 14].
- Digital Spectrum Processing. Allows near simultaneous detection of many tags on multiple frequencies and antennas.
- Post-processing software including proprietary versions to compile, review, filter, analyze logged data, GIS based analyses, and various visualization tools to help interpret and present complex information.

Radio, sonic, and acoustic telemetry techniques have all advanced significantly over the past 10-15 years along with the advancements in batteries, computers, software, and component miniaturization. Whereas Neill et al. had to rely on circumstantial evidence to estimate exposure to a thermal plume, today such exposure could be monitored directly via biotelemetry techniques [15]. Radio and sonic telemetry aspects are well covered in fisheries literature, so most of the focus of this paragraph will be on acoustic telemetry. This technique was developed to position tagged fish in three dimensions (3D) in a monitored volume. Under good environmental conditions, the resolution is often within 1 meter. Hydroacoustic Technology, Inc. (HTI, Seattle, WA), Vemco (Halifax, Nova Scotia), and Lotek Wireless, Inc. (Newmarket, Ontario) have systems that facilitate 3D positioning of fish. The HTI system is analogous to a global positioning system in that the acoustic tag (attached to or inserted in fish) emits an acoustic signal that is detected by an array of hydrophones (analogous to the satellites array). In simplistic terms, algorithms resolve the 3D location of the tag by considering the differences in time that it takes (and therefore the distance) the acoustic signal to reach each of the hydrophones. The burst rate of the tag signal can be set within bounds to either get finer movement resolution or extend the tag life (i.e., slower burst rate extends battery life). Another approach to 3D positioning is to estimate the 2D ($x$ and $y$) position and then through a pressure sensor tag, get the $z$ dimension, or depth.

Obtaining 3D positions of fish has been extremely useful in evaluating the migratory approach routes toward hydropower projects [e.g., 16, 17, 18], how fishway attraction flow nets affect fish (by comparing 3D tracks with the flow net data), among other important uses. With respect to thermal discharge plumes, a 3D track of fish moving through or past a plume is possible. This can be very useful for evaluating thermal exposure and migration delay or other issues. This author is not aware of any 3D acoustic tag studies have been conducted to evaluate fish interactions with thermal discharge plumes, however we have recommended this approach for one nuclear project that is being required to evaluate thermal plume impacts to anadromous fish. Three dimensional tracking of fish will likely become a popular approach to the evaluation of thermal discharges on fish.

One other potential telemetry tool is being supported by federal government organizations in the Pacific Northwest. It is called the juvenile salmon acoustic tracking system (JSATS) [19]. To date there have been research and development type projects over several years, but to my knowledge it is still in the development phase and no peer reviewed primary published literature is available and no data have been made readily available.

### Hydroacoustics

Hydroacoustic techniques for power plant fisheries applications have been used for approximately 30 years or so. In contrast to biotelemetry techniques that focus more on individual fish, hydroacoustics can often provide high sampling power for evaluation of fish populations or distribution. Essentially there are two basic approaches – mobile tracking and fixed aspect monitoring. The former can work well to estimate fish abundance and distribution within a body of water; the latter is often used to evaluate migratory fish passage at hydropower project with respect to proportional route selection, entrainment rates, and where in the water column the entrainment or fish passage occurs. Advancements in transducers over the past two decades have resulted in dual beam, multi-beam, and split beam systems. All have specific applications. Brandt [20] provides a thorough review of hydroacoustic methods. With respect to evaluations of the impacts of thermal plumes on fishes, hydroacoustic techniques could provide powerful sampling approaches to fish spatial distributions relative to water temperatures/plume thermal gradients.

### *Dual Frequency Identification Sonar (DIDSON)*

The DIDSON is some times called an acoustic camera. The DIDSON is a high tech sonar instrument that uses 48 (long range) or 96 (short range) individual narrow beam transducers to generate a very detailed sonar image. The field of ‘view’ is 29 degrees. The images are often so clear and vivid that they appear to be video, hence the name acoustic camera. The DIDSON is a relatively new tool and was developed by University of Washington Applied Physics Laboratory for use by the U.S. Navy. The Navy uses it for surveillance, inspection, and perhaps other uses. For fisheries applications, it can be very useful to obtain detailed behavioral information in a small localized volume. Because it is an acoustic instrument, it can be used effectively in no light situations including extreme turbidity. Besides viewing fish behavior, it can be used to inspect structures and several other applications. The limitations include increasing ineffectiveness with turbulence (air bubbles make good acoustic targets, or ‘noise’ in this case) and due to the 29 degree view, in my opinion it has limited value for enumerating fish passing by or through a structure. It does have great value as a supplemental tool to one or more of the others discussed herein. Interesting example video clips can be viewed at www.soundmetrics.com.

## Environmental Data

Several relatively new tools have been developed within the past decade or so that have a great deal of utility for evaluating thermal plume impacts on fish. Datalogging temperature monitors have greatly simplified the task of collecting accurate water temperature at frequent intervals and over extensive volumes simultaneously. Sampling frequency is user defined. Accuracy can be ±0.2 degrees Celsius (e.g., Onset Stowaway Tidbit). Dunham et al. [21] provide useful advice on selecting temperature dataloggers and how to use them effectively. Data as input to complex 2D or 3D hydrothermal models can be readily collected with these instruments. The cost of these, depending on brand and specifications can be as low as $30-40 U.S. up to $200-250 U.S. Time efficient means to download data have been developed by the various manufacturers so that all in all, they are an extremely cost effective tool for gathering data that are critically important.

Another relatively new tool is the acoustic Doppler current profiler (ADCP). This instrument can measure current velocity at intervals over the full water column or it can be deployed horizontally. It uses an array of acoustic transducers to ‘ping’ the water column. The acoustic waves hit particles in the water and return as echoes. In a simplistic description, particles that are moving away from the transducer have a lower frequency than those moving toward the transducer. This difference results in a Doppler shift and the instrument can translate that into current velocity. The instrument can be set in a fixed position, or a series could be placed in an array; it can also be towed by a boat or remotely operated vehicle (ROV). At least one company has available a wireless version that can be used on an ROV. The applications can be to estimate stream discharge, current velocity profiles near intake or discharge structures, to better understand the attraction flow net at fish passage entrances, and likely for at least several other useful applications.

Infrared thermal imaging has become a useful tool to evaluate the extent and shape of thermal discharge plumes, or for evaluation of stream habitats by determining the influence of tributaries, subsurface springs (hot or cold). Thermal imaging will only estimate surface temperature, so it cannot fully delineate a thermal disharge plume. However, this tool can be useful for understanding the extent of the plume. Images are collected by flying over the waterbody. The data are color coded for differences in temperature to provide a graphical presentation that can be coupled with GIS data layers for context. Once mobilized, a crew can collect thermal imaging data quickly. As an example, Dunham et al. [21] covered 65 miles of stream in 1.5 hours with a helicopter. Svejkovsky et al. [22] provide specific examples of thermal plume imagery at the San Onefre Nuclear Generating Station in California. Their paper provides more detail on this valuable tool.

## Potential Issues At Thermal Generating Stations

Some of the questions below are not new (e.g., see [23, 24]). However, when initial studies to address such questions were conducted soon after the Clean Water Act was passed, the suite of tools available to investigators was much more limited. Not surprisingly, the development of computer processing power and miniaturization of components has facilitated much of the development of the tools available today. Following are some potential questions related to impacts of thermal discharges on fish. Suggestions on how to answer the posed questions are provided.

One of the first aspects may be defining the extent of the thermal discharge plume and the temperature gradients for various environmental conditions such as flow, ambient water temperature, atmospheric conditions, and various combinations of each of these. This task may not be as simple as one might think. Such factors as atmospheric cooling or heating, additional thermal discharges, watershed characteristics, and perhaps other factors can complicate the definition of the thermal plume. Collecting temperature data from a matrix of locations (transects with multiple depth nodes) upstream and downstream of the discharge location is a fundamental step. However, in some locations, that may not be nearly enough to define the extent and gradients of the plume. Various modeling techniques (e.g., three dimensional time varying, two dimensional) may be helpful or necessary to refine the definition of the plume, especially to cover a range of varying environmental conditions [e.g., 25]. There are now at least a few high quality, reasonably priced temperature dataloggers that can be used to collect empirical data. Also, a newer approach that allows precise mapping of surface water temperatures includes thermal imaging [e.g., 22, 26, 27]. This may be appropriate and useful for covering extensive areas of waterbodies, but may have some limitations if thermal stratification is an important aspect of your evaluation.

Assume the fish of interest are anadromous. Potential questions (Q.) could be:

Q: Do fish pass the project without being impinged or delayed due to the thermal plume?

- Minimum data needs include **environmental** (river flow, river temperatures, plume definition and gradient); **biological** (fish migration timing, impingement estimates/census); plant operations; remote sensing (via telemetry, the date/time that tagged fish enter and leave the study area, whether tagged fish passed through, around, or under the thermal plume, and what other factors may cause a slow down to migration rates).

- Approach – radio, sonic, or acoustic tag actively migrating fish; install telemetry monitoring system that bounds the study area on upstream and downstream sides (and possibly at the lateral extent of the plume); count tagged fish impinged on screen system; place travel time through the study area into context with other studies; be careful with statistical analyses where behavior, delay, and other nebulous terms play into the evaluation.

Q: What is the exposure of migrating fish to the increased water temperatures?

- Minimum data needs include **environmental** (river flow, river temperatures, plume definition and gradients); **biological** (either specific travel routes of fish passing the study area or remotely transmitted real time data on thermal exposure; date/time tagged fish enter and leave study area).
- Approach – depending on the size of test fish, this could be conducted by either using radio tags with temperature sensors to log the actual thermal exposure of fish while passing through the study area, or by using three dimensional acoustic tags to accurately trace the travel route through the study area and overlay that with the thermal plume definition data during the period when the fish moved through the study area.

Q: Do adult pre-spawned fish exposed to the thermal plume find suitable spawning areas and spawn successfully?

- Minimum data needs – **environmental** (river flow, river temperatures, plume definition); **biological** (migratory run timing, likely spawning areas (if available), sex ratio of tagged population (if possible))
- Approach – If possible, tag fish throughout the migratory run period. Radio tag fish at a location sufficiently far downstream so as to not bias the upstream migration route through the study area. If spawning areas are well defined, set up fixed monitors to log the arrival date/time of pre-spawned fish, or use manual tracking to follow fish to spawning areas. Use manual tracking to pinpoint spawning locations and activity. Verify spawning success (or not) with egg collection or observation techniques, or via actual observations of spawning behavior.

Q: Do emigrating juvenile fish arrive in the estuary in adequate physiological condition to tolerate saline waters, or conversely does exposure to the thermal plume result in reversion from the smolt condition?

- Minimum data needs – **environmental** (river flows and temperatures); **biological** (migration run timing, periodic locations of test fish throughout the study period, possibly seawater challenge tests or other physiological tests)
- Approach – This can be a very difficult evaluation. Important considerations include distance to the estuary, definition of other factors that could affect safe and timely arrival in the estuary, thermal and migratory history of fish prior to reaching the study area, and perhaps other watershed/project specific considerations. Tagging enough fish to have an adequate sample size to obtain robust results once the fish reach the estuary is an important consideration. Inclusion of laboratory tests to supplement field study results may be valuable.

Use of sonic tags or a combination radio/sonic tag would be the best approach for the field evaluation. Once fish reach saline waters, only the sonic signal transmission will be effective.

Ideally, once tagged fish reach the estuary, a sample of them could be recaptured for evaluation of their physiological state. If this is not feasible, a supplemental laboratory test that mimics the in-field experience of tagged fish (i.e., duration of migration to the estuary, similar thermal exposure regime in the lab as what the in-field tagged fish experienced, etc.) could be used to evaluate the physiological state at the point when fish enter the estuary. A seawater challenge is one way that physiological state could be evaluated.

For potadromous or resident species, some questions might be:

- Minimum Data Needs – **environmental** (temperature history for plume and control volumes); **biological** (otolith, scale, or other means of measuring growth, knowledge of (or assumption about) where collected fish have spent time)
- Approach – Once past the likely conclusion that fish in warmer water will grow at a greater rate than those in colder water, all else being equal, the question gets interesting if such concepts as fitness or selection comes into play because of a greater rate of growth or extended active season. For example, are fish that reside in the plume, at least part time, more fit with respect to contribution to the population gene pool, because they grow at a greater rate, or because they can feed for longer periods of the year than fish of the same waterbody that are not influenced by the plume? Another aspect is that recreational fishermen will likely hone in on any significant differences in fish size and 'catchability'. This could result in differential exploitation and perhaps even a reduction in contribution to the population gene pool. To evaluate this, some combination of tools would be ideal.

Q Does exposure to the thermal plume affect fecundity or other fitness characteristics?

- Minimum Data Needs – **environmental** (definition of plume under various conditions of flow etc.); **biological** (life history information on species of interest, for fitness – growth, condition, or other measure of fitness, perhaps even gene flow information)
- Approach – Compare thermal exposure history of fish from outside the plume with that of fish that reside or spend considerable time moving in and out of the plume. These data could be collected with temperature sensitive telemetry tags. Other factors that might confound or bias the fecundity or fitness evaluation would need to be identified (and ideally controlled or adjusted for). Use standard techniques to evaluate fecundity or fitness.

Q: Does the thermal plume create refugia?

- Minimum Data Needs – **environmental** (definition of the plume, knowledge of bathymetry and habitat structure would be useful); **biological** (knowledge of general behavioral traits for species of interest; movement and behavioral data as collected by telemetry)
- Approach – use 3D acoustic, radio, or possibly sonic telemetry to characterize movement patterns on diel or other time scale. Releasing tagged fish near but outside the plume may provide some interesting insight depending on whether they move back into the plume readily. Tagging fish collected in the plume and outside the plume, releasing them at the same location, and then comparing behavior would be interesting. 3D acoustic telemetry could pinpoint resting or frequently visited locations.

Q How close do fish get to the intake trash racks and what is their behavior like in that vicinity?

- Minimum Data Needs – **environmental** (none necessary, but ADCP information on current velocities and vectors would be helpful, water temperature always has some value); **biological** (what species and sizes of fish frequent the area near the intake)
- Approach – Use ADCP to map current velocities and vectors near the intake. Use DIDSON acoustic camera to 'observe' fish in the vicinity of the intake. If information on movements is desired, use 3D acoustic tag system to get finescale positions and movement tracks, or use radio telemetry to get more generalized movement information.

## Useful Websites

**www.normandeau.com** – Normandeau Associates Environmental Consultants - application of many of the tools described herein

**www.lotek.com** – Lotek Wireless, Inc. - radio and acoustic telemetry equipment

**www.htisonar.com** – Hydroacoustic Technology, Inc. - acoustic telemetry and hydroacoustic equipment and services

**www.vemco.com** – VEMCO - acoustic/sonar telemetry equipment

**www.atstrack.com** – Advanced Telemetry Systems - radio telemetry equipment

**www.biosonics.com** – BioSonics – hydroacoustic equipment and services

**www.oceani.com** – Ocean Imaging – thermal imaging

**www.kema.com** – KEMA – THREETOX modeling

**www.didson.com** – Sound Metrics – DIDSON (dual frequency identification sonar)

**www.sonotronics.com** – Sonotronics – acoustic telemetry equipment

**www.esri.com** – GIS tools and software

**www.simrad.com** – Simrad – hydroacoustic equipment

**www.onsetcomp.com** – Onset – temperature dataloggers

**www.rdinstruments.com** – ADCP instruments

**www.sontek.com** – ADCP instruments

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# 14

# ESTIMATES OF FORCED EVAPORATION FROM THERMOELECTRIC POWER PLANTS THAT UTILIZE ONCE-THROUGH COOLING SYSTEMS

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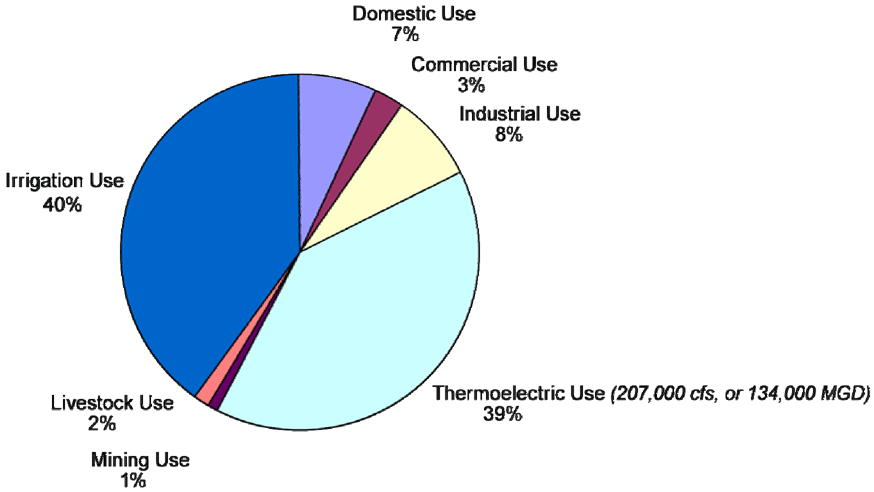
## Introduction

### *Background*

With the ever increasing demand for water in the United States, it is becoming increasingly important to more effectively manage this precious resource. Figure 14-1 shows both freshwater withdrawals and consumptive uses by major sectors of our society (Electric Power Research Institute, 2005). For water withdrawals, irrigation use (40 % of total withdrawals) and thermoelectric use (39% of total withdrawals, primarily for cooling water) are by far the largest two categories. However, for consumption, irrigation use (82 % of consumptive use) is far larger than thermoelectric use (3 %, primarily evaporative losses). The thermoelectric consumptive uses are approximately 3000 million gallons per day (mgd). The United States Geological Survey [1] made these estimates from data published by the Energy Information Administration (EIA) among others. For plants using once through cooling systems, estimates were "based on coefficients ranging from 1 to 100 percent of withdrawals" [1]. One reason that this coefficient-based approach is used is that the EIA's cooling water data base (*http://www.eia.doe.gov/cneaf/electricity/page/eia767.html*), from which the USGS's estimates were made, calculated consumptive losses based on the difference between withdrawals and discharges. For power plants that use once-through cooling systems, these differences are most often zero, or otherwise very small. Table 14-1 shows examples from 12 power plants contained in the EIA cooling water database. The plants shown in the table use a variety of cooling systems including once-through fresh water (OF), re-circulation induced draft (RI), and re-circulation forced draft (RF). The OF type cooling systems are highlighted in yellow, and the reported consumption (calculated as the difference between withdrawals and discharge) are either zero or very near zero. Thus the evaporation that occurs subsequent to discharge (called forced evaporation) is not accounted for in the EIA database for power plants with once-through cooling systems, and is approximated in the USGS report [1] as described above. A more recent study [2] noted the same constraint associated with the EIA database.

**a) Freshwater Withdrawal**

**489 billion $m^3$ per year (342 billion gallons per day)**



**b) Freshwater Consumptive Use**

**146 billion $m^3$ per year (100 billion gallons per day)**

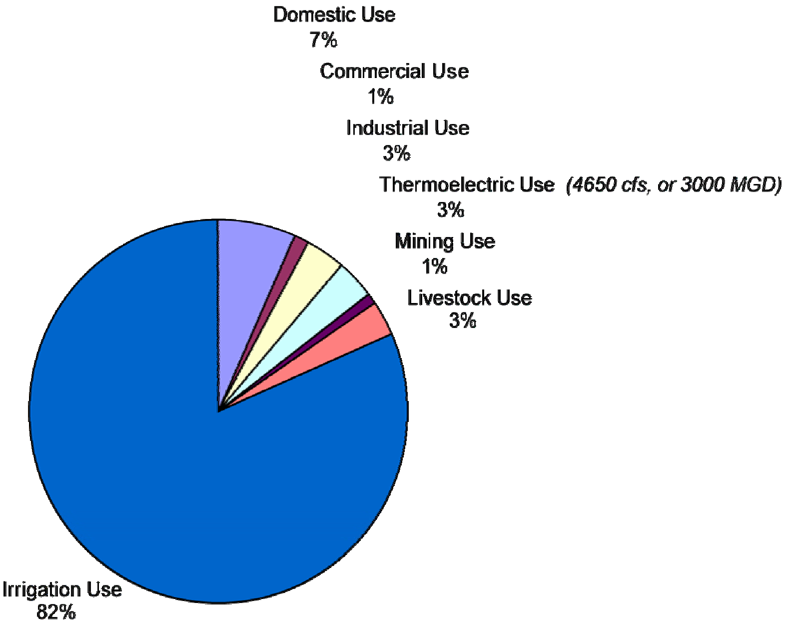


**Figure 14-1**
**Freshwater Withdrawal and Consumptive Use by Major Sectors of the Economy**

## Table 14-1
## Examples of Water Consumption Estimates for Power Plants that use once-through Freshwater Cooling Systems Based on Data from EIA 2002 Database

| Plant Name | County, State | Latitude/longitude | Primary fuel | nameplate capacity data are for year 2000, Mwe | Capacity factor | Generation,MWh | Heat Input, MMBtu | Heat Rate,Btu/kWh | # of generators | Cooling System type[a] | Withdrawal cfs | Discharge cfs | Consumption cfs | Cooling water source | Intake rate at 100%, cfs |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| North Omaha | Douglas, NE | 41.3/95.9467 | coal | 644.7 | 0.594 | 3,352,984 | 38,903,722 | 11,603 | 5 | OF | 945.7 | 945.7 | 0 | Missouri River | 109 |
| | | | | | | | | | | OF | NA | NA | NA | Missouri River | 133 |
| | | | | | | | | | | OF | NA | NA | NA | Missouri River | 133 |
| | | | | | | | | | | OF | NA | NA | NA | Missouri River | 167 |
| | | | | | | | | | | OF | NA | NA | NA | Missouri River | 254 |
| Gadsden | Etowah, AL | 34.0136/85.9703 | coal | 138 | 0.421 | 509,008 | 6,193,201 | 12,167 | 2 | OF | 247.9 (both units) | 247.7(both units) | 0.2 (both units) | Coosa River | 264 |
| Glen Lyn | Giles, VA | 37.3697/80.8633 | coal | 337.5 | 0.601 | 1,777,752 | 21,028,075 | 11,828 | 2 | OF | 159.2 | 159.2 | 0 | New River | 192 |
| | | | | | | | | | | OF | 246.7 | 246.7 | 0 | New River | 343 |
| E C Gaston | Shelby, AL | 33.2442/864567 | coal | 2034.1 | 0.708 | 12,623,222 | 134,667,594 | 10,668 | 5 | OF | 276.1 | 276.1 | 0 | Coosa River | 305 |
| | | | | | | | | | | OF | 276.1 | 276.1 | 0 | Coosa River | 305 |
| | | | | | | | | | | OF | 300.6 | 300.6 | 0 | Coosa River | 338 |
| | | | | | | | | | | OF | 300.6 | 300.6 | 0 | Coosa River | 338 |
| | | | | | | | | | | RF | 30.7 | 13.8 | 16.9 | Coosa River | 858 |
| John Sevier | Hawkins, TN | 36.3767/82.9639 | coal | 800 | 0.741 | 5,193,401 | 53,301,416 | 10,263 | 4 | OF | 1007.7 | 1007.7 | 0 | Holston River | 1012 |
| Shawnee | McCracken,KY | 37.1517/88.7750 | coal | 1750 | 0.551 | 8,440,601 | 103,654,305 | 12,280 | 10 | OF | 1947.9 | 1947.9 | 0 | Ohio River | 2398 |
| Nelson Dewey | Grant, WI | 42.858/90/7925 | coal | 200 | 0.61 | 1,068,814 | 14,162,479 | 13,251 | 2 | OF | 111.3 | 111.3 | 0 | Mississippi River | 111 |
| | | | | | | | | | | OF | 111.3 | 111.3 | 0 | Mississippi River | 111 |
| South Oak Creek | Milwaukee, WI | 42.8014/87.8314 | coal | 1211.2 | 0.62 | 6,573,867 | 73,189,429 | 11,133 | 5 | OF | 440.3 | 440.3 | 0 | Lake Michigan | 440 |
| | | | | | | | | | | OF | 431.2 | 431.2 | 0 | Lake Michigan | 440 |
| | | | | | | | | | | OF | 414.6 | 414.5 | 0.1 | Lake Michigan | 440 |
| | | | | | | | | | | OF | 415.6 | 415.5 | 0.1 | Lake Michigan | 440 |
| Apache Station | Chohise,AZ | 32.0556/109.8861 | coal/gas | 559.1 | 0.706 | 3,459,141 | 37,032,772 | 10,706 | 6 | RI | 0.7 | 0.1 | 0.6 | Wells | 2 |
| | | | | | | | | | | RI | 3 | 0.5 | 2.5 | Wells | 5 |
| | | | | | | | | | | RI | 3 | 0.5 | 2.5 | Wells | 5 |
| Muskogee | Muskogee,OK | 35.7653/95.2883 | coal | 1889 | 0.626 | 10,352,028 | 117,874,777 | 11,387 | 4 | RI | 15.4 | 6.2 | 9.2 | Arkansas River | 469 |
| | | | | | | | | | | RI | 15.4 | 6.2 | 9.2 | Arkansas River | 469 |
| | | | | | | | | | | RI | 17.4 | 7.0 | 10.4 | Arkansas River | 469 |
| | | | | | | | | | | OF | 35.2 | 35.2 | 0 | Arkansas River | 159 |
| Gadsby | Salt Lake, UT | 40.7667/111.9292 | gas | 251.6 | 0.326 | 718,120 | 8,779,510 | 12,226 | 3 | RI | 0.2 | 0.0 | .2 | Jordan River | 2 |
| | | | | | | | | | | RI | 0.3 | 0.0 | .3 | Jordan River | 2 |
| | | | | | | | | | | RI | 0.7 | 0.0 | .7 | Jordan River | 4 |
| Colstrip | Colstrip, MT | 45.8844/106.9139 | coal | 2,146.00 | 0.769 | 14,461,408 | 161,015,266 | 11,134 | 4 | RF | 6.6 | 0.0 | 6.6 | Yellowstone River | 229 |
| | | | | | | | | | | RF | 5.7 | 0.0 | 5.7 | Yellowstone River | 229 |
| | | | | | | | | | | RF | 10.9 | 0.0 | 10.9 | Yellowstone River | 489 |
| | | | | | | | | | | RF | 15.2 | 0.0 | 15.2 | Yellowstone River | 489 |

*[a] OF = Once-though freshwater cooling system*
*RI = Recirculating, induced draft cooling system*
*RF = Recirculating, forward draft cooling system*

The interest in forced evaporation is at least partially fueled by regulatory concerns.
For example, the Great Lakes Water Management Initiative of 2005 (*http://www.cglg.org/projects/water/index.asp*) includes a ban on new water diversions from the Great Lakes basin, with some limited exceptions. This initiative could impact new power plant design if forced evaporation were to be considered as an export of water from the basin.

### *Meaning of Forced Evaporation*

Forced evaporation, as defined here, is the evaporation above background that would occur when heated effluent is discharged into a waterbody. This concept is illustrated in Figure 14-2 for a power plant that uses a once-through cooling system and discharges into a river. The arrows in the figure represent the evaporation rates at the locations shown, and indicate an enhanced rate of evaporation within the thermal plume. If it is assumed that the limit of influence of the thermal discharge is downstream of section AA, and upstream of section BB, then the forced evaporation is the difference in the rates of evaporation between these sections with and without the power plant operating. This is an idealized representation of forced evaporation, and a more realistic representation would consider that:

- The rate of forced evaporation is constantly changing, as the meteorological conditions, thermal loading, and ambient flow rates change.
- The forced evaporation estimates are not sensitive to the location of sections AA or BB, as long as they are upstream and downstream, respectively, of the influence of the thermal discharge.
- While conceptually it is not difficult to calculate forced evaporation over a time frame such as a year, generating enough data to make accurate estimates may be much more difficult.
- For open systems, such as illustrated in Figure 14-2 a water balance approach alone is not a feasible way to estimate forced evaporation. Generally, some level of thermal modeling that predicts evaporation will be needed.
- The process of recirculation of water without thermal loading may cause some amount of differential evaporation. However, such a situation is not considered here in the definition of forced evaporation.

### *Purpose of this Paper*

The major goals of this paper are:

1. To develop and apply an alternative method to that used by the USGS to estimate forced evaporation on an annual basis from power plants that use once-through cooling systems.
2. To develop and apply a simple theoretical framework that provides useful indicators associated with forced evaporation, such as the fraction of cooling water withdrawn for once-through cooling systems that undergoes forced evaporation.
3. To examine how forced evaporation might change in the future, with a focus on climate change effects.

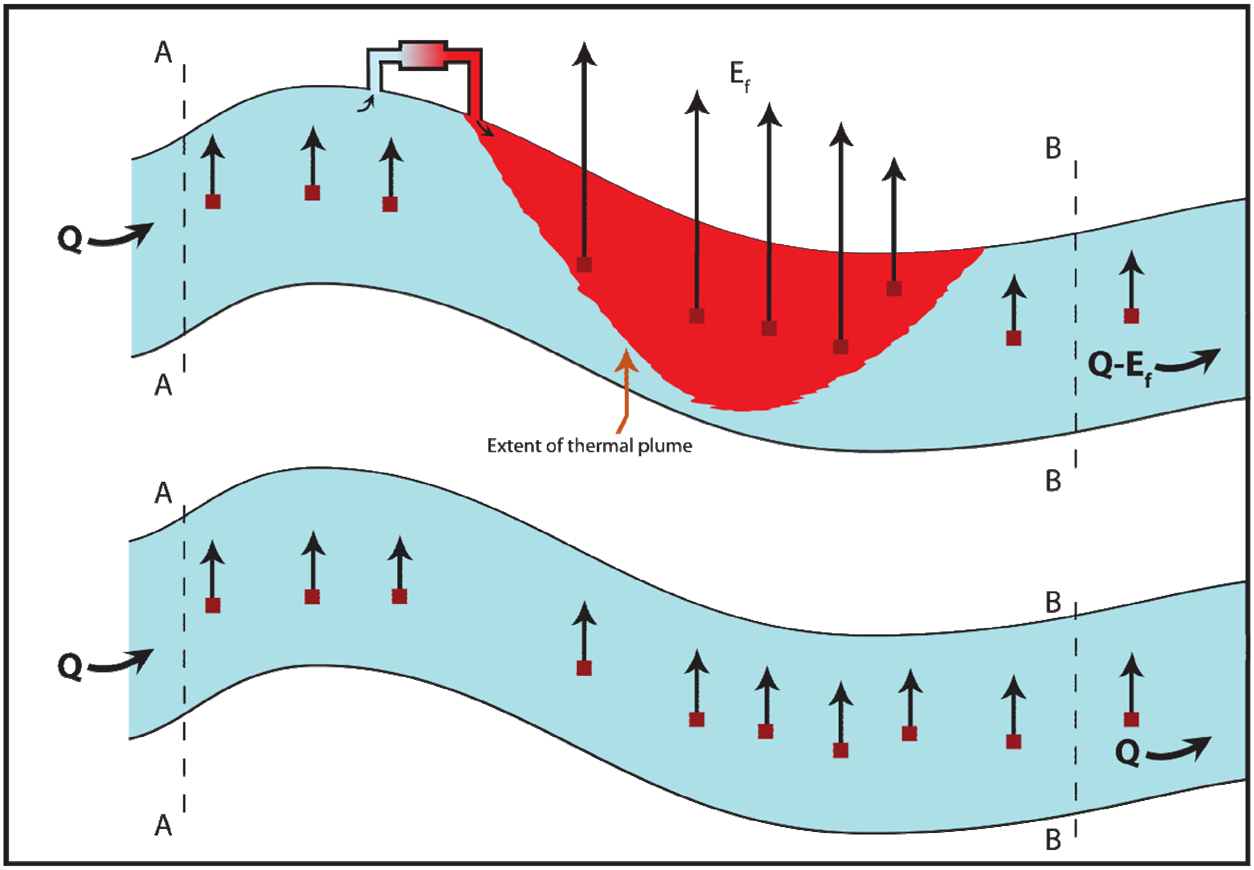


**Figure 14-2**
**Concept of Forced Evaporation from a Power Plant that uses a Once-Through Cooling System, where Heated Effluent is Discharged into a River**

Since there are a number of methods that can be used to estimate forced evaporation, some discussion is provided here on various approaches and why one particular approach has been chosen for this analysis. Forced evaporation could be calculated using one of the following approaches:

**Detailed thermal modeling** (with both energy and water conservation equations) that generate forced evaporation estimates at very high temporal (an hour or less) and spatial (at many locations within the thermal plume) resolutions that can be rolled up to generate annual estimates.

**Monitoring and field study data**. An extensive field program would be needed to generate these estimates, and would only be valid within the study period. The information could be used in conjunction with a modeling analysis, as described above.

**Remote sensing data**. These data help to delineate the spatial extent of the thermal plume, but are only applicable as snapshots in time.

**Water Balance studies**. These studies can be used to give direct estimates of forced evaporation, but are generally applicable to closed (recirculating) systems.

**Simplified Energy Balance**. This is the approach chosen here. It can be used to estimate long term average forced evaporation with relatively minimal data, and would be useful for scaling up to national estimates. The trade off is that such an approach will not provide high temporal or high spatial resolution results. Since, for this study, only annual estimates of forced evaporation data are calculated, the detail provided by the simplified energy balance study is sufficient. Further, an alternative method that performs detailed analysis on the thousands of power plants across the United States would be extremely expensive.

## Power Plants and Cooling Systems: A Nationwide Perspective

### *Overview*

As a first step in starting the analysis, data were collected to support this effort. The data used are primarily from the following two databases:

- eGRID 2006 V 2.1 (Emissions and Generation Resources Integrated Database): an EPA database of nationwide scope that contains information on electrical energy generation for hydroelectric and thermoelectric power plants across the United States. The present version of eGRID includes year 2004 statistics. The database does not include cooling water system information *(see: http://www.epa.gov/cleanenergy/egrid/index.htm)*. As an example of the types of information in the database, a summary of net generation and nameplate capacity by state, and generation mix from this database is shown in Table 14-2.
- National Energy Technology Lab(NETL) 2005 Coal Power Plant database (http://www.netl.doe.gov/energy-analyses). This database includes cooling system data from the EIA-767 database *(http://www.eia.doe.gov/cneaf/electricity/page/eia767.html)* and much more data as well.

Figure 14-3 shows the locations of the thermoelectric power plants from the NETL database. The different symbols denote different cooling system types. As shown in the figure, large numbers of once-through cooling systems are located on the Mississippi River, Missouri River, and Ohio River systems. Few once-through cooling systems are located in the western United States.

### *Summary of Data from NETL and eGRID Data Bases*

The number of power plants in eGRID is considerably larger than in the NETL database, which focuses on coal fired power plants only. A comparative summary of the two databases is shown below:

1) eGRID 2006 (year 2004 data):

    a) 4831 unique power plants

    b) Total nameplate capacity: 1,052,996 MW

    c) Total generation: 3,935 billion kWhr

**Table 14-2**
**Example Data from eGRID for Year 2004 State Resource Mix**
**(Source: eGRID2006 Version 2.1, April 2007)**

| | | | Generation resource mix (percent) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| State | Nameplate capacity (MW) | Net generation (MWh) | Coal | Oil | Gas | Other fossil | Biomass | Hydro | Nuclear | Wind | Solar | Geo-thermal |
| AK | 2,063 | 6,526,711 | 9.9 | 11.5 | 55.5 | 0.0 | 0.1 | 23.0 | 0.0 | 0.00 | 0.000 | 0.0 |
| AL | 33,295 | 137,328,137 | 54.4 | 0.2 | 11.6 | 0.1 | 2.8 | 7.7 | 23.0 | 0.00 | 0.000 | 0.0 |
| AR | 13,863 | 51,825,221 | 48.9 | 0.9 | 9.6 | 0.0 | 3.7 | 7.1 | 29.8 | 0.00 | 0.000 | 0.0 |
| AZ | 28,263 | 98,897,707 | 40.3 | 0.0 | 24.2 | 0.0 | 0.0 | 7.0 | 28.4 | 0.00 | 0.004 | 0.0 |
| CA | 64,910 | 192,809,576 | 1.2 | 1.2 | 51.7 | 1.0 | 3.1 | 17.3 | 15.7 | 2.22 | 0.296 | 6.2 |
| CO | 12,549 | 47,865,491 | 74.9 | 0.0 | 22.4 | 0.0 | 0.1 | 2.1 | 0.0 | 0.46 | 0.000 | 0.0 |
| CT | 8,454 | 32,562,800 | 13.1 | 5.1 | 24.9 | 1.7 | 2.9 | 1.4 | 50.8 | 0.00 | 0.000 | 0.0 |
| DC | 868 | 36,487 | 0.0 | 100.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 0.000 | 0.0 |
| DE | 3,610 | 7,502,542 | 63.3 | 9.6 | 22.2 | 4.8 | 0.0 | 0.0 | 0.0 | 0.00 | 0.000 | 0.0 |
| FL | 59,182 | 215,130,784 | 28.8 | 17.3 | 35.6 | 0.3 | 2.4 | 0.1 | 14.5 | 0.00 | 0.000 | 0.0 |
| GA | 38,487 | 126,725,244 | 63.1 | 0.7 | 4.8 | 0.0 | 2.5 | 2.2 | 26.6 | 0.00 | 0.000 | 0.0 |
| HI | 2,624 | 11,413,465 | 14.1 | 77.3 | 1.1 | 1.4 | 3.3 | 0.8 | 0.0 | 0.07 | 0.000 | 1.9 |
| IA | 11,643 | 43,240,158 | 81.6 | 0.3 | 1.9 | 0.0 | 0.3 | 2.2 | 11.4 | 2.41 | 0.000 | 0.0 |
| ID | 3,298 | 10,734,407 | 0.9 | 0.0 | 15.9 | 0.0 | 5.3 | 77.6 | 0.0 | 0.00 | 0.000 | 0.0 |
| IL | 51,438 | 191,864,321 | 49.2 | 0.4 | 1.8 | 0.2 | 0.3 | 0.1 | 48.0 | 0.04 | 0.000 | 0.0 |
| IN | 29,172 | 127,361,875 | 94.7 | 0.3 | 1.7 | 2.5 | 0.1 | 0.3 | 0.0 | 0.00 | 0.000 | 0.0 |
| KS | 11,731 | 46,780,900 | 73.9 | 1.8 | 1.8 | 0.0 | 0.0 | 0.0 | 21.7 | 0.76 | 0.000 | 0.0 |
| KY | 22,951 | 94,529,947 | 91.1 | 3.8 | 0.6 | 0.0 | 0.4 | 4.0 | 0.0 | 0.00 | 0.000 | 0.0 |
| LA | 28,391 | 91,692,052 | 25.8 | 4.5 | 44.3 | 1.6 | 3.3 | 1.2 | 18.6 | 0.00 | 0.000 | 0.0 |
| MA | 16,317 | 46,891,121 | 22.4 | 16.0 | 43.7 | 1.1 | 3.2 | 0.9 | 12.7 | 0.00 | 0.000 | 0.0 |
| MD | 13,380 | 52,052,768 | 56.1 | 6.3 | 2.3 | 1.2 | 1.3 | 4.8 | 28.0 | 0.00 | 0.000 | 0.0 |
| ME | 4,383 | 18,863,662 | 1.9 | 6.8 | 52.1 | 1.4 | 20.3 | 17.6 | 0.0 | 0.00 | 0.000 | 0.0 |
| MI | 33,323 | 118,374,150 | 58.0 | 0.8 | 12.7 | 0.2 | 2.2 | 0.4 | 25.8 | 0.00 | 0.000 | 0.0 |
| MN | 12,411 | 52,381,244 | 64.9 | 1.5 | 2.8 | 0.3 | 2.2 | 1.4 | 25.4 | 1.51 | 0.000 | 0.0 |
| MO | 20,612 | 87,222,401 | 86.0 | 0.2 | 3.3 | 0.1 | 0.0 | 1.4 | 9.0 | 0.00 | 0.000 | 0.0 |
| MS | 15,879 | 40,336,807 | 42.4 | 7.8 | 20.5 | 0.1 | 3.9 | 0.0 | 25.4 | 0.00 | 0.000 | 0.0 |
| MT | 5,214 | 26,776,348 | 65.0 | 1.6 | 0.1 | 0.1 | 0.2 | 33.1 | 0.0 | 0.00 | 0.000 | 0.0 |
| NC | 29,084 | 126,186,277 | 59.8 | 0.5 | 2.0 | 0.1 | 1.4 | 4.4 | 31.8 | 0.00 | 0.000 | 0.0 |
| ND | 5,021 | 31,341,612 | 94.0 | 0.1 | 0.0 | 0.2 | 0.0 | 4.9 | 0.0 | 0.68 | 0.000 | 0.0 |
| NE | 7,126 | 32,008,704 | 63.9 | 0.1 | 0.9 | 0.0 | 0.1 | 2.9 | 32.0 | 0.12 | 0.000 | 0.0 |
| NH | 4,543 | 23,892,859 | 17.1 | 8.1 | 22.6 | 0.2 | 3.9 | 5.5 | 42.6 | 0.00 | 0.000 | 0.0 |
| NJ | 21,680 | 55,680,410 | 18.4 | 2.5 | 28.4 | 0.7 | 1.6 | 0.0 | 48.4 | 0.00 | 0.000 | 0.0 |
| NM | 6,796 | 32,940,360 | 88.8 | 0.1 | 9.1 | 0.0 | 0.0 | 0.4 | 0.0 | 1.56 | 0.000 | 0.0 |
| NV | 9,812 | 37,553,015 | 48.6 | 0.3 | 43.6 | 0.0 | 0.0 | 4.3 | 0.0 | 0.00 | 0.000 | 3.2 |
| NY | 41,284 | 137,436,647 | 16.6 | 15.4 | 19.6 | 0.4 | 1.5 | 16.9 | 29.6 | 0.07 | 0.000 | 0.0 |
| OH | 37,004 | 148,075,516 | 86.6 | 0.9 | 0.9 | 0.2 | 0.3 | 0.3 | 10.8 | 0.00 | 0.000 | 0.0 |
| OK | 21,127 | 60,641,220 | 55.7 | 0.1 | 38.3 | 0.0 | 0.4 | 4.5 | 0.0 | 0.94 | 0.000 | 0.0 |
| OR | 12,548 | 51,526,306 | 6.9 | 0.1 | 26.2 | 0.1 | 1.4 | 64.1 | 0.0 | 1.20 | 0.000 | 0.0 |
| PA | 50,064 | 214,662,230 | 54.6 | 1.9 | 4.6 | 0.5 | 1.0 | 1.1 | 36.1 | 0.14 | 0.000 | 0.0 |
| RI | 1,997 | 4,837,893 | 0.0 | 1.0 | 98.9 | 0.0 | 0.0 | 0.1 | 0.0 | 0.00 | 0.000 | 0.0 |
| SC | 24,091 | 97,834,338 | 39.8 | 0.9 | 3.9 | 0.1 | 1.7 | 1.3 | 52.3 | 0.00 | 0.000 | 0.0 |
| SD | 2,826 | 7,510,214 | 48.2 | 0.3 | 1.5 | 0.0 | 0.0 | 47.9 | 0.0 | 2.10 | 0.000 | 0.0 |
| TN | 22,753 | 97,578,245 | 59.8 | 0.2 | 0.3 | 0.0 | 0.6 | 9.8 | 29.3 | 0.00 | 0.000 | 0.0 |
| TX | 107,170 | 380,659,334 | 38.5 | 0.6 | 47.3 | 1.2 | 0.3 | 0.3 | 10.6 | 0.82 | 0.000 | 0.0 |
| UT | 6,496 | 38,211,975 | 95.8 | 0.1 | 2.4 | 0.0 | 0.0 | 1.2 | 0.0 | 0.00 | 0.000 | 0.5 |
| VA | 24,487 | 76,378,503 | 46.3 | 5.1 | 7.1 | 0.4 | 3.4 | 0.5 | 37.1 | 0.00 | 0.000 | 0.0 |
| VT | 1,087 | 5,470,376 | 0.0 | 0.3 | 0.1 | 0.0 | 7.2 | 21.7 | 70.5 | 0.21 | 0.000 | 0.0 |
| WA | 27,420 | 101,547,794 | 10.3 | 0.1 | 8.3 | 0.3 | 1.6 | 70.5 | 8.8 | 0.15 | 0.000 | 0.0 |
| WI | 16,133 | 60,543,245 | 69.6 | 1.2 | 4.0 | 0.1 | 1.9 | 3.3 | 19.6 | 0.17 | 0.000 | 0.0 |
| WV | 17,269 | 90,021,580 | 97.3 | 0.3 | 0.3 | 0.2 | 0.0 | 1.8 | 0.0 | 0.18 | 0.000 | 0.0 |
| WY | 6,872 | 44,806,793 | 96.7 | 0.1 | 0.2 | 0.0 | 0.0 | 1.3 | 0.0 | 1.38 | 0.000 | 0.0 |
| **U.S.** | **1,052,996** | **3,935,071,766** | **50.2** | **3.0** | **17.4** | **0.5** | **1.4** | **6.6** | **20.0** | **0.34** | **0.015** | **0.3** |

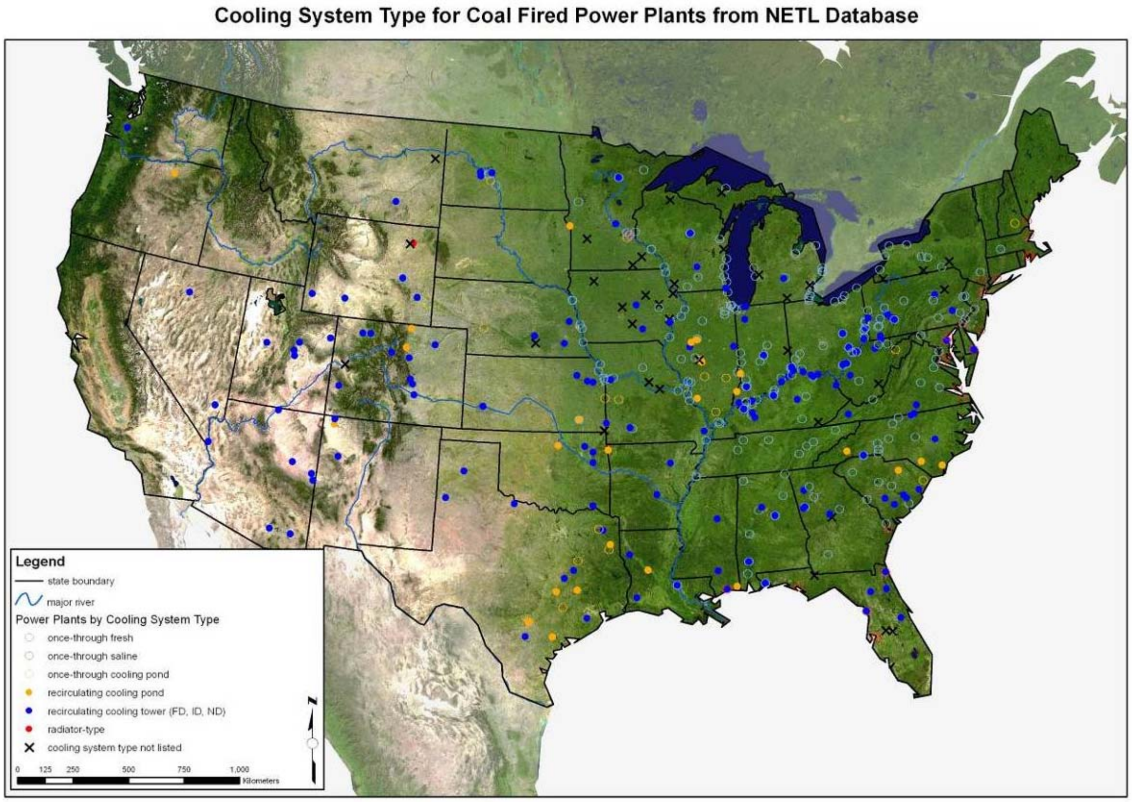


**Figure 14-3**
**Locations of Coal-Fired Power Plants Based on Data from the NETL 2005 Coal Power Plant Database**

2) NETL 2005 (year 2003 data):

  a) 361 unique power plants

  b) Total nameplate capacity: 264,531 MW

  c) Total generation: 1,597 billion kWhr

The summary from the NETL database does not include those power plants shown in Figure 14-3 where the cooling system type is not known.

For comparison with eGRID, the statistics on annual electricity production compiled by the Energy Information Administration (http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html) for 2004 were used. The EIA data indicate that 3,972 billion kWhr of electricity were generated in 2004, practically the same as in the eGRID database, thus confirming that eGRID provides a complete nationwide picture of electricity generation.

Figure 14-4 shows the distributions by nameplate capacity and MWhr, respectively, of power plants in each of the two databases. It is apparent that the NETL database consists of only larger power plants, while the eGRID data base includes both small and large power plants. For example, in Figure 14-4 a, only 40% of the power plants in the NETL database have a name plate capacity of 400 MWe or less, while in the eGRID database, 80% of the power plants are in the same capacity range.

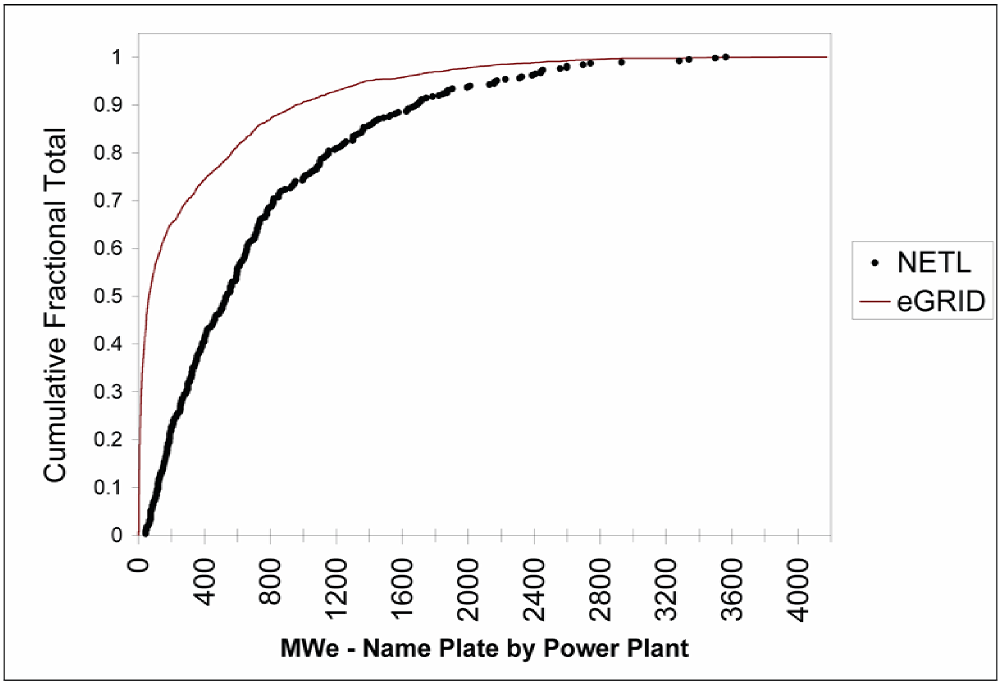
Figure 14-5 shows bar charts of the data from the NETL database. As shown in Figure 14-5 a the once-through fresh water system is the most common type (399), and exceeds the number of recirculating cooling systems combined (290). However, the name plate capacities for recirculating systems (Figure 14-5b) and the MWhr generated from recirculating systems (Figure 14-5c) exceed the comparable figures for once-through cooling systems. As expected, the water withdrawn from once-through freshwater cooling systems (71,000 cfs) far exceeds the amount withdrawn for all other cooling system types combined (Figure 14-5d). The amounts of water consumed by cooling system type are also shown in Figure 14-5d. However, no estimates on water consumption are available from the database for once-through cooling systems. A comparison of withdrawals and consumptive uses with the data shown previously in the USGS database is shown in Table 14-3.

## Estimates of Forced Evaporation on an Annual Timescale

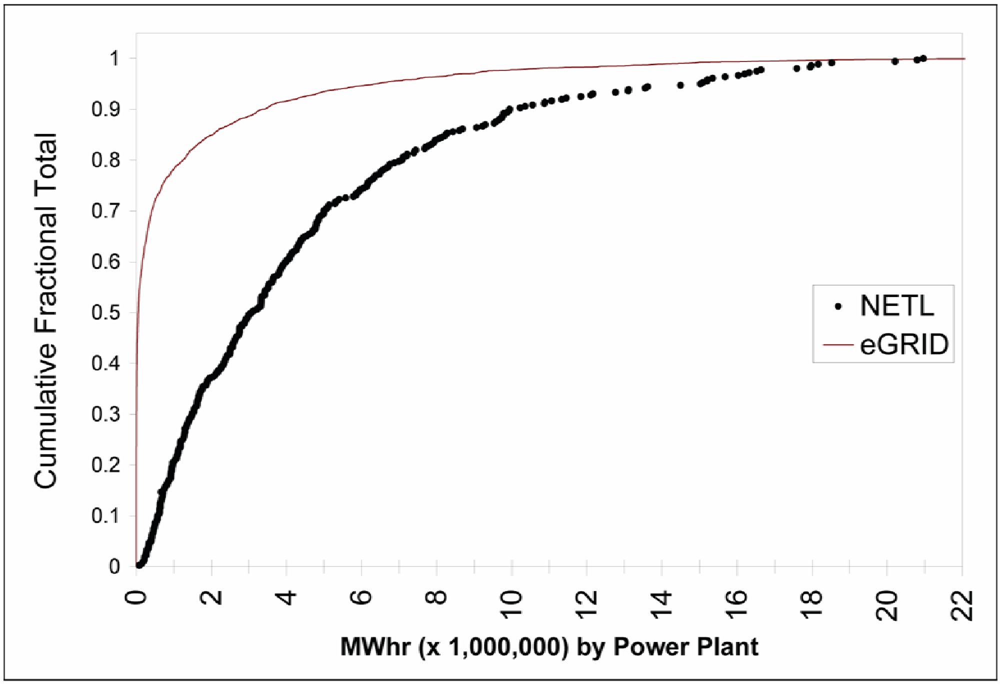
In this section estimates of forced evaporation for once-through cooling systems are made. Also, normalized indices are calculated, such as gal-evaporated/MWhr, or gal-evaporated/gallon-withdrawn. Such indices are often useful indicators of the significance (or lack of significance) of forced evaporation.

It is worthwhile to begin calculating estimates of forced evaporation ($E_f$), first assuming $\alpha_\Delta = 1$($\alpha_\Delta$ is the fraction of waste heat discharged to the receiving water that is converted to latent heat). This assumption produces an upper limit estimate of $E_f$. As will be shown subsequently, $\alpha_\Delta$ typically ranges between 0.4 to 0.6, but depends on season and location within the United States. Results of assuming $\alpha_\Delta = 1$ are shown in Figure 14-7. The horizontal axis is the net electrical energy generated annually (MWhr) by a single power plant. These data can be found in databases such as in eGRID. Estimates for forced evaporation are shown for a large range of MWhr, and three typical types of power plants:

- Steam cycle fossil fueled power plants
- Steam cycle nuclear power plants
- Combined cycle natural gas power plants



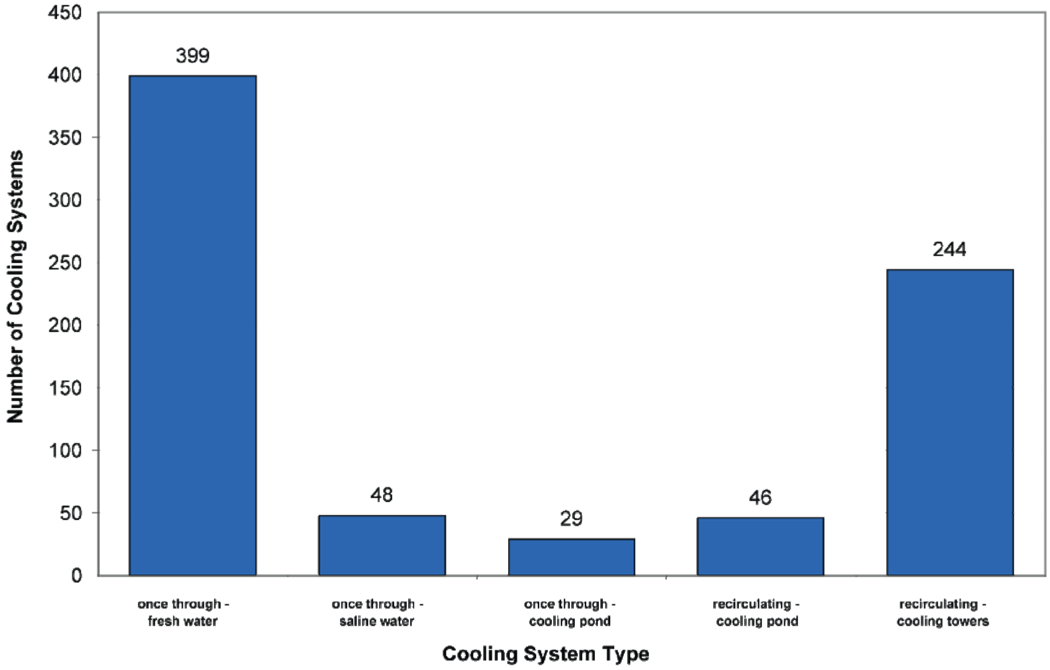
a) Power plants sorted by name plate capacity



b) Power plants sorted by MWhr

**Figure 14-4**
**Power Plants in NETL and eGRID Databases Sorted by Name Plate Capacity and MWhr Generated**

(a) Bar Chart of Cooling System Types from NETL Database



(b) Bar Chart of MWhr from NETL Database

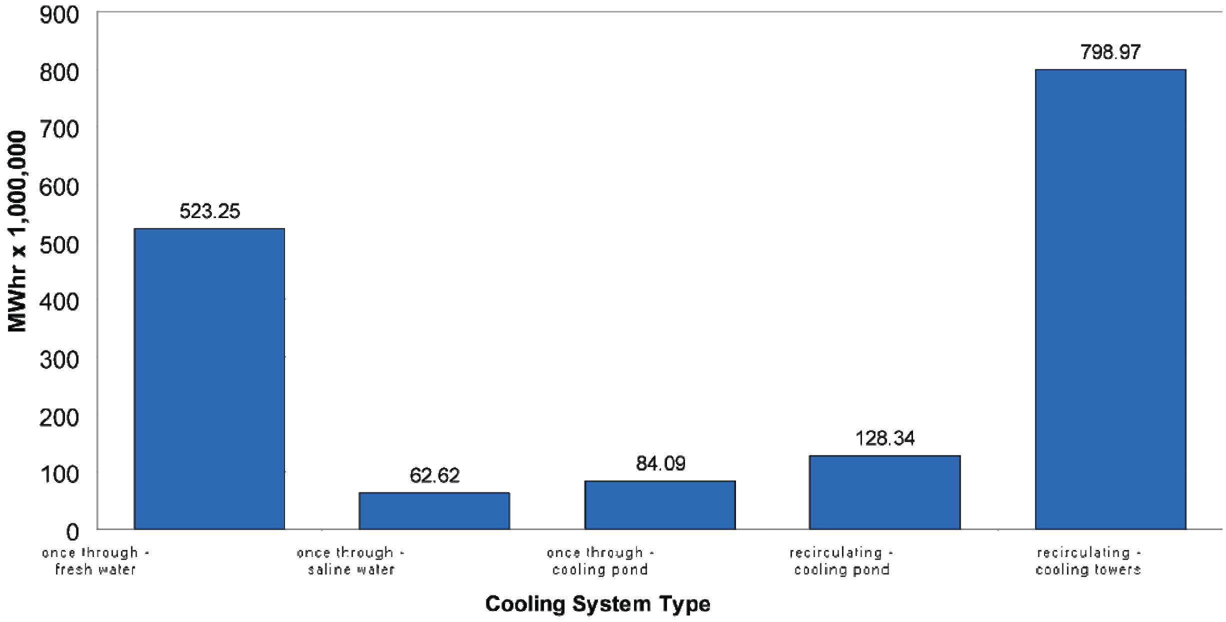
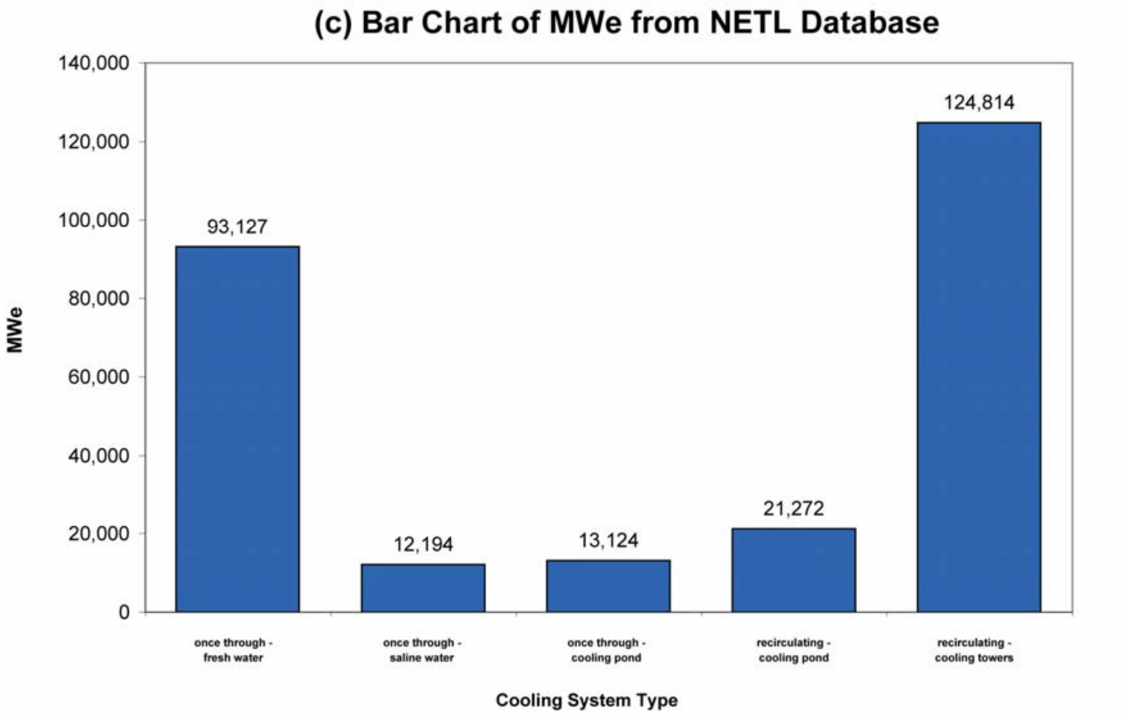


**Figure 14-5**
**Bar Charts Created from NETL Power Plant Database**



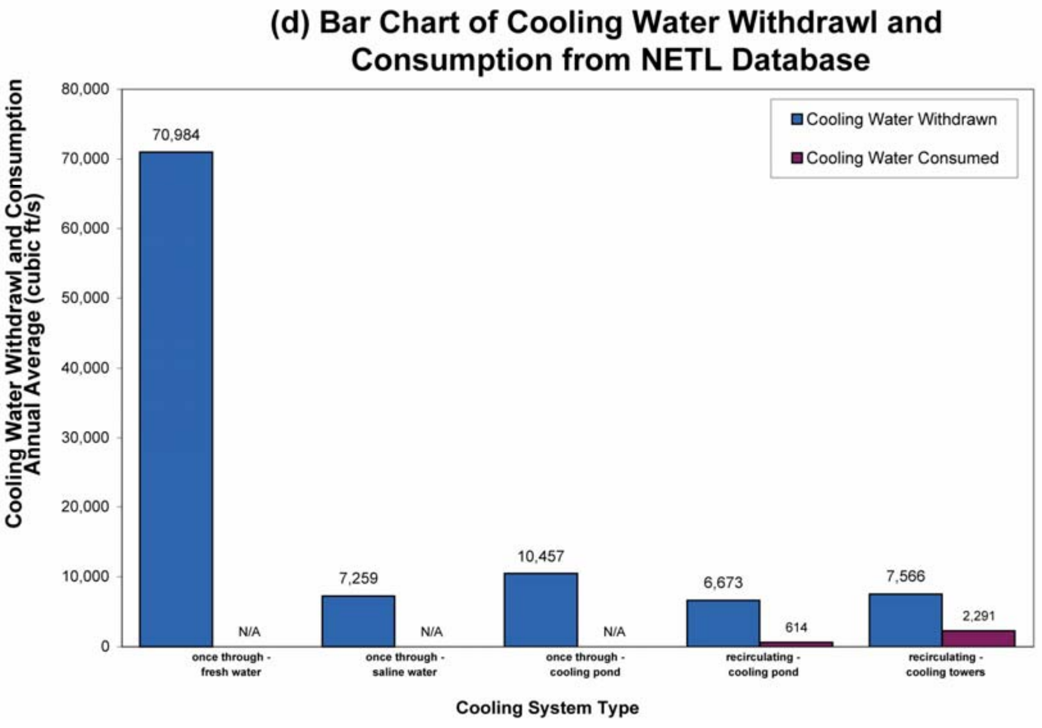


**Figure 14-6**
**Bar Charts Created from NETL Power Plant Database**

**Table 14-3**
**Comparisons of Freshwater Withdrawals and Consumptive use from USGS Database and NETL Database**

| Data Base | Consumption, cfs[1] | Withdrawals, cfs |
|---|---|---|
| USGS | 4,650[2] | 207,000[2] |
| NETL | 2,905[3] | 95,680[2] |

[1] Consumptive use is primarily from evaporation of cooling water, but also contains smaller amounts of boiler make-up and wet FGD make-up

[2] Estimates are based on both once-through and recirculating cooling systems

[3] Estimates are based on only re-circulating cooling systems

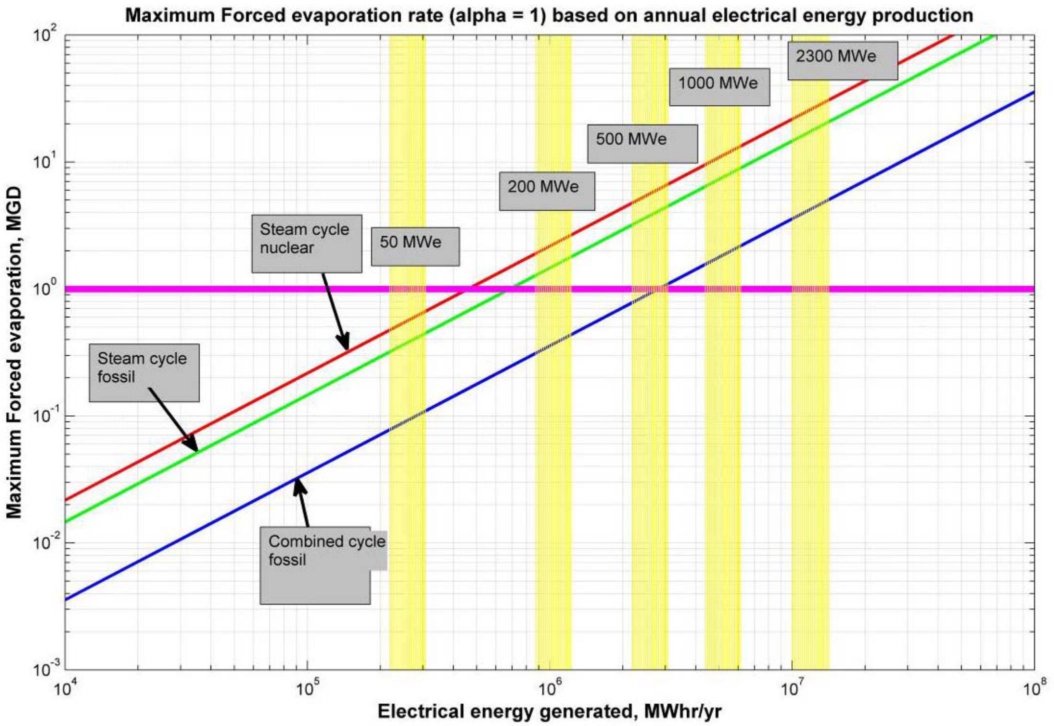


**Figure 14-7**
**Forced Evaporation Rate Assuming $\alpha_{\Delta}$ = 1 Based on Annual Electrical Energy Production (Typical Results Only Assuming Capacity Factors Range from 0.5 to 0.7)**

The yellow lines show typical ranges of power generated by the power plant with name plate capacity shown. The horizontal magenta line denotes 1 MGD forced evaporation. The plot shows that for power plants of about 200 MWe or larger, maximum forced evaporation can be in the range of 1 to 20 MGD. The actual forced evaporation would be estimated by multiplying the rate shown by $\alpha_{\Delta}$, where $\alpha_{\Delta}$ is calculated as shown subsequently. For combined cycle power plants, forced evaporation is reduced by a factor of approximately 4 (compared to single cycle fossil) to 6 (compared to nuclear).

The ratio of forced evaporation to cooling water withdrawal is a useful index. Since cooling water withdrawal rates are routinely known, this ratio can be used to estimate forced evaporation. Figure 14-8 shows this ratio for a broad range of ambient water temperatures and temperature increases across the condenser. For the range shown the ratio is typically between 1% and 2%. Assuming $\alpha_\Delta \approx 0.5$, the ratio is about 1% or less.

To this point in the analysis, forced evaporation estimates from once-through cooling systems have not accounted for how the waste energy is dissipated. Below, this is discussed both from case study data and from a theoretical approach.

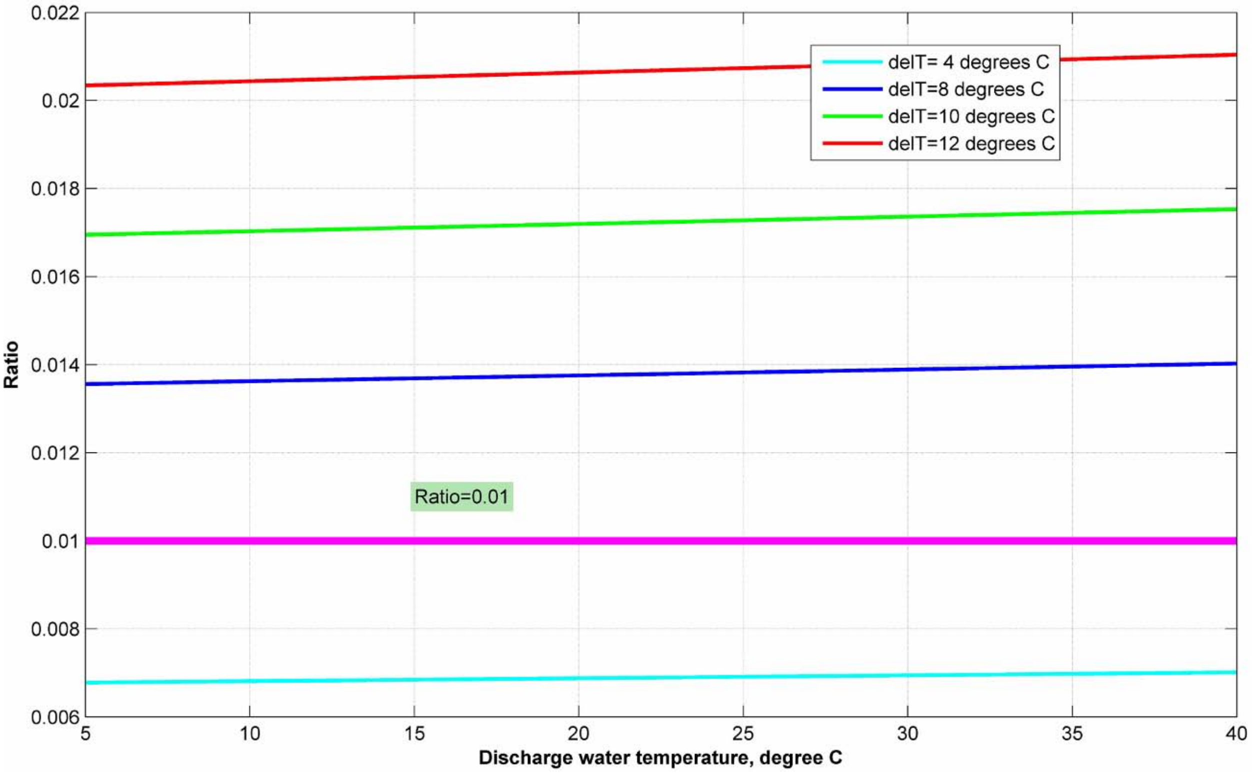


**Figure 14-8**
**Ratio of Maximum Forced Evaporation to Cooling Water Withdrawal**

While case studies of thermal discharge analysis do not directly make estimates of $\alpha_\Delta$, several studies were found where the data and modeling results were available such that estimates. A summary of results is found in Table 14-4. For each study $\alpha_\Delta$ and $E_f / Q_c$ are both shown, if information were available to calculate both indices. As shown in the table, $\alpha_\Delta$ values range from about 0.24 to 0.8 for the various studies and average about 0.54. The ratio of $E_f / Q_c$ ranges from 0.5% to 2%, and averages about 1%, very similar to the theoretically based results shown previously.

Values for $\alpha_\Delta$ were then generated theoretically for four different locations around the United States:

- Detroit, MI
- Duluth, MN
- El Paso TX
- Mobile, AL

**Table 14-4**
**Summary of $\alpha_\Delta$ and $E_f/Qc$[1] Values from Case Studies**

| Location | $\alpha_\Delta$ | $E_f/Q$[1] | Reference |
|---|---|---|---|
| Lake Anna, VA[2] | 60% | 1% | [3] |
| Chesapeake Bay Area[2] | 64% | 0.4% - 0.6% | [4] |
| Lake Colorado, TX[2] | 56%-58% | 0.5% | [5] |
| Lake Hefner, AZ[2] | 54% | - | [5] |
| Lake Hyco, NC[2] | - | 0.7% | [7] |
| Midland Cogen, MI[2] | 13% | 0.5% | Personal communication |

[1] $E_f/Qc$ = ratio of forced evaporation to cooling water discharge for once-through cooling systems
[2] Thermal discharge to cooling pond

The results are displayed in the following figures. In Figure 14-9, the forced evaporation ratios $\alpha_\Delta$ are shown on a monthly basis at each of the four locations. A clear seasonal variation is observed, with the highest values occurring in the summer. The range of $\alpha_\Delta$ values (0.26 to 0.7) is nearly the same as in Table 14-4. Values are distinctly higher in the southern part of the United States, and lower in the northern United States.

Since field determinations of $\alpha_\Delta$ may require significant data collection efforts (should such effort be made in lieu of data provided here), it is worthwhile to calculate $\alpha_u$, which is the unperturbed fraction of waste heat that is converted to latent heat, (for which data may be more readily available) and to decide if $\alpha_u$ could replace $\alpha_\Delta$. As shown in Figure 14-10, the values of $\alpha_u$ are about half or higher as $\alpha_\Delta$ values. Should it be possible to readily calculate $\alpha_u$ at a site, multiplying such values by 2 provides an approximation to $\alpha_\Delta$.

It is of interest to calculate how $E_f$ compares to natural evaporation. That ratio provides one index of the importance of forced evaporation. Figure 14-11 illustrates some examples for a range of background relative humidity values and a range of temperature increases across the condenser. As water temperature across the condenser increases, it is more likely that forced evaporation will exceed natural evaporation. Also the relative humidity plays a very important role.

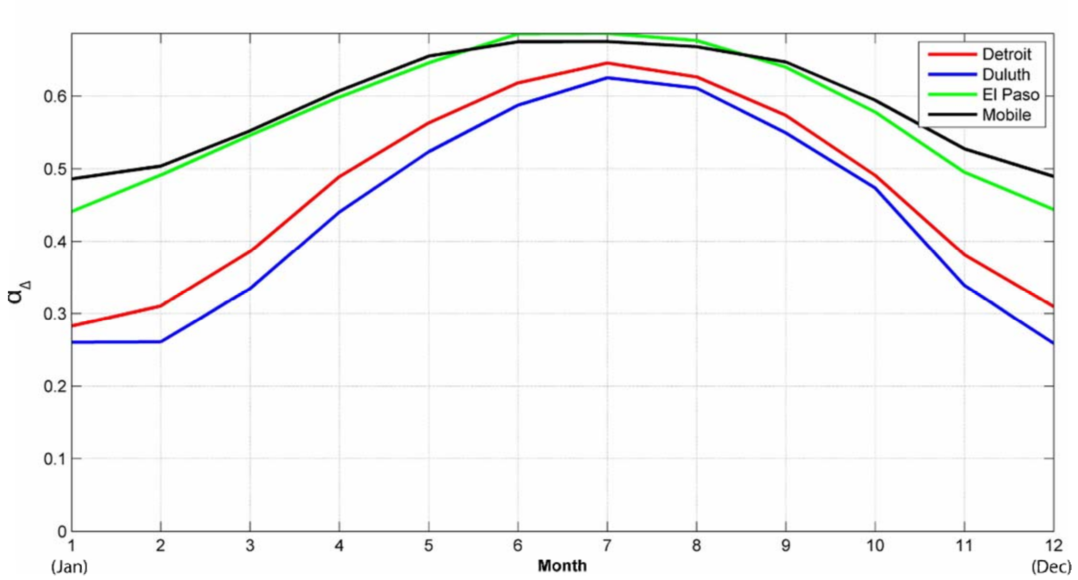


**Figure 14-9**
**Forced Ratio of Energy Components for Four Case Study Applications**

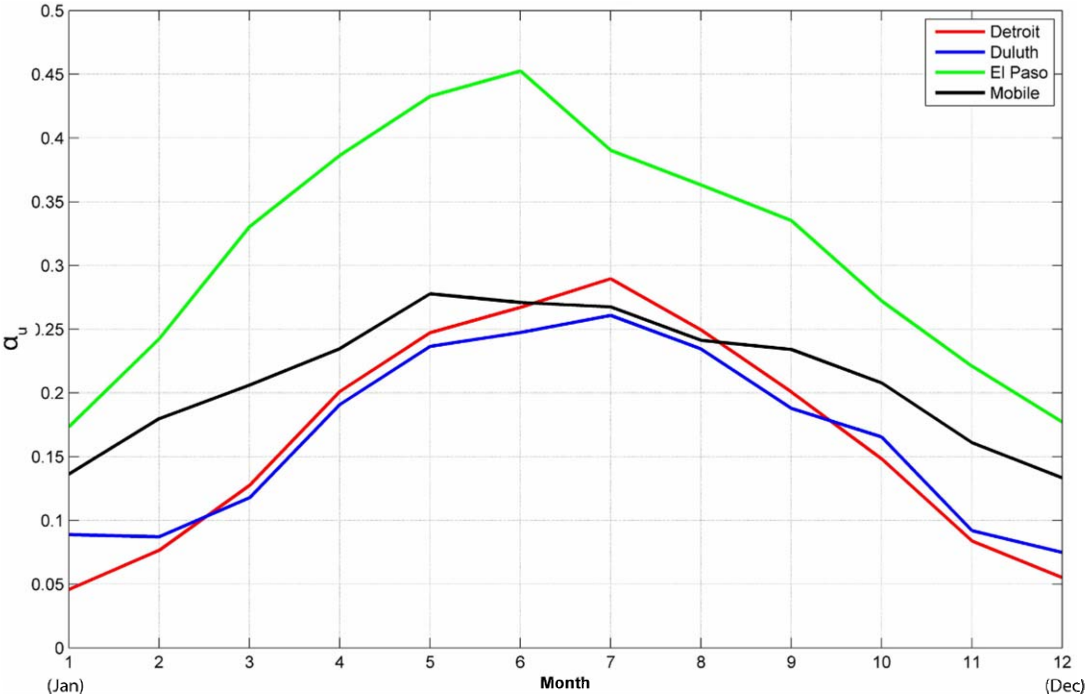


**Figure 14-10**
**Unperturbed Ratio of Energy Components,** $\alpha_u$

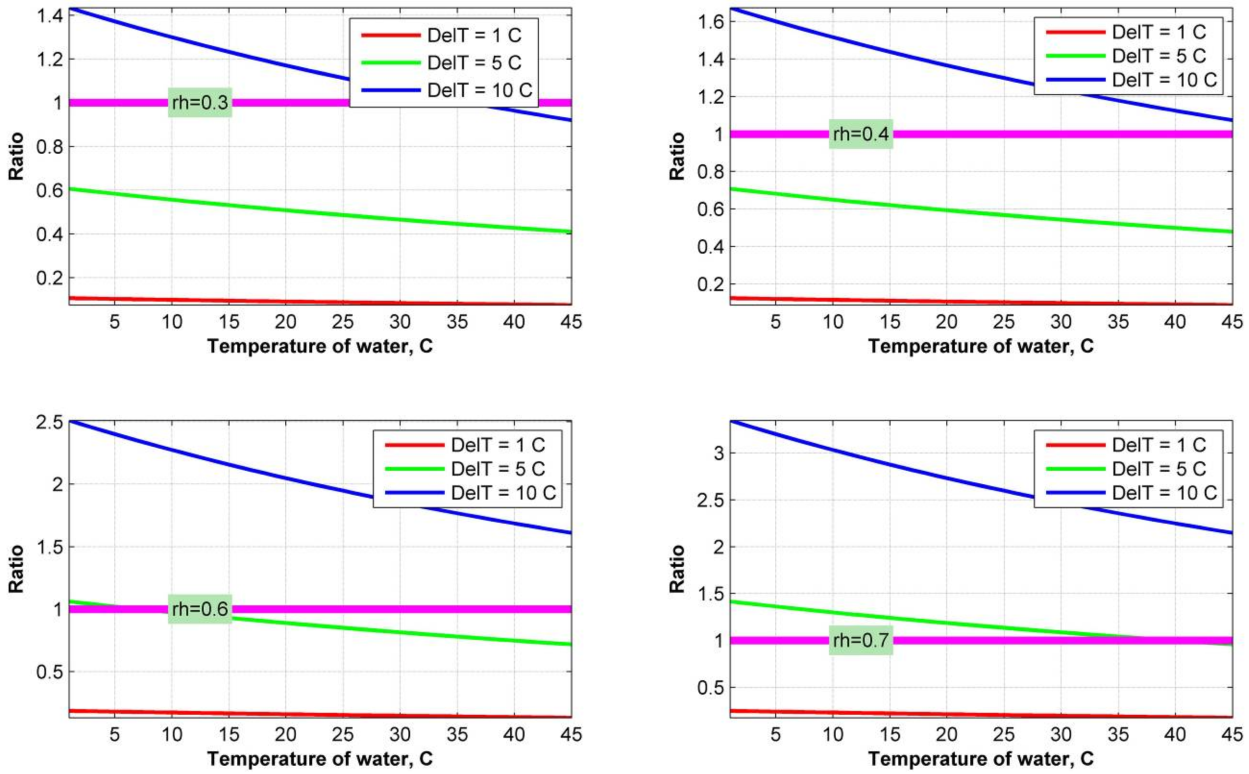


**Figure 14-11**
**Ratio of Forced Evaporation to Natural Evaporation (on a Unit Area Basis, and Not A Plume Wide Basis)**

Table 14-5 provides a summary of withdrawal and consumption factors for fossil and nuclear power plants that use once-through cooling systems. The withdrawal factors range from 22.6 gal/kWhr to 31.6 gal/kWhr for coal, nuclear and natural gas (single cycle). For the single combined cycle plant, the withdrawal factor is only 9.01 gal/kWhr.

In comparison to these factors, theoretically based values of consumption are shown in Figure 14-12. Both single cycle and combined cycle estimates are shown, with values of $\alpha_{\Delta}$ ranging from 0.3 to 0.7. In general, normalized water consumption values are somewhat higher than in Table 14-5. For example, consider a single cycle power plant with an efficiency of 0.36. The normalized consumption rates vary from about 0.2 gal/ kWhr to 0.4 gal/kWhr, 2 to 4 times higher than in Table 14-5. In an earlier EPRI study [8], normalized water consumption for fossil fuel power plants using once-though cooling systems was estimated to be 0.3 gal/kWhr, similar to the values in Figure 14-12.

**Table 14-5**
**Withdrawal and Consumption Factors (gal/kWhr) for Fossil and Nuclear Power Plants for Once-Through Cooling Systems**

| Fuel Type | Boiler Type | FGD Type | Factors(gal/kWh) | | Consumption/Withdrawal, Ratio (Percent) |
|---|---|---|---|---|---|
| | | | Withdrawal | Consumption | |
| Coal | Subcritical | Wet | 27.1 | 0.14 | 0.52 |
| | | Dry | 27.1 | 0.11 | 0.41 |
| | | None | 27.1 | 0.07 | 0.25 |
| | Supercritical | Wet | 22.6 | 0.12 | 0.53 |
| | | Dry | 22.6 | 0.10 | 0.44 |
| | | None | 22.6 | 0.06 | 0.27 |
| Nuclear | NA | NA | 31.5 | 0.14 | 0.44 |
| Oil & NG | NA | NA | 22.7 | 0.09 | 0.39 |
| NGCC | NA | NA | 9.01 | 0.02 | 0.20 |

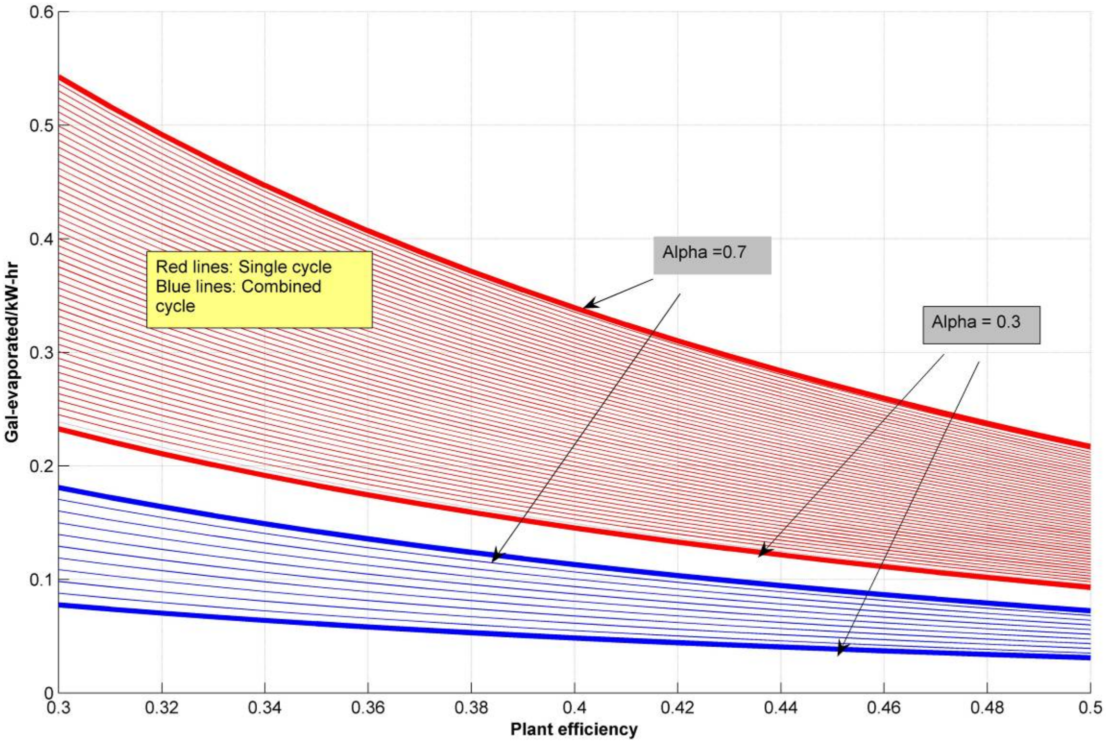


**Figure 14-12**
**Water Evaporated from Once-Through Power Plants, Normalized to kWhr Generated**

## A Look to the Future: Factors That May Influence Forced Evaporation

### *Approach*

As shown in Figure 14-13, forced evaporation can be examined from the point of view of two components: the natural environment and the power plant.

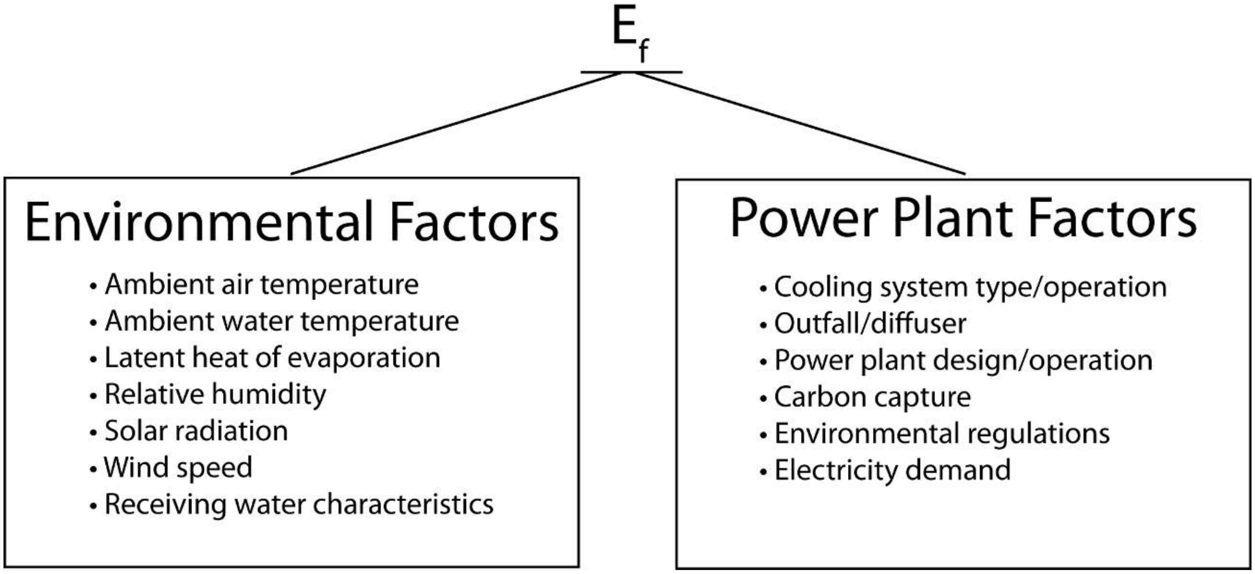


**Figure 14-13**
**Factors that Influence Forced Evaporation**

### *Factors that will Influence the Future Magnitude of Cooling Water Requirements and Forced Evaporation*

Electricity in the United States is generated using a mix of fuels, as shown in Figure 14-14. As indicated in that figure, power plants that use fossil fuels today generate 71 % of all the electricity. Nuclear plants comprise 20 % of the total, followed by renewables at 9 %. This mixture of fuels is likely to change in the future, and therefore will influence cooling water requirements. Recently, NETL completed a report that describes freshwater needs to meet future thermoelectric generating requirements. In that report freshwater withdrawal and consumption were estimated for five scenarios. Each scenario made different assumptions about future generating profiles. The report did not specifically focus on forced-evaporation from once-through cooling systems, but nevertheless provides an analysis of many of the issues associated with water consumption on a nationwide basis.

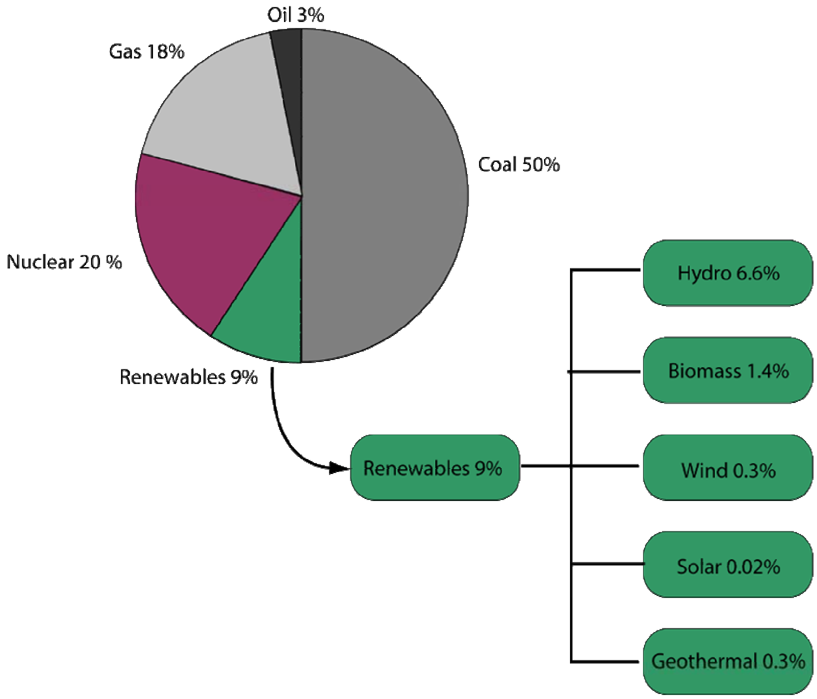


**Figure 14-14**
**Present Mixture of Energy Sources Used In Electricity Generation in USA**

One factor not considered is how cooling water requirements might be associated with carbon capture technologies for geological sequestration purposes as a climate mitigation strategy. However, a recent presentation by NETL does address this issue [9]. Ciferno indicates that water consumption from pulverized coal power plants could increase 40 % on a net power output basis, and could increase by 18 % for IGCC power plants when carbon sequestration is being implemented. Given that carbon sequestration could be implemented at hundreds of power plants in the United States over the coming decades, total consumptive use could significantly be affected.

## *Changes in climate related factors that influence forced evaporation*

Ongoing research, such as that reported in various IPCC reports published in 2007 all point to global temperature increases and global precipitation increases through the 21st century. Figure 14-15 shows a summary of predicted temperature and precipitation changes globally over this time period. Different global climate change models and greenhouse gas emission scenarios are shown, and they all predict that precipitation and temperature will increase globally. Precipitation is predicted to increase by 2% to 6% over this time interval, with an average increase of 3%.

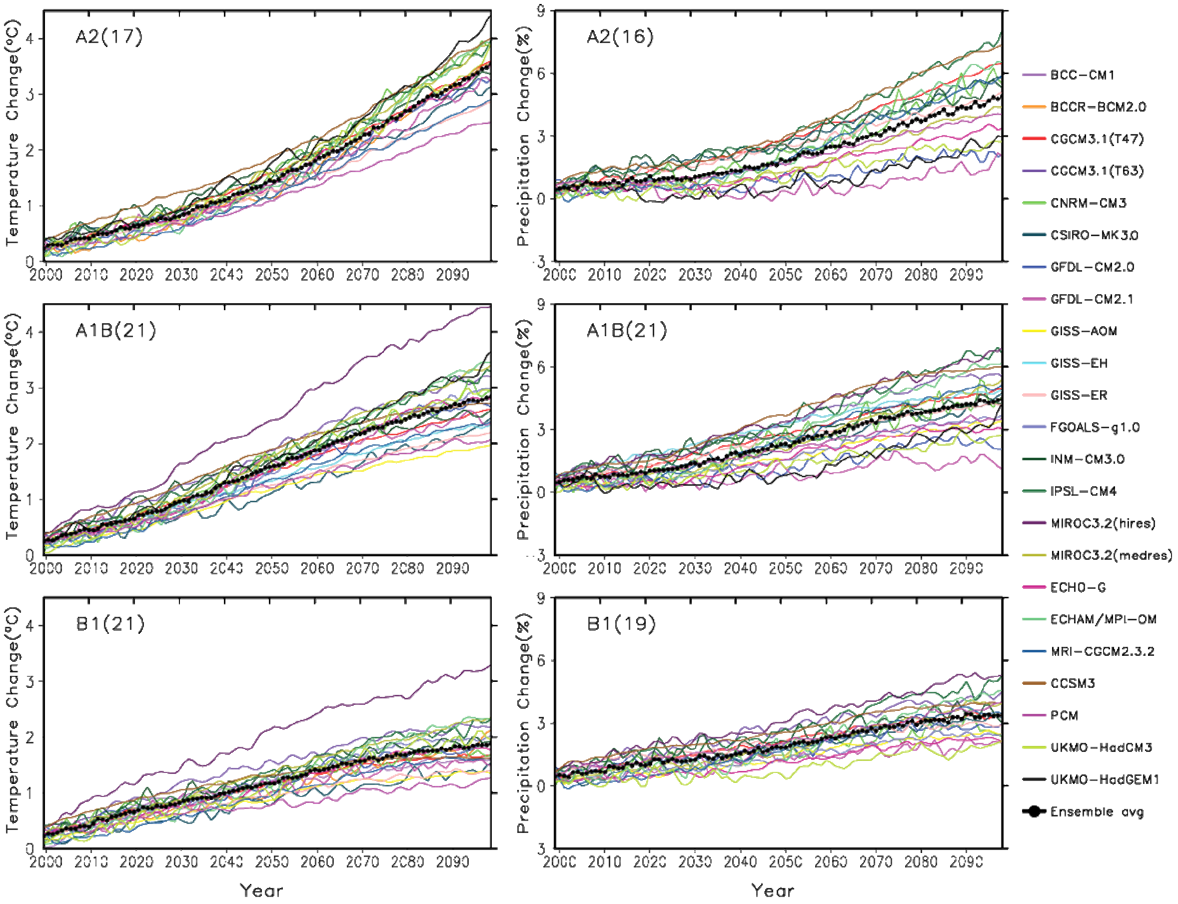


**Figure 14-15**
**Time Series of Globally Averaged (Left) Surface Warming (Surface Air Temperature Change, °C) and (Right) Precipitation Change (%) from Various Global Climate Change Models [10]**

Researchers have concluded that globally evaporation will increase concurrently with precipitation and will provide additional water to the atmosphere to supply the increased precipitation. Thus, it can be inferred that by the end of the 21st century, evaporation will increase by about 3% or so. However, on a local scale precipitation and evaporation may decrease in some parts of the world, such as anticipated in the U.S. Southwest, so that global averages are not appropriate for local estimates.

To examine how forced evaporation is likely to change as climate changes, tendencies of the influential variables are needed, as shown in Figure 14-16. The important point conveyed by Figure 14-16 is that several anticipated climate change factors could either tend to increase evaporation or reduce it. The one surprising factor in Figure 14-16 is the incoming shortwave solar radiation, and its tendency to decrease. Within the past several decades, incoming solar radiation has been decreasing in many parts of the world, a phenomenon called “solar dimming”. Solar dimming is thought to be due to increasing stratospheric aerosols associated with emissions from our industrialized society (such as sulfur dioxide emissions from power plants). Future control of aerosol emissions may cause this trend to change, however, and appear to already be doing so.

| Factor | Climatic Change Tendency | Evaporation Tendency |
|---|---|---|
| Air temperature | ↑ | ↑ |
| Water temperature | ↑ | ↑ |
| Relative humidity | ↑ | ↓ |
| Short wave solar radiation | ↓ or ↑ | ↓ or ↑ |
| Cloud cover | ↑ | ↑ |
| Wind Speed | ↑or ↓ | ↑or ↓ |
| Local Precipitation | ↑or ↓ | ↑or ↓ |

**Figure 14-16**
**Tendencies of Climatic Factors to Influence Evaporation**

To estimate the potential importance of each of the factors in Figure 14-16 have on evaporation, Figure 14-17 was created. This figure shows the fractional change in evaporation from a baseline condition to nine other conditions where one variable at a time was changed within a range plausible in the 21st century. The air temperature is assumed to increase by 3°C (in many parts of the United States, air temperature increases are expected to exceed this increase by the end of the 21st century) while the other variables were allowed to increase or decrease, consistent with what might actually occur. Water temperature is assumed to be in equilibrium with the environmental variables, and was calculated by RIVRISK [11].

The single largest influence on evaporation is associated with the 3°C increase in air temperature that produces an 18% increase in evaporation. Note that this is much larger than the projected global 3% increase in global evaporation predicted for the end of the 21st century. However this 18% increase could be offset by other factors, as seen in the figure. For example, should local wind speed decrease, relative humidity increase, cloud cover decrease, and net incoming solar radiation continue to decrease, those factors together could offset air temperature increase impacts on evaporation, or could act to reinforce larger evaporation increases (up to 30% or more). Determining specific changes would require basin scale analysis that captures local, regional, and global forcings. For example, widespread irrigation in California has been shown to cool summertime surface temperatures there by 1.8°C to 3.2°C during the 20th century, despite increasing concentrations of greenhouse gas forcings [12]

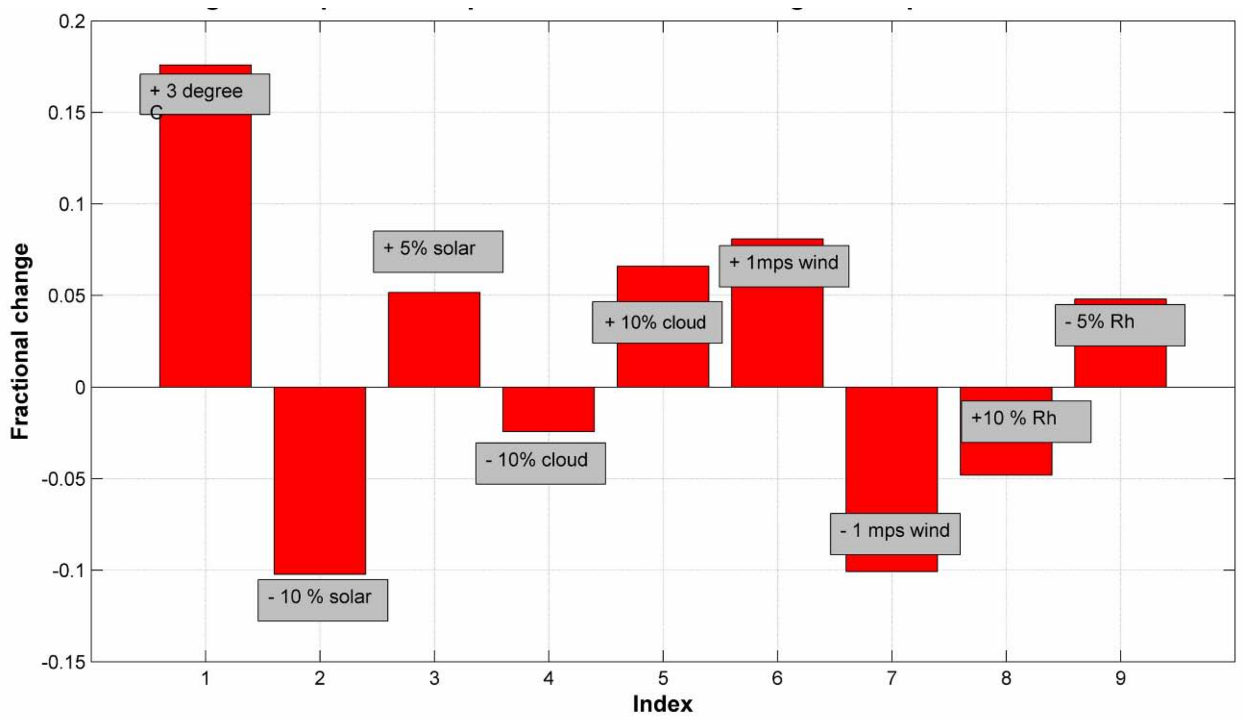


**Figure 14-17**
**Fractional Change in Evaporation Based on Variables that Might Be Influenced by Climate Change**

## Summary

In this paper an approach to estimate forced evaporation from power plants that use once-through cooling systems was developed. Forced evaporation, as defined for this analysis, is the evaporation that occurs, beyond natural background, once heated effluent is released into a receiving water. Databases used to estimate evaporation from power plants typically define consumptive use as the difference between withdrawals and discharges, and is appropriate for recirculating systems. For once-through cooling systems, additional analyses must be done to generate forced evaporation efforts, The USGS, for example, uses a coefficient-based approach, as described earlier. Here, a more theoretical approach is developed which is still quite simplified, that can be used to estimate annual forced evaporation rates. The effects of seasonality and location within the United States (north to south) can be approximated.

Case studies of thermal discharges were reviewed to compare against the theoretical approach. While only a few case studies were found, in general, estimates of forced evaporation were similar to those generated in this paper. It may be possible to extend the database generated here by more thoroughly reviewing sites where detailed thermal modeling and monitoring analysis has been done in the past. Of particular interest would be case studies of large discharges into the Great Lakes.

Looking to the future, impacts of climate change on forced evaporation were examined. Global climate change models predict an increase in global evaporation of 2% to 6% over the 21st century. However, on a watershed scale, evaporation might not decrease, and forced evaporation could be suppressed. One reason for this is that evaporation depends not only on temperature increases associated with global warming, but also on many other factors, such as solar radiation, relative humidity, wind speed, and cloud cover. Some of these factors could change on a watershed scale in a way that tends to reduce forced evaporation.

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# 15

# ETHERM: EPRI'S WEBSITE ON ASSESSMENT AND MANAGEMENT OF THERMAL PLUMES

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## Introduction

In 2004, the Electric Power Research Institute (EPRI) sponsored development of eTherm (http://www.epri.com/etherm), a web-based resource document to assist power companies in assessing and managing their thermal plumes, particularly with respect to Clean Water Act (CWA) Section 316(a) variances. Since the passage of the CWA in 1972, thermal dischargers have been allowed to seek a variance from otherwise applicable technology and water-quality based limits. Section 316(a) of the CWA provides that thermal dischargers can be granted less stringent alternate thermal limits if they can demonstrate the current effluent limitations, based on water quality standards, are more stringent than necessary to protect the aquatic organisms in the receiving water body. Usually submitted in the form of a variance request, the 316(a) demonstration must document completely and comprehensively that alternate thermal effluent limitations will not adversely impact the balanced indigenous aquatic community in the receiving water body, or any other designated water use. eTherm seeks to provide current information about 316(a) variances and related scientific/technical and policy/regulatory topics as well as preserve the wealth of information developed in the 1970s and 1980s when much research was done on the topic. This paper will describe the evolution and structure of eTherm, its primary data sources, and some examples of how eTherm can be used to address thermal issues.

## The Evolution and Structure of eTherm

One of the initial drivers of the development of this website was to be able to disseminate information from the EPRI-sponsored Thermal Ecology and Regulation Workshop held in October 2003 in Columbus, Ohio. The workshop included over 20 presentations on 316(a) and related topics, including legal and regulatory perspectives, fish physiology and behavior, community balance and multimetric indices, thermal modeling, water quality trading, ecosystem enhancement and temporary cooling towers. Much of the early work on this topic was initiated in the 1970s when the 316(a) variance program began. There has recently been resurgence in interest in this topic, as exhibited by the large number of attendees at the 2003 workshop. As the original researchers on these topical areas have retired, or have begun to devote their energies to other research topics, there is a danger that the knowledge base that began in the 1960s and 1970s will disappear. eTherm is intended to preserve that information, as well as be a source of the most recent information available.

The topics for eTherm evolved from the 2003 workshop. Major topics included a national perspective, plant permit and 316(a) variance information, thermal plume assessment, thermal plume modeling, new power plant technologies, thermal TMDLs, water sustainability and electrical power production, and research and emerging issues related to thermal effluents. In addition to a discussion of the topic and links to related information and documents, each topic has a reference section where references related to the topic are provided. Figure 15-1 shows the organization and major topics of eTherm.

The national perspective provides an overview of power plant locations and a look at cooling systems and water withdrawal rates by cooling system type. The plant permit and 316(a) variance section gives background and guidance information on Section 316(a) of the Clean Water Act, provides an overview of legal and regulatory issues, and gives information on how to view some examples of completed NPDES permits. Thermal plume assessment discusses new monitoring techniques, such as remote sensing, provides information on how to design and conduct sampling programs for a 316(a) variance, and addresses issues unique to cooling lakes. The topic thermal plume modeling provides information on models typically used for thermal plumes, common issues associated with thermal modeling, and gives some examples of plume visualizations. New power plant technologies addresses portable cooling systems, dry cooling systems, and spray cooling enhancement. The thermal TMDL topic provides an overview of the process and links to EPA listed waterbodies. Within the water sustainability topic, the issue of water sustainability for power production is defined, some tools for addressing the issue are presented, and some case studies related to water sustainability are presented. Research and emerging issues addresses:

- Multiple simultaneous stresses on aquatic ecosystems and how they may exacerbate thermal issues.
- Climate change and how stream temperatures are expected to respond.
- The issue of optimizing of power plant operation to maximize energy production without violating water quality standards.
- Temperature effects on aquatic biota; in particular, in-situ versus lab response of biota.
- An introduction to water quality trading and watershed scale impacts and how thermal effluents fit in.
- A discussion of evaporative losses from power plants using once-through cooling systems.
- The impacts of changes to the 316(a) regulations on the electric power industry.

One of the primary purposes of eTherm was to maintain a library of reference documents related to thermal effluents. A reference library was developed, in the form of an excel spreadsheet, to hold references in this subject area. Complete reference information is provided, as well as a link to the document if available. Categories were assigned to the references for ease of use. A similar library was created specifically for case studies as well.

**National Perspective**
- Locations of power plants
- Cooling systems
- References

**Plant Permits and 316(a) Variance Information**
- Background and guidance information
- Legal and regulatory issues
- Examples of demonstration studies
- Examples of completed permits
- References

**State Water Quality and Thermal Standards**
- U.S., regional and state-specific water quality standards
- Thermal standards
- Thermal discharge-related guidance documents

**Thermal Plume Assessment**
- New monitoring techniques
- Sampling programs
- Cooling lake issues
- References

**Thermal Plume Modeling**
- Available models
- Modeling Issues
- Thermal plume visualizations
- References

**New Power Plant Technologies**
- Portable cooling systems
- Dry cooling
- Spray cooling enhancement
- References

**Thermal TMDLs**
- Overview of thermal TMDL process
- EPA listed waterbodies
- References

**Water Sustainability**
- Definition
- Withdrawals/consumption
- Tools to evaluate water usage
- Drought impacts on electrical energy production
- Case studies related to water sustainability
- Use of reclaimed water for power plant cooling
- References

**Research and Emerging Issues**
- Multiple stresses
- Climate change
- Optimization of power plant operation
- In-situ vs. lab response of biota
- Water quality trading and watershed-scale impacts
- Evaporative losses from power plants using once-through cooling systems
- Impacts of changes to 316(a) regulations on electric power industry
- References

**Libraries**
- Case study library
- Reference library
- Dictionary of terms

**Figure 15-1**
**Topic Areas of eTherm**

In 2005, eTherm was expanded to include a database of examples of 316(a) demonstration studies. Power companies, consulting firms, and state regulators were contacted to obtain the 38 studies included on eTherm. provides a summary of the studies collected and Figure 15-2 shows their locations. Most studies collected were for power plants in the Midwest (17), followed by the East (13), South (6), and West (2). Studies were primarily for plants with discharges to rivers (16) and estuaries (14) with some to lakes/reservoirs (8). Most studies were performed in the late 1970s (17) and early 1980s (9) when the 316(a) program was initiated. An effort was made to acquire these studies and digitize them to make them available on eTherm. While over 25 studies from this era were acquired, many more studies exist but have been lost over the years. A number of more recent studies (seven from the 1990s and seven from the 2000s) were also acquired and are provided on eTherm.

For each site where a study was collected, a summary was developed to highlight the key elements of the study. The summary includes the title, table of contents, and a brief summary of the study. The summary is an easy-to-read, searchable PDF which allows the user to quickly find what they are looking for. This is important for older documents in particular, which are hardcopies that have been scanned in. These documents are not searchable and are, in some cases, hard to read. In addition to the summary, the actual study itself is available for viewing or download. Also, a link is provided to Google Maps, where you can view the site on satellite imagery.

In 2005, links to state water quality and thermal standards were added to eTherm. eTherm provides a clickable map (Figure 15-2) which takes the user to a list of links to water quality and thermal standards for that state. These include U.S. EPA water quality standards, regional EPA water quality standards, state-specific water quality standards, thermal standards, and thermal discharge related guidance documents. In some states, other standards may be available, such as the Ohio River Valley Water Sanitation Commission (ORSANCO) temperature endpoints; links to these documents are provided for those states.

## Sources of Information

The primary source of information for the topics on eTherm was the 2003 Thermal Workshop. This information was supplemented by other sources, including:

- EPRI reports
- EPA's and individual state's websites
- Energy Information Administration (EIA) databases
- Other external websites
- Individual utilities

**Table 15-1**
**Summary of 316(a) Demonstration Documents on eTherm**

| Plant Name | Utility | Date of Study | State |
|---|---|---|---|
| Arthur M. Williams Station | South Carolina Electric and Gas Company | 1977; 1994 | South Carolina |
| Bailly Station | Northern Indiana Public Service Company | 1976 | Indiana |
| Bayshore Power Plant | Toledo Edison | 1994 | Ohio |
| Belle River Power Plant | Detroit Edison | 1977 | Michigan |
| Brayton Point Station | US Gen New England Inc. | 2002 | Massachusetts |
| Browns Ferry Nuclear Plant | Tennessee Valley Authority | 1998 | Alabama |
| Chalk Point Station | Potomac Electric Power Company | 1983 | Maryland |
| Council Bluffs Power Station | Iowa Power and Light Co. | 1977 | Iowa |
| C.P. Crane Power Plant | Baltimore Gas and Electric Company | 1981 | Maryland |
| Dean H. Mitchell Station | Northern Indiana Public Service Company | 1976 | Indiana |
| Delaware City Power Plant | Delmarva Power and Light | 1990 | Delaware |
| Edge Moor Power Plant | Delmarva Power and Light | 1990 | Delaware |
| Indian River Power Plant | Delmarva Power and Light | 1990 | Delaware |
| Dickerson Steam Electric Station | Potomac Electric Power Company | 1979 | Maryland |
| South Bay Power Plant | Duke Energy | 2004 | California |
| E.W. Stout Generation Station | Indianapolis Power and Light Company | 1976 | Indiana |
| George Neal | Iowa Public Service Company | 1970s-1980s | Iowa |
| H.A. Wagner Power Plant | Baltimore Gas and Electric Company | 1988 | Maryland |
| John P. Madgett Station | Dairyland Power Cooperative | 1982 | Wisconsin |
| J.P. Pulliam Power Plant | Wisconsin Public Service Corp | 1976 | Wisconsin |
| Keuwanee Nuclear Power Plant | Wisconsin Public Service Corp | 1976 | Wisconsin |
| Mirant Kendall Station | Mirant Corporation | 2004 | Massachusetts |
| Monroe Power Plant | Detroit Edison | 1976 | Michigan |
| Morgantown Station | Potomac Electric Power Company | 1977 | Maryland |
| Oak Creek Plant and Elm Road Generating Station | We Energies | 2004 | Wisconsin |
| Ohio River Plants | Various | 1974 | Ohio |
| Oyster Creek | Amergen Energy Company | 2005 | New Jersey |
| Petersburg Generating Station | Indianapolis Power and Light Company | 1976 | Indiana |
| Point Beach Nuclear Plant | Wisconsin Electric Power Company | 1977 | Wisconsin |
| Potrero Power Plant | Mirant Corporation | 2006 | California |
| R. Paul Smith Power Station | Potomac Edison Company | 1980 | Maryland |
| Riverside Generating Station | Iowa-Illinois Gas and Electric Co | late 1970s | Iowa |
| Salem Generating Station | Public Service Energy Group Nuclear | 2001 | New Jersey |
| Savannah River Nuclear Plant - D Area | U.S. Department of Energy | 1990 | South Carolina |
| Savannah River Nuclear Plant - L Reactor | U.S. Department of Energy | 1989 | South Carolina |
| Savannah River Nuclear Plant - P Reactor | U.S. Department of Energy | 1985 | South Carolina |
| Sequoyah Nuclear Plant | Tennessee Valley Authority | 1989 | Tennessee |
| Weston Power Plant | Wisconsin Public Service Corp | 1976 | Wisconsin |

## Uses of eTherm

The potential uses of eTherm are broad. eTherm was designed to assist power companies in all kinds of research related to thermal discharges. Some example situations in which a power company might find itself that eTherm can help address are:

- An important issue in this state is impacts to smallmouth bass. Are there other power plants that are concerned about this species?
- How can I find out more information on response of fish growth to temperature?
- What exactly is 316(a) and are there any guidance documents on the subject?
- I ran across the term "forced evaporation" the other day. What is forced evaporation and are there particular areas of the U.S. that are interested in it?
- I hear a lot of talk about water sustainability. Where do power plants fit in to the issue of water sustainability and are there any studies that have been done for power plants?
- My power plant discharges to a body of water for which the State is doing a thermal TMDL. Where can I get more information on TMDLs?
- What are the emerging issues related to 316(a) and how can I get more information on them?
- I am interested in power plants and their cooling systems on a nationwide level. Can eTherm help me with this?

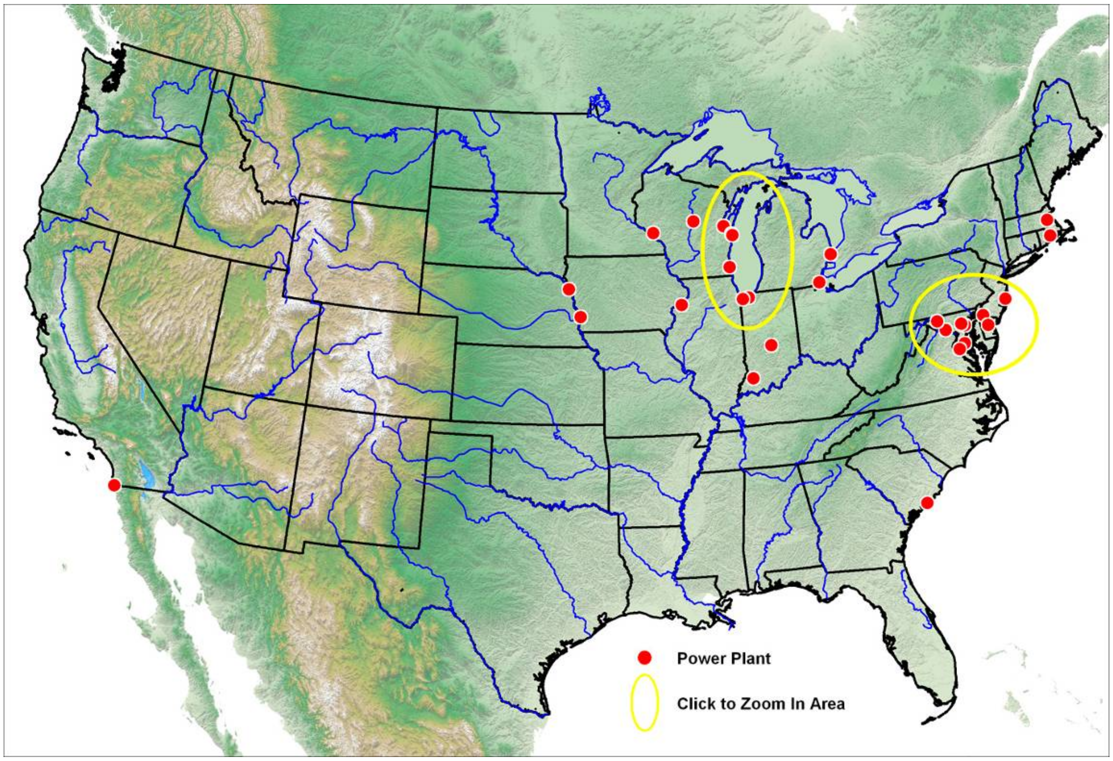

**Figure 15-2**
**Locations of 316(a) Demonstration Studies Collected**

To illustrate how eTherm can be used for these types of specific situations, three examples are provided below.

### *Example 1: We Need to Perform a 316(a) Study. How can I use eTherm to help Design my Study?*

To begin, look at Background and Guidance Information under the topic Plant Permit and 316(a) Variance Information. The second EPA guidance document listed, Interagency 316(a) Technical Guidance Manual and Guide for Thermal Effects Sections of Nuclear Facilities Environmental Impact Statements, provides information on the different types of demonstration studies and how to choose the most appropriate one.

Another approach to addressing this question is to review examples of 316(a) demonstration studies that have been performed. Under the topic Plant Permit and 316(a) Variance Information is the sub-topic Examples of Demonstration Studies. This brings up a map of example studies available on eTherm. Below the map is a table showing the studies and some basic information about them. Using this table, studies that are similar to the one being performed (i.e., same state, waterbody type, study type, etc.) can be reviewed.

### *Example 2: Our State Is Decreasing the Maximum Hourly Temperature Change Allowed. What Do Other States in The Area Allow?*

eTherm provides links to state water quality and thermal standards. Choosing State Water Quality and Thermal Standards from the menu will bring up a map of the United States. View the links to water quality and thermal standards for that state by clicking on the state's name. Click on the link for Thermal Standards Website to view the thermal standards for that state. Note that next to the Thermal Standards Website link a page or section number is provided to help you find the thermal standards quickly.

### *Example 3: We are Concerned about Recirculation on Our Estuary. How Should we Model Ponding and Backflow that may be Occurring?*

eTherm provides information on thermal modeling under the menu item Thermal Plume Modeling. Choosing Available Models from the submenu brings up a list of potential models that can be used to model thermal plumes. Brief descriptions of the models are also provided to help the user identify the correct model for their situation. Modeling ponding and backflow would require a 2-D or 3-D model, such as RIVRISK or MIKE3. Clicking on the name of the model brings up the model's website, where more specific information about the model can be found.

The other three items on the Thermal Plume Modeling menu may be helpful as well. The Issues topic discusses some important issues that should be considered when choosing a model. The Thermal Plume Visualizations topic shows some examples of visualizations which can help facilitate the understanding of the complex movement of thermal plumes. The References topic provides references on thermal plume modeling that may be useful.

## Summary

eTherm was developed by EPRI to provide a resource to utilities concerned with thermal discharges and related topics. The scope of eTherm is nationwide, for all types of receiving water and cooling system types. It provides information on guidance for 316(a) variances and thermal discharges, examples of 316(a) demonstration documents, links to state water quality standards, and current research related to thermal modeling, cooling technologies, thermal plume assessment, and water sustainability. Emerging issues such as climate change and water quality trading are also discussed. All of this is provided in a website (*http://www.epri.com/etherm*) so information can be kept current and is easily accessible by EPRI members.

## Acknowledgements

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The author would like to thank Dr. Robert Goldstein of EPRI for his input on this paper.

# 16

# TEMPERATURE CHANGE: HOW FAST IS TOO FAST?

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## Introduction

Under Section 316(a) of the Clean Water Act, thermal discharges to surface waters, as often occur from power generating facilities with once-through cooling, typically have been regulated through permit limits consistent with water quality standards for heat. In 316(a), Congress recognized the unique qualities of heat as a pollutant: it rapidly dissipates and does not persist in the aquatic environmental. Consequently Congress allowed a more flexible regulatory scheme for 316(a). Alternative thermal discharge effluent limitations can be sought if it can be demonstrated that limits based on water quality standards are more stringent than necessary to assure protection and propagation of a balanced indigenous community of fish, shellfish, and wildlife in and on the receiving waterbody.

There is an oft-stated principle that water quality standards (including those for temperature) should be based on "good science" embodied in relevant criteria that are supported by adequate data. Given this common objective, it is difficult to understand the variety of approaches to regulating rate of temperature change.

In some jurisdictions (states with delegated NPDES programs or EPA Regions) that specifically regulate rate of temperature change, there are narrative criteria, such as in New York (6 NYCRR Part 704.2),

> (3) Large day-to-day temperature fluctuations due to heat of artificial origin shall be avoided.
>
> (6) For the protection of the aquatic biota from severe temperature changes, routine shut down of an entire thermal discharge at any site shall not be scheduled during the period from December through March.

In other cases, for example Pennsylvania, the limits are expressed numerically (025 PA Code §96.6):

> (b) Heated wastewater discharges may not cause a change of surface water temperature of more than 2°F during any 1-hour period.

Iowa (1°C/hr), Montana (2°F/hr), Tennessee (2°C/hr), and Virginia (2°C/hr) also are among the 11 states that have numerical standards, but most other states and regulating authorities have not placed numeric limits on the rate of temperature change [1].

The potential benefits of regulating rate of temperature change are twofold: gradual temperature changes would avoid direct adverse effects, and gradual changes allow organisms time to acclimate and thereby withstand more extreme exposures.

We review the anecdotal and scientific information for regulating rate of temperature change, and then consider what types of information could be developed and presented to regulatory agencies in support of a site-specific numeric standard as would be permitted under 316(a).

## Basis for Regulating Rate of Temperature Change

It has seemed almost self-evident from the earliest days of studying temperature effects on aquatic life that large, abrupt changes in temperature can be detrimental. Most aquatic organisms are poikilothermic, i.e. their body temperature varies with the temperature of the water in which they live. Thus, temperature changes due to thermal effluents or other causes directly affect animal bodies internally, and might have lethal or serious sublethal consequences, including increased activity, increased susceptibility to predation, increased energy costs of metabolism, disruption of normal endocrine activity, and other negative effects. The more immediate effects of sudden or instantaneous temperature changes are generally referred to as “thermal shock” as contrasted with longer-term “thermal tolerance” of particular warm or cold temperatures.

Personal anecdotes and long-standing traditions bolster the perceived importance of thermal shock as a feature of “thermal pollution” to be regulated. Nearly forty years ago, Mount stated:

*The second area [where information on thermal requirements of fishes is needed] is to determine how much or to what extent temperatures may fluctuate without interfering with growth and reproduction. While most biologists are convinced that temperature fluctuations are very damaging to fishes, there is very little hard evidence to support this view. This statement is not intended to imply that fluctuating temperatures have no adverse effects, but only to point out that we do not have sufficient evidence to support such a statement fully. [2]*

Some of the evidence leading to this view came from transfers of hatchery-reared fish between waters with differing temperatures. More than a century ago, fish hatchery managers observed that such transfers can lead to visibly stressed fish (erratic swimming, sometimes temporarily going “belly up”) or even death [3], which lead them to promote thermal “tempering” (bringing temperatures of the fish gradually to the new temperature over a few minutes to hours). The aquarium trade recommends that newly purchased fish be held in the transfer container until the fish’s temperature matches that of the new environment. In the field, predators on small fish have occasionally been seen feeding on fish that have passed through thermal discharge plumes [4]. Fast-moving cold weather fronts that induce rapid temperature declines have been correlated with fish cold kills [5, 6]; freshwater clupeid fishes are especially susceptible to weather-related cold kills [7].

Temperatures change in many ways and over many time scales in the aquatic environment, due to both natural and human influences. Fish and other aquatic organisms are adapted to accommodate such changes and a substantial literature exists on both thermal tolerances (used loosely here as maximum and minimum temperatures at which organisms can survive) and the natural thermal regimes under which aquatic organisms exist. The former topic is studied primarily through controlled laboratory experiments, often involving instantaneous temperature changes, and the latter by observing distributions of organisms in the wild, although there is some crossover. However, most of this literature is of limited utility for determining vulnerability to high rates of temperature change because any potential effects of the rate of change, if it can be determined, are often confounded with exposures to temperatures exceeding lethal limits [8].

### *Diel Fluctuations*

Most water bodies, particularly small streams, show temperature changes over a daily cycle. This is perhaps the most pervasive sort of temperature change. Solar heating in daytime is matched by cooling at night to induce a nearly sinusoidal temperature curve. The maximum rates of change in morning and evening depend largely on the magnitude of change, and can be several degrees C per hour.

There has been considerable research conducted on the effects of daily cycles on survival, growth and other responses of fish and some invertebrates. The dominant factor affecting growth and/or survival was the upper temperature the fluctuations attained and whether this temperature (and the duration of exposure) exceeded recognized upper thermal tolerance limits. When similar rates of change were experienced within the thermal tolerance range, there were no detrimental effects shown. Most often, studies of fluctuations below the long-term thermal tolerance limits provided evidence that the temperature changes during diel thermal fluctuations aided survival and growth (likely by enhancing acclimation to warmer temperatures).

There is evidence that a rapid cooling rate of change may induce a detrimental thermal shock more clearly than does a slower cooling rate of change (see below). Relevant information specific for effects of rate of temperature change is limited, however, because this variable has typically been poorly isolated from confounding variables such as magnitude of change and the high (or low) temperature attained.

### *Mixing Zones*

In natural environments where waters of different temperatures converge (e.g., when cool streams enter warmer rivers or vice versa), as well as in thermal discharges, there is a zone where temperatures change over small distances and short times. These “thermal plumes” are characterized by dilution of the introduced water by nearby ambient-temperature water resulting in rapid temperature changes in much of the turbulent near-field mixing zone and more gradual (but often still fairly rapid) temperature change in the far field as the final mixed temperature is attained. Thermal shock in the heated plumes of power stations was an early concern, leading to the development of techniques to predict survival of fish and invertebrates that were caught up in the mixing plume (plume entrainment). For example, calculation methods and tabular data on resistance time from worst-case, instantaneous shock thermal tolerance tests were presented in the National Academy of Sciences/National Academy of Engineering review of water quality criteria in 1972 [9] and amplified by Coutant [10,11]. These analytical procedures assumed that any rate of temperature change slower than instantaneous would be less detrimental and thus, using data from instantaneous change would be protective.

One limitation of most thermal resistance data available for thermal shock analyses was that the endpoint defined was usually 50% mortality, which, while statistically sound, is not particularly satisfying for environmental protection. Also, using death as the sole endpoint did not take into account sublethal behavioral or physiological effects that could affect predation (also know as "ecological death"). Therefore, tests of susceptibility to predation after thermal shock, also at the worst-case instantaneous rate, were conducted with salmon and trout [12]. A relationship between 50% mortality, visible loss of equilibrium and increased vulnerability to predation was developed that yielded a "correction factor" for 50% mortality data after heat shock [13], amounting to a decrease in the effective resistance-time temperature by 2°C for likely "ecological death" by predation. This correction factor has been applied to accumulated data on fish thermal resistance times [9].

Survival effects of different rates of change have been tested using a Critical Thermal methodology (CTM). The emphasis, however, has been on selecting standard rates of change for rapid heating (or cooling) of fish in test containers in order to determine a critical thermal maximum or critical thermal minimum (the temperature at which the fish loses equilibrium) [14]. CTM results are useful for comparative purposes when a standard rate of heating or cooling is applied to species or other conditions to be compared. The results are less useful for estimating the upper or lower tolerance limits, however, because endpoints are known to be higher (for heat shock) and lower (for cold shock) than other tests because temperatures continue to rise (or cool) while fish are responding Few studies have compared enough different rates of change to provide useful generalizations. Attempts to relate results from CTM and other tolerance tests have proved difficult and unwieldy [15]. Therefore, CTM data are generally not useful for evaluating thermal shock in real-world situations.

### *Discharge Canals (Cold Shock)*

Cold shock also became of interest because of fish deaths from power station shutdowns in winter with rapid cooling of fish congregated in warm discharge canals [16]. Cold shock in winter appears to have been an important stimulus for Pennsylvania's 2°F/hr rate of change standard.

Slower rates of cooling appear to reduce the lethal effects, although insufficient rate-of-change studies have been conducted to provide sound generalizations. Because prominent sublethal (behavioral) effects were evident at cold temperatures close to lethal, research was conducted on the vulnerability of several species to predation after cold shocks, usually involving instantaneous thermal exposures as the worst-case thermal-shock scenario. For example, cooling rates slower than 1.5°C per minute (2.7°F/min or 162°F/hr) did not induce selective predation on juvenile channel catfish by unshocked largemouth bass predators, but rates of 2°C/min (3.6°F/min or 216°F/hr) cooling increased susceptibility to predation when the total temperature differential was about 6°C (10.8°F) or more [17].

Despite a few studies showing better survival with slower rates of cooling, data from the worst-case, instantaneous temperature change continued to be used as a conservative (more protective) basis for guidelines to protect aquatic life from cold shock [18] because very little directly applicable information is available on what rates of temperature change are harmful. Additional data on the effects of rates of change on cold shock damages are needed.

### Sublethal Effects

Temperature fluctuations do not appear lethal unless minimum and maximum temperatures exceed lethal limits of a fish species. However, thermal instability may have sublethal effects, such as alteration of tolerance levels, behavior, distribution patterns, growth rates, and reproductive capacity that can either deteriorate or improve individual fish health and risk of mortality depending on the temperature ranges to which they are exposed. However, laboratory studies have focused on regularly fluctuating cycles rather than sporadic temperature changes that may occur at thermal effluents [8].

Fish can respond to even small temperature fluctuations as seen with increased swimming activity. Elevated activity levels in turn expedite metabolism and may decrease feeding efficiency. However, behavioral responses may depend on how close the maximum or minimum temperature is to optimum and lethal limits. Proximity to optimum temperatures likely explain why distribution studies indicate that fish may remain in warm, thermally instable regions, such as below power plant thermal effluent discharges.

Growth rates also appear to depend on the temperature range in relation to optimum species temperature. Below optimum temperatures, temperature fluctuations tend to enhance growth. Above optimum temperatures, fluctuations can depress growth. Effects on growth rates are important because body mass may determine chance of survival [19]. Growth that is delayed, if not prevented, may result in longer periods of vulnerability to particular predators, and therefore higher mortality rates for particular life stages.

Effects of temperature changes on reproductive success remain unclear due to contradictory findings. Rapid temperature changes often disrupt spawning behavior. Some studies found no detrimental effects on reproductive success while others observed asynchronous egg cell development and egg mortality with large temperature increases. Overall, the rate and magnitude of temperature change may be less important to fish health and survival than the actual temperatures to which spawners or early life stages are exposed.

Despite the number of studies we have reviewed that deal to some degree with effects of rates of temperature changes, it is clear that there has been no concerted effort to separate the effects of rate of change from other factors. Any effects of rates of change are usually confounded by the temperatures reached. Studies of diel fluctuations usually have rather low rates of change. For rates of change to be distinguished from other factors, studies at different change rates need to be conducted within the range of tolerance.

From a regulatory perspective, there is scant evidence in the published literature we reviewed that supports a generally applicable rate-of-change temperature standard to protect aquatic life.

## Supporting Alternative Rate of Change Criteria

Given the lack of a sound scientific foundation for a widely-applicable limit on rate of temperature change, any site-specific criteria would need to account for site-specific characteristics such as physical size and thermal characteristics of the water body, the magnitude (volume) and variability of the thermal discharge, and the local aquatic species and human uses to be protected. It would not be a simple task to develop site-specific criteria, and we would not in general recommend attempting to do so. However, if a thermal discharge is being regulated by a numeric limit on rate of temperature change that appears more stringent than is necessary, a site-specific criterion may need to be developed through a 316(a) variance process or other technical demonstration in support of alternative thermal limitations.

### *Site-Specific Information*

#### Plant Operations

Detailed operating records for the facility can be used to establish the temporal pattern in intake and effluent temperatures, and the way in which the through-plant temperature change (ΔT) varies with generation level (including plant or unit shutdown). Ideally these records should be available at least on an hourly basis, and more frequently if possible, in order to establish a frequency distribution for the temporal rate of change of effluent temperature. It is important that the operating history accurately reflects the ongoing operating pattern. For example, if a plant previously operated as a base-load facility, but will in the future operate as a peaking facility, then the past operating data will be of limited use in establishing expected frequencies of temperature change for the future. The records for each generating unit should contain instantaneous values (or averages over a short period of time) of generating load, cooling water flow, intake temperature, and discharge temperature. When multiple units contribute flow to a single discharge, the temperature of the combined discharge flow at a point where the discharges are completely mixed (if that occurs) is also desirable. If the plant has a long discharge canal with temperature change along its length, the temperatures at various points in the canal should also be recorded.

Analysis of the data will establish frequency distributions for hourly temperature changes (or other time interval appropriate to the regulatory criteria). The analysis will also relate these distributions to the operating patterns to establish whether rapid fluctuations (that approach or exceed the criteria) are caused by changes in generation, in flow, or both, and how the instances of rapid fluctuations are distributed daily, monthly, and seasonally (Figure 16-1).

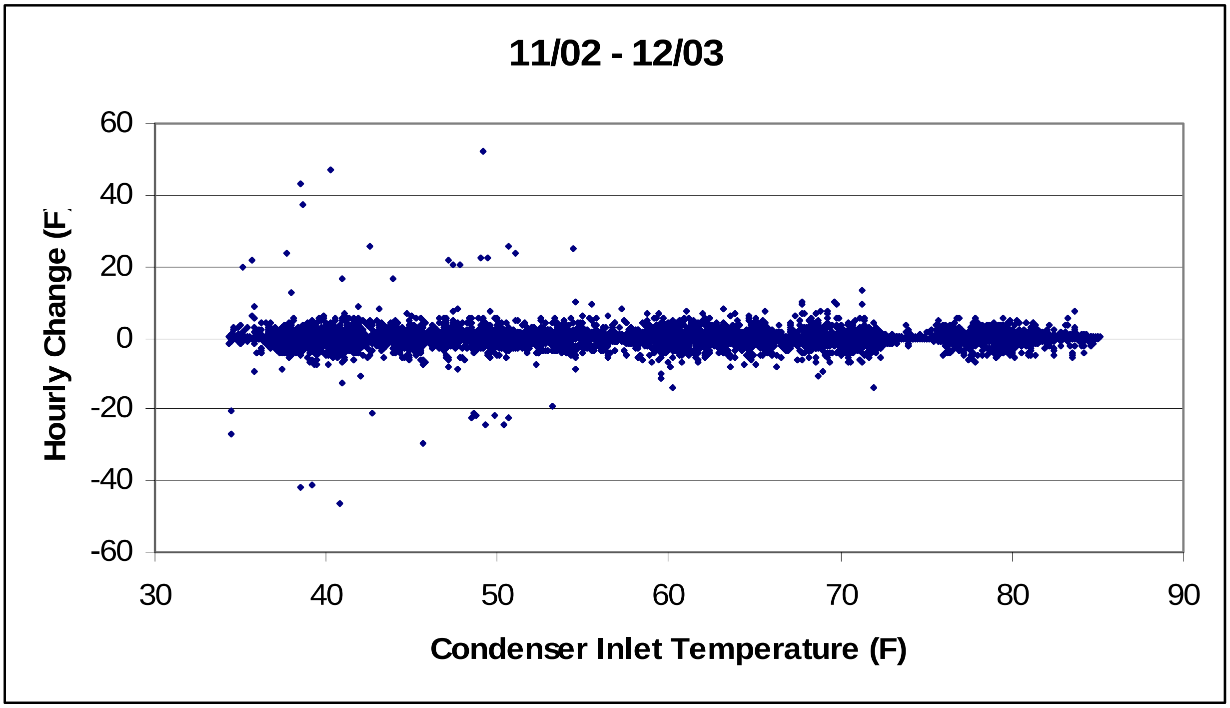

**Figure 16-1**
**Example of Plot of Hourly Changes in Discharge Temperature as a Function of Inlet Temperature**

## Receiving Water Temperatures

Because thermal water quality criteria typically apply to the receiving water rather than directly to the effluent, it is important to have an empirical description of the patterns of temperature fluctuations in the receiving water body from an array of locations at various distances from the discharge. Data from locations that are affected by the effluent, and from locations that are unaffected, such as a distant location in a lake or upstream location in a stream, are needed. If a regulatory mixing zone is defined, data should be collected within, at the edge of, and outside the mixing zone.

Analysis of the data will establish frequency distributions for hourly (or other time interval appropriate to the regulatory criteria) temperature changes (Table 16-1). These distributions must also be compared to the operating data patterns to establish whether rapid temperature fluctuations (that approach or exceed the criteria) are caused by changes in generation, in flow, or both, and how the instances of rapid fluctuations are distributed daily, monthly, and seasonally.

**Table 16-1**
**Example of Summary of Thermal Monitoring Data that Could Be Used to Assess Frequency of and Rapidity of Temperature Fluctuations**

| Difference in Hourly Average Temperature | Station | | | |
|---|---|---|---|---|
| | Upstream | Discharge Canal | Downstream Plume | Downstream |
| > + 8°F | 0.00% | 0.09% | 0.01% | 0.00% |
| > + 6°F | 0.00% | 0.65% | 0.21% | 0.01% |
| > + 4°F | 0.00% | 3.02% | 0.95% | 0.37% |
| > + 2°F | 0.02% | 8.04% | 2.79% | 2.10% |
| > - 2°F | 0.07% | 8.55% | 3.27% | 2.17% |
| > - 4°F | 0.03% | 3.52% | 1.05% | 0.30% |
| > - 6°F | 0.00% | 0.76% | 0.22% | 0.02% |
| > - 8°F | 0.00% | 0.07% | 0.03% | 0.01% |

An important consideration is that, when the criteria apply to the receiving water body, these data may represent documentation of criteria exceedances, which could result in enforcement actions.

## Empirical Tolerance

For existing generating facilities, a wide range of operating conditions and unusual events are likely to have occurred over the period of operation. If there are records of fish kills associated with these historical operations, the correspondence of the kill events with operating data should be examined. The empirical data might demonstrate some levels of temperature variation that were not accompanied by fish kills and others that were. If it can be reasonably established that any significant fish kill event would have been observed and recorded, then the operating data, particularly ambient river temperatures, discharge temperatures, and rates of temperature change, when fish kills occurred can be contrasted with the operating data that did not produce fish kills.

It is unlikely that there will be complete separation of kill events from non-kill events, but patterns in the data may emerge that will help determine the combinations of conditions that can lead to fish kills at the site.

## *In-Situ* Avoidance Capability

Because fish are generally highly mobile, they have some capability to avoid harmful environmental conditions, if they are not trapped by the physical geography and their own temperature preferences. Thus, even if conditions within a discharge canal or within a mixing zone were to exceed lethal limits, fish may avoid harm by moving to more favorable conditions. Although the movement itself represents some ecological cost to the fish (reduced feeding opportunities, increased predation risk, higher bioenergetic costs), this cost is preferable to the potentially lethal result of remaining.

Movement of fishes in thermal plumes has been studied in a number of places [20,21,22], with some of the most technologically advanced studies being recently completed on smallmouth bass at the Nanticoke Thermal Generating Station on Lake Erie [23,24,25,26,27]. These have demonstrated the capability to monitor fish locations and movements in thermally fluctuating environments to establish their preferred locations.

Despite the detailed information on fish locations and environmental conditions that could be obtained with this type of study, the resulting data must be relatable to rate of temperature change in order to be useful in the present effort. Therefore, this type of study would need to be accompanied with a planned series (optimally) of manipulations that create a range of temperature fluctuations so that fish responses could be evaluated and related to the rate of change. Unless a generating facility typically operates over a wide range of generating loads, it is likely that considerable modification of operations would be required to produce the required variation in thermal outputs. The cost of modifying operations, particularly if lost generating opportunity is involved, is likely to be substantially more that the cost of the study.

### *In-Situ* Tolerance

*In-situ* tolerance studies could demonstrate the ability (or inability) of organisms to survive the thermal conditions occurring at fixed locations in a discharge canal, mixing zone, or mixed downstream location if they are forced to endure those conditions rather than avoid them. A reasonable-sized sample (e.g. 20 or more) of fish could be placed in a cage (or cages) anchored at predetermined locations indicative of the ambient (control) conditions, inside the mixing zone, and downstream of the mixing zone. The survival and growth of the individuals at each location then could be related to the thermal conditions recorded during the experiment.

In order to relate the results to the rate of temperature change, some of cages would need to be placed at locations where temperature changes were rapid, and others where temperature changes were gradual. Test organisms should be monitored daily so that mortalities can be recorded and potentially related to the relevant thermal experiences. During the data analysis phase, it will be necessary to analytically separate the effects of differences in mean temperature at the different locations from the effects of differences in rate of temperature change. Therefore, the experiment should use species whose temperature relationships with growth and survival are relatively well-known. As with the in-situ avoidance studies, this type of study would probably be most informative if a planned series of thermal manipulations could be instituted.

### Exposure Duplication

Field-derived information on thermal exposures is often criticized as being imprecise because free-swimming fish may find micro-environments with more suitable temperatures. Therefore, it is desirable to duplicate in the laboratory the exposure conditions observed in the field. With adequate sample sizes and a controlled experimental design, the more anecdotal information obtained from field studies can be translated to more useful quantitative tolerance data.

An exposure duplication study would subject organisms in the laboratory to the fine-scale temperature variation described in the detailed temperature records from selected stations in the temperature monitoring array. This study is similar in concept to the in-situ tolerance study except that it is performed in the laboratory, where temperature and other factors can be closely controlled. The advantage of this type of study is that the entire set of data from the monitoring array can be examined beforehand to identify patterns of variation that actually occurred and that will provide contrast in rate of temperature change. The selected temperature patterns can then be duplicated, using computer-controlled test conditions, and the survival and growth of the test subjects monitored.

Ideally, fish and/or invertebrate species commonly found in the vicinity of the subject facility would be used. However, it is important to use species that can be easily collected or obtained, and that can be maintained in laboratory conditions over a prolonged period. A large range in individual sizes, and species which display aggression to conspecifics, should be avoided.

## *Physiological Analysis*

The ability of aquatic organisms to withstand temperature fluctuation is largely controlled by their physiology, which is, in turn, generally determined by the genetics of the species or subspecies, although variations among populations can also be important. For many common species of fish and some invertebrates, a considerable literature exists on aspects of thermal tolerance [14, 28, 29]. This information can provide a good overview of a species' ability to withstand temperature extremes, and their temperature preferences. Although, as determined in the literature review, the effects of rates of temperature change are not often found, the existing information can be summarized and used as the basis for interpreting existing exposure data, or for designing experimental studies of rate of temperature change.

### Thermal Tolerance Polygons and Resistance Times

Thermal tolerance polygons have been used at least since 1952 to assess the thermal niche of a species [30]. Tolerance polygons describe the combinations of acclimation and exposure temperatures at which a species would generally be able to exist. Species with broad thermal tolerances would have a large tolerance polygon, while those with more restricted thermal requirements have smaller polygons.

Thermal tolerance data on key fish species, and invertebrates if possible, should be gathered from existing literature sources and used to construct tolerance polygons (Figure 16-2) and resistance time curves. Once the polygons are constructed, data from past operational incidents can be entered on the polygons. For instance, mean discharge canal temperature prior to a winter shutdown could be entered as the acclimation temperature, and discharge canal temperature after the shutdown could be entered as the exposure temperature. This should be done both for instances which caused a fish kill, and for instances which did not cause a fish kill, with symbols indicating whether or not a kill was observed for the species.

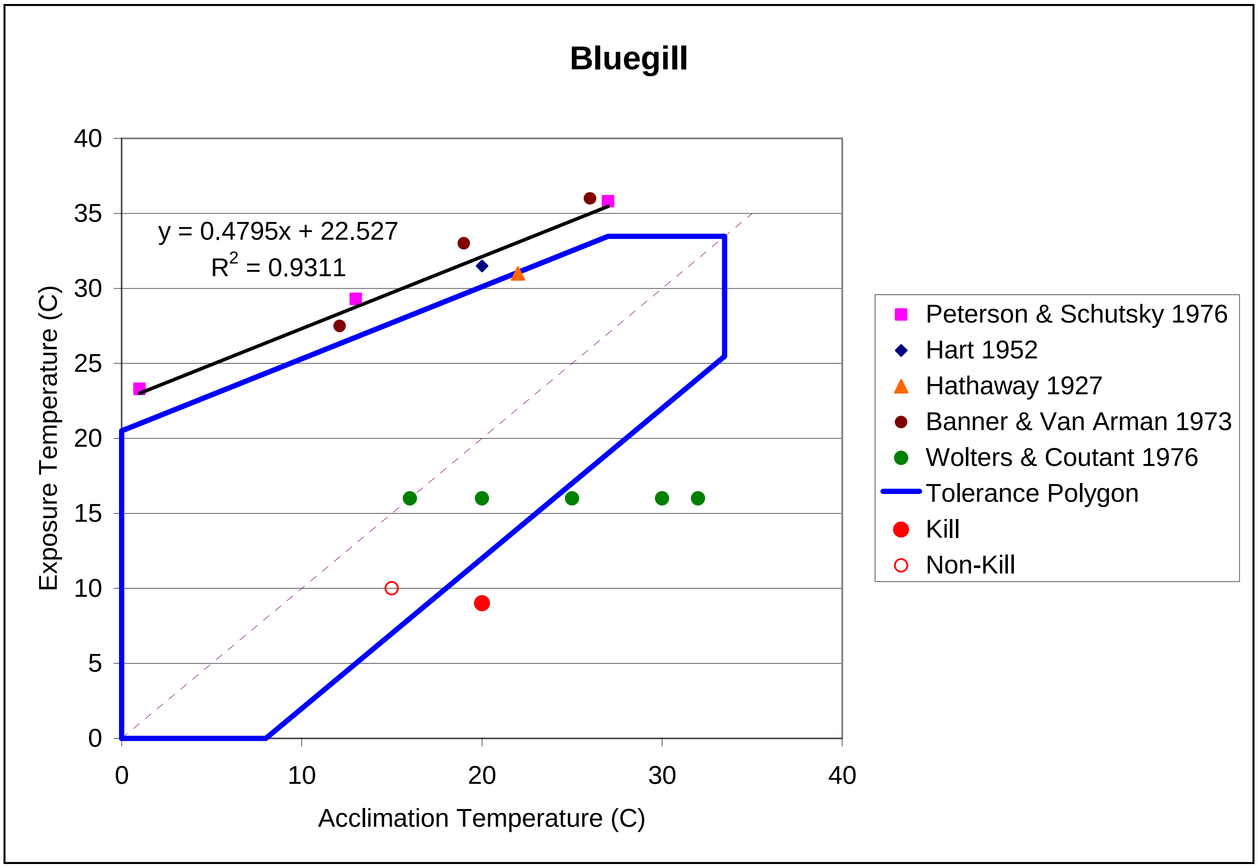

**Figure 16-2**
**Example Thermal Tolerance Polygon for Bluegill Developed from Ilt Estimates, and Coldshock Predation Studies. Upper Acclimation-Dependent Boundary is 2c Less than the Predicted Ilt Temperature Based on All Ilt Estimates (Solid Black Line). Lower Acclimation-Dependent Boundary is 1c above the Delta-T Causing Increased Mortality in Predation Experiments. Dashed Line is the Isothermal Line (Exposure Temperature = Acclimation Temperature**

The second potential use of the thermal tolerance polygon and resistance time curves is in the design of temperature fluctuation challenge experiments. The tolerance polygons will determine the upper and lower bounds for test temperatures, dependent upon the acclimation temperatures chosen.

## Designed Rate of Temperature Fluctuation Challenge

The difficulty in deriving a rate of temperature standard from available experimental information is that the experiments were not intended to determine the effects of rate of temperature change independent from the effects of the final exposure temperatures. The few studies that have experimentally examined the effects of fluctuating (cycling) temperatures on growth rates [31, 32, 33] have not specifically addressed rates of change.

It is difficult to extract information on the effects of different rates of change from existing fluctuating-temperature experiments, such as those cited above, because rate of temperature change is confounded with magnitude of change. Thus, experiments designed explicitly to test the effects of rate of temperature change on survival and growth are needed to define precisely the appropriate limits on rate of temperature change for any individual species. These tests should be conducted in the zone of thermal tolerance where the restricting effects of the high or low temperatures themselves are not an influence.

An example challenge experiment for northern largemouth bass might acclimate the fish to 15°C, and use maximum and minimum exposures temperatures of 25°C and 5°C respectively (Figure 16-3), a range within the species' tolerance polygon. The average rate of change would be determined by the period of the fluctuation cycle. In the example, the cycles vary from 6 to 48 hours, and average rates of change vary from 3.33°C/hr to 0.83°C/hr respectively. The test subjects would undergo a different number of cycles of fluctuation at the different rates of change, but over the period of a 2 to 4-week experiment each treatment would have spent approximately the equal amounts of time at any temperature. The restriction to stay within the bounds of the tolerance polygon will eliminate acute thermal effects and should allow clear interpretation of the outcomes as the result of different rates of change.

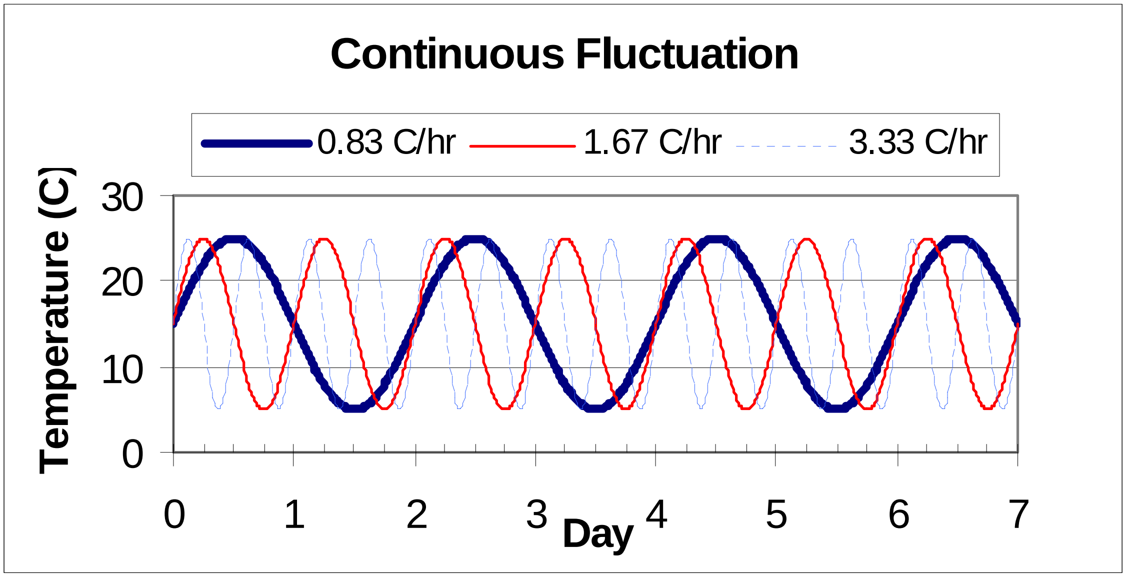

**Figure 16-3**
**Example Challenge Experiment for Continuous Temperature Fluctuation**

For a site-specific assessment, the experimental design could be varied to account for the nature of the thermal fluctuations of concern at a particular site. If rapid temperature changes of large magnitude occur (e.g. rapid temperature drop following unanticipated winter shutdowns), then that type of change could be evaluated. In that case, acclimation temperature would be relatively high and rapid change would occur only in the negative direction (Figure 16-4). The example, again using northern largemouth bass, indicates acclimation to 20°C, and rapid drop to 5°C occurring every other day of the experiment. Rates of change in the example vary from 15°C/hr to 1.88°C/hr, with recovery to the acclimation temperature at the same rate for all treatments. Additional treatment levels could be added as desired.

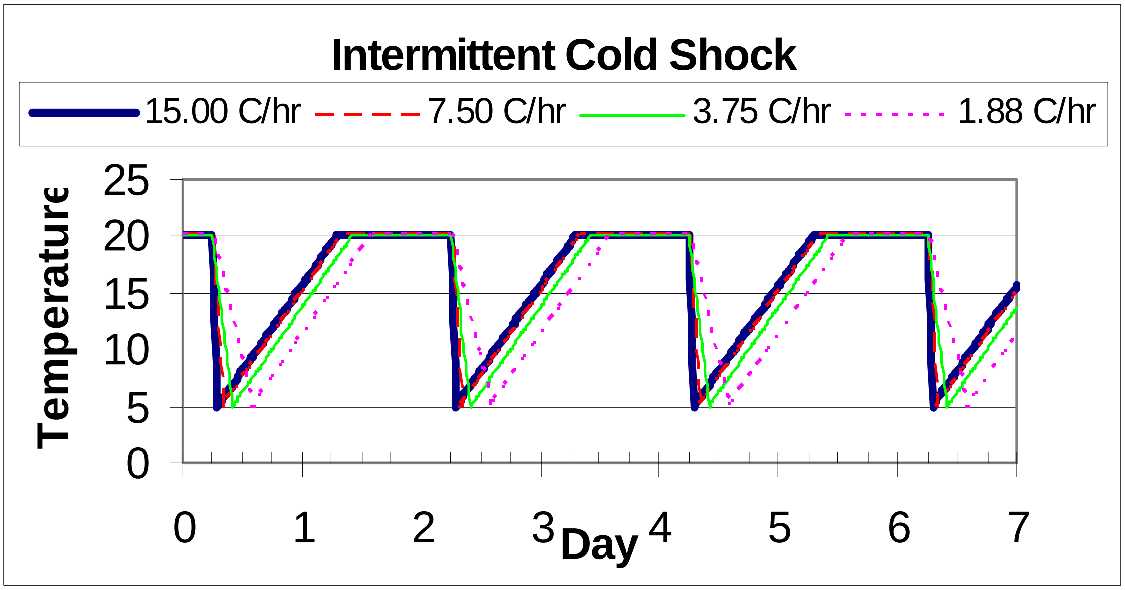

**Figure 16-4**
**Example of Challenge Experiment for Cold Shock**

In addition to growth and survival, vulnerability to predation has been shown to be a sensitive measure of thermal stress in fish [12, 17] and would be a useful test of whether different rates of temperature change within the zone of tolerance are stressful. However, tests of actual differences in predation susceptibility are lengthy, complex, and use large numbers of prey fish. A short-cut technique, measuring the predator-avoidance “C-start” escape behavior of individual fish [34] has been developed as a simpler alternative [35] that has been applied to potentially stressful hydropower turbine passage [36, 37]. The technique could be used to measure and evaluate the effects of different rates and magnitudes of temperature change.

## Conclusion

A review of the scientific literature found no body of rigorous scientific studies that explicitly examined the effects of different rates of temperature change while minimizing the effects of other factors, such as magnitude of change or temperature extremes [8]. Thus, the principle that rates of change are important for aquatic life protection remains poorly quantified, and there is no scientific basis for broadly applicable regulatory limits. Presumably, this is why only a few states regulate rate of change using numerical standards.

However, when numeric standards are imposed, they can often be modified to site-specific values if it can be shown that an alternative limit would be adequately protective. This demonstration would not be a simple undertaking, but multiple lines of evidence could be developed that, taken together, have the potential to support an alternative numeric standard.

Site specific information includes (1) historical and current temperature changes obtained from records of plant operations, (2) descriptions of seasonally and daily changing receiving-water temperatures, (3) descriptions of any historical fish kills or other ecological damages with related thermal data, (4) evidence of movements of fish in and out of thermal areas both seasonal and at times of operational changes, (4) live-cage tests of survival or behavior in thermally altered locations, and (5) duplication in laboratory experiments of temperature exposures recorded in the field but where observations of effects are difficult.

Physiological information in the form of tolerance polygons and resistance curves can help summarize existing information, and aid the design of thermal challenge experiments on appropriate taxa. The challenge experiments need to be carefully designed to isolate the effects of rate of temperature change from exposure temperatures. This information will have general value for many power stations or other thermal discharges that have the same species. The rigorous experiments may settle the ongoing debate over whether the rate of temperature change, in itself, is an important temperature feature worthy of regulation.

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# 17

# NEW COOLING WATER DISCHARGE GUIDELINES IN THE NETHERLANDS

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## Introduction

In the Netherlands, the average temperature of river Rhine at the border has increased with 3,3°C during the last 100 years. This is the result of an increased cooling water application in neighbouring countries, canalisation (narrowing) of the river and the general temperature increase due to climate change. During summer, the average background river water temperature of the rivers Rhine and Meuse entering the Netherlands rises up to 26 – 28ºC at the border. After passage at the border, the river Rhine water temperature drops about 3°C before the water is discharged into the North Sea, despite all heat discharges within the Netherlands. Thus, the Netherlands is in fact a cooling down nation for the river Rhine. The same cooling aspect has been found for the river Meuse.

Forecasts with respect to climate change show an increase of the surface water temperature in summer time and also unpredictable large fluctuations in river flow especially with low river discharge during dry periods in the summer. Also, forecasts with respect to the future electricity demand show an increase of 80% in 2030. Figure 17-1 shows the occurrences of heat waves in the Netherlands of 1900–2006. During the summer of 2003, which was a very hot summer with low river discharge, the danger of a shortage in electricity supply arose (“stage-4” situation). The summer of 2006 was again a very warm period with the hottest July-month in 300 years, with two official heat waves, from June 30–July 6 (with maximum temperature of 32ºC) and from July 15–July 30(with maximum temperature of 35.7ºC). It seems that hot summers and heat waves are occurring more frequently, although the summer of 2007 was cool.

During the last extreme warm summers, problems with heat discharge occurred more frequently, reaching “stage-4” conditions, i.e. shortage in electricity supply due to river water temperatures > 30º. The Dutch water authorities had a zero-tolerance policy on permit exceeding. The former guideline was formulated by the Algemene Beraadsgroep Koelwater (ABK) (i.e. the General Commission for Cooling Water Issues) in 1975 and existed largely in emission-demands. This regulation was however inadequate to cope with extreme summer conditions. As a consequence, from 1991, it was common practice to tolerate discharge temperatures > 30ºC due to ‘stage-4’conditions.

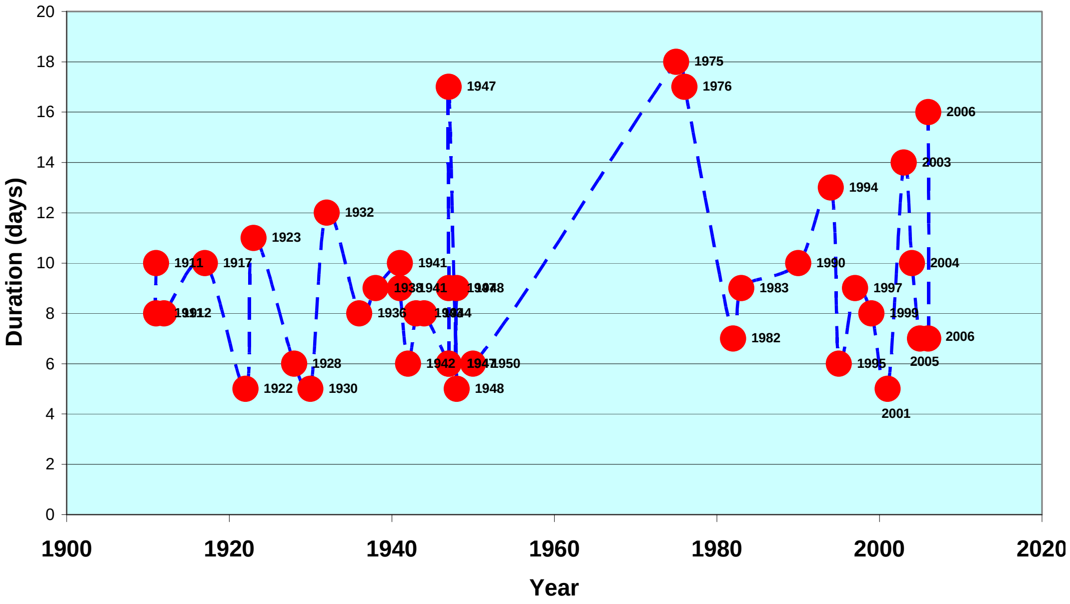


**Figure 17-1**
**Duration and Occurrence of Heat Waves 1900 – 2006 in the Netherlands**

The problems that occurred during the last extreme hot summers and the developments with respect to the climate and surface water temperature increasing, have increased the need for new guidelines for evaluating the discharge of heat. Particularly under extreme summer conditions, a meticulous consideration between the emission of heat on one side and the effects in the surface water on the other hand is of crucial importance.

The new guidelines [1] have been developed by a working group of the Commission for Integral Water Management. The new guidelines are based on information from available literature and followed the CIW-immission procedures for substances (2000). In order to realize this aim, literature studies have been performed in the area of effects on the aquatic environment due to discharge of heat. Also 3D-modeling studies on the distribution of discharged heat have been performed. From these studies the test criteria for the evaluation systematic have been derived: withdrawal, mixing zone and heat discharge. The guidelines provide a systematic for channels, tidal harbors, rivers, North Sea and estuaries. For lakes it is proposed to derive one generic criteria as it holds that situations are mostly very different and in itself are difficult to compare. The new cooling water discharge guidelines are attuned to the new European legislation, i.e. the Integrated Pollution Prevention and Control guideline (IPPC) (96/61/EC) (including the European IPPC Reference Document on the application of Best Available Techniques to Industrial Cooling Systems) and the Water Framework Directive (WFD) (2000/60/EC) [2, 3, 4]. These regulations and guidelines request for adequate instruments to assess and control emissions and surface water quality.

## *New Cooling Water Guidelines*

The guidelines include 3 criteria: withdrawal, mixing zone and heating.

## Table 17-1
## Old and New Heat Discharge Guidelines

| Parameter | Old ABK-Guidelines[1] | New Guidelines |
|---|---|---|
| **Emission-Demands (Generic)** | | |
| T cooling water | Fresh water : ≤ 30ºC | |
| T cooling water | Marine water : ≤ 30ºC | |
| ΔT cooling water | Fresh water: ≤ 7ºC (summer)<br>≤ 15ºC (winter) | |
| | Marine water: ≤ 10°C (summer)<br>≤ 15°C (winter) | |
| **Immission-Demands (Generic)** | | |
| Heating[2] | ≤ 3ºC | ≤ 3ºC in relation to background temperature [3] to a maximum of 28[4]°C[7] |
| **Immission-demands (water system related)** | | |
| **Channels/tidal harbours** | | |
| Withdrawal | - | no significant effects in spawning and nursery areas of juvenile fish, proper fish return system, reduced cooling water flow (optimisation)[8] |
| Mixing zone[5] (T> 30ºC) | - | < 25% cross section[7] |
| **Rivers** | | |
| Withdrawal | - | no significant effects in spawning and nursery areas of juvenile fish, proper fish return system, reduced cooling water flow (optimisation)[8] |
| Mixing zone[5] (T>30ºC)[6] | - | < 25% cross section |
| **North Sea** | | |
| Withdrawal | - | striving for the least possible withdrawal, not in spawning and nursery areas of juvenile fish or migration route, proper fish return system[8] |
| Mixing zone[5] (T> 25 ºC)[9] | - | the mixing zone may no touch the sea bed |
| **Estuaries** | | |
| Withdrawal | | striving for the least possible withdrawal, not in spawning and nursery areas of juvenile fish or migration route, proper fish return system[8] |
| Mixing zone[5] (T> 25ºC)[9] | - | < 25% cross section |

1 The criteria mentioned in the table apply according to the outlines. For the full overview is referred to the appendix 2 of the guideline.

2 Permitted heating: 3°C for cyprinid waters, 2°C for shellfish water and 1, 5°C for salmonid waters.

3 Heating is related to the background temperature on the border of (parts of) the water system.

4 28°C for cyprinid waters, 25°C for shellfish waters and 21, 5°C for salmonid waters.

5 The part of the water system (in the vicinity of the point of discharge), that due to the discharge of heat is brought to a temperature of ≥30°C and is bounded by the spatial 30°C-isotherm (fresh waters) or the 25°C-isotherm (marine waters).

6 Exceptional case at high background temperatures (> 25°C): during one continuous period of maximal one week in July/August, the temperature at the border of the mixing zone is allowed to be 32ºC. If this approach leads to problems with its practical implementation, the administrator can make a reasoned deviation.

7 The administrator can, based on specific information with respect to the considered water system, make a reasoned deviation.

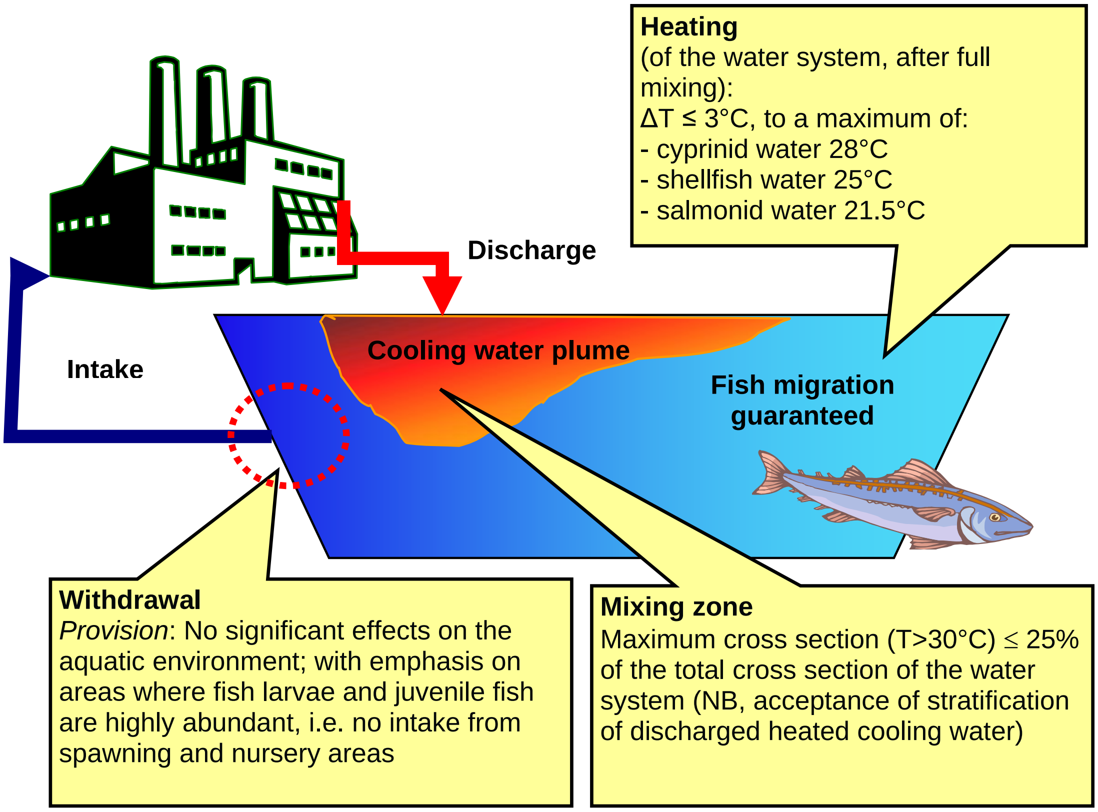
8 For fresh water particularly important during the biological spring (March 1 – June 1) and for marine waters during the biological spring (February 1 – May 1) and the biological autumn (September 1 – December 1). Quantitative, generic criteria for withdrawal cannot be provided. For new situations it must be assessed through EIA-procedures whether, based on local specific information, the activity can be allowed or not.

9 Assuming a background temperature of 22°C

Within the effect studies, the effects of impingement, exposure to the cooling water circuit and heating of the receiving environment have been studied for different aquatic organisms. It was found that fish are the most sensitive organisms to these stressors. For the determination of criteria, fish are therefore chosen as the main target organism.

Discharges of heat are assessed by the extent of its influence on the water system, both locally and at water system level. From literature studies it follows that the restriction of cooling water flow is important for the protection of the aquatic environment, but also that uncertainty exist with respect to the effects on a population level, as well as to the standard that should be applied for the assessment.

Starting point is that significant effects due to the withdrawal of cooling water may not occur. As a consequence, the generic temperature limit for cooling water discharge has been dropped. Instead of the temperature limit, the criteria of mixing zone has been introduced. Fish larvae and juvenile fish are highly abundant in spawning and nursery areas during the biological spring. Due to there small dimensions, these organisms are vulnerable to being drawn into the cooling water system. For fresh water systems the biological spring is the period from the first of March to the first of June. For marine water systems, next to the biological spring from the first of February to the first of May, the biological autumn from the first of September to the first of December is also of importance. Large scale withdrawal of cooling water from spawning and nursery areas during these periods is not desired.



**Heating**
(of the water system, after full mixing):
ΔT ≤ 3°C, to a maximum of:
- cyprinid water 28°C
- shellfish water 25°C
- salmonid water 21.5°C

**Withdrawal**
*Provision*: No significant effects on the aquatic environment; with emphasis on areas where fish larvae and juvenile fish are highly abundant, i.e. no intake from spawning and nursery areas

**Mixing zone**
Maximum cross section (T>30°C) ≤ 25% of the total cross section of the water system (NB, acceptance of stratification of discharged heated cooling water)

**Figure 17-2**
**Graphical Summary of the New Cooling Water Discharge Demands**

The second ministerial Indicative Long-range Plan for water (Indicatief Meerjaren Programma (IMP)-water), states that the objectives for water quality do not apply within the mixing zone in the vicinity of the point of discharge. For this aspect, the evaluation systematic relates the volume of the mixing zone with the level of Ernstig Risico (ER) (i.e. the level of Serious Risk), which is analogous to the immission-procedures for substances. Based on the literature study, the ER-level for heat has been established at respectively 30ºC for fresh water and 25ºC for marine waters. The mixing zone is furthermore bounded by the maximum cross section of 25% of the total wet cross section of the water system. The mixing zone determines the maximum allowable discharge temperature at a given water system discharge and cooling water discharge, provided that the criteria for heating and withdrawal are also met. From calculations it appears that the "cross-section-criteria" also limits the volume of the mixing zone for discharges with a temperature ≥ 30ºC. For this reason, the criteria of mixing zone volume has not been incorporated in the evaluation systematic separately.

The literature study on the effects of heat discharges on fresh water environments indicates that in exceptional situations, when the (natural) background temperature of the surface water increases above 25ºC, the temperature at the boundary of the mixing zone is allowed to be 32ºC during a period of maximum 1 continuous week per year. The frequency of this allowed exceeding is strictly limited to 1 week per year to provide the ecosystem enough time to acclimate.

The way cooling water is discharged may influence the behaviour of fish in the receiving waters. The discharge velocity and the angle to the water flow determine the spatial dimensions and temperatures within the plume. Table 17-2 the discharge aimed at mixing is compared with stratified discharge in which the warm water 'floats' on top of the cool receiving water.

**Table 17-2**
**Comparison of Cooling Water Discharge Aimed at Mixing and Stratified Cooling Water Discharge**

| Way of Discharge | Influence on Plume | (indirect) Effects |
|---|---|---|
| Discharge with relative high velocity, aimed at maximal mixing in initial mixing zone | - ΔT = small (gradual T-transition<br>- Area that in which the T is increased is relatively large | Lower T in plume: small chance on exposure to extreme T-levels<br>Due to gradual T-transition: no deterring effect: attracting impulse may dominate, and fish might remain within area with less proper conditions<br>Cooling in far-field is less than with stratified discharge |
| Stratified discharge: discharge with low velocity, whereby the discharge velocity equals the river velocity | - ΔT is larger (higher T in plume)<br>- Remaining volume of water system (outside plume) is less influenced<br>- Escape area for fish is nearby and of a lower T-level | By sharp, relative large T-difference between the plume and the receiving water system, a deterring effect is created for fish to pass this T-barrier. Fish will less often enter the plume and there is a sufficient volume of water of a lower T-level nearby (better escape possibilities)<br>Cooling down in the far field is better: smaller reciprocal influence of discharges |

In accordance with the EU-Directive on the quality of fresh waters for fish [5,6] heating is also incorporated as a criteria, for limitation of heating at both local and water system level. The heating is determined compared to a reference point, the background temperature at the boundary of a basin area or water system.

Experience during the past years have shown that during hot summer conditions, the temperature of the surface water, before it enters the Netherlands at the border, may considerably increase (up to 28ºC). Establishing the water quality objectives, as determined in the Dutch national Ministerial Directive (Algemene Maatregel van Bestuur (AmvB)) for cyprinid waters, is in practice under such conditions not possible. Based on practical experience with the former cooling water regulation (ABK) and the effect studies, it was found reasonable, until a basin-based standard based on the Water Framework Directive becomes operative, to, in accordance with the European guideline for the quality of fresh waters for fish, apply a maximum temperature of 28ºC for cyprinid waters. The European guideline for the quality of fresh waters for fish will be incorporated within the Water Framework Directive.

For lakes it holds that situations are mostly very different and in itself are difficult to compare. Following the ABK-guidelines, it is proposed to derive one generic criteria for lakes. In the Netherlands, large scale heat discharges on lakes only occur at the IJssel Lake and Lake Bergumermeer.

## Consequences

To test whether the criteria withdrawal has possible consequences for the location choice, can possibly be limiting for the cooling water flow. The means that this has to be regulated through the Wwh-permit (Dutch law on water management procedures).

Based on the criteria of mixing zone, the new evaluation systematic may, compared to the ABK-guidelines, lead to increased spatial space for the discharge of heat, provided enough discharge and cooling surface are present. The dimension of this space is depended on the receiving surface water. For fast-moving water systems (like rivers) this space shall be larger due to the larger mixing than for to slow-moving, (semi-)stagnant water systems. Whether the extra space will actually be present, also depends on the parameters of heating and withdrawal.

For channels, application of the new evaluation systematic, based on the parameter heating, leads to a limitation of the allowable heat load. For existing situations, for these circumstances a realistic transitional period can be determined, in which for the parameter heating the old ABK-criteria can be followed, provided that the experience with respect to water quality justify this procedure.

Because in the new evaluation systematic, next to the heating criteria, the mixing zone criteria directly limits a heat discharge through the discharge of the water system, the meaning of discharge is more prominent in the new systematic compared to the old ABK-guidelines. This means that the water distribution and regulation of discharge (if possible) may have further consequences for the actual allowable heat load. Wherever the discharge can be regulated by the local water authorities, choices and consideration in this matter can have an effect on the available cooling capacity and therefore and effect on the available electricity production capacity of power plants or production capacity of process industry.

In order to perform an assessment of cooling water discharges by means of this new evaluation systematic, the local water authority needs to have sufficient knowledge on the water system. This applies to data with respect to water quality, year-round surface water temperatures and water quantity and the year-round discharge.

The assessment results in a maximum heat load, whether or not related to the momentary discharge and temperature. This means that the maintainer also needs access to adequate momentary data on the water system

## Conclusions of the Literature Study and 3D-Modeling Studies

Literature studies on the effect of heat discharge on the aquatic environment and 3D-modeling studies of heat discharge distribution brought up new insights:

- Mortality of zoo-/phytoplankton >30ºC recovers in < 14 days
- Direct fish mortality is not or hardly found, indirect effects exist: attraction of fish to the heated water plume and fish can detect heated quite well and take refuge if necessary
- Due shifts in spawning seasons of fish species, there is an increased possibility for the occurrence of hybridisation and a mismatch between nursery period and food availability
- Stratification is to be encouraged rather than quick vertical mixing

With the new guideline, a shift is made from emission to immission conform the European Directives.

Higher cross-plant temperature rise and lower cooling water intake flow for a given thermal discharge rate are preferred.

As part of the permit system, cooling water discharge of both existing and new power plants are being modeled (3D) to investigate the available heat capacity of the receiving surface water and compliance with the new guideline demands.

The results of 3D modeling of power plant cooling water discharges for worst-case scenarios (hot summers conditions) have shown no problems with complying to the new guideline demands at different surface waters, i.e. estuaries, lakes, canals, harbours and rivers in the Netherlands.

## Recommendations

The discussion on heat and background temperature shows that foreign influences are, as reflected in the temperature at the border, in the river Meuse at Eijsden and in the river Rhine at Lobith, to a very large extent qualifying for the possibility to, under hot summer conditions, meet the water quality objectives in the Netherlands. It is highly desired to pay attention to ‘heat-discharge-issue’ during the negotiations to achieve international harmony for basin areas with accompanying discussion on establishing the basin area based standards for the Water Framework Directive.

There is more insight into the effects on organisms due to ingress into cooling water intakes (impingement and entrainment) than into the effects on the aquatic environment on a population level. Also, field studies paid little attention to the influence of a mixing zone on migration possibilities for fish. Additional research in these areas is necessary.

Proper execution and enforcement of the new evaluation systematic in practice, asks for implementation of a monitoring network in which data with respect to water temperature and discharge are registered on-line.

As part of the Water Framework Directive, the next years several actions need to be taken. With respect to heat discharge this holds:

- Attention for heat issues, both national and international. The subject needs to be put on the agenda of the Water Framework Directive (WFD) and International Commission for the Protection of the Rhine (ICPR);
- Per water system of parts of a water system, it must be stated whether is it is a ‘natural water’, ‘heavily modified water’ or ‘artificial water’, which is important with respect to the final standard;
- For each area, specific limiting conditions with respect to temperature need to be determined in order to meet the Good Ecological Status or the Good Ecological Potential as mentioned in the Water Framework Directive. To attune this on an international level is a necessity;
- In order to guarantee a proper compliance with the limiting conditions with respect to temperature in the Netherlands, and to achieve harmonisation of area-based standards, positioning the heat problem from a Dutch perspective is of great importance.

It is proposed to thoroughly evaluate the new evaluation systematic after, for example, 5 years, for which the new perceptions from the Water Framework Directive are taken into account. Experience from EIA-studies, in which considerations are based the new evaluation systematic, can play a role in this. Based on the information, completed with information derived from the ongoing development of the Water Framework Directive implementation, the aim is to give further area-based content to the standards.

Possibly an evaluation of the gained experiences with the new evaluation systematic is already meaningful on short term.

In order to perform a proper evaluation of the systematic, a proper monitoring of the problems is a necessity. This would include the (preferably) on-line monitoring of temperature and discharge and the establishment of monitoring campaigns, possibly combined with IR-scans by means of planes.

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# 18

# APPLICATION OF 3D NUMERICAL MODEL THREETOX TO PREDICT COOLING WATER TRANSPORT AND MIXING

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## Abstract

A modeling system – THREETOX – has been developed to simulate the transport and mixing of cooling water in both the freshwater and the marine environment. A 3D hydrostatic free-surface model describes the heat dispersion in the far-field, whereas an integral buoyant jet model coupled with a far-field model is applied to the near-field. Special attention is paid to the parameterization of heat fluxes between water and atmosphere and between water and bottom sediments. Wetting and drying processes were built into the model to describe areas where tide and floods play a dominant role. The model was enhanced by processes describing the effects of ship traffic on the dispersion of the discharge heat in stagnant canals. In this article several examples of the application and validation of the THREETOX model are presented. Studies were performed on the dispersion of cooling water, discharged by various power plants in the Netherlands, located at different types of aquatic systems, varying from rivers, canals to tidal river reaches.

## Introduction

Power plants and other facilities are often applying once-through cooling water systems to remove the excess heat from the condensers. Although cooling water discharges in rivers were normally not critical in terms of environmental impact, the recent combination of low volumetric flow rates combined with relatively high water temperatures (e.g. the warm summers of 2003 and 2004 in Europe) showed the limitation of once-through cooling in a changing climate. This change in thermal regimes of large rivers in Europe made it necessary to implement regulations in which industries are obliged to assess the thermal impact of water bodies to prevent damage on aquatic organisms. Since these assessments focus on the environmental impact, special model tools are required to evaluate the effect of cooling water releases.

In the Netherlands, new guidance on the acceptability of thermal discharges has been developed and is incorporated in a new law in 2006 [1, 2]. The new guideline provides a systematic for cooling water discharges at different types of water bodies. The new regulations focus on the different aspects of the cooling water dispersion; criteria are set for the near-field, and the far-field. The far-field has as criterion that the maximum temperature should not exceed the temperature (time and depth averaged) of 28°C for cyprinid waters, 25°C for shellfish waters and 21.5°C for salmonid waters. Also, the temperature maximum heating of the water system caused by the thermal discharge (after full mixing) should be not higher than ΔT 3°C in case of cyprinid waters, ΔT 2°C in the case of shellfish water and ΔT 1.5°C in case of salmonid waters. For the near-field region, instead of the temperature limit (maximum of 30°C end of pipe), the criteria of mixing zone has been introduced. The mixing zone is the part of the water system (in the vicinity of the point of discharge), that due to the discharge of heat is brought to a temperature of ≥30°C and is bounded by the spatial 30°C-isotherm (fresh waters) or the 25°C-isotherm (marine waters, estuaries, and brackish water regions). Also, the new regulatory regime requires that no more than 25% of the cross-sectional area in the receiving surface water does not exceed a temperature of >30ºC, averaged over 24 hours. In extremely hot summers, in the exceptional ones with high background temperatures of > 25°C, the temperature at the border of the mixing zone is allowed to be 32ºC during one continuous period of maximal one week during July and August. As part of the permit system, cooling water discharges of both existing and new power plants are being modeled (3D) to investigate the available heat capacity of the receiving surface water and compliance with the new guideline demands. The 3D modeling of cooling water discharges are performed with worst-case scenario conditions (hot summers).

For such precise criteria simple approaches are not sufficient to evaluate whether the discharge match the criteria. The complexity of the transport and mixing of the cooling water is high due to buoyancy, which determines the hydrodynamics of both the discharged water and the ambient water, and due to the heat exchange with the atmosphere. Commonly three zones around the cooling water conduit are defined: (a) the near-field, where the transport is dominated by turbulent entrainment of the incoming buoyant jet, (b) the intermediate field, where buoyancy forces in the plume are dominating, and (c) the far-field, where the cooling water is transported passively by the ambient currents. The trajectory of the jet in the near-field is governed by the ambient flow and stratification. The spreading buoyant plume interacts with the currents in the intermediate field, while the stratification in the plume suppresses the ambient turbulence. The accurate description of the jet near the outfall is complicated due to the often non-hydrostatic character of the flows and geometry of outfall. The heat exchange with the atmosphere plays only a role in closed and semi-closed water bodies such as lakes, harbors, and canals, but less in river systems, estuaries, and coastal waters.

In the past decades different approaches have been developed to simulate the heat dispersion in water bodies. The developed methods comprised physical modeling [3, 4], expert systems [5] such as Cornell Mixing Zone Expert System (CORMIX) [6] and a variety of mathematical models. Integral jet models [7, 8], and non-hydrostatic models [9, 10] were applied for the near-field zone. A number of numerical hydrodynamic 2D models [11, 4] and 3D hydrostatic models [12, 13, 14] were applied to the far-field problems in inland and coastal waters.

In this paper applications of the 3D-modeling system THREETOX to the cooling water dispersion are described. This code initially was developed within the framework of the EU-decision support system RODOS (Real-time Online Decision support System) for supporting the emergency response to nuclear accidents [15]. The model was adapted later to the problem of heat dispersion in surface waters [12, 16] and was applied in many different studies for the heat dispersion in inland and coastal waters. The recent improvements in the physics and numerics of the THREETOX model include the parameterization of the heat exchange between the water and the bed sediments, the nesting procedures in curvilinear coordinates, and the sub-model for the near-field processes. Several examples of model applications on cooling water dispersion in a river, in a ship canal, in a lake, and in a tidal delta reach of a river, and in a semi-enclosed bight connected to a canal, are presented in this paper. In each example it is shown which specific modification of THREETOX was implemented to match the complexity of modeling area.

## The THREETOX Model

The modeling system THREETOX simulates the transport and mixing of cooling water in both the freshwater and the marine environment. A 3D hydrostatic free-surface model describes the heat dispersion in the far-field, whereas an integral buoyant jet model coupled with a far-field model is applied to the near-field. The equations of hydrodynamics of the far-field model are completed by equations for heat and salt transport, and by the $k$–$\varepsilon$ turbulence model. The prognostic variables in far-field model are the horizontal velocity field, the temperature $T$, the salinity $S$ and the surface elevation $\eta$. The governing averaged Reynolds' equations of continuity and horizontal momentum, the conservation equations for temperature and salinity, and the state equation and hydrostatic relation are solved by finite-difference methods. The model describes a number of physical processes that are important for heat dispersion. The numerical algorithm was adjusted to accurately simulate specific problems of spreading and dispersion of buoyant plumes in the domain of complicated form. These special features of modeling system are briefly outlined below.

### *The Surface Fluxes of Heat and Momentum*

The heat exchange air-water plays especially a role in stagnant water, canals, and harbors, and to a lesser extent rivers and estuaries. The downward surface heat flux of solar insolation is calculated from solar radiation at the top of atmosphere and then corrected for relative humidity, cloudiness and inclination. It is absorbed in the water column and by bottom in shallow areas. The surface fluxes required by the model are momentum flux, heat and mass fluxes. The upward net heat flux on the surface includes the latent heat flux, the sensible heat flux and the long-wave radiation. The sensible and latent heat fluxes into the water are estimated by bulk formulae [17] based on theory stratified surface layer. The total required data set are surface air temperature, relative humidity, cloudiness, wind speed, and air surface pressure.

### The Bottom Fluxes of Heat and Momentum

Heat transfer with the sediment bottom is often neglected due to the fact the water-atmosphere exchange and the dispersion by currents is dominant. In shallow lakes, en semi-enclosed reservoirs the heat interaction with the bottom can contribute significantly to the heat balance not only for the cooling water but also for natural flows, in diurnal and seasonal scale. Although in shallow lakes and rivers the daily-averaged heat flux between the bottom and the overlying water column is near zero, the heating up of the water layer and bottom by incoming solar radiation during the day and cooling down by outgoing long-wave radiation during the night can create an essential heat exchange. This flux can also be important in seasonally-dependent processes in lakes of cold regions. The temperature in the sediment layer simulated using the differential heat conduction equation. The flux of heat through the bottom includes the turbulent heat flux and the shortwave radiation. The turbulent heat flux is calculated using the simple bulk formula for mixed convection that includes both forced convection and free convection.

A sound choice of the bottom roughness parameter is especially important for heat and momentum budget in shallow lakes where bottom vegetation plays an important role in formation the bottom roughness. To deal with this effect a function has been introduced which relates this parameter which the density of the vegetation.

### The Near-Field Processes

To simulate near-field processes, two different approaches can be used in THREETOX. The non-hydrostatic sub-model [18] can provide representation of transport processes in the near-field but it is too laborious to be coupled with THREETOX. Therefore the procedure of dynamic coupling of the integral Lagrangian model JETLAG [7] and THREETOX code was employed, following [19]. The Lagrangian model predicts the buoyant jet trajectory, jet velocity, radius and entrainment rate at given ambient velocity and stratification. The feedback to the ambient flow is modeled by the distribution of sinks of mass, temperature and salinity along the jet trajectory and an equivalent diluted source flow at the predicted terminal height of the plume rise (water surface or plume trap height in stratified ambient). The corresponding volumetric sink representing entrainment to the jet from ambient flow was introduced in the continuity equation and relevant sinks of heat and salt were introduced in the transport equations for the temperature and salinity. The diluted source flow at the terminal height is calculated as integration of entrainment flows along the jet trajectory. In this way, a two-way dynamic link is established between the near and far-field models.

### Effect of Shipping Traffic on Heat Dispersion in Canals

In shallow and narrow canals, vessels can effect the mixing the cooling water plume discharged into the canal. Intense shipping traffic can affect the heat dispersion by enhanced vertical mixing in the canal. It is assumed, that the influence of the number of moving ships can be represented as a time-averaged influx of turbulent energy in the upper layer of a channel and that the mixing of water by moving ships is related to the jet caused by the ship's propeller. In THREETOX a module has been implemented to include this effect. The consequence of intensive shipping are a lower surface temperatures in the canal due the mixing and a higher heat content due to the resulting lower temperature difference with the atmosphere.

### The Lock Exchange Parameterization

Locks located between the sea and brackish water canals are affected by the salinity of such canals due to the flow into the canal when the locks are opened. At the sea side of the lock the brackish water flows into the sea bight, creating a low salinity upper layer. This bidirectional exchange have been modeled in THREETOX using two approaches (a) direct modeling of lock exchange process and (b) using lock coupler that parameterizes exchange processes between two domains where parallel computations are carried out.

### Solution Techniques

The governing equations together with the boundary conditions are solved by finite difference techniques. A numerical algorithm was implemented in the horizontal curvilinear-orthogonal coordinate system. The sigma coordinate in the upper layer can be combined in the lower layer with a second sigma coordinate system or with a coordinate system. The vertically integrated equations of continuity and momentum (external mode) are separated from the equations for the vertical structure of the flow (internal mode). Splitting on the external and internal modes was utilized following [20]. The 2D equations for the external mode variables were solved explicitly, using a short external time. The 3D velocity and scalar fields (temperature, salinity, and turbulent quantities) were computed semi-implicitly with larger internal step. The parallelization of the code was realized using MPI standard. A computational domain was horizontally partitioned on a set of smaller overlapped sub-domains to divide computational work among processors.

Wetting and drying (WAD) occur in low-lying coastal zones. It can be caused by tidal or storm flooding and by river floods. The effects of WAD can play an important role in heat dispersion in tidal flats. Therefore the efficient WAD-scheme, developed for the terrain-followed coordinate models [21], was implemented into THREETOX. Dry cells in the model are cells with a depth lower than a certain user-defined depth (order or centimeters). After the cell is classified as ‘dry’, the heat exchange with the adjacent wet cells and with the atmosphere is blocked, as well as the turbulent exchange. The temperature in ‘dry’ cell is computed from the heat budget of the thin film and of the underlying bottom layer.

Embedding a high resolution grid within a low resolution grid (nesting) makes it possible to describe the transport of cooling water in the near- and intermediate zones [13] adequately. The heat transport in the intermediate field is not passive advection and processes of spreading of the buoyant plume affect the ambient currents. Therefore, a two-way information exchange between the coarse and the fine grid is necessary. The nesting algorithm includes calculations on coarse and fine grids and exchange of information between them. At each time step on coarse grid large scale forcing is provided to the embedded fine grid cells on the coarse grid. The calculated fine grid variables, averaged over the nested grid, replace the coarse values on the output interface. The input interface is separated from the feedback interface which prevents numerical noise [22].

## Applications

### The River Waal

In this example the dispersion from the coal-fired power plant Gelderland-13 (G-13) situated on the bank of the river Waal (main branch of the River Rhine) has been evaluated for a late autumn period (i.e. 3–4 December 2003) and then compared with measurements data performed in the same time period. The model area covers a river section from 400 m upstream of the discharge up to 800 m downstream of the outfall. A system of groins was built along the river to prevent bank erosion. The flow in the groin field is dominated by large trapped vortices forming dead zones. The number and configuration of these vortices depend on the aspect ratio groin length to distance between groins [23]. Figure 18-1 shows the computed surface currents in the river Waal at 11 hr December 4, 2003.Water from cooling system of thermal power plant is released into the river through a wide channel whereas the inlet was placed in a harbour in the Maas-Waal Canal.

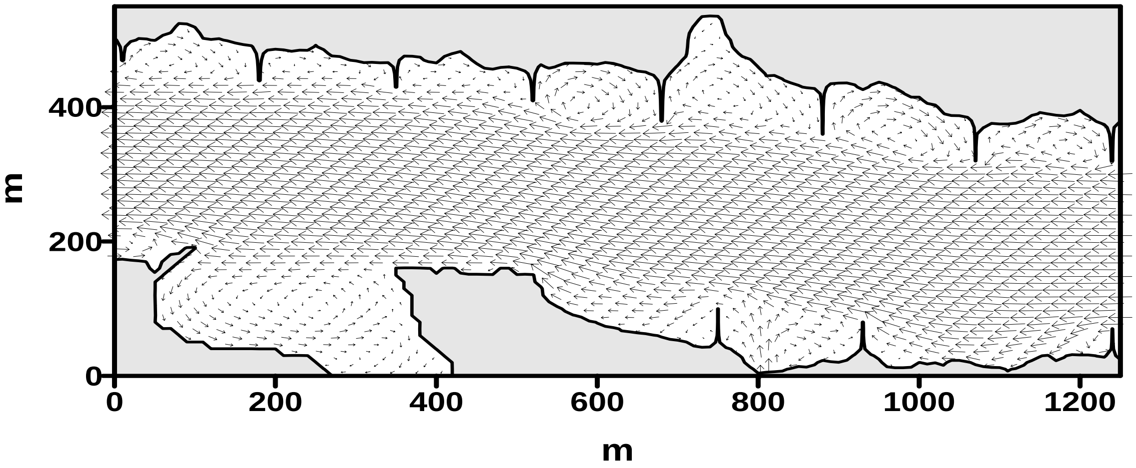


**Figure 18-1**
**Computed Surface Currents in the Waal River at 11 hr December 4, 2003**

Dispersion of heat was modeled using Cartesian horizontal coordinates with horizontal resolution of 10 m and using 20 sigma layers in vertical direction. Data set on the meteorological station “Volkel”, south-west of the city of Nijmegen, were used. Rijkswaterstaat (RWS, the Dutch Directorate for Public Works and Water Management) performed temperature measurements on the River Waal close to the model boundaries. The discharges and elevations were also measured with a frequency of one hour 3 – 4 December 2003. Figure 18-2 show results of calculations for December 4, 2003, when the measurements of temperature in the plume were carried out. The real discharge and temperature data in the outfalls 3 – 4 December 2003 were used in the simulations. The correlation coefficient R of modeled versus observed surface temperature was 0.96, root-mean-squared error RMSE = 0.54ºC or 3.6% of observed temperature range, bias error (mean difference between modeled and observed temperature) BE = 0.24ºC. As seen in the Figure 18-1 and Figure 18-2, the groins produce large trapped vortices. Such vortex causes the backward flow along the coast where the outfall is placed. Therefore cooling water was trapped by the groin field. The dead zones in the groin field essentially affect the exchange with the river main stream which makes it impossible using the simplified models for the calculation of heat waste water transport from outfalls on the shoreline.

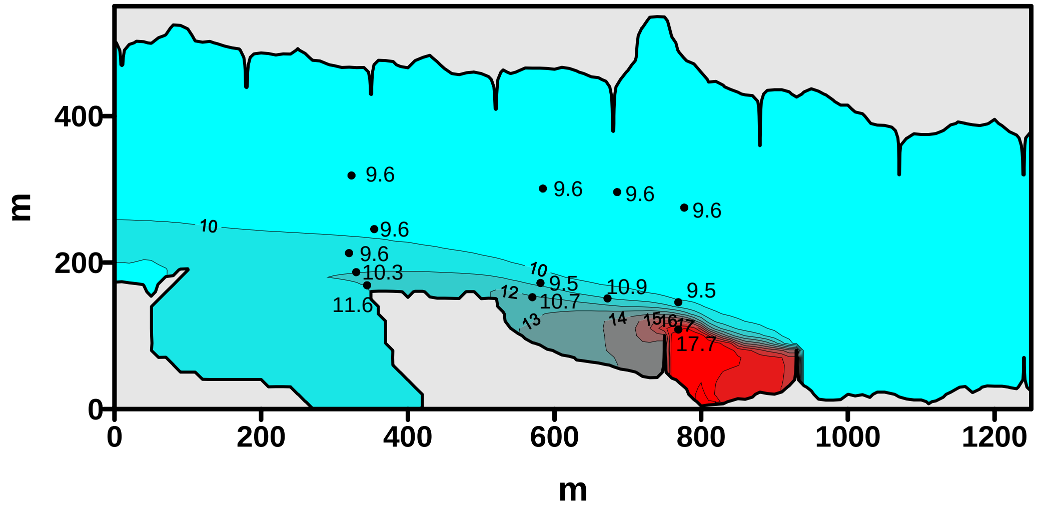


**Figure 18-2**
**Computed vs. Measured Surface Temperature in the Waal River at 11 hr December 4, 2003**

### *Amsterdam-Rhine Canal*

Discharges of excess heat are critical in canals, since the loss of heat in this type of aquatic environment is mainly due to the cooling effect to the atmosphere; a canal has due its stagnant characteristic a limited cooling capacity. The model was applied to simulation of dispersion of cooling water discharged by the gas-fired power plant Lage-Weide-6 (LW-6) in the Amsterdam-Rhine Canal (“ARC”) and different harbors in the City of Utrecht connected to ARC: Kernhaven, Protonhaven, and Uraniumkanaal (Figure 18-3). The canal is characterized by almost stagnant water. The intense shipping traffic in ARC can affect the heat dispersion by enhanced vertical mixing in the canal. To parameterize this effect we assumed, that (i) the influence of the number of moving ships can be represented as a time-averaged influx of turbulent energy in the upper layer of channel and (ii) the mixing of water by moving ships related to the jet caused by the ship’s propeller.

The developed parameterization was implemented in the heat dispersion model for a section of the ARC with length of 12 km whereas in the harbors the additional mixing was set to zero. The orthogonal curvilinear boundary-fitted grid contains horizontally 4300 cells with a minimal grid size of 10 m near the LW-6. The water depth was resolved by 20 evenly-spaced sigma layers. The discharges by LW-6 take place in the west corner of the Kernhaven harbour via a wide cooling water channel (Figure 18-3), so in this case the far-field model is applicable for the near-field as well.

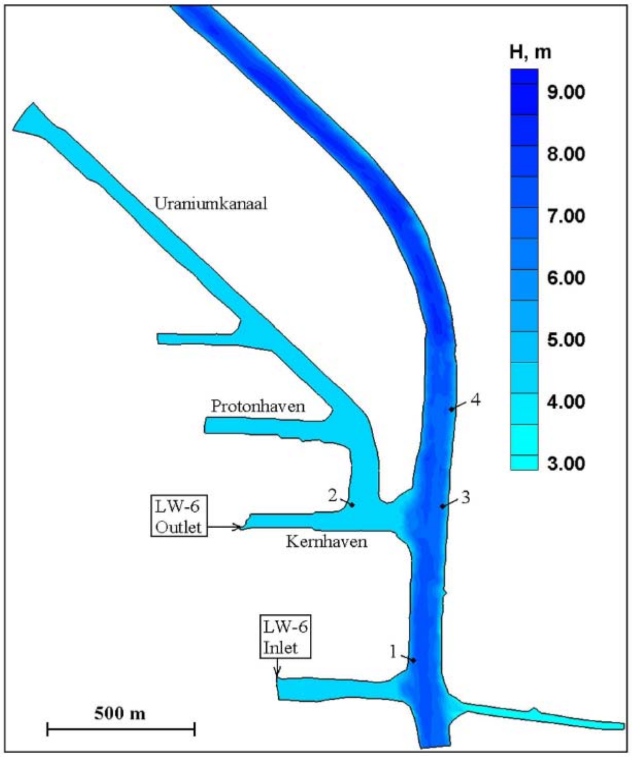


**Figure 18-3**
**Bathymetry of the Amsterdam-Rhine Canal and Positions of Inlet and Outlet of Lage-Weide Power Plant. The Numbers Correspond to the Measurement Points**

The simulations were carried out for 9-12 August 2004 for which period measurement data were available. Real discharge and temperature data on the outfalls were used in the simulations. Hourly-averaged meteorological data from meteorological station “De Bilt”, west of the city of Utrecht, for the month August 2004 were used. The cross-section-averaged velocity and - temperature, calculated from discharge and temperature in the Lek Canal were used as upstream (south) boundary conditions. At the north boundary a constant water level was prescribed. Figure 18-4 shows the effect of ship traffic on the surface plume caused by the discharged cooling water.

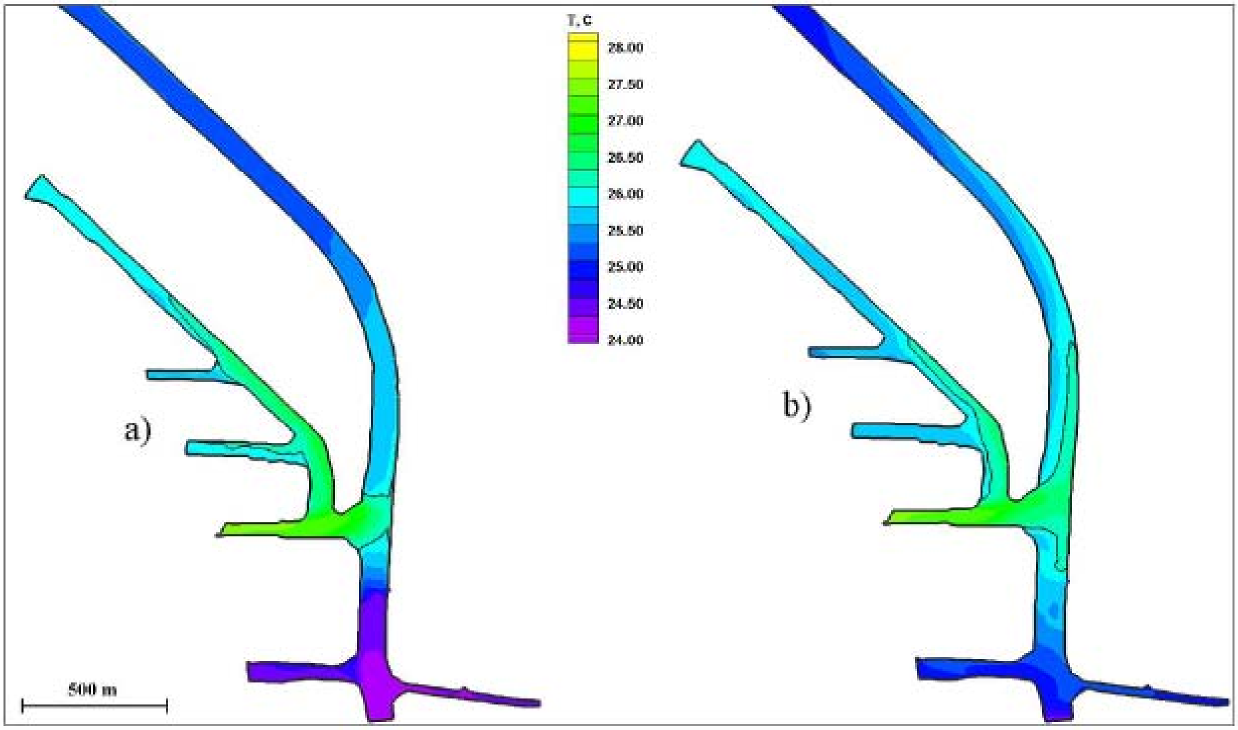


**Figure 18-4**
**Computed Surface Temperature in the Amsterdam-Rhine Channel at August 12, 2004 (a) With Shipping Parameterization, (b) Without Shipping Parameterization. Black Line Corresponds to the Temperature of 26°C**

Additional mixing by ships resulted in dispersion of cooling water in whole water column (Figure 18-5) and in consequence mixing influenced the heat exchange with the atmosphere; the difference with the atmosphere became less which resulted in a higher averaged temperature. Another effect was that the peak temperature was lower due to mixing of the top layer of the canal. The vertical temperature profiles, shown in Figure 18-5 agree well with the simulations if the effect of ship traffic is taken into account. The correlation coefficient of modeled versus observed temperature was 0.87, RMSE = 0.42ºC, BE = -0.04. The profiles 2-4 in Figure 18-5 shows a gradual transformation both for the observed and the calculated temperature fields due to mixing of ships. The temperature profile in the Kernhaven harbour (point 2) without additional mixing shows the presence of a thermocline beneath the cooling water plume, whereas profiles 3 and 4 in the ARC are transformed into linear and well mixed temperature distributions. It supports the validity of physically justified parameterization.

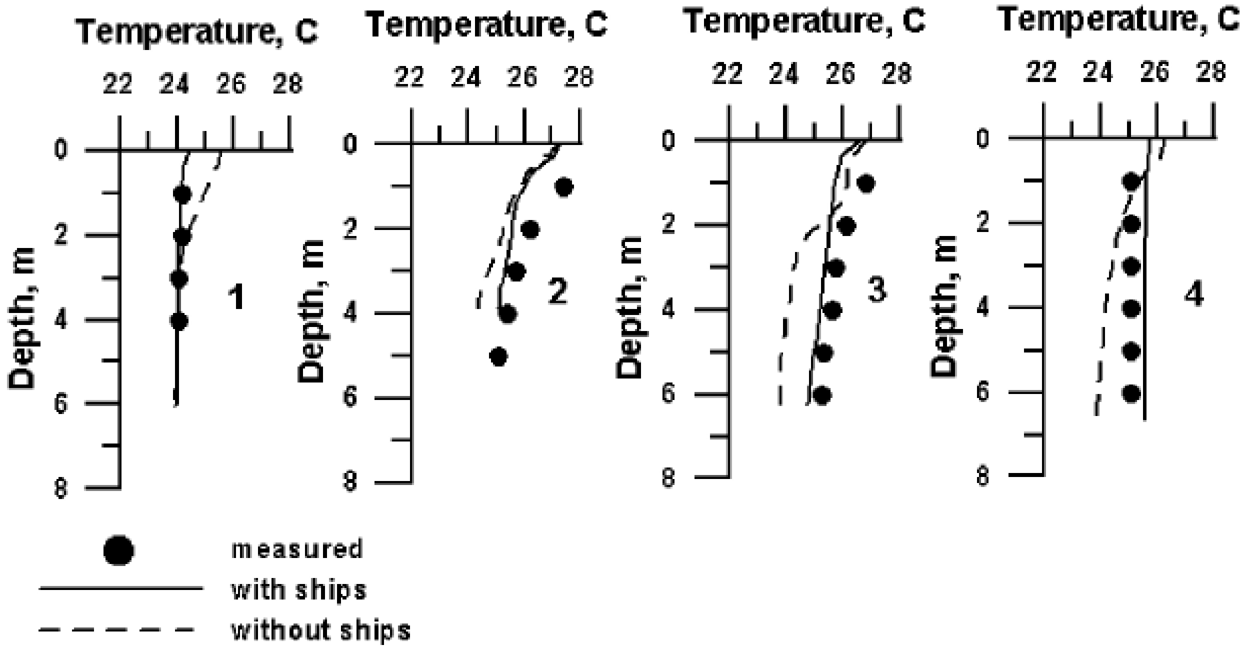


**Figure 18-5**
**Computed vs. Measured Temperature Profiles in the Amsterdam-Rhine Canal August 12, 2004**

### *Hollandsch Diep*

Hollandsch Diep is a part of Rhine-Meuse River delta. This reach is isolated from the North Sea by dams. However, the tide affects the Hollandsch Diep through a system of waterways connecting the delta of the river with sea at the northern part of the delta in Rotterdam. Other important factors for heat dispersion are wind drift and discharge from the Amer River (Meuse reach) and from the river branch Dordtse Kil. The model was applied to the dispersion of cooling water discharged by a power plant and by two heat discharges by a chemical plant. The WAD scheme and the parameterization of the heat exchange with the bottom were used to describe tidal flood plains (Figure 18-6). Curvilinear grid with nesting was used to describe the area of interest in detail in the computational domain. The minimal size of the coarse grid was around 45 m, whereas the nested grid size near the power plant's discharge channels was 15 m. There were 20 evenly distributed sigma layers. The outfall of the power plant was a wall of 40 m with 16 subsurface holes, whereas the width of the chemical plant outfall wall was 16 m, each with 68 and 30 subsurface holes for each discharge of the chemical plant, respectively. The real discharge and temperature data on the outfalls were used in the simulations. Hourly-averaged meteorological data from meteorological station Gilzen-Rijen for the month of June 2005 were used.

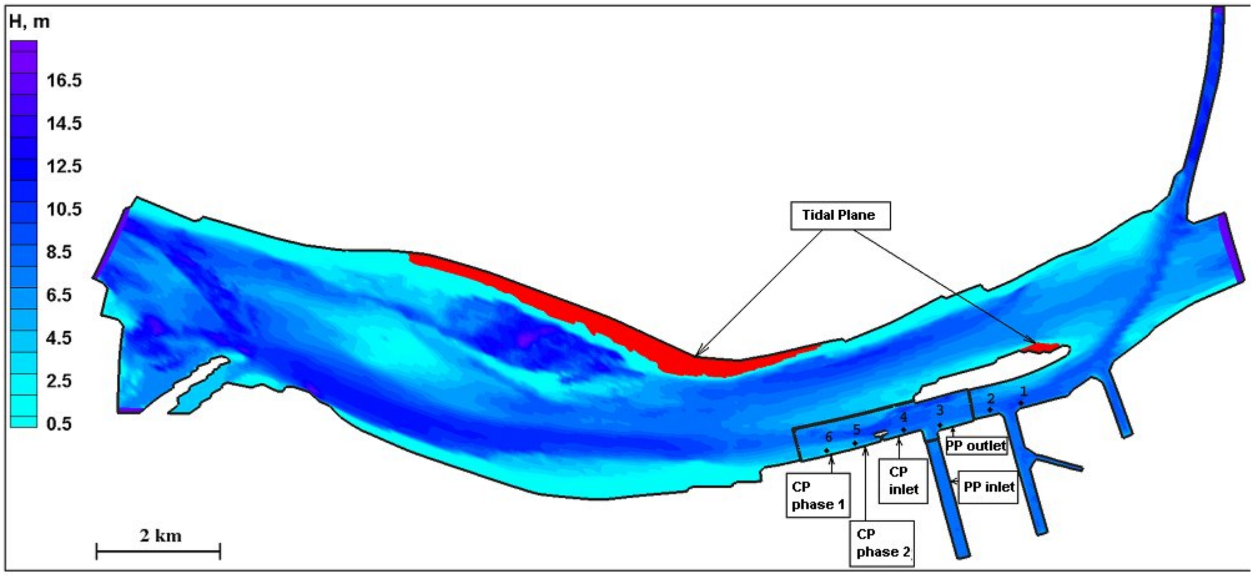


**Figure 18-6**
**Bathymetry of the Hollandsch Diep and Positions of Inlet and Outlet of the Power Plant (PP) and Chemical Plant (CP). The Numbers Correspond to the Measurement Points in Figure 18-9. The Tidal Flood Plains are Marked. The Borders of Area of Interest are Shown by the Thin Double Line**

The calculated river discharge by the 1D model SOBEK [14] on the right (east) and upper (north) open boundary and the water elevation on the left (west) open boundary and the observed temperature were provided by RWS. The simulation results are shown in Figure 18-6 and Figure 18-8. The surface temperature field for flood tide is given in Figure 18-7.

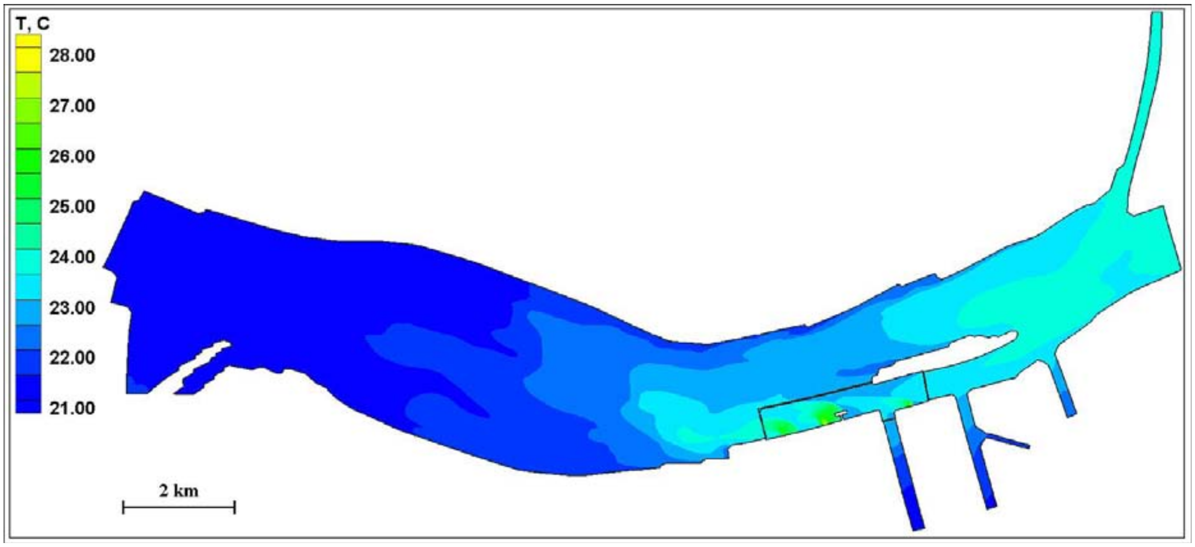


**Figure 18-7**
**Computed Surface Temperature in the Hollandsch Diep June 23, 2005 (Low Tide)**

Figure 18-8 shows the nested area in detail. The fine resolution allowed to describe details of cooling water dispersion during the conditions of weak circulation (e.g. for the most eastern outlet of the chemical plant, phase I) and the interaction of far and intermediate temperature fields.

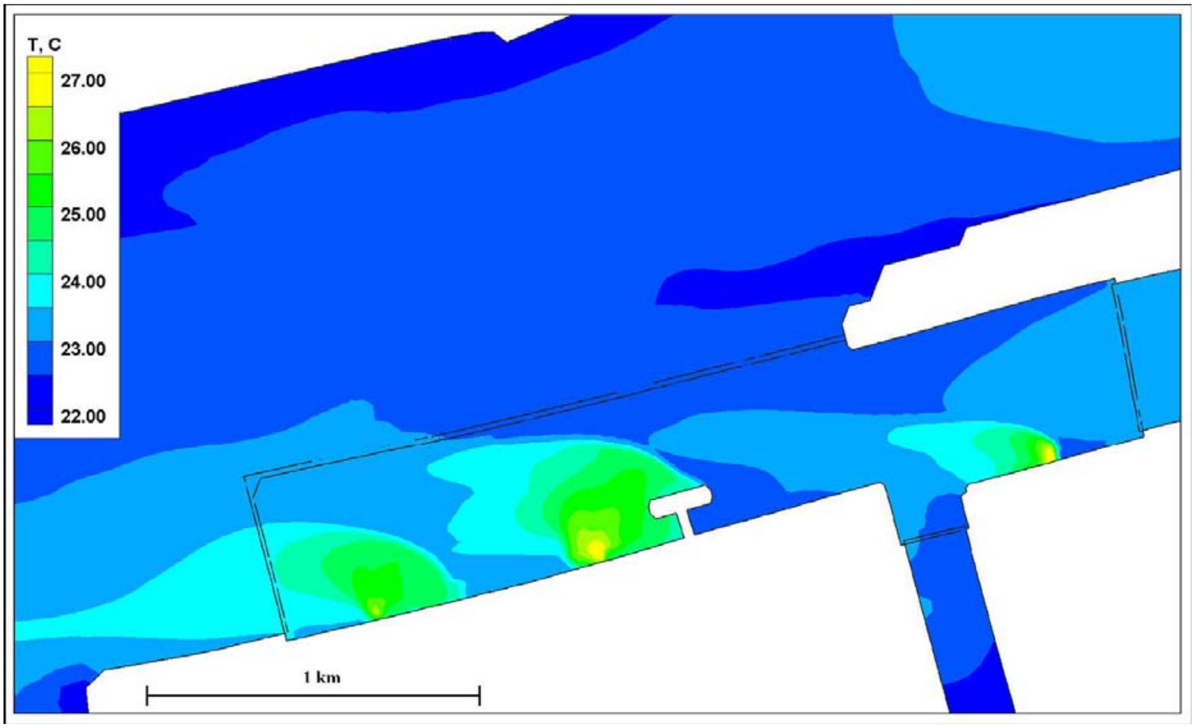


**Figure 18-8**
**Computed Surface Temperature in the Nested Area of the Hollandsch Diep, for June 23, 2005 (Flood Tide)**

The measurements and simulations as shown in Figure 18-9 agree well. The correlation coefficient was 0.74, root-mean-squared error RMSE = 0.67ºC or 9.7% of observed temperature range, BE = 0.15ºC. These values are lower than in previous case studies that can be explained by complex flow regime in this area and incomplete data set. We would had to use predictions by 1D model SOBEK of flows and levels at the boundaries of the domain with complicated topography and tidal currents that resulted in phase shift of plume position.

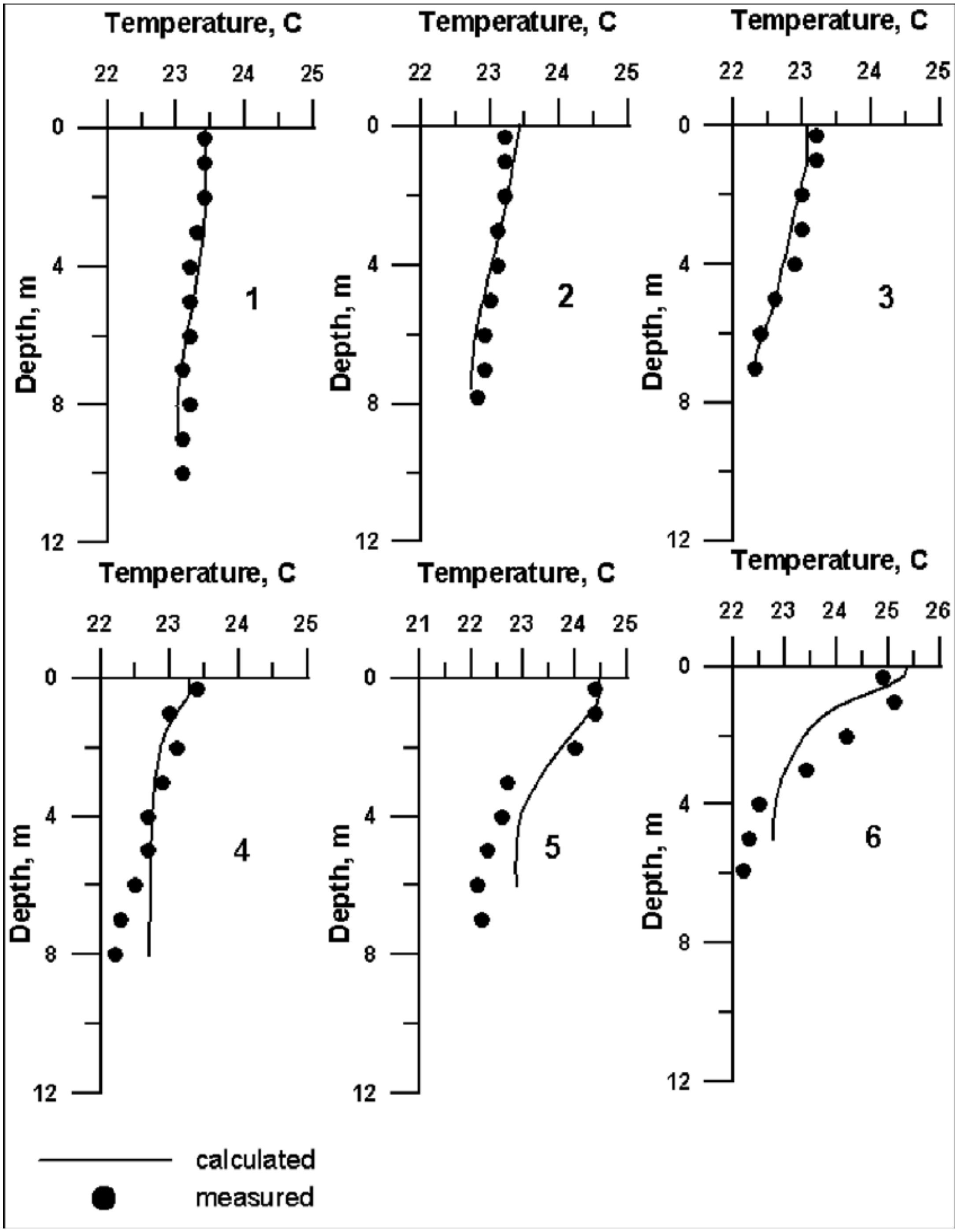


**Figure 18-9**
**Computed vs. Measured Temperature Profiles in the Hollandsch Diep June 23, 2005**

### Lake Markermeer

A gas-fired power discharge cooling water on the Lake IJmeer, which is a part of a large shallow lake Markermeer, centrally located in the Netherlands, with an averaged depth of 3.8 m. In the IJmeer however, depths are below 3 m, and around the islands are varying between 0.5 – 1.5 m. Due to its relatively long residence time, varying from 400 days (summer) till 550 days (winter) Lake Markermeer has almost stagnant water; mixing is caused mainly by wind-induced currents. In summer periods water is discharged via sluices into the adjacent North-Sea Canal, while in the winter the water is transferred via two sluices complexes to the adjacent Lake IJsselmeer. Therefore precise evaluation by means of THREETOX is needed to identify the plume dispersion into the lake. The temperature regime of the entire lakes therefore has been calculated by means of THREETOX; the heat exchange with the atmosphere and the dispersion of the heat by currents dominates the thermal situation of the Lake.

The THREETIOX model was applied to calculate the dispersion of cooling water discharged by the gas-fired power plant located for the entire lake Markermeer. The WAD scheme was not applied since Lake Markermeer has no tidal flood plains. The average depth of the lake is 3.8 m and a significant part of the area is covered by plants affecting the circulation in the lake. To take into account the influence of plant covered bottom areas, the possibility of using of space varying roughness heights was implemented into the model. Distribution of roughness heights was estimated by using digital maps with percentages of plant cover. In the model the roughness parameter $z_0 = 0.008\ m$ was used for plant-free bottom and $z_0 = 0.258\ m$ for fully covered areas. Curvilinear grid with 300x300 m nodes was used to describe the area of interest in detail in the computational domain. Grid resolution varied from 20 m near inlet of the power plant inlet and -outlet to 300 m at the northern boundary of the lake Markermeer. A vertical resolution of 20 vertical sigma layers with a refinement near the bottom and surface was chosen. The outfall of the power plant is a channel with a width of 33.4 m and a height of 2.4 m submerged 1 m under the surface. Hourly-averaged meteorological data from the meteorological station Lelystad for August 2003 and 2004 were used for meteorological forcing.

Figure 18-10 depicts the calculated temperature in the summer time (2003). The detailed 2D figures of the surface temperatures show the difference between the situation without (upper picture) and with the islands (bottom picture) which are to be realized in the near future. The results show clearly that although the plume is not much different in surface, the spreading is hindered by the new islands, and the plume with high temperature borders to the shore of the new islands.

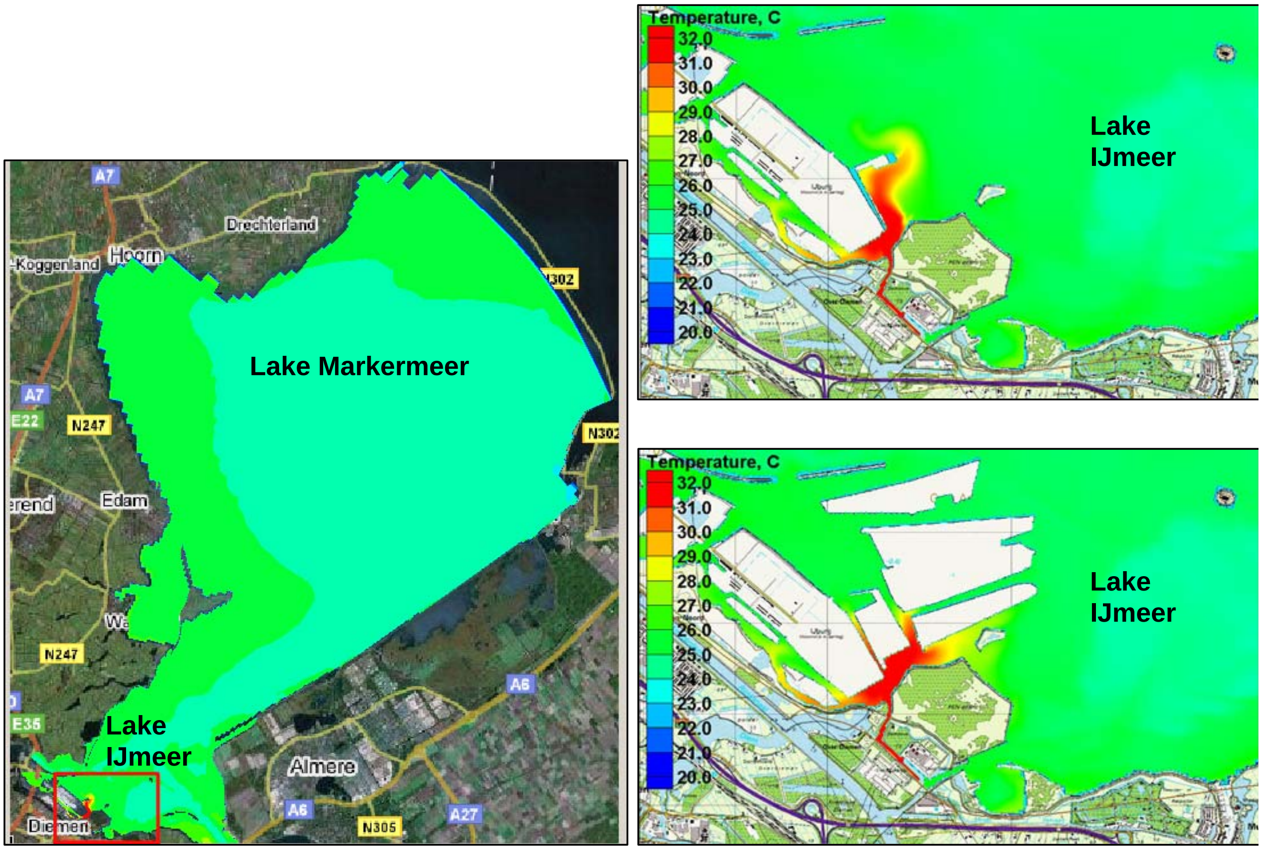


**Figure 18-10**
**THREETOX Model Results for the Lake IJmeer. Left-hand Picture: Entire Markermeer. Right-hand Picture: Current Situation of Lake IJmeer without Islands (Upper Picture), Future Situation Lake IJmeer with Islands (Lower Picture)**

### *North Sea Canal*

Various cooling water discharges take places in the North Sea Canal and in the bight, which are separated from each other by a complicated system of three locks and sluices. THREETOX was applied on both sides of the locks/sluice system. In the industrial area two gas-fired power plants discharge in the harbors at the east side of the locks, one gas-fired power plants at the west side of the locks. Furthermore in the harbors north of the North Sea Canal, 5 minor discharges takes places, and three minor discharges takes places in east of the harbors in the North Sea Canal. At the west side of the locks, a steel industry discharges major amounts of cooling water in the marine environment. The model takes recirculation into account, the salinity and temperature of the inlet water is calculated by the model as well. For this purpose two different regions were considered; west and east of the locks. Each region was modeled by its own model connected by a coupler that parameterizes the exchange through the locks. Interaction between the two model areas via the coupler assumes a flow via the sluices every seven minutes. The two model domains were run in the parallel mode. A curvilinear grid was used to describe area of interest in detail in the computational domain. The minimal size of the grid cell was around 10 m. There were 20 evenly distributed vertical (sigma) layers. Hourly-averaged meteorological data from meteorological station “De Kooy” for the month of August 2004 were used. The calculated water elevation by the 2D model on the right (east) and left (west) open boundaries and the observed temperature were provided by RWS. The resulting 2D surface temperatures are given in Figure 18-11.

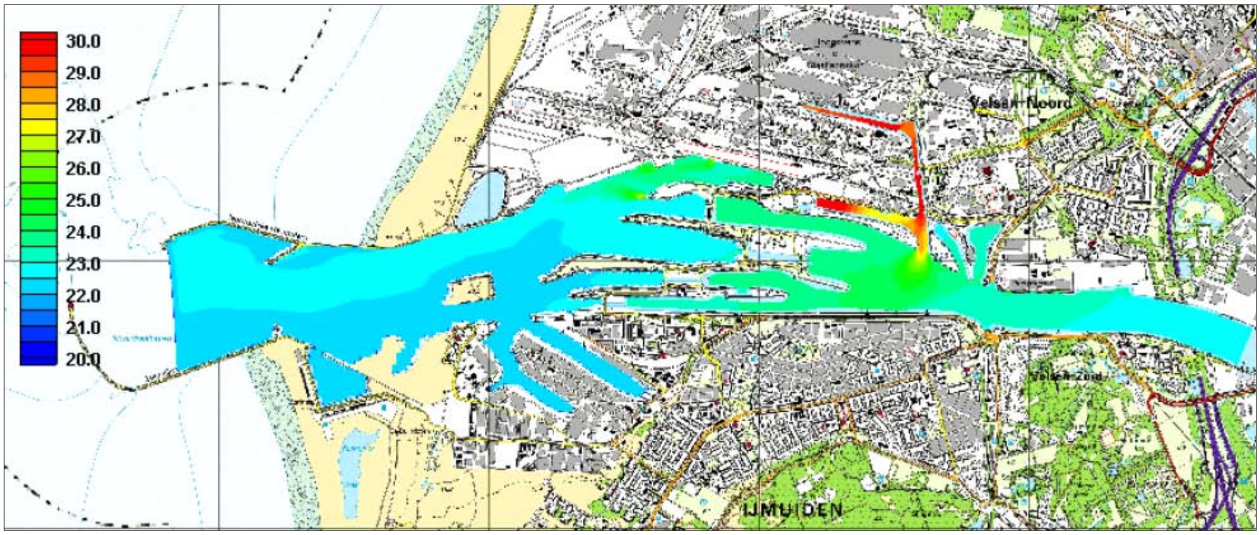
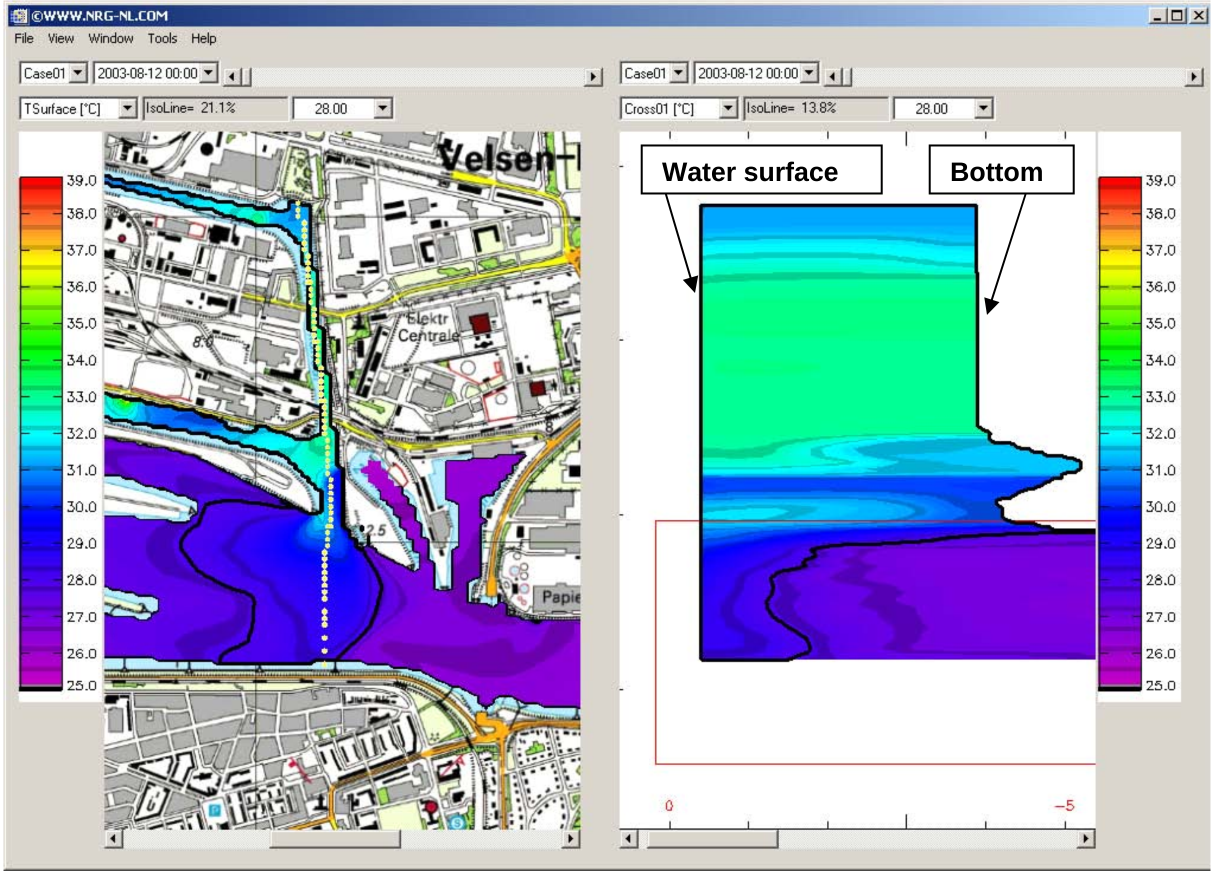


**Figure 18-11**
**THREETOX Model Results for the North Sea Canal with Locks and Sluices**

## Compare Tool

The THREETOX model is used as decision support tool for the acquisition of permit and for supporting for Environmental Impact Study. To facilitate this, a result-viewer has been developed by means of which the results of the different scenarios can be compared.

This tool, the CompareTool, presents the model results by means of two windows, in which the surface temperatures, the near-bottom temperatures, the 2D depth-averaged temperatures, the maximum and minimum temperature in the water column, and the vertical cross-section temperatures can be shown and compared. The tool can also view the results frame by frame as an animation. The tool is considered as a product that is used to evaluate the impact of different kind of discharges in the aquatic systems. With this tool, the ambient temperatures can be compared, the locations where the maximum allowed temperatures can be found identified and the criterion of 30ºC/25% in the cross-section can be evaluated for each scenario (Figure 18-12).



Case01 2003-08-12 00:00 | TSurface [°C] | IsoLine= 21.1% | 28.00

Case01 2003-08-12 00:00 | Cross01 [°C] | IsoLine= 13.8% | 28.00

**Figure 18-12**
**Result-viewer (CompareTool) by Means of Which Different Discharge Scenarios can be Evaluated. The Left-Hand Side (Top View) Shows Surface Temperatures and Location of the Cross-section (Yellow Dotted Line). The Right-Hand Side (Side-View of the Cross Section) Shows the Temperature Distribution in the Cross-section. The Area of Interest for the Regulation is Indicated by the Red Line**

## Conclusions

In this paper, the 3D numerical model THREETOX was described and several applications to the heat dispersion in rivers, in ship canals and in the tidal delta reach of rivers were presented. In the model development special attention was devoted to the physics of the model: parameterization of heat fluxes between water and atmosphere, between water and the sediments and description of near field processes. Despite the incomplete input data sets, the model demonstrated the ability to reproduce the variations of the thermal regime in different water bodies, affected by weather conditions, by ambient flows and by cooling water discharges.

The 3D models with a detailed description of water transport, mixing, air-water and bottom-water energy exchange, is an appropriate tool to predict the water temperature of cooling ponds, lakes, rivers or coastal areas, in order to anticipate on the consequences of hot summer periods, and to predict necessary strategies to avoid restrictions in the capacity of the power plants and other industries, as the only countermeasure against exceeding the maximum allowed ambient water temperature. It has also proven to be an appropriate support tool in the design phase of factories as for determining the optimal location and configuration of the conduits (inlet/outfall) to minimize recirculation, to avoid exceeding the maximum allowed temperatures in the ambient water, as for reducing the transfer of heat to the cooling water inlets of other companies in the vicinity.

## Acknowledgments

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# 19

# THERMAL ISSUES AND A HYBRID COOLING TECHNOLOGY IN SITING NORTH ANNA UNIT 3

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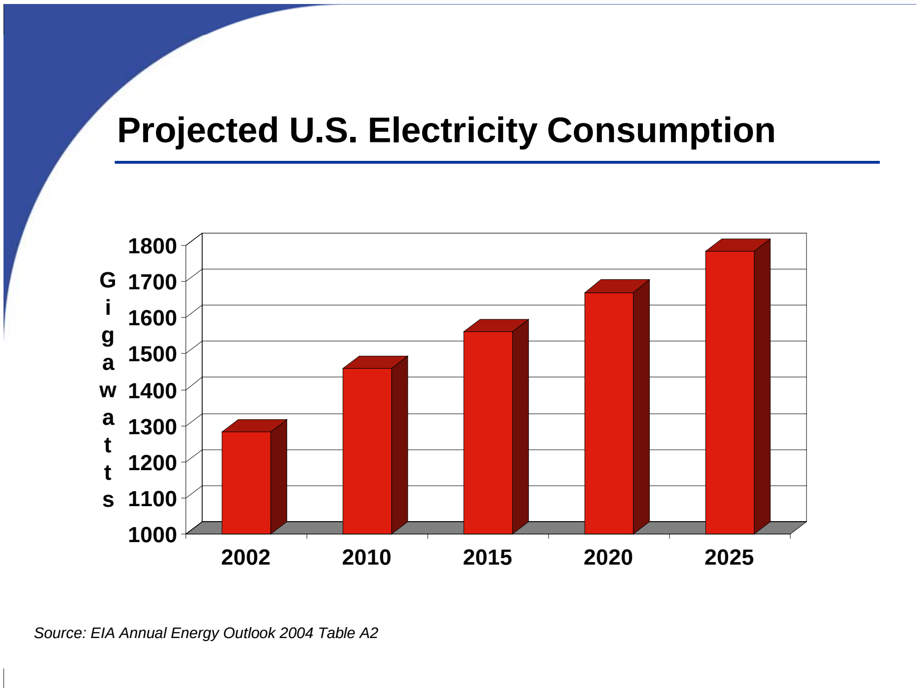
## Introduction

Electricity consumption in the United States continues to increase. Meeting future demand will be a challenge to the industry in maintaining a diversity of supply while ensuring protection of environmental resources. In this paper, we describe Dominion's proposal to help meet our future energy needs with nuclear power, the environmental issues (temperature and water loss) at the selected site, and the resolution of those issues by use of a hybrid cooling technology.

## Growth Rates and Supply Diversity

In the 1960's the growth rate in electrical consumption was 7% per year, twice the rate of economic growth. This ratio declined to 1.5 and 1.0 in the 70s and 80s, respectively. According to the Energy Information Administration (EIA) of the U.S. Department of Energy, the current electricity growth rate has increased to about 1.8 % per year (Figure 19-1).

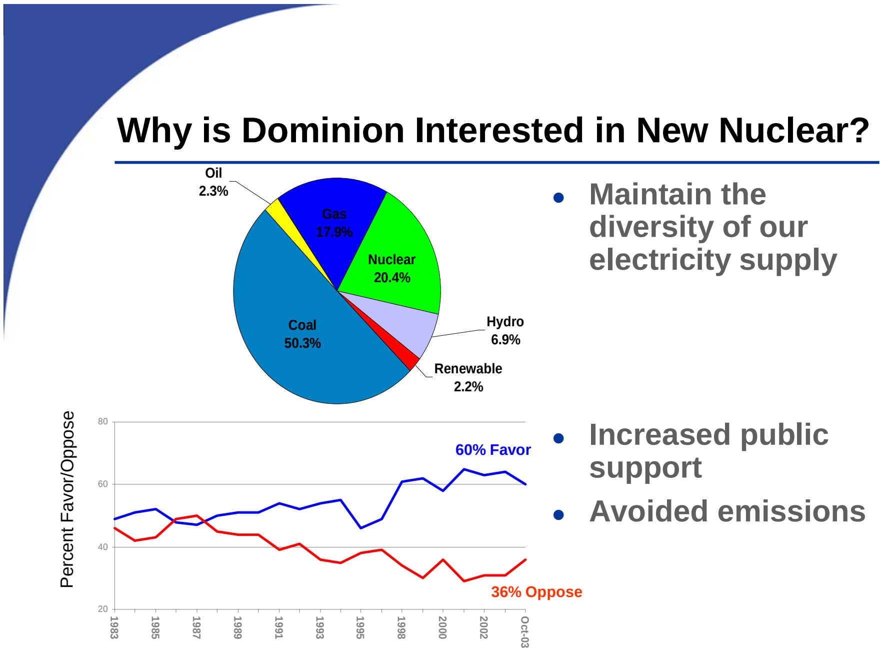
The U.S. has 104 nuclear power reactors in 31 states. Nuclear energy is the second largest source of electricity after coal and provides electricity for one of every five homes and businesses (Figure 19-2). Some states are clearly more dependent on nuclear energy than others. For example, Vermont gets 76% of its electricity from nuclear reactors; New Hampshire, 58%; And South Carolina, 55%. In Virginia, nuclear power provides more than 33% of the electricity used. There is a general trend of increasing public support for nuclear power (Source: Nuclear Energy Institute).



## Projected U.S. Electricity Consumption

Source: EIA Annual Energy Outlook 2004 Table A2

**Figure 19-1**
**Projected U.S. Electricity Consumption**



## Why is Dominion Interested in New Nuclear?

- Maintain the diversity of our electricity supply
- Increased public support
- Avoided emissions

**Figure 19-2**
**Diversity of Electricity Supply in U.S.**

With the current rate of increase in energy consumption, a large amount of new generation will still be needed to meet the demand. To maintain the existing energy supply diversity, it has been estimated that approximately 50,000 MWe of new nuclear will be needed in the U.S by 2020. To help meet the increasing demand and to maintain the nuclear option, Dominion is engaged in the Nuclear Regulatory Commission (NRC) licensing process for a new nuclear unit at the North Anna Power Station located in Mineral, Virginia. Using the new and improved streamlined regulatory process developed by the NRC with input from industry stakeholders, Dominion submitted an Early Site Permit (ESP) application to the NRC in 2003. The ESP is related to a site suitability determination and provides for an environmental review before large investments occur. Subsequently, the National Environmental Policy Act (NEPA) process commenced in 2003 and the Final Environmental Impact Statement for the ESP was issued in December 2006. Dominion is expected to file a Combined License (COL) application in late 2007 with potential for actual construction to begin in 2010 followed by commercial operations in 2015.

## Site Selected

The North Anna facility in Louisa County, Virginia was selected for the proposed addition of a new nuclear unit. The location was originally planned for 4 units and currently has two operating nuclear units. The site was considered superior to other sites for a number of factors, including available space, a good source of cooling water and other environmental attributes. As seen in Figure 19-3 below, the North Anna Power Station is located on a man-made 9600 acre reservoir called Lake Anna that was formed after damming the North Anna River in 1972. Lake Anna provides cooling water for the existing open cycle cooling systems of the two units. The facility also has an adjacent 3400 acre Waste Heat Treatment Facility (WHTF) that was designed and built to allow cooling of the heated effluent from the power station before discharging back to Lake Anna.

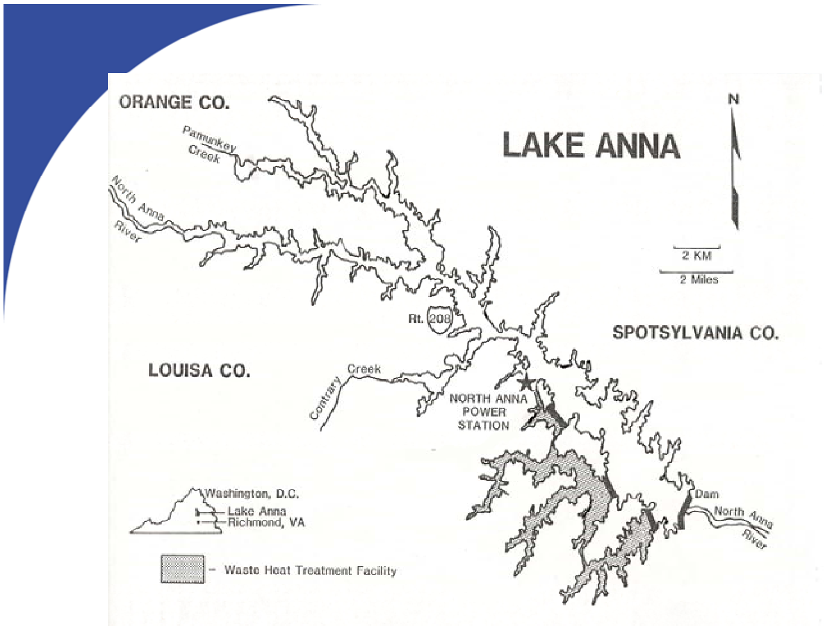


**Figure 19-3**
**Lake Anna, Virginia**

## State Regulatory Process

During the NEPA process, the NRC required a Federal Consistency Certification from the Commonwealth of Virginia under the Coastal Zone Management Act (CZMA) prior to issuance of an ESP. The CZMA was passed by Congress in 1972 to balance economic development with environmental conservation in coastal zone areas in the U.S. The Commonwealth of Virginia administers the Act through a National Oceanographic and Atmospheric Administration (NOAA) approved Coastal Resources Management Program that reviews impacts or concerns on wetlands, fisheries, coastal/sub-aqueous lands, dune/beaches, shoreline sanitation, air quality, water quality, and non-point sources. The Unit 3 project at North Anna was included because the North Anna River drains to the coastal Chesapeake Bay and a portion of Lake Anna is part of the Chesapeake Bay Preservation Area. The Virginia Department of Environmental Quality serves as the lead agency for the program and coordinates the review with other cooperating resource agencies in the Commonwealth. The State is asked for concurrence with an applicant's coastal zone certification and the State may approve, deny, or approve with conditions.

The CZMA process took several years to complete and required extensive analyses and negotiations with state agencies and the public. The original cooling system proposal for Unit 3 was an open cycle design using the WHTF to dissipate most of the heat similar to the operation of the existing units. There were two major concerns raised during the public process: 1) the additional thermal input to Lake Anna and the WHTF, and 2) water loss in the reservoir due to evaporative cooling in the WHTF and how it impacts the flow regimes in the downstream North Anna River, especially during drought periods. The hydrograph below models the lake level changes expected from operation of Unit 3 (Note: 250 ft msl is considered normal lake level, 248 ft msl is considered drought conditions. Minimum dam release is 40 cfs for normal conditions and 20 cfs for drought conditions).

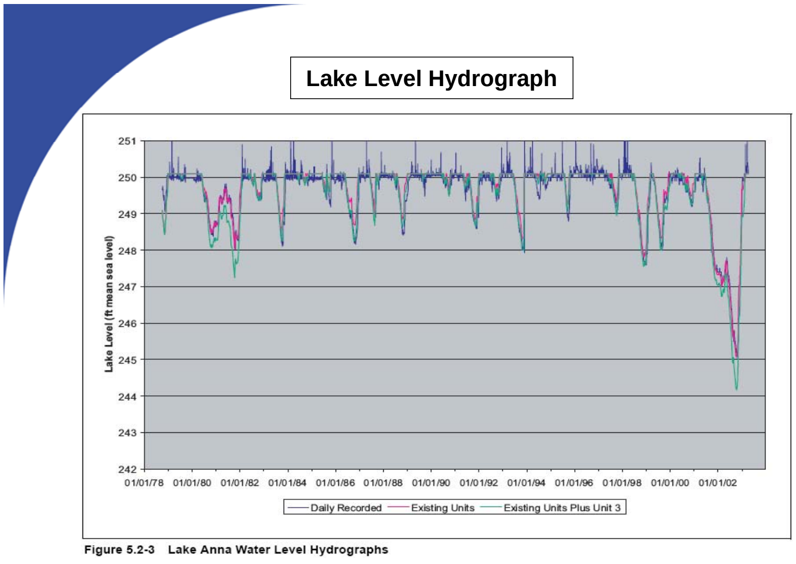


**Figure 19-4**
**Lake Anna Water Level Hydrographs**

As a result of the concerns raised, the company committed to install a unique closed cycle cooling system for Unit 3, described below, and also agreed to conduct an In-stream Flow Incremental Methodology (IFIM) study in the North Anna River below the Lake Anna dam. The IFIM study is a useful tool for assessing the effects of changing flows on river habitats for fish and recreation and will allow for a more thorough regulatory determination of appropriate flows in the river. The IFIM study is expected to be completed in 2008.

## An Approach to Hybrid Cooling

The thermal impact of the new nuclear unit was virtually eliminated with the decision to incorporate closed cycle cooling in the design. Concern about the potential effect of water consumption required a different approach than simply using conventional cooling towers. A significant portion of the cooling needed to be accomplished without evaporating water. A portion of the cooling would require dry cooling.

Conventional “wet” cooling towers involve evaporating a significant amount of water to reject the heat from the power cycle. These towers can result in water consumption rates exceeding that for open cycle reservoir cooling, such as was originally proposed for the new nuclear unit. Incorporating a portion of non-evaporative dry cooling reduces the average quantity of water consumed through evaporation in the cooling tower. The type of dry cooling to be used is indirect cooling, where the hot water is circulated through finned tubes while air is forced across the tubes to provide cooling. The rate of cooling is dependent on the temperature difference between the circulated water and the ambient dry bulb temperature of the air.

The conceptual design for the cooling system for North Anna 3 is a dry cooling tower in series with a single round hybrid tower. The hybrid tower includes both wet and dry sections. The circulating water passes through the dry section of the hybrid tower in the upper level before passing to the wet (conventional) lower level portion. Since the wet air exiting the wet section is mixed with warmer dry air before leaving the tower, the hybrid tower has an added aesthetic benefit of not having a visible plume.

Two operating modes have been evaluated for the cooling system: (1) energy conservation and (2) water conservation. These operating modes are designed to balance the use of competing resources for the plant. When water is available the energy intensive dry tower is shut down and bypassed to conserve energy. This is the energy conservation mode. When the level of the lake indicates that water is not being sufficiently replenished to the lake, the dry tower is placed in service and a minimum of one-third of the heat rejection is by non-evaporative dry cooling. The remainder of the heat load is removed by the hybrid tower.

As has been noted, the water conservation mode is used during times when the lake level cannot be maintained at its normal “full” level while releasing the required flows to the river downstream. The period of time allowed for delay before entering the water conservation mode will be determined in consultation with state regulatory agencies based on the results of the IFIM study. A reasonable timeframe for switching between operating modes will take into account the negative effects of cycling the system and impacts on short term transmission planning. Additionally, there may be times when it is desirable to return to energy conservation mode during periods of high energy demand. These times are usually coincident with high ambient dry bulb temperature, when the dry cooling is least efficient. As the energy demand and high temperature decline, the fans for the dry tower can be started to return to water saving operation. The overall impact on lake level of delaying the switchover to water conservation by several days or turning off the dry tower fans to help meet energy demand is negligible.

The basic system configuration for the water conservation mode places the dry tower downstream of the power station's main condenser. Hot circulating water leaves the condenser and enters the dry tower at the maximum temperature of the cooling cycle. The higher temperature is required by the indirect dry cooling process to maximize the temperature difference between the water being cooled and the dry bulb temperature of the cooling air being forced across the tubes. The smaller the difference in temperature between the water exiting the dry tower and the dry bulb temperature of the entering air, the larger in size the dry tower will be to remove the same heat load.

After rejecting approximately one-third of the heat at the design dry bulb temperature in the dry tower, the circulating water passes to the dry section of the hybrid tower and then to the wet section to complete the heat rejection process. The cooled circulating water is then pumped back to the plant condenser to complete the cycle.

The water savings of the system while in the water conservation mode increases with decreasing ambient dry bulb temperature. Lower air temperature enables the dry tower to achieve more heat removal, reducing the heat load to be cooled in the water consuming wet section of the hybrid tower. At some low ambient air temperature, the dry tower is capable of removing the total heat duty and the evaporative cooling is terminated. At these lower ambient temperatures the station is capable of using virtually no water for condenser cooling.

## How Much Dry Cooling?

The North Anna 3 cooling system is a conceptual design that will be refined during the detailed design phase of the project. The goal of the concept stage was not an optimized design, but an achievable approach that could be modeled to assess the relative impact of the water used by the power station. The analysis results for the water use form the basis for the site specific water consumption targets. These targets needed to show a significant reduction in water consumption for the plant. Optimization of the final design will involve the economic use of operational strategies to maintain the water use within these values while maximizing the efficiency of electrical power generation by the plant.

Capital cost, land area required, and operational cost of the system are negatively affected by increasing the percentage of dry cooling in the cooling system. Additionally, the high condenser temperatures required to accommodate the inefficiency of the indirect cooling process significantly affect the plant's efficiency, resulting in less power generated. This not only results in lower net electrical power generated by the plant, but at very high percentages of dry cooling during hot summer operation, the cooling system may not be capable of providing cooling water at temperatures that are low enough to support reliable plant operation. This occurs during times of high demand when adequate and reliable generation is critical.

After evaluating several cases of varying percentages of dry cooling, the conceptual design of one-third dry/two-thirds wet cooling was selected. This combination for the North Anna site provided the capability to significantly reduce the water consumption for the new unit, while maintaining the ability to conserve energy when water is available or when power demand is critical.

## Resulting Performance

The projected performance of the conceptualized system shows that, using readily available technologies, significant water savings over conventional wet cooling can be achieved. The impact of adding a new nuclear unit at North Anna on water consumption was evaluated by modeling the lake level and downstream discharge history for the more than 24 years of operation of the existing power station. (See Figure 19-4) Since the original proposal for condenser cooling was an open cycle arrangement with cooling in a series of lagoons, the results were available for comparison with the system on a closed cycle cooling configuration using the hybrid cooling system. The long term average water consumption was reduced by over 30% from that of the open cycle cooling for the hybrid system operated on the energy conservation and water conservation strategy described above.

As would be expected, the system showed the highest water savings during periods of the local water cycle when water is usually sufficient to use the energy conservation mode. Low water availability typically occurs during summer operation when dry bulb temperatures are high and dry cooling is at or near the system design minimum. This also coincides with a higher probability of peak electrical demand for the region.

The system model results showed very good performance during prolonged droughts, which last into seasons with reduced average dry bulb temperatures. These lower air temperatures enable higher efficiencies in dry cooling and result in more than 70% reduction in long term average water use for extended operation in the water conservation mode.

The effectiveness of the hybrid cooling system can be further shown by assessing the unit's impact on the incidence of the lake level contingency plan. The lake level contingency plan is entered during drought conditions, indicated by lake level below 248 ft msl (Figure 19-4), by reducing the downstream flow out of the dam to the North Anna River to 20 cfs. The percentage of time the downstream release is at the minimum is an indication of the scarcity of water. The model for open cycle cooling predicted that the release would be at its minimum 11.6% of the time over the 24+ year history compared to the 5.2% with the existing units. Changing the cooling system design to the closed cycle hybrid cooling system reduced the time at the minimum flow to 7%, representing more than 70% reduction in impact as indicated by time in the lake level contingency plan.

## Conclusion

In conclusion, more electricity will be needed in the future and nuclear energy will play a vital role. While the NRC is the lead federal agency for licensing a new nuclear unit, the State in which a new unit is being considered has an important regulatory role to play in determining environmental impacts. The State's resource agencies have considerable authority in reviewing projects that require coastal zone certifications. Responding to concerns of key stakeholders with innovative approaches to plant design may be needed to obtain agreement on the acceptability of new generation facilities. Effective, continual, and early communications among the NRC, the State, the public, and the applicant are essential for project success.

## Reference

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# 20

# LONG TERM MONITORING OF THERMAL EFFECTS AS PART OF THE OHIO RIVER ECOLOGICAL RESEARCH PROGRAM (ORERP)

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## Introduction

For over 30 years, various utilities have sponsored fish studies on the Ohio River as part of the Ohio River Ecological Research Program (ORERP). The principal purpose of the studies has been to determine what, if any, effect the thermal discharge from each plant has on the local fish community. For the first 15 years of the program, a variety of sampling techniques were used and electrofishing was done during the day. However, beginning in 1991 and continuing through the present, electrofishing has been done at night. Because the results at night are quite different than the previous daytime results, we limit our comparisons in this paper to data collected in 1991 and later. Due to fish entrainment and impingement issues, participation in the ORERP in 2005 was the highest it has ever been, with 17 power plants participating. This level of participation led to nearly complete longitudinal coverage of the river. Also, 2005 was a low flow year, which minimized dilution and heat dissipation. This allowed for a unique opportunity to examine the data set to determine how widespread thermal effects might be and which community-level measures were most affected, as well as which were the most sensitive in terms of detecting upstream versus downstream differences. Even though 17 plants participated in the 2005 ORERP, the average distance between plants was 56 miles, meaning that the thermal plume from one plant did not affect ambient (upstream) temperatures at the next plant downstream.

## Methods

From 1991 through 2005 (the last year in which data were available), the ORERP consisted of daytime seining and nighttime pulsed DC electrofishing at six locations near each power plant; three upstream and three downstream. Because seining is more qualitative and is often dominated by only one or two species, the seining data are not discussed here.

Night electrofishing was conducted using a boat-mounted electrofishing system powered by a 5,000 watt generator with the output controlled by a Coffelt Model VVP-15 electrofisher (or equivalent). The sampling protocols described herein follow those developed by the Ohio River Valley Water Sanitation Commission (ORSANCO) [1]. Output settings were typically maintained at 100 pulses per second and 25-40 percent pulse width. Two circular anode arrays connected to extendable booms were used to conduct current to the water with the boat acting as the cathode. For safety purposes, a safety foot-switch was placed at the bow of the boat, providing power to the electrodes only when a dipnetter was standing on it. The sampling crew consisted of one driver and two dipnetters. A 3/16-inch mesh dip net was used to collect stunned fish. Sampling began at the upstream end of each zone and continued in a downstream direction. The amount of time spent at each zone depended on factors such as current velocity, as well as the amount and type of instream cover (e.g., logs/woody debris, riprap) encountered. All fish stunned during a sampling run were placed in a holding tub until processed. The length of each electrofishing location was 500 m. With rare exceptions, electrofishing was conducted when river stage was within three feet of normal pool and Secchi disk depths were greater than 300 mm.

To the greatest extent possible, fish were processed in the field so that they could be returned to the water alive. However, fish of uncertain taxonomy and/or extreme abundance (e.g., small cyprinids such as emerald shiner and channel shiner) were preserved in formalin and brought back to the laboratory for further examination and processing. Identification (typically to species) was made primarily using Pflieger [2] and Trautman [3]. Nomenclature followed the most recent guidance of the American Fisheries Society [4].

For each location, a maximum of 30 specimens of each species collected was measured for total length (mm) and weight (g). If over 30 individuals of a species were collected at any location, then 30 representative individuals were measured and weighed. The remaining individuals were counted and batch weighed. Minnows (excluding common carp, Asian carp, goldfish, common carp x goldfish hybrid, and emerald shiner) and other small species (e.g., silversides and darters) were identified, counted, and batch weighed. A gross examination of each fish was made to determine the incidence of external disease, parasites, or physical abnormalities. The classification of external anomalies followed Ohio EPA [5, 6] guidelines. A voucher collection containing a representative of each species collected was compiled and is maintained by EA's Deerfield, Illinois office. Young-of-the-year (YOY) fish were noted as such on field data sheets.

Sampling was conducted seasonally in June, August, and October. In 2005, 17 plants were studied, encompassing nearly the entire length of the Ohio River (Figure 20-1). The Cardinal, Kyger Creek, and Tanners Creek plants have been studied regularly since 1991. For these plants, results for the 15 year period, 1991-2005, are also presented herein.

Data from the three seasonal surveys each year were used to compute CPEs, which are reported herein as number or biomass of fish per kilometer. CPE values both by number and weight were compared upstream and downstream of each plant to assess potential effects of power plant discharges.

**Figure 20-1**
**Ohio River Ecological Research Program 2005 Study Sites**

In addition to CPE values, the following community-level catch parameters were also calculated for each electrofishing sample: species richness, modified Index of Well-Being (IWBmod) [5, 7], the Ohio River Fish Index (ORFIn) [8], and Shannon diversity. Because CPE, IWBmod, and diversity values can be strongly influenced by large numbers of emerald shiner, gizzard shad, and/or threadfin shad, they were calculated with and without one or more of these three irruptive species as recommended by Seegert [9]. This resulted in nine community-level measures being compared at each site.

Analysis of variance (ANOVA) and Tukey's Studentized Range Test were used to test for spatial differences in each of the community-level measures. Before each data set was statistically evaluated using these methods, it was analyzed to determine whether or not the data were normally distributed. If data were not normally distributed, they were transformed using Log (Y+1) and reanalyzed for normal distribution. If log transformed data were not normally distributed, statistical tests were conducted on ranked data.

To look for long-term trends, four community-level measures (CPE without irruptive species, total species richness, IWBmod scores, and ORFIn scores) were plotted by year. Using BPJ, we determined whether there was any trend over the 15-year period and whether there were any consistent upstream versus downstream differences.

In conjunction with each biological collection, water temperature, dissolved oxygen, specific conductance, and Secchi disk depth were measured. River flow data were obtained from appropriate gaging stations. Habitat was assessed once each year using a protocol developed by ORSANCO.

Detailed descriptions of all protocols followed during these studies can be found in the 2005 ORERP Report [10].

## Results

### *2005*

In 2005, 153 upstream versus downstream comparisons were made (9 community-level measures per plant x 17 plants) [10]. Despite 2005 being a low-flow year, only 27 (18%) significant upstream versus downstream differences were found [10]. In 23 of these 27 cases, values were significantly higher upstream suggesting that thermal avoidance contributed to the observed spatial pattern.

There were no significant differences at 7 of the 17 plants and at 5 plants, there were ≤ 2 upstream/downstream differences. At two plants, there were three significant differences but the spatial pattern was mixed, i.e., some measures were higher upstream, others were higher downstream. Thus, 14 of the 17 plants showed no consistent upstream versus downstream differences in the nine community-level measures that were compared.

However, at three plants, there were 4 to 5 significant upstream versus downstream differences and in all of these cases, values were higher upstream of the plant, suggesting that thermal avoidance may have caused or contributed to this pattern. However, differences in habitat between the upstream and downstream areas at these three plants were also found, indicating habitat quality may have also played a role in the observed spatial distribution. Of the nine community-level measures considered, the ORFIn score was the measure most frequently affected.

In addition to the community-level comparisons, using best professional judgment (BPJ) based on numerical CPEs, 32 common and widely distributed species were placed into one of three categories: equally common in both areas, more common upstream, and more common downstream.

Half the species (16) were equally common upstream and downstream of the plant. This group included gizzard shad and emerald shiner, probably the two most common fish in the river, most centrarchids, all *Morone,* channel and flathead catfish, walleye, common carp, and silver chub.

Four species were more common downstream: longnose gar, river carpsucker, quillback, and bluntnose minnow. All of these, except perhaps the bluntnose minnow, are thermally tolerant species.

Twelve species were more common upstream, with about half of them being thermally sensitive. The thermally sensitive species included three redhorse species (smallmouth, golden, and silver), northern hogsucker, mooneye, logperch, and sauger. The species that were more common upstream which are not thermally sensitive were skipjack herring, spotfin shiner, channel shiner, spotted bass, and freshwater drum.

### *Trends During the Past 15 Years*

In this analysis, we attempted to determine whether there are any distinct trends since nighttime electrofishing began in 1991. The three plants with the most continuous data sets during this 15-year period were evaluated; i.e., Cardinal and Kyger Creek Plants in the upper river and Tanners Creek Plant in the middle river (Figure 20-1). These data sets were also examined for consistent upstream/downstream differences. For these evaluations, we focused on the four community-level measures that have historically been the most responsive; CPE (without gizzard shad and emerald shiner), total species richness, IWBmod scores, and ORFIn scores.

#### CPE

Catch rates near the Cardinal Plant were high at the beginning and end of the 15-year period, but fairly consistent in between (Figure 20-2). Upstream and downstream catches were similar over the course of the study (Figure 20-2). Catch rates at the Kyger Creek Plant were also high at the beginning and end of the period (Figure 20-3). CPEs increased steadily from 1999 through 2005. No consistent upstream/downstream differences were apparent.

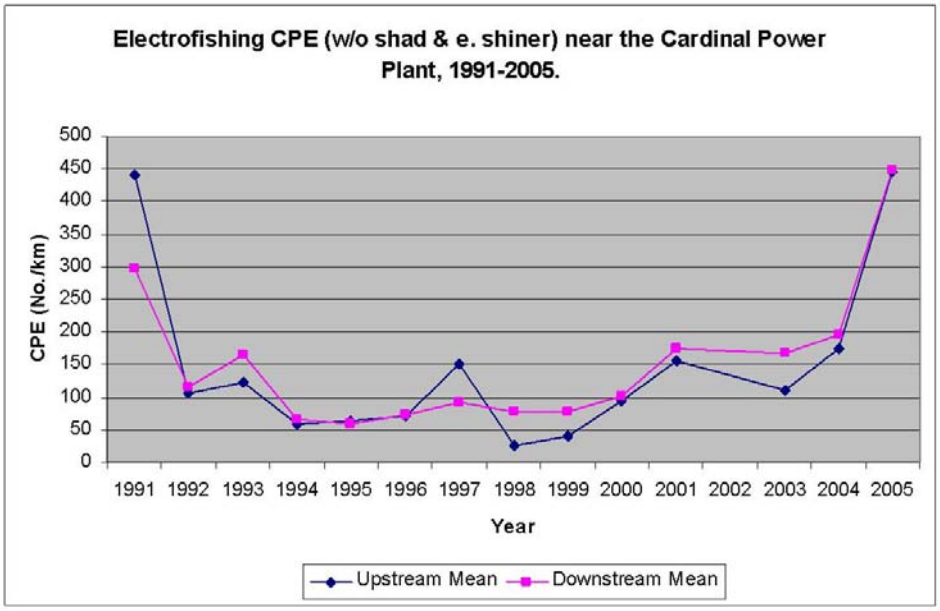

**Figure 20-2**
**Electrofishing CPE (without Shad and E. Shiner) near the Cardinal Power Plant, 1991-2005**

Catch rates near the Tanners Creek Plant were erratic over the 15-year period and no long-term pattern is evident (Figure 20-4). In most years, catches were similar in both areas, but in 1991, 1996, 1997, and 2005, catches were higher upstream of the plant.

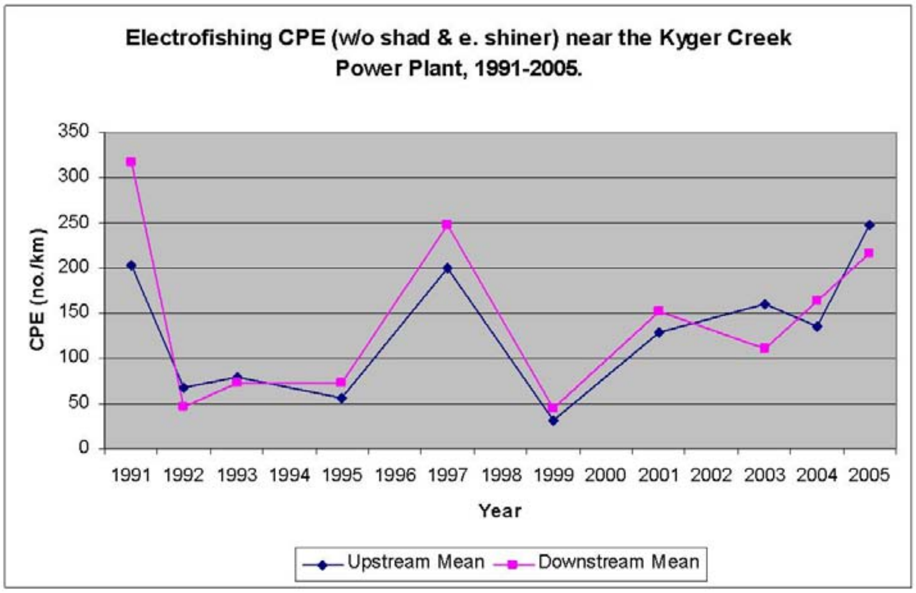

**Figure 20-3**
**Electrofishing CPE (without Shad and Emerald Shiner) near the Kyger Creek Power Plant, 1991-2005**

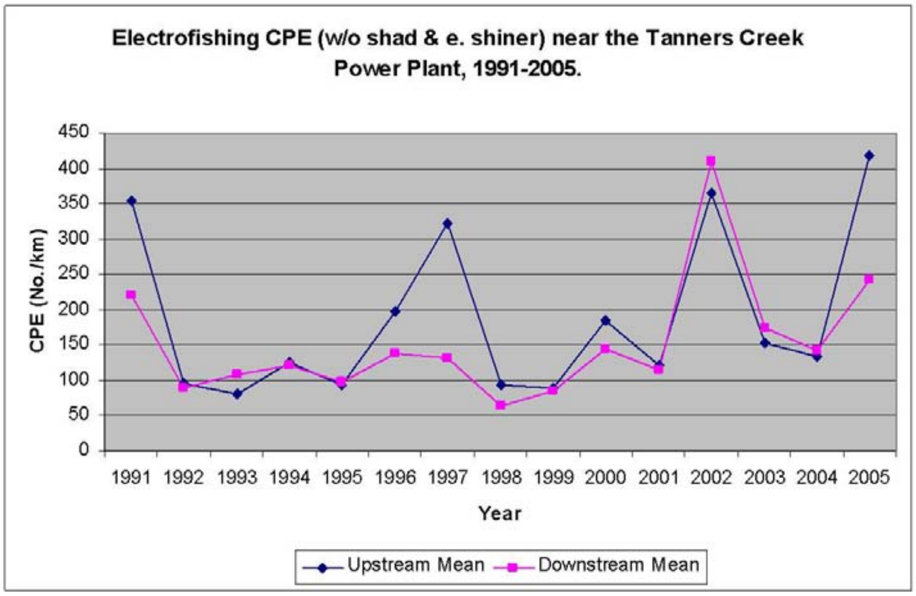

**Figure 20-4**
**Electrofishing CPE (without Shad and Emerald Shiner) near the Tanners Creek Power Plant, 1991-2005**

## Species Richness

There was no trend over time, and no consistent upstream/downstream differences near the Cardinal Plant (Figure 20-5). Species richness did not exhibit any obvious pattern over time near the Kyger Creek Plant (Figure 20-6). Overall, there was no upstream/downstream pattern in species richness: in three years, richness was higher upstream; in four years it was higher downstream; and in three years, richness was similar in both areas (Figure 20-6).

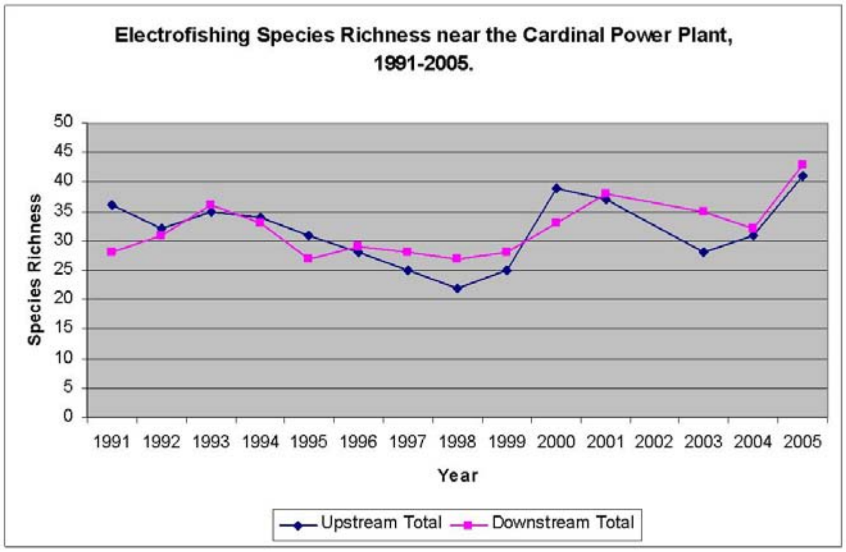

**Figure 20-5**
**Electrofishing Species Richness near the Cardinal Power Plant, 1991-2005**

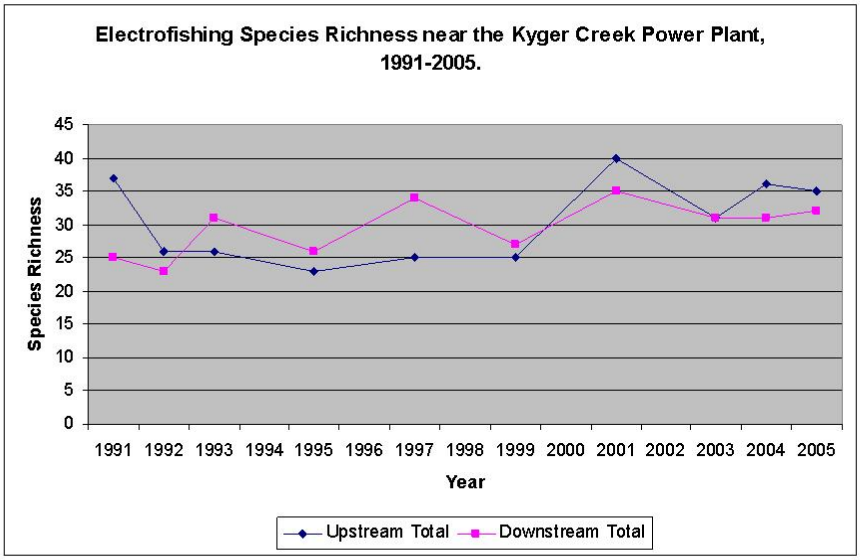

**Figure 20-6**
**Electrofishing Species Richness near the Kyger Creek Power Plant, 1991-2005**

Species richness near the Tanners Creek Plant gradually increased from about 27-28 species in 1991 to 36-40 species in 2005 (Figure 20-7). In some years more species were collected upstream and in others more were collected downstream; overall there was no difference.

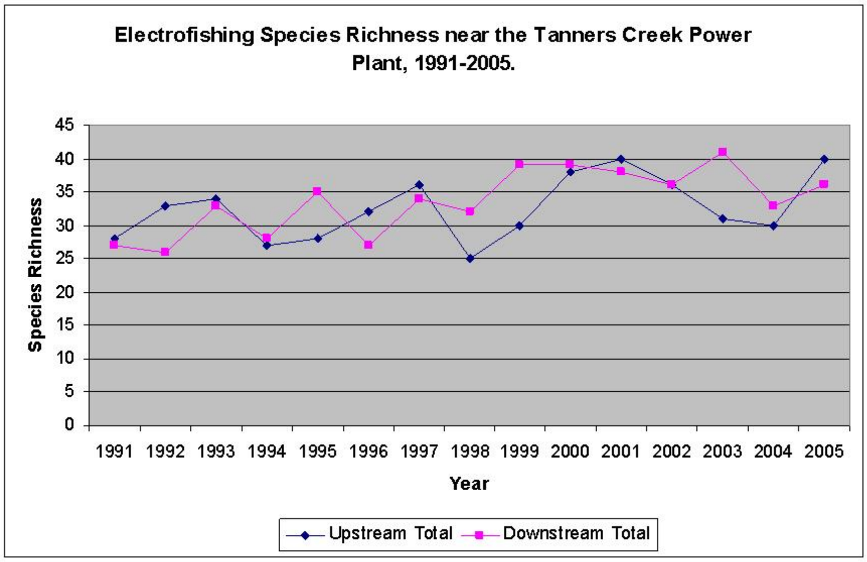

**Figure 20-7**
**Electrofishing Species Richness near the Tanners Creek Power Plant, 1991-2005**

## IWBmod

There were no differences in IWBmod scores near the Cardinal Plant, either over the 15-year study period or between the upstream and downstream areas (Figure 20-8).

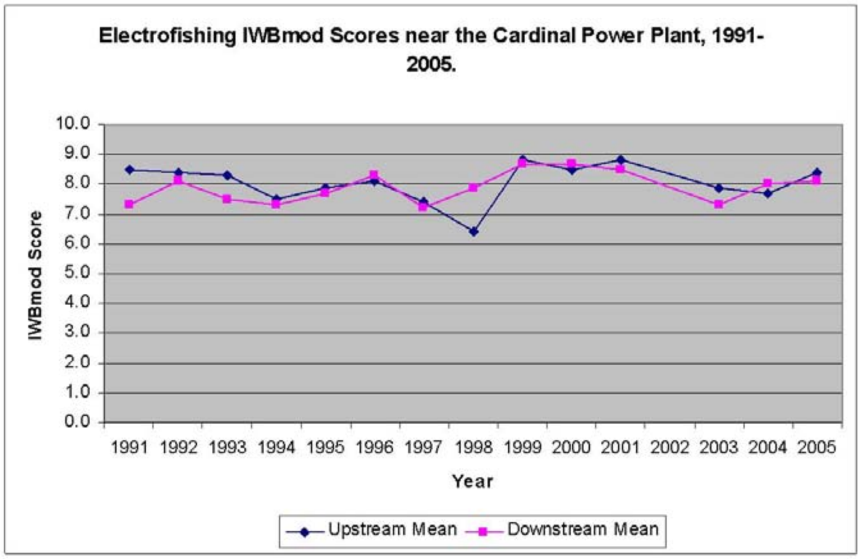

**Figure 20-8**
**Electrofishing IWBmod Scores near the Cardinal Power Plant, 1991-2005**

No trend over time was apparent near the Kyger Creek Plant (Figure 20-9). From 1995 through 1999, IWBmod scores were slightly higher downstream of the plant, but prior to and after this period, scores were similar (Figure 20-9). There was no trend over time near the Tanners Creek Plant (Figure 20-10). In six years, scores were very similar in the two areas, but in nine years, scores were marginally to moderately lower downstream of the plant (Figure 20-10).

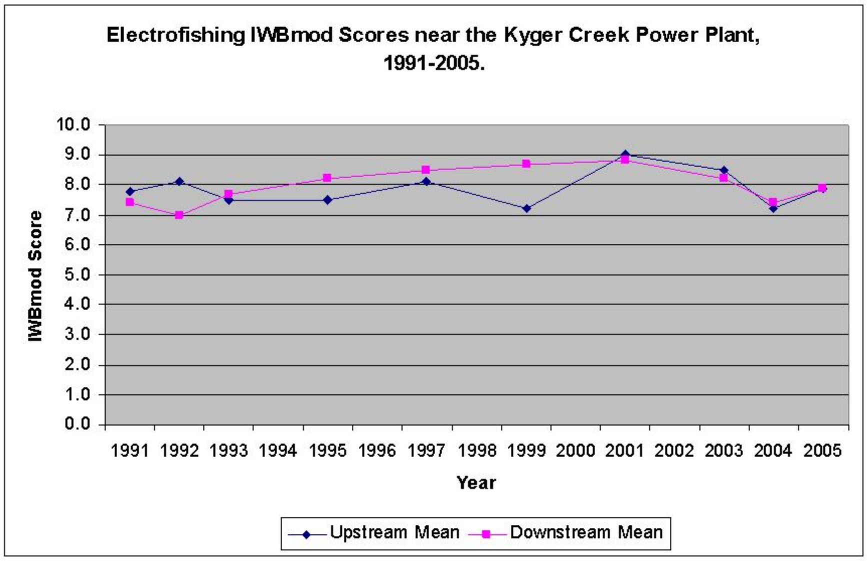

**Figure 20-9**
**Electrofishing IWBmod Scores near the Kyger Creek Power Plant, 1991-2005**

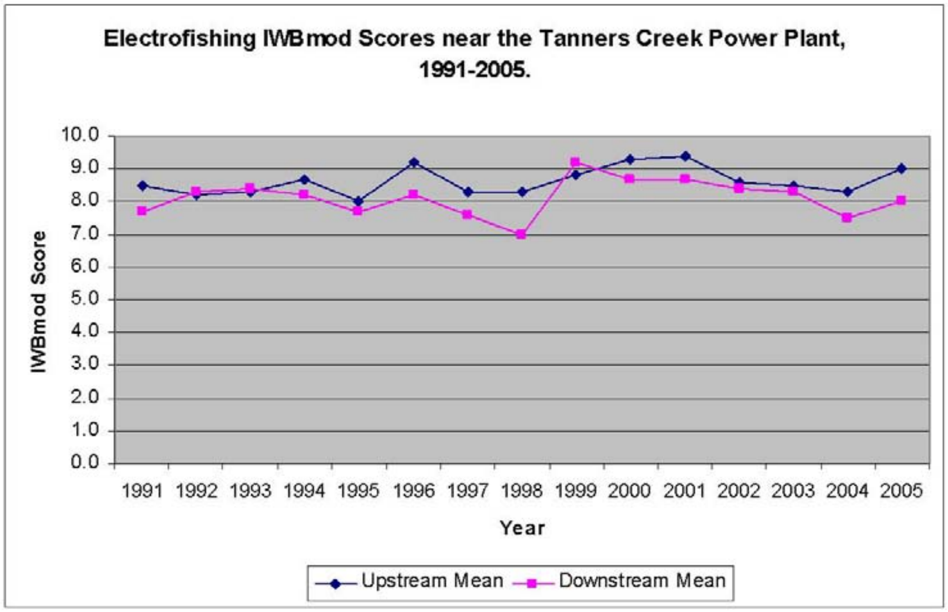

**Figure 20-10**
**Electrofishing IWBmod Scores near the Tanners Creek Power Plant, 1991-2005**

Although the upstream/downstream difference in individual years was not always significant, the fact that the pattern was consistent suggests that, on average, IWBmod scores are slightly depressed downstream of the Tanners Creek Plant.

## ORFIn Scores

ORFIn scores near the Cardinal Plant varied over the course of the study, typically increasing for about three years, then decreasing the next three years (Figure 20-11). Overall, however, there was little change; scores were 37-40 at the beginning of the period and 36-38 at the end of the study period. During the first four years, scores were slightly lower downstream, but after that scores in both areas were very similar in all years, except 2004 (Figure 20-11).

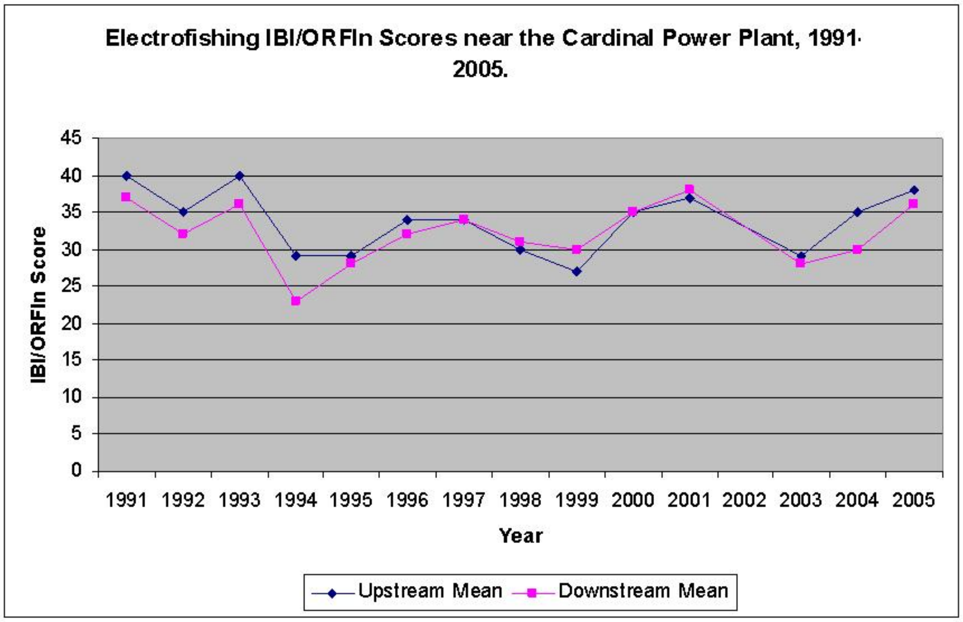

**Figure 20-11**
**Electrofishing IBI/ORFIn Scores near the Cardinal Power Plant, 1991-2005**

No trend over time was apparent near the Kyger Creek Plant (Figure 20-12). In five of the 10 years in which data were collected, upstream and downstream scores were similar, but in the other five years (1991-1992 and 2001, 2003, and 2004) scores were lower downstream, indicating a modest downstream skew in scores (Figure 20-12). ORFIn scores near the Tanners Creek Plant were very consistent from 1991 through 1999 in both the upstream and downstream areas (Figure 20-13). Scores in the downstream area remained in the same range during the remainder of the study, but scores in the upstream area improved somewhat after 1999 (Figure 20-13). ORFIn scores were consistently lower downstream of the Tanners Creek Plant. This may be due to avoidance of the thermal plume but also may be due to slight habitat differences between the two areas [10].

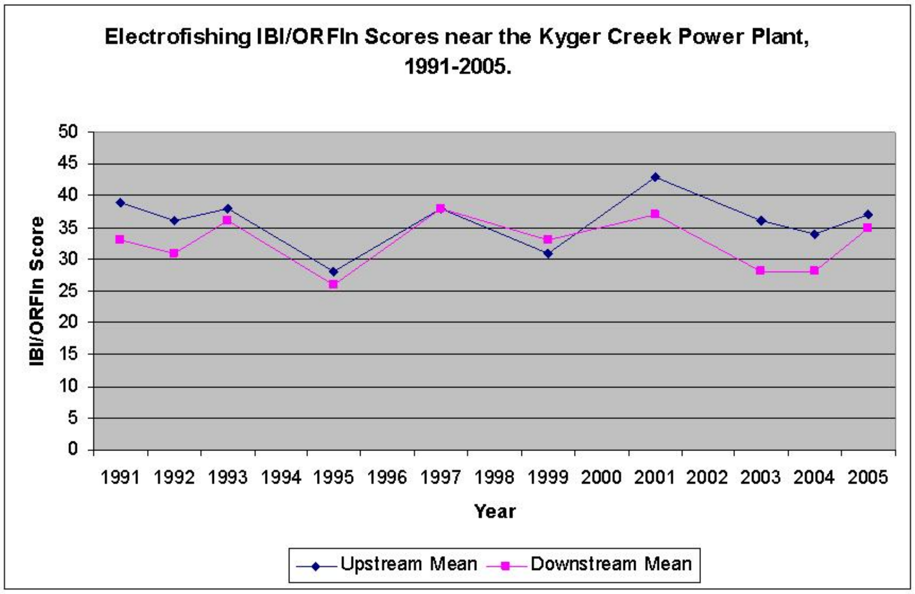

**Figure 20-12**
**Electrofishing IBI/ORFIn Scores near the Kyger Creek Power Plant, 1991-2005**

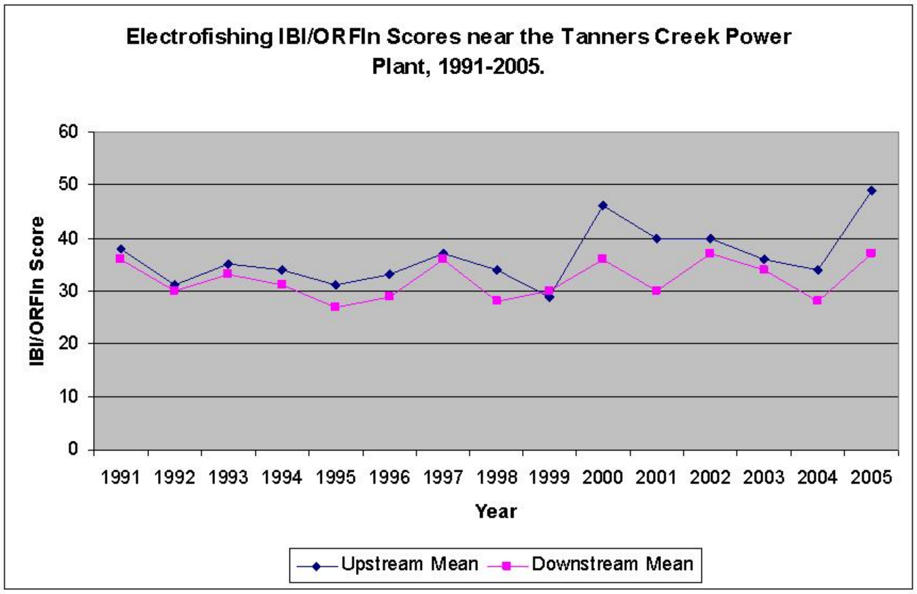

**Figure 20-13**
**Electrofishing IBI/ORFIn Scores near the Tanners Creek Power Plant, 1991-2005**

## Summary

Even in 2005, which was a low flow year during which thermal effects would be expected to be most evident, no consistent upstream/downstream differences in community-level measures were found at 14 of the 17 plants studied.

At three of the seventeen plants, biological endpoint measures were higher upstream on a fairly consistent basis, suggesting that thermal avoidance did occur at these plants in 2005. However, habitat differences may have also played a role.

Several thermally sensitive species were consistently more common upstream, suggesting that these species avoid the thermally enhanced areas, at least during low flow years like 2005.

Over the past 15 years, most endpoint measures did **not** show consistent temporal or spatial differences, suggesting that community-level response is largely unaffected at most plants.

Of the endpoint measures used, ORFIn scores were most likely to show differences between areas, whereas catch rate was the least likely to show differences.

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## 21

# THERMAL LOAD, DISSOLVED OXYGEN, AND ASSIMILATIVE CAPACITY; IS 316(A) BECOMING IRRELEVANT?–THE GEORGIA POWER EXPERIENCE

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## Introduction

Section 316(a) of the Clean Water Act (CWA) provides that the U.S. Environmental Protection Agency (USEPA) and delegated states may authorize alternate thermal discharge limitations in National Pollutant Discharge Elimination System (NPDES) permits where the effluent (thermal) limitation is more stringent than necessary to assure the protection and propagation of a balanced, indigenous community of shellfish, fish, and wildlife in and on the body of water into which the thermal discharge is made. The party seeking the thermal variance has the burden of making the necessary scientifically-supported demonstration that a variance is justified.

In Georgia, use of §316(a) to avoid costly closed-loop cooling system retrofits is becoming unavailable as state regulators increasingly apply dissolved oxygen (DO) criteria to force reductions in heat loads in receiving waters. Since 2002, Georgia Power Company has undertaken the retrofit of cooling towers on three coal fired power plants, involving eleven generating units totaling 2,620 megawatts (MW). On one of these plants, a successful 316(a) demonstration proved that a partial capacity, once-through helper tower was sufficient, thereby saving upwards of $60 million compared to a full capacity, closed loop cooling system. However, on the other two plants, the utilization of a 316(a) thermal variance provided no defense when the receiving stream was 303(d)-listed as impaired for temperature in relationship to its effect on dissolved oxygen and waste assimilation capacity rather than the thermal effect on fish and wildlife. Political pressure to support the region's economic growth through increased receiving stream waste assimilation capacity drove the utility away from consideration of 316(a) variances as a means to avoid costly retrofits. Similarly, a fourth plant located on a DO impaired stream in another developing region of Georgia is facing the same pressures to remove its thermal loading. A §316(a) variance will be of no help in addressing the plant's thermal load as it relates to impacts on in-stream DO resources and related reduction in assimilative capacity.

This paper details the circumstances driving Georgia Power's decisions to retrofit cooling towers on three plants, the similar considerations expected regarding a fourth plant, and the potential implications for use of 316(a) demonstrations going forward.

## Plant Branch

Plant Branch is a four-unit, coal-fired steam electric generating station with a nameplate generating capacity of 1,540 megawatts (MW). The plant occupies a 716-acre site on a peninsula between the Little River arm of Lake Sinclair and the Beaverdam Creek embayment in Putnam County, Georgia (Figure 21-1). Units 1 through 4 utilize once-through cooling with water drawn in from the Little River arm of Lake Sinclair. After passing through the plant, the heated water discharges into a constructed discharge basin and then into the Beaverdam Creek embayment.

**Figure 21-1**
**Plant Branch**

## Background

Georgia Department of Natural Resources, Environmental Protection Division (EPD) regulations specify that water temperature is: "*Not to exceed 90°F. At no time is the temperature of the receiving waters to be increased more than 5°F above intake temperature…*" [1]. Until the most recent NPDES permit cycle, the point of compliance for state temperature criteria was at the edge of an allowed mixing zone. Given the buoyant nature of the thermal plume, the mixing zone was necessarily large; extending approximately two miles from the discharge point, out of Beaverdam Creek and into the main body of Lake Sinclair. Under this scenario, Plant Branch consistently maintained compliance with effluent limitations for over 35 years.

During the 1990s, the Plant Branch thermal discharge was implicated in a number of fish kills in the Beaverdam Creek embayment. Heretofore, there had been no history of fish kills at the facility. The fish kills occurred during the heat of summer coinciding with high electrical demand. The cause of the fish kills was cited by the state Wildlife Resources Division (WRD) as excessive water temperatures combined with low water column DO creating lethal conditions for fish passage in Beaverdam Creek embayment. The fish kills were never massive, but nonetheless attracted the attention of EPD who took enforcement actions and environmental advocacy groups who pressured EPD, as well as Georgia Power, to implement evermore stringent corrective measures.

On 30 November 1995, EPD renewed the Plant Branch NPDES permit. Concurrently, EPD issued Order No. EPD-WQ-3209 directing the company to evaluate operational measures to provide a zone of passage for fish in Beaverdam Creek embayment during summer. As a result, Georgia Power initiated development of design plans for a cooling system that would reduce the heat load discharged to Lake Sinclair and provide the necessary zone of passage. Georgia Power also initiated thermal modeling and biological assessment studies to support a §316(a) Demonstration. During the latter half of the five-year permit cycle, conditions lethal to fish developed again in Beaverdam Creek during critical summer months resulting in additional unwanted attention to the facility thermal discharge.

Subsequently, Georgia Power filed the Plant Branch NPDES renewal application with EPD in June 1997, which included the proposed helper cooling tower. EPD issued the permit with the cooling system as proposed and the Sierra Club immediately challenged the permit, maintaining that anything less than a full capacity closed-loop cooling tower system would not be protective of fish and wildlife. After three years of contentious litigation, the parties to the suit, Georgia Power Company, Sierra Club, EPD and USEPA, reached settlement in September 2000, through a Memorandum of Agreement (MOA). The MOA provided for issuance of a permit that allowed Georgia Power to operate the plant for five years with the 50 percent capacity helper cooling tower while proving the validity of the hydrothermal modeling on which the cooling concept was based. Additionally, on the basis that the State's water temperature criteria were more stringent than necessary to protect and maintain a balanced, indigenous aquatic community in Lake Sinclair, Georgia Power agreed to conduct a re-designed two-year 316(a) Demonstration Study to justify alternate thermal limits for the Plant Branch discharge. The new Plant Branch NPDES permit was issued on 14 December 2000 and included a compliance schedule incorporating the corrective elements of the MOA.

Interestingly, Georgia EPD cited the requirements of the permit/MOA as addressing Total Maximum Daily Load (TMDL) implementation for the Beaverdam Creek embayment; the waterbody had been listed on Georgia's CWA §303(d) list of impaired waterbodies due to exceedence of the state's temperature criteria.

### *Actions Taken*

With a total construction cost of approximately $36 million (including engineering and design costs), Georgia Power installed (retrofit) and operated a new cooling tower system at Plant Branch beginning in the summer of 2002 to establish non-lethal conditions for reservoir fish in the Beaverdam Creek embayment. Operations of the cooling tower system coincided with field studies to support the 316(a) Demonstration. Non-lethal conditions were defined by EPD in the Plant Branch NPDES permit as measuring a water temperature *in Beaverdam Creek embayment* of not greater than 93°F (33.9°C) at a depth somewhere in the vertical water column that contains DO concentrations of not less than 3.0 milligrams per liter (mg/L). Water quality parameters defining non-lethal conditions for fish were initially determined by the WRD and included in the 30 November 1995 Administrative Order No. EPD–WQ-3209.

The cooling tower system is designed to cool one-half of the 800,000 gallons per minute (gpm) condenser cooling water for the four-unit, 1,540 MW plant. The cooling tower system is a 100-foot wide, 900-foot long and 60-foot high conventional mechanical draft, counter-flow type that utilizes electric motor-driven fans to provide airflow through the system. The cooling system is constructed of fiberglass and designed to cool water from 106°F to 86°F at an ambient wet bulb temperature of 80°F. Georgia Power operates the tower only during the summer months. The tower may be operated with any combination of four pumps and thirty-two fans to provide capacity to cool 50 percent of the plant's condenser heat rejection. A beneficial side effect of the cooling system is that the discharges are typically saturated with DO. This addition of DO is beneficial to aquatic life in Beaverdam Creek and Lake Sinclair, particularly during summer months when saturated dissolved oxygen conditions in southern reservoirs are atypical.

The cooling system is located on the west side of the Plant Branch powerhouse, and discharges the cooled water to the bottom of the Beaverdam Creek embayment upstream of the existing plant discharge tunnels (Figure 21-2). A discharge basin with overflow weir openings was constructed to enclose the two existing plant discharges. The purpose of the weir is to force the plant discharge flow that does not enter the cooling tower to the surface of Beaverdam Creek embayment so that a cooler water wedge can be established at depth. This configuration provides non-lethal conditions for fish by creating a thermally stratified condition in Beaverdam Creek embayment where the oxygenated cooler water is in the lower portion of the water column. Georgia Power designed the discharge structure using a computer-based, three-dimensional hydrothermal model[1] of Beaverdam Creek embayment to maximize the stratification effect.

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[1] The hydrothermal model and cooling tower discharge structure design concepts were developed by J. E. Edinger Associates, Inc. (JEEAI) of Wayne, Pennsylvania; now a part of Environmental Resources Management, Inc. (ERM) since October 2005.

**Figure 21-2**
**Configuration/Design of Plant Branch Cooling Tower System**

## *Remarks*

For Plant Branch, a solution that included discharge cooling was inevitable due to thermal and related DO impacts to fish (mortality) during critical conditions of summer. The innovative hydrothermal solution and successful 316(a) Demonstration (i.e., alternate thermal limits) saved Georgia Power upwards of $60 million over a fully closed-loop system due to the extreme difficulties in retrofitting closed-loop piping to the congested site and existing intake/discharge tunnel configuration.

After five years of critical condition summertime operation, the cooling system has performed as designed and maintained non-lethal conditions for fish in Beaverdam Creek embayment. The 316(a) Demonstration confirmed the protection and propagation of a balanced, indigenous community of shellfish, fish, and wildlife in Beaverdam Creek embayment and Lake Sinclair and absence of “prior appreciable harm”. The study findings were accepted by the Georgia Department of Natural Resources (EPD and WRD) and a CWA §316(a) Variance was granted in March of 2005.

It is interesting to note that Beaverdam Creek embayment (i.e., that portion of Lake Sinclair) remains on Georgia's 303(d) list as "not fully supporting designated uses" (recreation/fishing) due to water temperature (http://www.gaepd.org/Documents/305b.html). Though Georgia Power's compliance actions as specified in the MOA were cited by EPD as implementation of a TMDL for water temperature in Beaverdam Creek embayment and that TMDL is currently noted as "developed and approved", the fact that water temperatures may still at times exceed ambient water quality criteria apparently requires that the waterbody (segment) remain 303-listed.

## Plants Yates and McDonough

Both Plants Yates and McDonough are located on the Chattahoochee River in the greater Atlanta, Georgia metropolitan area. Plant Yates is a seven-unit, coal-fired steam electric generating station with a total capacity of 1,250 MW. Units 1-5 (550 MW) previously used once-through cooling; units 6 and 7 were initially constructed with closed-loop cooling systems. The plant occupies a 2,396-acre site along the Chattahoochee in Coweta County, Georgia (Figure 21-3).

**Figure 21-3**
**Plant Yates**

Plant McDonough is a two unit, coal-fired steam electric generating station with a total rated capacity of 530 MW. Currently, these units use a once-through cooling system. Located approximately 43 miles upstream from Plant Yates in the heart of metro Atlanta in Cobb County (Figure 21-4), Plant McDonough is currently positioned within the lowermost reach of the state-designated secondary trout waters segment of the Chattahoochee River which extends from the U.S. Army Corps of Engineers' (USACE) Buford Dam (impounding Lake Sidney Lanier) southwest to the Interstate 285 west bridge.

**Figure 21-4**
**Plant McDonough**

The reach of Chattahoochee River where Plant McDonough is located is 303(d)-listed as "not fully supporting designated uses" (recreational fishing) due to elevated water temperature and other parameters (www.gaepd.org/Documents/305b.html). Interestingly DO is *not* one of those parameters, yet as described later, concerns for DO would be the ultimate basis for the 303(d) listing and associated TMDL.

## *Background*

In August 2000, Georgia Power made news among environmental activist, regulators, local governments and the business community when it was announced that the company would make a considerable investment to build cooling towers for Plants McDonough and Yates; converting their once-through cooling systems to full closed-cycle systems, and thus removing their effect on the temperature of the Chattahoochee River. Three independent factors were the basis for this decision including: 1) correction of existing deficiencies, 2) compliance with more stringent regulations expected in the future, and 3) a corporate sense of responsibility to contribute to solutions for a regional problem – rapid population growth. These factors are presented in additional detail in the following text.

**Correction of Deficiencies –** Central Georgia experienced severe drought conditions from 1998 through 2002. In August 1999, near record low flows were present in the Chattahoochee River near Plant Yates. Sustained high ambient air temperatures raised river water temperatures near the tolerance level for fish and created power demands that necessitated the continuous full-load operation of Plant Yates for several days. These conditions combined to create critical conditions for fish in the river downstream of the plant resulting in a fish kill. Georgia EPD subsequently executed a Consent Order requiring Georgia Power to conduct an engineering study to evaluate cooling technology and/or operational measures to meet state water quality criteria for temperature.

**Compliance with More Stringent Future Regulations** – Plant McDonough's NPDES permits have, in effect, allowed the discharge of once-through condenser cooling water at up to 18°F above ambient river temperature on the basis that Chattahoochee River water temperatures in the affected reach were unnaturally cool (supporting secondary trout waters) due to the upstream influence of hypolimnetic discharges from the USACE's Buford Dam. The 7Q10[2] flow of this regulated river is 750 cubic feet per second (cfs), and the Plant McDonough full-load condenser flow is 608 cfs; thus approximately 81 percent of the river is withdrawn under these conditions. The NPDES permit invoked the standard 5°F $\Delta T$ limit on the discharge, but allowed an adjustment calculation for the intake temperature to determine compliance with the permit.

During the development of the Chattahoochee River Modeling Project, fully discussed below, Georgia EPD notified Georgia Power that, beginning the next five-year permit cycle, Plant McDonough would, at a minimum have to meet the water quality standard 5°F $\Delta T$ without the benefit of the intake temperature adjustment calculation. The primary driver for this action by EPD was to address water quality concerns associated with the heated discharge's affect on DO as it relates to the capacity of the river to assimilate wastes. The potential effect of the heated discharge on the fish community was not in the equation. Consequently, for Plant McDonough to achieve compliance in future permits, some degree of cooling for the plant's once through cooling water will be required. And while consumptive water use associated with the evaporative effects of cooling towers was a point of discussion at the time, the matter was trumped by the greater economic concerns associated stymied growth due to a lack of assimilative capacity in the river.

**Contribution to Solutions for a Regional Problem** – In response to increased requests from local city and county water utilities for new and expanded wastewater treatment facilities, EPD initiated the Chattahoochee River Modeling Project (CRMP). The model was designed to make predictions about water quality conditions in the Chattahoochee River from Buford Dam downstream to West Point Lake; one of the most threatened river reaches in the country due to its small size and great demand by metropolitan Atlanta for its drinking water and waste assimilative capacity.

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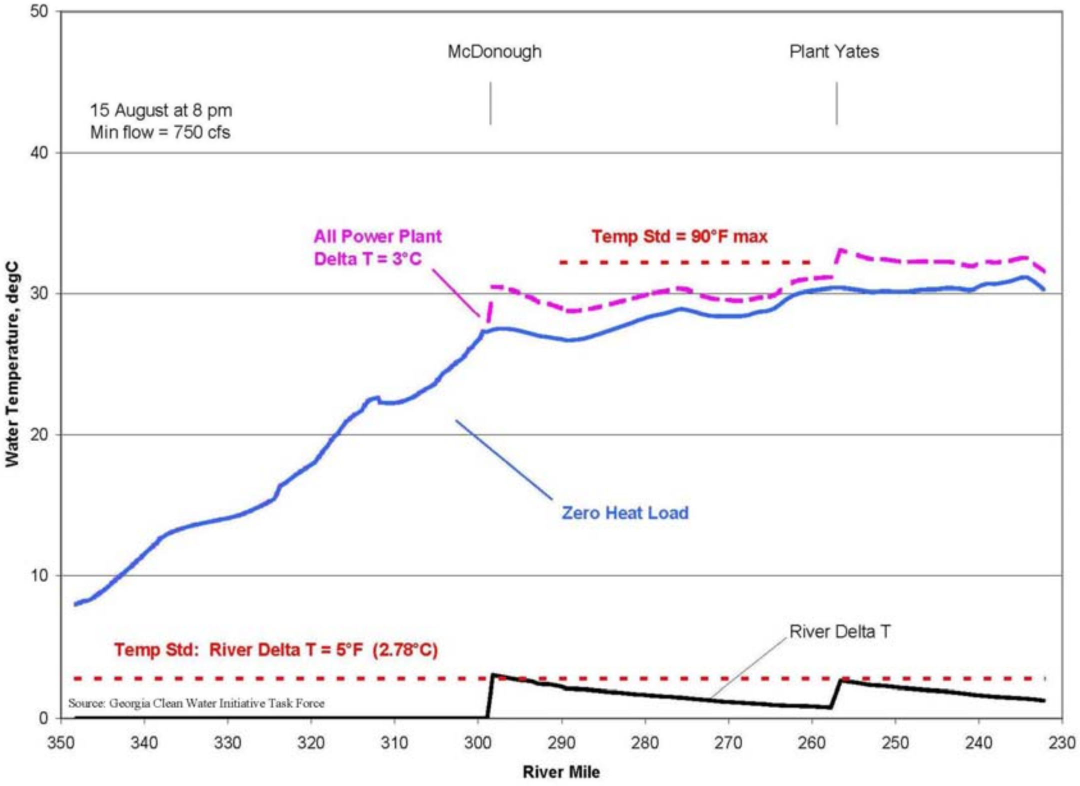
[2] 7Q10 - Seven-day, consecutive low flow with a ten-year return frequency; that is, the lowest stream flow for seven consecutive days that would be expected to occur once in ten years.

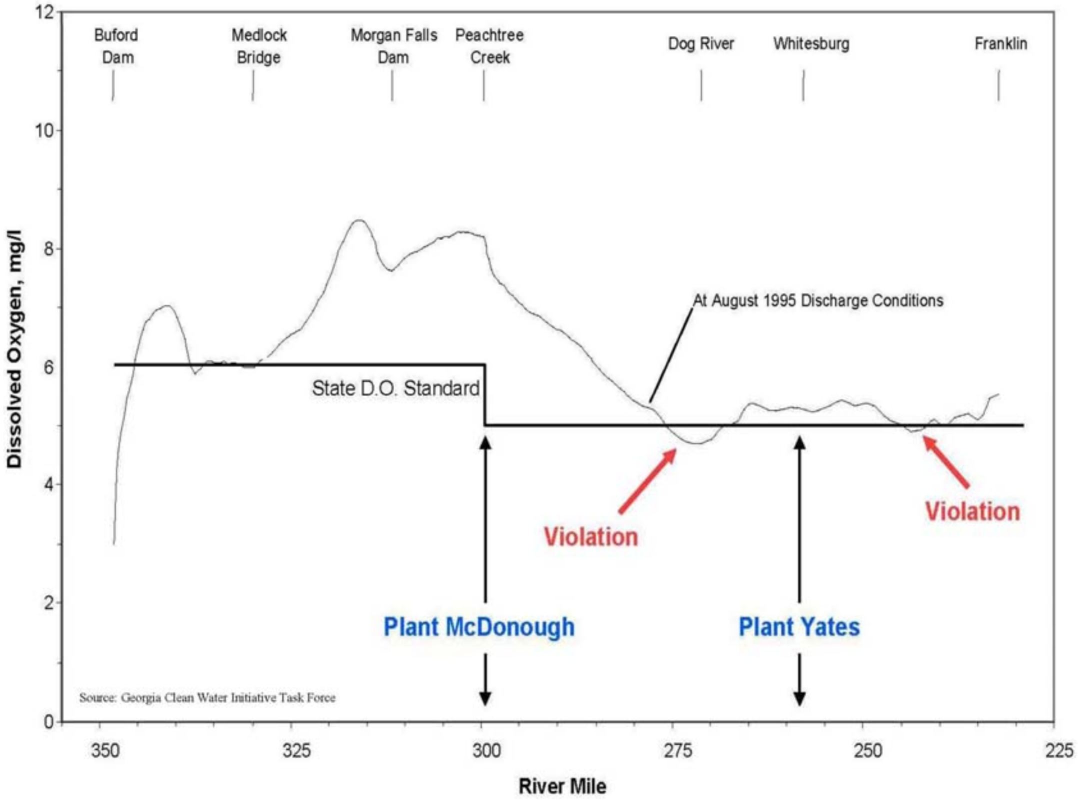
The CRMP team modeled the water quality in the river under critical conditions of low flow (7Q10) and maximum volume of pollutant input allowed by the numerous NPDES permitted dischargers along the river reach of interest. Pollutants from non-point sources were also considered in the analyses. This modeling effort indicated that the river would not meet water quality criteria for DO at locations downstream of Plants McDonough and Yates during critical conditions *under then current NPDES permit effluent limits for all discharges*.

Plant McDonough was identified as a significant contributing factor to the model findings due to its once-through thermal additions resulting in the lowering of water column DO saturation potential, and thus waste assimilative capacity. Figure 21-5 and Figure 21-6 present modeled critical condition water temperatures and DO concentrations, respectively, for the Chattahoochee River from Buford Dam to West Point Lake.



Source: Georgia Clean Water Initiative Task Force

**Figure 21-5**
**Chattahoochee River Water Temperature Modeled at Critical Conditions**



Source: Georgia Clean Water Initiative Task Force

**Figure 21-6**
**Chattahoochee River Dissolved Oxygen Concentrations at Critical Conditions**

The Chattahoochee River Model demonstrated to Georgia Power and other stakeholders that the waste assimilative capacity of the Chattahoochee River had been reached; no new or expanded NPDES permits exacerbating the problem could be issued. The consequences of this finding were staggering in that the tremendous economic growth of the Atlanta metropolitan area could not be sustained under the status quo – all dischargers would have to equitably contribute to solving this problem. The collective concern of business and community leaders resulted in the formation of the Clean Water Initiative Task Force (CWITF) by the Atlanta Metro Chamber of Commerce to evaluate potential solutions for maintaining water quality objectives for the Chattahoochee River. Georgia Power was an active member of this task force, with Bill Dahlberg, Chairman and CEO of Southern Company[3], serving as Chair.

A number of potential solutions were evaluated by the CWITF including:

- Conservation
- Wastewater re-use
- Seasonally-based permit limits
- Increase in river flow

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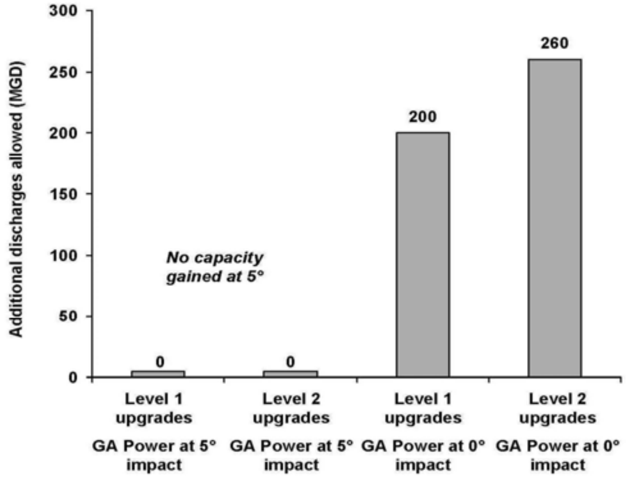
[3] Southern Company is the parent firm of Georgia Power Company.

- Direct aeration of the river
- Non-point pollutant source reductions
- Reducing heat load
- Upgrading wastewater treatment plants (WWTP)

Technical input from EPD based on a number of Chattahoochee River modeling scenarios narrowed in on two solutions that would have the greatest impact on improving water quality (i.e., DO) in the river: 1) upgrading WWTPs with "best available technology", and 2) reducing heat load from Plants McDonough and Yates. With regard to heat load, however, Georgia Power's simple compliance with the state's 5°F ΔT criterion would still not allow for any additional wastewater discharges to the river; only the achievement of DO criteria under existing permitted limits. Additional assimilative capacity in the river could only be achieved if Georgia Power agreed to implement technological measures that would go beyond the 5°F ΔT criterion[4] resulting in *zero heat load* to the river (Figure 21-7).



Source: Georgia Clean Water Initiative Task Force

**Figure 21-7**
**Assimilative Capacity Gains in the Chattahoochee River from Wastewater Treatment Plant Upgrades Combined with Heat Load Reductions**

NPDES-permitted wastewater treatment capacity in 2000 was 533 million gallons per day (MGD) serving an Atlanta metropolitan area population of approximately 3.5 million. If an additional 260 MGD can be assimilated, a population of approximately 5.2 million could be accommodated. According to the latest U.S. Census Bureau statistics [2], the Atlanta metropolitan area population in 2005 was 4.3 million; an annual growth rate from 2000 of approximately 4.5 percent. At that rate, the additional assimilative capacity associated with upgrading WWTPs and reducing heat load from Plants McDonough and Yates would be reached by 2009. Thus, Georgia Power's commitment to reduce heat loads offered only a short-term solution for achieving water quality objectives for the Chattahoochee River in the face of rapid growth of the Atlanta metropolitan area.

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[4] Georgia Power's "volunteered" commitment to go above and beyond the 5°ΔT compliance obligation was a point of discussion before the Georgia Public Service Commission. However, the company successfully avoided a disallowance in recovering costs for installing cooling towers at Plants McDonough and Yates.

In August 2000, Bill Dahlberg while chairing a meeting of the Metro Atlanta Chamber of Commerce and the Regional Business Coalition's CWITF announced:

"*We* [Georgia Power] *are going to build the cooling towers because it is the right thing to do for our region, it is the right thing to do for the river and ultimately it will be the right thing to do for our business". "However, this is just the first step in solving the problem. We now need our local, county, state and private officials to support a regional solution to protect the future of this very valuable river.*"

### Actions Taken

Georgia Power retrofitted a cooling tower system at Plant Yates which began operation in January 2004 (Figure 21-8). The $83 million Yates tower consists of five segments of eight cells each, constructed in a single structure to form the largest mechanical draft cooling tower in the world. It measures 100 feet wide, 1,000 feet long and 60 feet high. The five-unit total condenser flow is 500,000 gpm. For operational flexibility, the segments can be interchanged among the five formerly once-through cooled generating units which total 550 MW. As the system is fully closed loop, EPD modeling deems the heat load from Plant Yates to be negligible.

**Figure 21-8**
**Configuration/Design of Plant Yates Cooling Tower System**

The Plant McDonough cooling tower retrofit is currently underway with operation scheduled for summer 2008. Each of the two 265 MW McDonough units employs one 10-cell closed-loop tower to cool 137,500 gpm of condenser and service water flow. Each tower is 50 feet wide, 500 feet long and 66 feet high (Figure 21-9). Before cascading through the tower baffles, the hot leg condenser water will warm the tower fan plenum to provide plume abatement in the congested urban Atlanta location. The towers are expected to cost $96 million, which includes engineering and design costs.

**Figure 21-9**
**Configuration/Design of Plant McDonough Cooling Tower System**

Both Yates and McDonough cooling towers are mechanical-draft, counter flow cooling towers constructed of fiberglass and designed to cool water from 106°F to 86°F at an ambient wet bulb temperature of 80°F.

## *Remarks*

A solution that included discharge cooling was inevitable due to fish kills at Plant Yates, tightening thermal discharge limits, and temperature associated impacts on DO (i.e., assimilative capacity). While 316(a) was a regulatory option for Georgia Power; it was negated by the need to remove all heat loads from the river. In hindsight, given the realized population projections for the Atlanta metro area, Georgia Power believes the decision made to retrofit Plants McDonough and Yates with 100 percent capacity cooling tower systems was a good one; albeit not one without significant capital costs and associated energy cost penalty. Further, by acting when it did, Georgia Power essentially removed itself from what was obviously becoming an intense controversy in 2000; a situation that will only intensify as the short-term gains in assimilative capacity are exhausted.

Additionally, though not effectively in play at the time Georgia Power made the decision to retrofit cooling towers at Plants McDonough and Yates, compliance with USEPA’s Phase II CWA §316(b) Cooling Water Intake Structure rules issued in July 2004 requiring reductions in fish impingement, and as applicable, entrainment, was also achieved by the retrofits.

## Plant Hammond

Plant Hammond is located in Floyd County, Georgia approximately ten miles west of Rome, Georgia along the Weiss Lake shoreline (Figure 21-10). It is a coal-fired steam electric power generating facility consisting of four generating units with a gross plant output of 800 MW. It uses a once-through cooling water system that withdraws cooling water from the headwaters of Weiss Lake, an impoundment of the Coosa River.

**Figure 21-10**
**Plant Hammond**

### *Background*

Plant Hammond faces the same concerns over attainment of DO criteria as have already been addressed at Plants McDonough and Yates. It's location on Lake Weiss is very close to the point where the Coosa River flow meets the backwaters of the lake. Annual mean flow rate of the river just upstream of the plant is nearly 7,000 cfs. When the river flow is above 2,100 cfs, the thermal dilution capacity of the river is sufficient to easily provide permit compliance at the mixing zone boundary, about one mile downstream of the plant discharge point. At flows less than 2,100 cfs, the lake backwater effect brings into play significant factors affecting temperatures at the compliance point, such as lake surface heating and plant discharge recirculation back upstream into the intake. The 7Q10 flow for the river just upstream of its entry to the lake is about 1,400 cfs and varies widely on an instantaneous basis depending on generation schedules of the USACE's Allatoona Dam, located 85 miles upstream of the plant. Full-load condenser flow for the four units is 614 cfs, which comprises approximately 65 percent of the river withdrawn at 7Q10 flow.

In 2004, the segment of the Coosa River, (actually Lake Weiss headwaters) near the plant was 303(d) listed for DO impairment. Subsequently, a draft TMDL was developed using a critical conditions riverine water quality model similar to the Chattahoochee River model discussed earlier. The TMDL called for significant reductions of pollutant loads from all NPDES permittees discharging to the river. Northwest Georgia communities strongly reacted citing economic hardship of compliance and fear that the reductions would likely trigger closure of a paper mill (a major employer for the Rome, Georgia area). The heat load reductions required of Plant Hammond by the draft TMDL dictated retrofit of a cooling tower, projected to cost over $100 million. A coalition of permittees commented on the draft TMDL, identifying technical faults with the modeling, including such issues as the omission of non-point nutrient sources and the applicability of a riverine model to lake headwater hydraulics. Acknowledging the weak science supporting the TMDL, USEPA, Georgia EPD and the Alabama Department of Environmental Management (ADEM) began a four-year study to refine the modeling and revise the TMDL, which should be re-issued in late 2008.

### *Actions Under Consideration*

Georgia Power will closely review the design and execution of the new modeling and the next version of the Coosa River DO TMDL to assure proper consideration is given to the unique hydrothermal conditions at Plant Hammond.

### *Remarks*

The political pressures associated with waste assimilation capacity of the Coosa River will not be the same as experienced with Atlanta and the Chattahoochee River. The Coosa is a much larger river than the Chattahoochee, and the population in the Coosa basin is much smaller. Regional economic development in northwest Georgia will not be impacted at the same scale as in metro Atlanta. Therefore, decisions regarding equitable allocation of waste loads should focus only on scientific facts associated with DO. However, with numerous municipalities in the basin facing huge investments in sewage treatment plant upgrades, cooling towers at Plant Hammond may be a component of an overall least-cost solution.

Recent conditions (occurring even as this report is being prepared) may supersede DO as a controlling issue. This summer (2007), the Coosa River basin has experienced record drought and heat. Lake levels at Allatoona, Lake Weiss, and downstream lakes were threatened as never experienced before. Minimum flow releases from USACE’s Lake Allatoona yielded Coosa River flows near Plant Hammond as low as 700 cfs; about half the 7Q10 flow. Weekday peaking hydroelectric power generation provides average flows of about 1,400 cfs, peak flows near 2,000 cfs and low flows of around 800 cfs. With river flows often less than the plant condenser flows (614 cfs full load); plant management has taken steps to mitigate thermal impacts while preserving plant availability to assure transmission system reliability. The plant has reduced load to a minimum from 10:00 pm to 10:00 am each night. Aeration spargers have been placed near the plant intake to aid intake temperatures and supplement DO. And temporary mobile cooling towers have been installed to cool about one-fifth of the condenser flow rate by about 20°F.

The measures taken during summer 2007 to guarantee reliable generation capacity and transmission system integrity in this region will weigh heavily in Georgia Power's consideration of options in the development of the DO TMDL Implementation Plan.

Additionally, compliance with USEPA's Phase II CWA §316(b) Cooling Water Intake Structure rules will also be considered in any decision to retrofit a closed-loop cooling system at Plant Hammond.

## Closing

Georgia's population is expected to double from nine million to 18 million residents in the next 25 years, with the bulk of growth occurring in the Atlanta metropolitan area. This will place a great demand on water resources in the state and region, both for potable use and for waste assimilation. Climate change in the form of more frequent and intensive droughts (i.e., low river flows) and high ambient temperatures combine to create potential future compliance challenges for power plants operating with once-through cooling. This will be particularly true for power plants located in headwater areas and/or that withdraw a proportionately greater volume of cooling water in relation to critical in-stream flow (e.g., 7Q10 flow).

In urbanized watersheds, where source cooling waterbodies have impaired DO resources, viability of the CWA §316(a) regulatory option will diminish as greater emphasis is placed on heat load reduction to increase waste assimilative capacity to accommodate population growth.

## References

1. *Rules and Regulations for Water Quality Control, Chapter 391-3-6(6)(b)(iv).* Georgia Department of Natural Resources, Environmental Protection Division, Atlanta, Georgia.

2. State and Metropolitan Area Data Book: 2006. www.census.gov/compendia/smadb/. U.S. Census Bureau, Washington, DC.

# 22

# FLOW MANAGEMENT: KEEPING A §316(B) SOLUTION FROM BECOMING A §316(A) PROBLEM

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## Introduction

Section 316(b) of the Clean Water Act requires that "…the location, design, construction, and capacity of cooling water intake structures reflect the best technology available for minimizing adverse environmental impact." On July 9, 2004, the United States Environmental Protection Agency (USEPA) issued Phase II regulations for §316(b) which applied to existing facilities withdrawing at least 50 mgd of cooling water from the waters of the United States. Among other items, these Phase II rules included national performance standards that required existing facilities to reduce annual impingement mortality by 80 to 95 percent and, if applicable, to reduce entrainment by 60 to 90 percent.

On January 25, 2007, the Second U.S. Circuit Court of Appeals issued its decision in litigation over the Phase II regulations that remanded several key provisions of the Rule on various grounds. As a result of this rule, USEPA suspended the Phase II Rule on July 9, 2007 but required all permits for Phase II facilities to address §316(b) on a Best Professional Basis. While USEPA has yet to issue new Phase II regulations, it is likely that any such new regulations will mandate reductions in impingement and entrainment at many facilities.

Issuance of the Phase II regulations in 2004 prompted a thorough review of intake alternatives which could be used, either alone or in combination with others, to meet the national performance standards [1]. The reviews revealed a variety of economically viable intake alternatives that could meet the national performance standards for impingement mortality. However, far fewer alternatives were available to meet the entrainment standards, other than reductions in cooling water flow. While such flow reductions can be met through the use of cooling towers or forced outages, such alternatives are very costly and can have significant energy, air quality and other environmental impacts.

For Phase II facilities that typically operate in either a load-following or peaking mode, variable-speed pumping provides a more practical alternative for reducing flow commensurate with variations in station generating load. Pump operating regimes can be designed to manage effects of reduced flow on condenser performance and energy efficiency while still achieving substantial reductions in entrainment and impingement at some facilities. In addition, use of variable-speed pumping has the potential to reduce operating costs by reducing auxiliary electrical demand associated with pumping of cooling water, and avoiding sub-cooling of the condensate. It is for these reasons that variable-speed pumping has been adopted as part of a §316(b) compliance package for several Phase II facilities in New York State.

While variable-speed pumping can be an attractive alternative for reducing entrainment for Phase II facilities, it is important to remember that any alteration of cooling water flows has the potential to alter the characteristics of the facility's thermal discharge. These alterations, in turn, could have the potential to affect compliance with NPDES discharge temperature limitations and/or thermal water quality criteria. Moreover, changes in the thermal plume characteristics could undermine the validity of previous biothermal assessments upon which a §316(a) variance was granted. Such effects can be real or imagined on the part of permit writer. In either case, any facility considering variable-speed pumping as an alternative to achieve §316(b) compliance should also consider the potential impacts on compliance with thermal requirements, including §316(a).

This paper provides an overview of the potential thermal issues that need to be evaluated when considering variable-speed pumping as a means to achieve §316(b) compliance. We do this by illustrating changes in the characteristics of the thermal plume associated with installation of variable-speed pumping at an existing generating station located in New York State. We discuss these changes in light of compliance with thermal permit limits and the §316(a) variance process.

## Example Facility

The facility selected for illustrative purposes consists of two units. Each unit has a capacity of approximately 200 MWe and a design cooling water flow rate of approximately 100,000 gpm provided by identical two cooling water pumps. Cooling water is withdrawn from the source waterbody through an intake structure at each unit and is routed through the interiors of tubes within the steam condensers of each unit. The low-pressure steam exiting the turbines is directed to the condensers where it contacts the outer surface of the condenser tubes. The temperature difference between the low-pressure steam and condensers tubes causes a heat exchange that results in the steam's being converted back to water. Both units typically operate both cooling water pumps when on line. The facility's current NPDES permit limits the temperature increase in the cooling water system ($\Delta T$) to 30°F and a maximum discharge temperature of 110°F.

This facility operates in a load-following mode as requested by the Independent System Operator. Actual daily mean electric output from a recent year is provided in Figure 22-1. This figure illustrates the typical seasonal pattern in both electric output and cooling water flow rates.

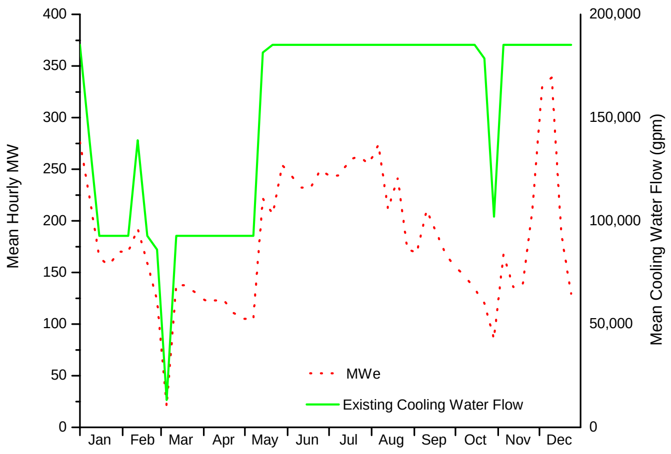

**Figure 22-1**
**Seasonal Electrical Output and Cooling Water Flow for Existing Pump Operation**

Operation was limited to a single unit from mid-January through April when one unit was off-line for annual maintenance. Thereafter, generation increased and remained near 60 percent of capacity throughout the summer months. During fall, electrical demand and, hence, generation drops although a brief period of elevated demand can occur during the winter months as a result of unusually low temperatures or supply disruptions. Under current operations the ΔT typically varied between 5 and 15°F (Figure 22-3). Not surprisingly, the pattern in ΔT is clearly related to the pattern in electrical output as modified by the number of cooling water pumps in operation.

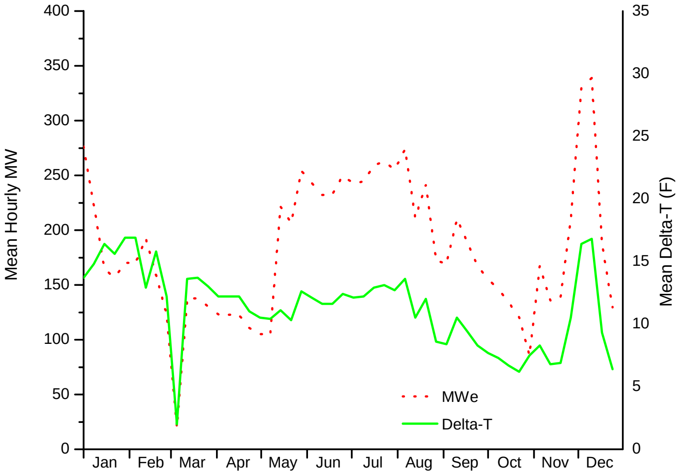

**Figure 22-2**
**Seasonal Pattern in Electrical Output and ΔT under Existing Pump Operation**

In addition to the typical seasonal pattern discussed above, this facility exhibits a strong diel pattern in electrical output. This pattern is illustrated by the hourly electrical output for a representative day in late June when entrainment should be near its peak (Figure 22-4). On this day, output is low in the overnight hours as a result of low demand. Electrical output increased during the morning and remained high into early evening as a result of increased demand, especially for air conditioning. Without variable-speed capabilities, cooling water flow remained constant across the entire 24-hour period, regardless of the electrical output. The pattern in electrical output and cooling water flow yielded ΔT's which varied from approximately 5°F overnight to more than 15°F from late morning into early evening (Figure 22-5).

## The Proposed Variable-Speed Pumping System

Since this facility operates at less than design capacity during the entrainment season, modification of the cooling water system to allow for variable-speed pumping was considered a viable option for substantially reducing entrainment from the full-flow baseline case. Modifications to allow variable-speed pumping would consist of adding adjustable speed drive (ASD) systems to the existing CWS pump motors or replacing the existing pump motors with new pump motors and adjustable speed drives. The reduction in CWS flow would also require, the addition of a vacuum priming system to maintain water level in the condenser waterboxes.

The configuration of the existing intake structure would remain essentially the same, with only those modifications necessary to install the variable speed drive systems. The existing circulating water pump motors are induction motors, which are compatible with the ASD. Therefore, to minimize capital costs, the existing CWS pump motors may be utilized with the ASD. This will require additional maintenance on the motors, such as rebuilding the motors every few years.

## Variable Speed Pumping Effects on Thermal Discharge

In order to estimate the maximum benefits potentially achievable with variable-speed pumping, the facility operators analyzed a scenario in which variable speed pumps would be operated to maintain the ΔT at permit limit of 30°F to the extent possible without having the discharge temperature exceed the permit limit of 110°F. Owing to the design of the existing condensers, this scenario would result in a substantial heat rate penalty and associated increases in fuel consumption, cost and air emissions.

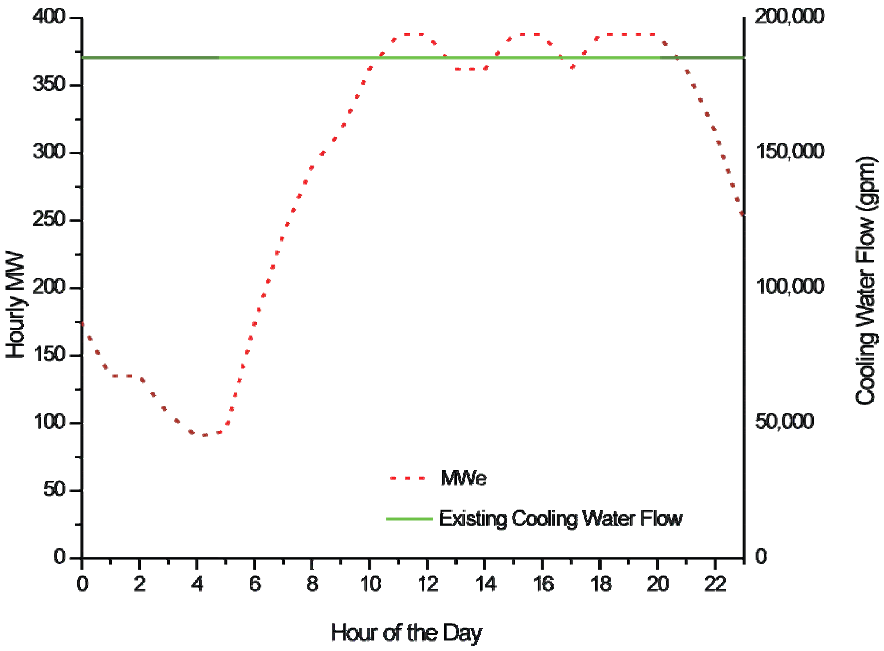

**Figure 22-3**
**Typical Diel Pattern in Electrical Output and Cooling Water Flow under Existing Pump Operation**

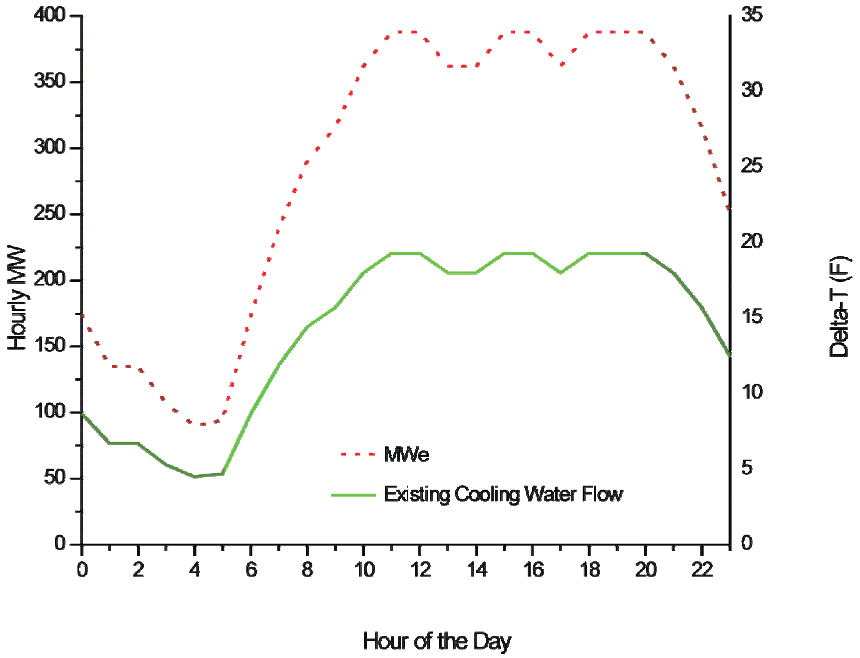

**Figure 22-4**
**Typical Diel in Electrical Output and ΔT under Existing Pump Operation**

The relationship among generating load, cooling water flow, intake temperature and discharge temperature is given by

$$(T_d - T_i) = \Delta T = \frac{\beta \times Load}{Flow},$$

where

$\beta$ = Constant combining the thermal efficiency of generation (BTU/MWe) with appropriate unit conversions and thermal constants.

Load = Electrical output (MWe)

Flow = Cooling water flow rate (gpm)

$T_d$ = Discharge temperature

$T_i$ = Intake temperature

$\Delta T$ = Temperature change across the condenser

This equation illustrates the linear relationship between generating load and $\Delta T$ and the inverse relationship of $\Delta T$ and flow.

To estimate flow under this operating scenario with variable-speed pumping, the equation above was rearranged as follows:

$$Flow = \frac{\beta \times Load}{\min(\Delta T_{\max}, T_{d\max} - T_{amb})}$$

where:

Flow = Cooling water flow rate (gpm)

B = Unit specific constant combining the thermal efficiency of generation (BTU/MWe) with appropriate unit conversions and thermal constants.

Load = Electrical output (MWe)

$\Delta T_{max}$ = Maximum permit temperature rise = 30°F

$T_{dmax}$ = Maximum permitted discharge temperature = 110°F

$T_{amb}$ = Ambient water temperature.

If the 30°F permit limit for ΔT caused the discharge temperatures to exceed 110°F, then the cooling water flow rate would be increased to insure discharge temperatures would remain at or below the 110°F permit limit.

Using the above equation, cooling water flow rates were projected to typically average only 50 to 60 percent of flow under current operations (Figure 22-6). Entrainment reductions also should be substantial and proportional to the reductions in cooling water flow achievable during the entrainment season. However, this decrease in cooling water flow yielded a substantial increase in the ΔT compared to current pump operation (Figure 22-7).

On a diel basis, substantial reductions in cooling water flow are evident, especially at night when reductions in cooling water flow approaching 60 percent appear possible (Figure 22-8). This is especially important as biological monitoring at this and many other facilities have demonstrated that most of the entrainment occurs during the night. Hence, reductions in flow at this time are especially important in reducing entrainment. However as observed in the seasonal patterns, this reduction in flow coincides with a substantial increase in ΔT compared to current pump operation, especially at night (Figure 22-8).

## Considerations for Potential Use of Variable-Speed Pumping

As clearly illustrated by this example, variable-speed pumping has the potential to substantially reduce cooling water flows at any facility operating at less than design electrical output. Such reductions in cooling water flow can result in concomitant reductions in entrainment when the flow reductions extend through all or part of the entrainment season. It is for this reason, that variable-speed pumping has received considerable interest by both facility operators and permit writers as an economically viable means of reducing entrainment compared to other flow reduction methods. At least one permitting authority (New York State Department of Environmental Conservation) has accepted variable-speed pumping at several New York facilities as part of a package which they conclude complies with §316(b).

However, it is important to remember that use of variable-speed pumping has the potential to alter the characteristics of the thermal discharge and resulting thermal plume. Thus, while clearly a potential part of a §316(b) solution, use of variable-speed pumping has the potential to become a §316(a) problem.

To minimize the potential for§316(a) problems, we recommend the following approach:

- Keep discharge permit limits for temperature in mind when designing variable-speed pumping. While discharge limits defined in terms of heat load (e.g., daily maximum BTUs) will not be affected, limits defined in terms of ΔT or maximum discharge temperature determine the minimum flow achievable. Operation at lower flows, if operationally feasible at a station, would require modified permit limits and therefore would trigger additional permit review.
- Similarly, evaluate the likely effects of variations in discharge flow and temperature elevation due to variable speed pump operation on the, characteristics of the thermal plume. Changes in the distribution of plume temperatures could affect compliance with mixing zones dimensions defined by the NPDES permit, with narrative mixing zone criteria required by state regulations, or with the numerical or narrative water quality criteria themselves. Hence, compliance involving mixing zones and water quality criteria should also receive careful consideration.

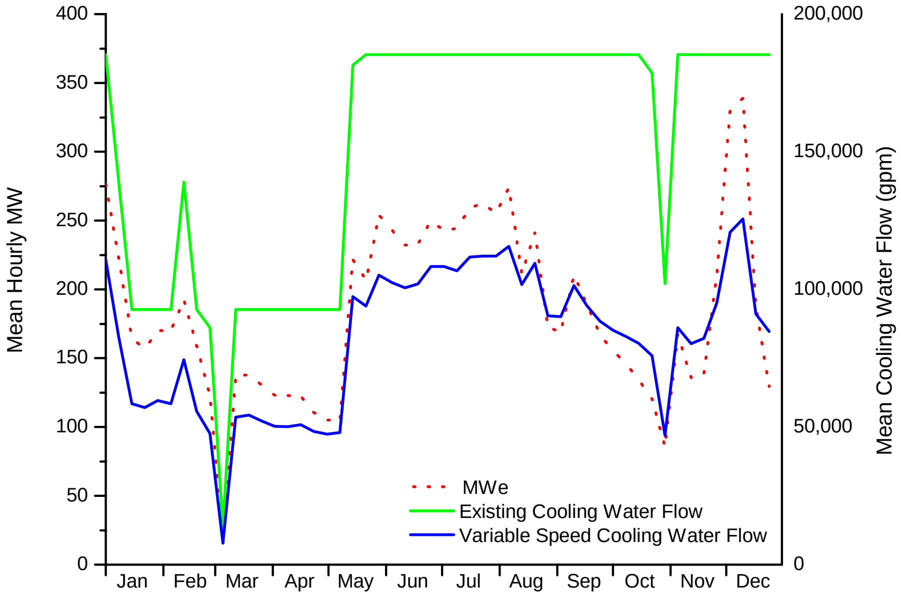

**Figure 22-5**
**Seasonal Patterns in Electrical Output and Cooling Water Flow Under Existing and Variable-Speed Pump Operation**

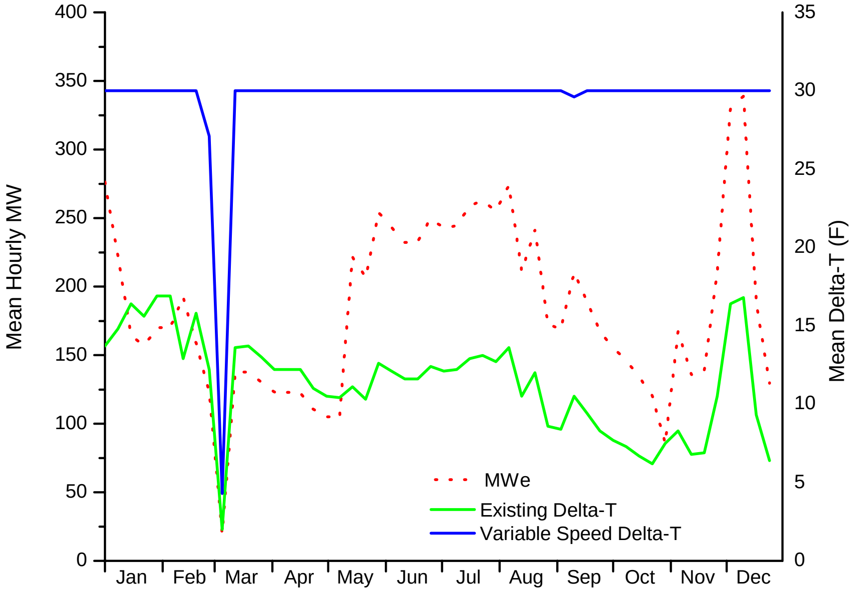

**Figure 22-6**
**Seasonal Patterns in Electrical Output and ΔT under Existing and Variable-Speed Pump Operation**

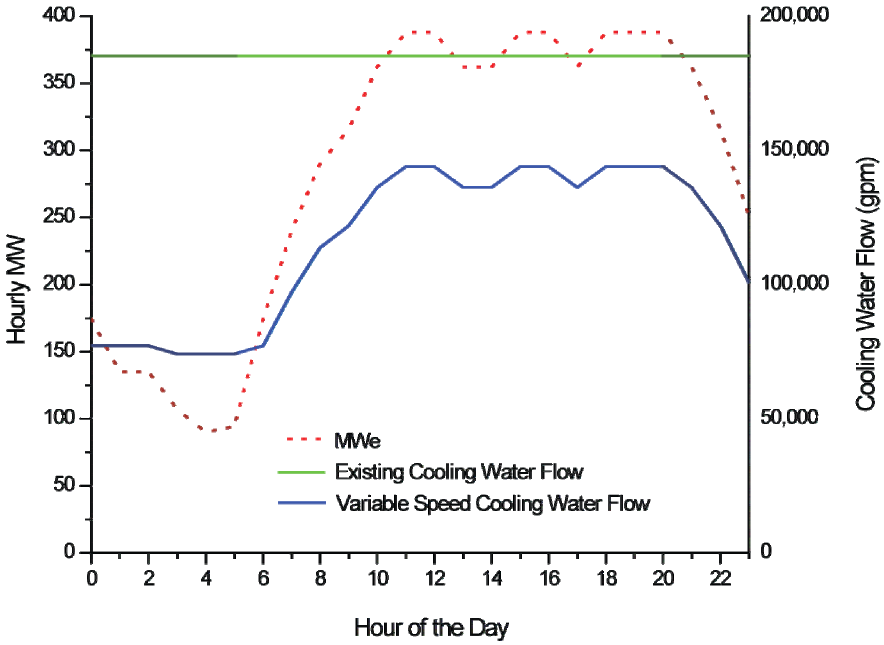

**Figure 22-7**
**Typical Diel Patterns in Electrical Output and Cooling Water Flow under Existing and Variable-Speed Pump Operation**

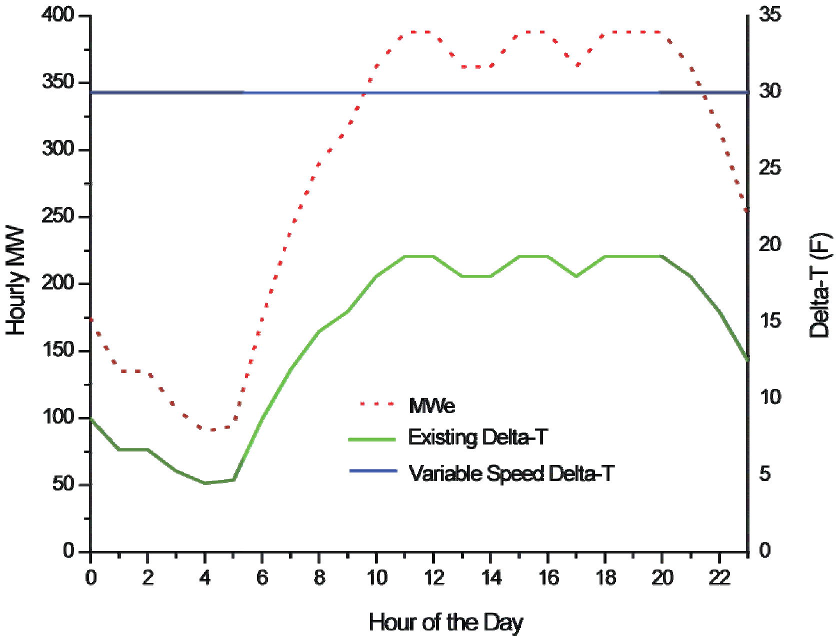

**Figure 22-8**
**Typical Diel Patterns in Electrical Output and ΔT under Existing and Variable-Speed Pump Operation**

- The potential for variable speed pump operations to affect compliance with the Clean Water Act's overall standard of protection and propagation of the balanced indigenous community must also be considered. If the facility was granted a 316(a) variance in the past, the technical basis upon which the variance was based should be carefully reviewed in light of potential changes in the thermal discharge and resulting plume associated with variable-speed pumping. For example, if the variance was based on a retrospective "no prior appreciable harm" evaluation, changes in the characteristics of the thermal discharge might trigger a need for a new thermal impact assessment. In addition, if the variance was based on an RIS predictive evaluation and the thermal discharge evaluated was based on historical rather than design basis, then a new thermal impact assessment might also be required.
- The need for a new impact assessment would be due to the fact that changes in the characteristics of the thermal plume have the potential to increase effects on biological communities for the following reasons. First, as evidenced by the seasonal pattern in elevated temperatures (Figure 22-6), at least some areas of the receiving waterbody will be exposed to higher temperatures for a much longer period of time, even though thermal exposures of other areas will be lessened. The increased exposures will be especially true for sessile organisms located close to the facilities discharge. In addition given the lower volumes of cooling water and associated momentum-based dilution, transient organisms could be exposed to higher temperatures for longer periods of time as a result of slower passage through the thermal plume. Second, it is likely that variable-speed pumping will result in higher discharge temperatures although these temperatures will be distributed over smaller areas of aquatic habitat. However, the temperature increase associated with variable-speed pumping could be sufficient induce thermal effects that would otherwise not exist. Finally, as evidenced by the changes in diel patterns of elevated temperatures (Figure 22-7), use of variable-speed pumping reduces or eliminates the lower temperatures which can occur at night. These lower temperatures at night allow organisms to recover from thermal exposures during the day and survive temperatures that would be detrimental without this daily time for recovery. Use of variable-speed pumping could result in limited or no recovery time for organisms closest to the point of discharge.
- Finally, we recommend that all permittees work closely with their permit writer if variable-speed pumping is being considered. While it is clear that such a pumping alternative can provide substantial benefits by reducing entrainment, the permit writer must understand the ramifications with regard to potential thermal effects. By considering these issues up front and preparing to address them, many concerns over potential issues can be allayed.

## References

1. *Fish Protection at Cooling Water Intakes: Status Report.* Palo Alto, Electric Power Research Institute (EPRI). 1999. EPRI TR-114013.

# 23

# THERMAL DISCHARGE EVALUATION AND REGULATORY APPROVAL–OAK CREEK EXPANSION PROJECT

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## Introduction

On February 1, 2002, subsidiaries of Wisconsin Energy Corporation (WEC) filed an application with the Public Service Commission of Wisconsin (PSCW) to add advanced technology coal-fueled electrical generating units at the Oak Creek Power Plant (OCPP) site (a.k.a., Elm Road Generating Station or Oak Creek Expansion project). On November 10, 2003, the PSCW approved two coal units to be added at the OCPP site. The Wisconsin Department of Natural Resources (WDNR) issued a Wisconsin Pollutant Discharge Elimination System (WPDES) permit on March 30, 2005 [1]. This WPDES permit, issued to Wisconsin Electric Power Company (the "Company" d/b/a We Energies), authorizes point source discharges associated with all six generating units at the OCPP site.

Condenser cooling water discharges, authorized by the permit, result in the release of heat to the receiving water body Lake Michigan. Heat limits were included in the WPDES permit after the WDNR reviewed power plant operating information, thermal discharge modeling results and environmental studies relevant to the OCPP site along Lake Michigan. Current environmental information and modeling were compared to the results of extensive studies done in the 1970s in Lake Michigan at the OCPP site and at other large power plants on the lake. Modeling work was used to demonstrate to the WDNR that the thermal plumes for the existing and future generating units at the OCPP site would be smaller than plumes measured during extensive environmental studies done during the 1970s when eight units were in operation.

Based on current and past information, the Company demonstrated that the species assemblage in Lake Michigan present in the 1970s is still present today, although the relative abundance of some species differs. It was also demonstrated that the heat discharge quantity and mixing zone size for the additional units would not differ substantially from the thermal plumes measured at Oak Creek in the 1970s. In conclusion, the scientific evidence presented to the WDNR supported their decision that the thermal discharges from the existing OCPP, the proposed expansion units and the combined discharges from all units, will assure the protection and propagation of a balanced, indigenous population of shellfish, fish and wildlife in and on Lake Michigan. This thermal variance decision was documented in the WPDES permit record assembled by the WDNR.

## Power Plant Background Information

The OCPP is located on the southwestern shore of Lake Michigan approximately 14 miles south of the City of Milwaukee, Wisconsin. The OCPP site location is shown on Figure 23-1. The existing facility utilizes a once-through condenser design to transfer heat from process steam to the lake cooling water. Cooling water is withdrawn from Lake Michigan from an onshore intake channel, travels through the steam condensers and is discharged to the Lake along the shoreline just south of the intake channel. OCPP originally consisted of eight coal-fueled units (Units 1-8) with a total generating capacity of 1670 MW. Units 1-4 comprised the North Plant, whereas Units 5-8 comprise the South Plant. All of the North Plant units have been retired; OCPP Units 1 and 2 (120 MW each) were retired on December 31, 1989 and OCPP Units 3 and 4 (each 130 MW) were retired earlier on April 1, 1988. The total condenser cooling water flow of the original OCPP facility was 1,232,000 gallons per minute (gpm) plus 38,000 gpm of service water, with a temperature rise across the steam condensers of about 12°F.

The four existing OCPP units ("existing units") generate about 1170 MW. Units 5 and 6 are each rated at 275 MW, Units 7 and 8 are each rated at 310 MW. Units 5-8 combined have an approximate condenser cooling water flow of 792,000 gpm (plus 25,000 gpm of service water). Each condenser has a design temperature rise of about 12°F above the ambient water temperature under maximum flow conditions. Actual discharge temperatures will vary depending on a variety of factors, including the unit load (% of full power) and the flow rate (during periods of cooler lake temperatures fewer pumps are in operation).

Two additional 615 MW units ("expansion units") are under construction about 1000 feet north of retired Units 1-4. The condensers have a design temperature rise of about 15°F above the intake water temperature at the maximum two unit flow rate of about 740,000 gpm. During winter conditions condenser cooling water flow will be reduced and the discharge temperature will rise to about 21°F above the intake water temperature.

## Intake & Discharge Structures

Both the four existing and two additional units at Oak Creek have on-shore discharge structures. The existing on-shore discharge structure locations for OCPP Units 5-8 are shown on Figure 23-2. Each of the four existing units has a separate condenser cooling water outfall. An on-shore discharge structure for both of the expansion units, shown on Figure 23-3, is under construction to the north of the existing coal dock.

Starting in 2008, water will be withdrawn from intake structure equipped with 24 wedge-wire screens located about 8000 feet off-shore at a depth of about 43 feet below low water datum. Water withdrawn from the off-shore intake will typically be about 5°F cooler than the water withdrawn from the existing on-shore intake. As shown on Figure 23-4, lake water will be conveyed through the wedge-wire screens and into manifold piping before dropping into one of the four 12-ft diameter vertical drop shafts leading to a 27-ft diameter tunnel. The tunnel is drilled through bedrock located below the bed of Lake Michigan. Finally, water from the tunnel is moved up through two vertical shafts leading to on-shore pump houses serving both the existing and expansion units. A photo of a wedge-wire screen being lowered into position for installation is included as Figure 23-5.

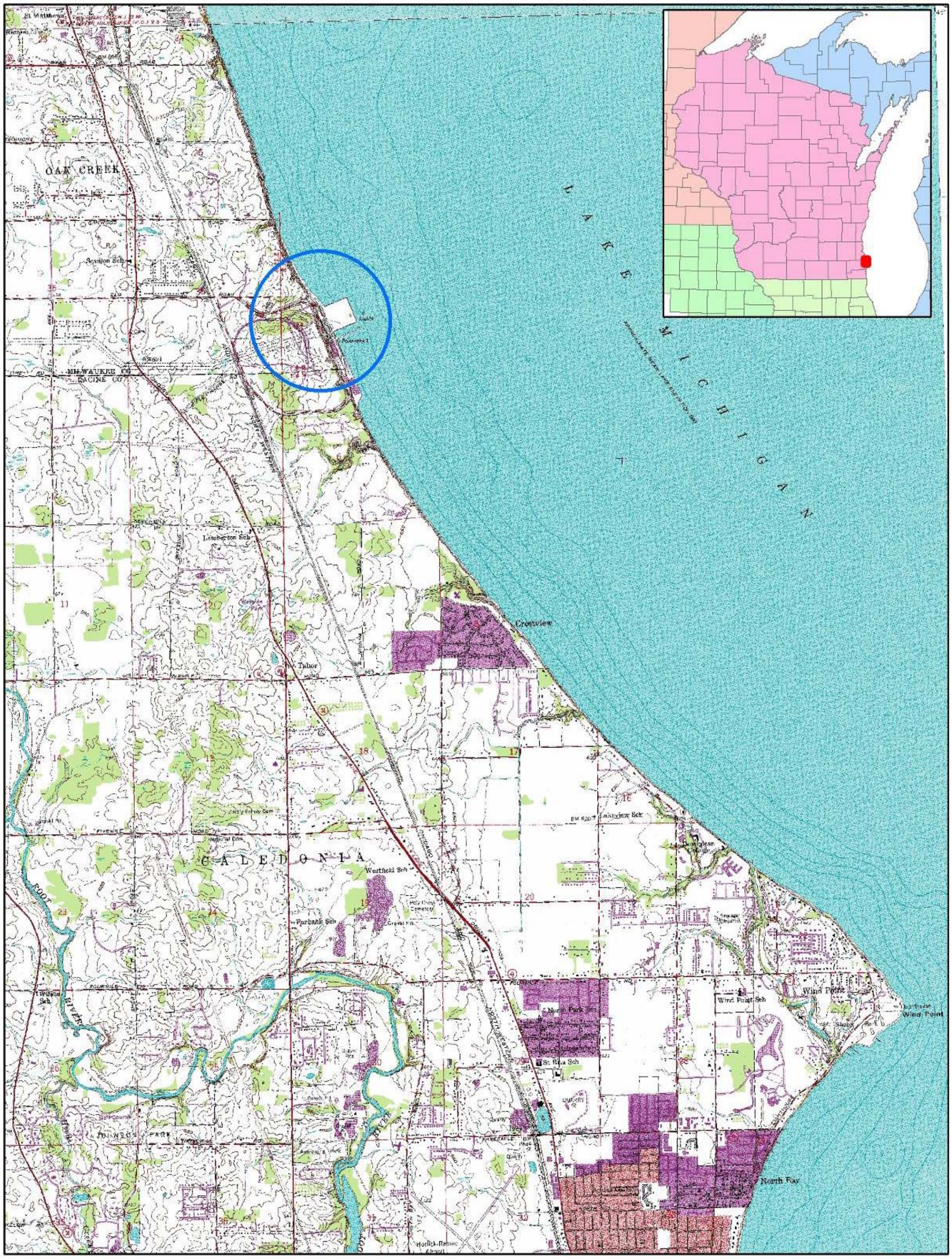
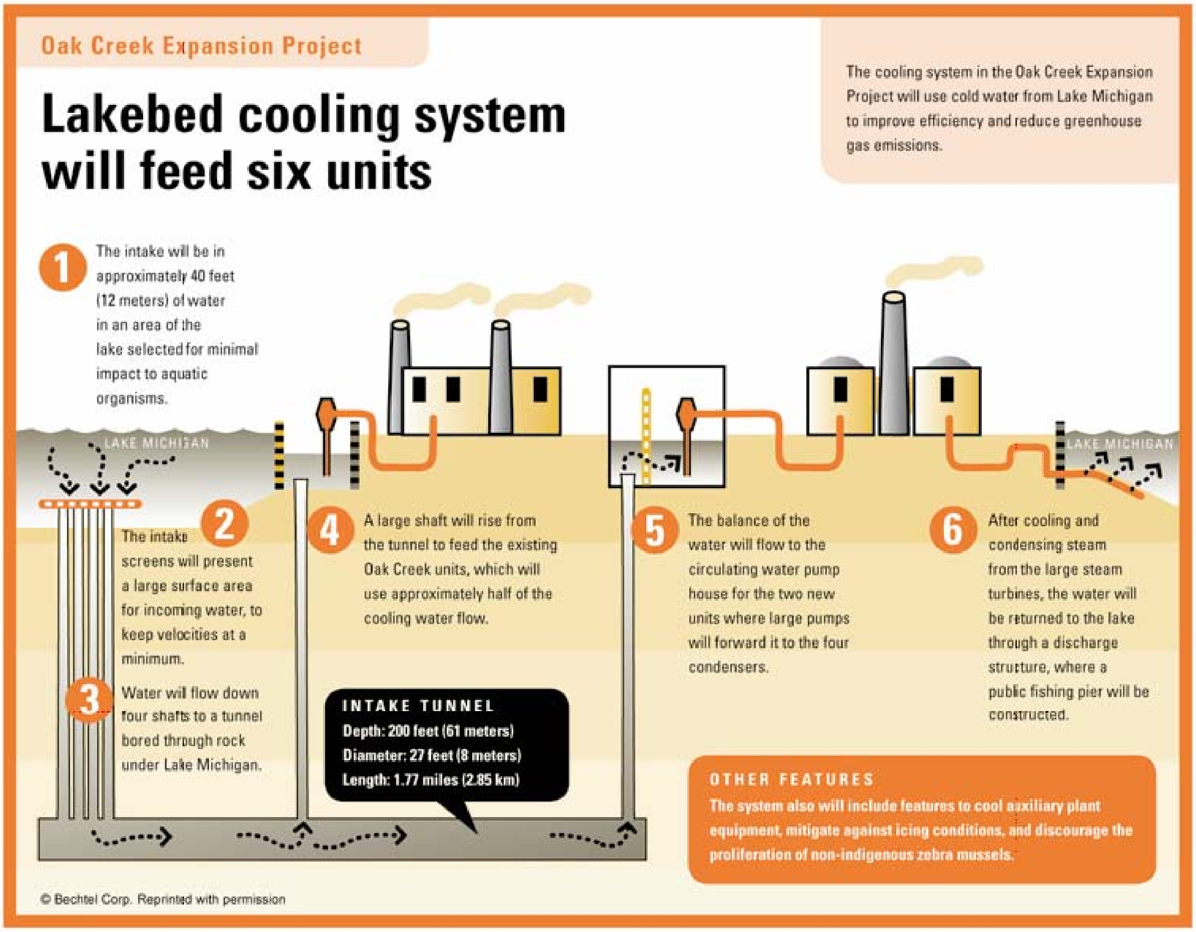


**Figure 23-1**
**Location Map - Oak Creek Power Plant Site South of Milwaukee, Wisconsin**

**Figure 23-2**
**Existing Oak Creek Power Plant – Shoreline Discharge Locations**

**Figure 23-3**
**OCPP Expansion Units Discharge Structure**



**Oak Creek Expansion Project**

**Lakebed cooling system will feed six units**

The cooling system in the Oak Creek Expansion Project will use cold water from Lake Michigan to improve efficiency and reduce greenhouse gas emissions.

1 The intake will be in approximately 40 feet (12 meters) of water in an area of the lake selected for minimal impact to aquatic organisms.

2 The intake screens will present a large surface area for incoming water, to keep velocities at a minimum.

3 Water will flow down four shafts to a tunnel bored through rock under Lake Michigan.

4 A large shaft will rise from the tunnel to feed the existing Oak Creek units, which will use approximately half of the cooling water flow.

5 The balance of the water will flow to the circulating water pump house for the two new units where large pumps will forward it to the four condensers.

6 After cooling and condensing steam from the large steam turbines, the water will be returned to the lake through a discharge structure, where a public fishing pier will be constructed.

**INTAKE TUNNEL**
**Depth: 200 feet (61 meters)**
**Diameter: 27 feet (8 meters)**
**Length: 1.77 miles (2.85 km)**

**OTHER FEATURES**
**The system also will include features to cool auxiliary plant equipment, mitigate against icing conditions, and discourage the proliferation of non-indigenous zebra mussels.**

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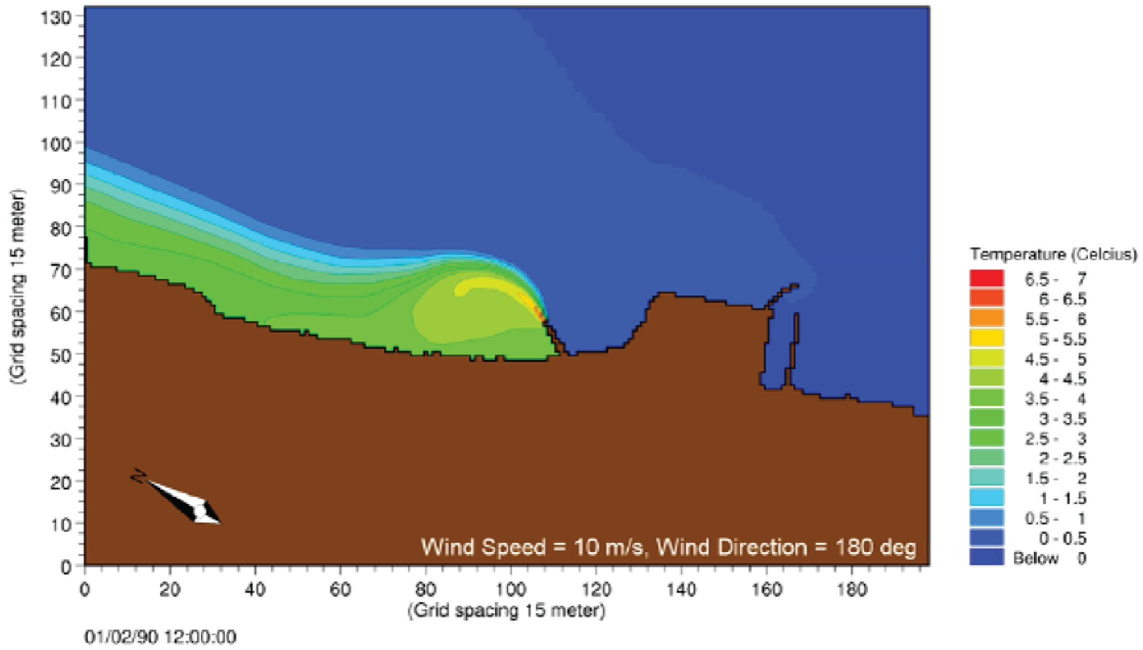
**Figure 23-4**
**Cooling Water Intake & Discharge Schematic**

**Figure 23-5**
**Wedge-Wire Screen Installation at Off-Shore Intake Location**

## Thermal Discharge Modeling

Thermal discharge modeling was done to predict the mixing zone characteristics for the expansion units and for all units combined under a variety of scenarios [2, 3, 4]. Modeling thermal plumes is dependent upon a number of factors, including: discharge flow rate, outfall configuration, condenser heat addition, near-shore water depths, ambient current patterns, wind speed/direction and the temperature of the receiving water body.

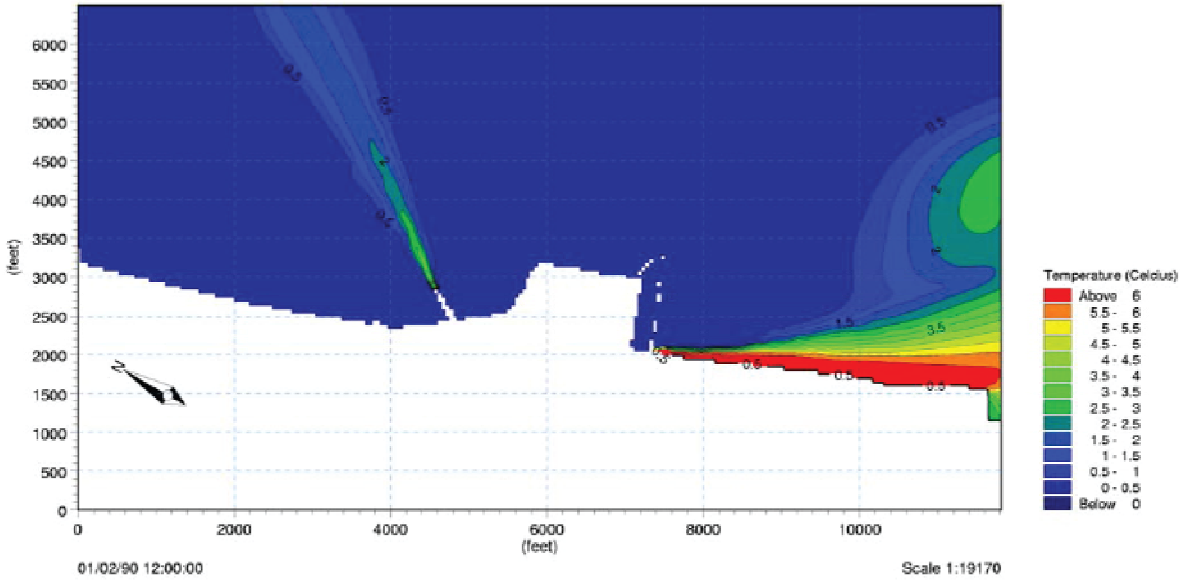
Initial discharge plume dispersion analysis was done using the Environmental Protection Agency supported CORMIX3 mixing zone model. CORMIX3 analyzes surface discharges that result when an effluent enters a larger water body laterally, through a canal, channel, or near-surface pipe. Following the CORMIX3 modeling, a more detailed numerical simulation of the thermal plume dispersion was done using a two dimensional hydrodynamic model developed by the Danish Hydraulic Institute called MIKE21. The thermal discharge plume modeling was simulated using the advection/dispersion module of the MIKE21 model. A series of MIKE21 simulations were performed to assess the effects of differing operating conditions and wind speed/directions. Following the modeling results, thermal plume mapping was done and the areas within each isotherm were calculated. Examples of the thermal plume mapping are included as Figure 23-6, Figure 23-7 and Figure 23-8 [2]. These figures depict the near-shore lake water temperatures above the ambient temperature assumed for a given modeling simulation.



Wind Speed = 10 m/s, Wind Direction = 180 deg

01/02/90 12:00:00

**Figure 23-6**
**Thermal Plume Mapping - Expansion Units, Wind from South at 22.4 mph (10 m/s)**



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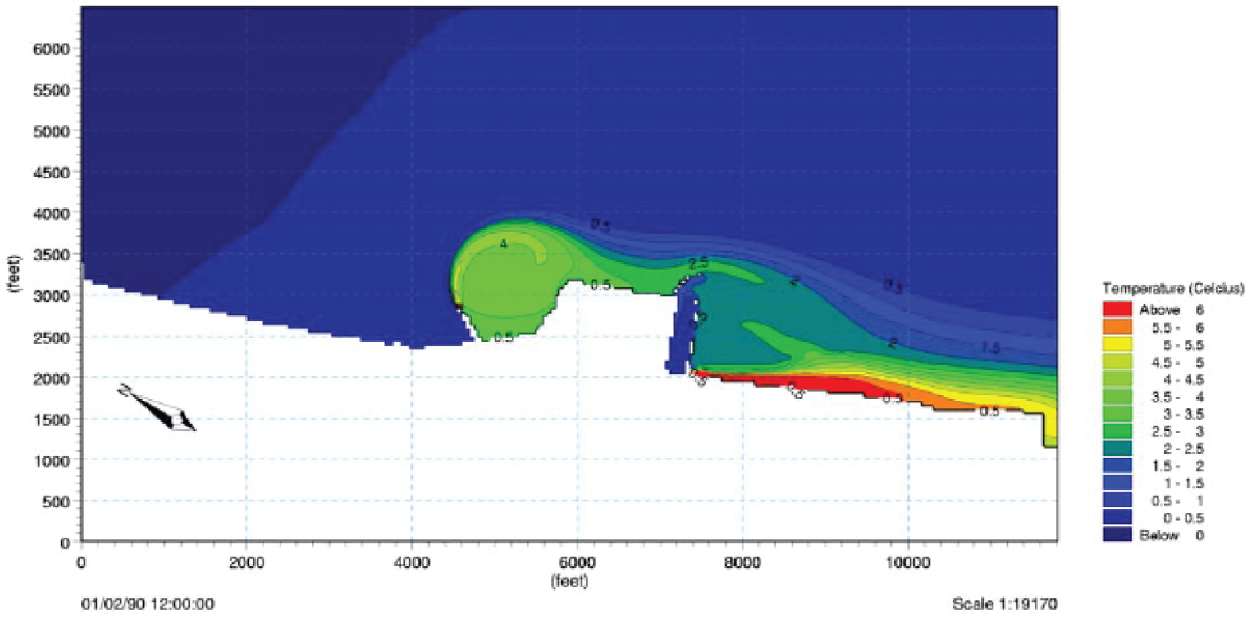
Scale 1:19170

Wind Direction = 0 degree, Wind Speed = 0 m/s, Water Level = +1.5 ft LWD

**Figure 23-7**
**Thermal Plume Mapping, Existing and Expansion Units - Calm Conditions**



Wind Direction = 0 degree, Wind Speed = 22.4 mph (10 m/s), Water Level = +1.5 ft LWD

**Figure 23-8**
**Thermal Plume Mapping, Existing and Expansion Units - North Wind at 22.4 mph (10 m/s)**

## Regulatory Background

Section 283.31 Wis. Stats. requires a WPDES permit for the discharge of a pollutant from a point source into waters of the state [5]. The term "pollutant" includes the addition of heat from a point source. Because the existing and expansion units at the OCPP site have point source discharges of heat to Lake Michigan, a WPDES permit is required.

In Wisconsin, the federal Clean Water Act §316(a) process is implemented through §283.17 Wis. Stats. and NR 209 Wis. Adm. Code [5, 6, 7]. The §283 state law and the NR 209 rule essentially align with the federal approach that most utilities are familiar with. Therefore, although not directly applicable in Wisconsin, it is most useful to look to the federal process and procedures that have been utilized in assessing thermal impacts under Section 316(a) of the Clean Water Act to evaluate the thermal discharge impacts at the OCPP site.

Under the CWA, as described below, any source of thermal discharge, existing or new, may seek a §316(a) variance from any limitation on heat that can be shown to be more stringent than necessary to assure the protection and propagation of a balanced, indigenous community (BIC) of aquatic life [6]:

*With respect to any point source otherwise subject to the provisions of section 301 of this title or section 306 of this title, whenever the owner or operator of any such source, after opportunity for public hearing, can demonstrate to the satisfaction of the Administrator (or, if appropriate, the State) that any effluent limitation proposed for the control of the thermal component of any discharge from such source will require effluent limitations more stringent than necessary to assure the projection and propagation of a balanced, indigenous population of shellfish, fish, and wildlife in and on the body of water into which the discharge is to be made, the Administrator (or, if appropriate, the State) may impose an effluent limitation under such* *sections for such plant, with respect to the thermal component of such discharge (taking into account the interaction of such thermal component with other pollutants), that will assure the protection and propagation of a balanced, indigenous population of shellfish, fish, and wildlife in and on that body of water.*

Starting in the early 1970s, utilities nationwide began the process of conducting very extensive environmental studies to attain §316(a) variances as allowed under the CWA. In general, these studies demonstrated that the limits based upon the state water quality standards were more stringent than necessary for the protection and propagation of a balanced indigenous community (BIC) of aquatic life. Studies done throughout the Great Lakes, and in particular those done for power plants on Lake Michigan, were no exception to that trend.

Guidance on how to conduct such "Demonstrations" was prepared by the U.S. Environmental Protection Agency (EPA) in a document entitled "Interagency 316(a) Technical Guidance Manual and Guide for Thermal Effects Sections of Nuclear Facilities Environmental Impact Statements" [8]. The §316(a) Guidance Manual describes a variety of approaches (i.e., Type I, II and III) that applicants may choose for completing §316(a) thermal discharge variance demonstrations.

## Evaluation of Thermal Discharge Effects

Based on the discharge modeling and past environmental studies, an evaluation the effects of thermal discharges at the Oak Creek site was completed [9]. This evaluation relied on the results of extensive thermal plume studies done in the 1970s when the OCPP was an 8-unit, 1670 MW facility. These studies provided the technical basis for Wisconsin Electric Power Company's §316(a)-type demonstration in 1975 and subsequent WDNR exemption from the state's thermal mixing zone standards [10, 11].

In 1972-73, a Type I study was conducted at the OCPP, which then was operating as an 8-unit, 1670 MW facility. The Type I study is used for facilities that have commenced discharge and allows one to demonstrate an absence of prior appreciable harm. The maximum heat discharge rate from all eight units during the 1972-73 Type I study period was 6,444 million British Thermal Units per hour (MBTU/hr). Based on thermal plume measurements conducted during this study, the largest plume measured was about 1.26 square miles (806 acres) and extended over 4.9 miles from the outfall [12].

The 1972-73 study also involved an investigation of all trophic levels of aquatic life, from phytoplankton through fish [12]. Using the Limnetics data, the Company prepared a thermal discharge variance demonstration. The demonstration concluded that the thermal discharge from the OCPP did not result in appreciable harm and that a BIC was present [10]. Therefore, the Company believed that a thermal variance should be granted. In 1976, WDNR reviewed the Type I Demonstration and concurred with the Company's conclusions that a BIC was present and that no appreciable harm had occurred [11].

In 2004, EA Engineering, Science and Technology reviewed the OCPP Type I Demonstration and the decision reached by the WDNR [9]. Results of the Type I study were reviewed in light of the results of recent in-lake biological sampling, plume modeling of the OCPP and ERGS discharges and a review of other Lake Michigan data [2, 3, 4, 13, 14]. Set forth below is a summary of our conclusions with respect to the continuation of the thermal variance for the OCPP units and the predicted thermal impact from the expansion units at the OCPP site.

With respect to the cooling water discharges from the existing OCPP units, the results and conclusions of the 1972-1973 Type I Demonstration continue to support the thermal variance for the current OCPP operations because [9]:

1. The maximum heat load for the currently operating OCPP Units 5-8 (4,924 MBTU/hr) will be about 24% lower than the maximum eight unit OCPP heat load (6,444 MBTU/hr) evaluated during the Type I Demonstration.
2. The predicted maximum area of the Units 5-8 thermal discharge plume will be smaller than the measured maximum area of the original eight-unit OCPP plume.
3. There have been no changes in the aquatic community which preclude reliance on the Type I Demonstration i.e. the aquatic community was and continues to be "balanced."
4. The conclusion with respect to OCPP is consistent with assessments undertaken at other power plants on Lake Michigan.

With respect to the predicted impacts from the expansion units, the addition of the proposed cooling water discharge will not endanger, either alone or in combination with the existing OCPP discharges, the protection and propagation of a balanced, indigenous population of shellfish, fish and wildlife in and on Lake Michigan. The bases for this conclusion include [9]:

1. The OCPP Type I demonstration established that the original and larger OCPP thermal plume did not cause "prior appreciable harm."
2. The thermal plume from the cooling water discharge outfall for the expansion units will be smaller than the plume from the 8-Unit, 1670 MW OCPP facility.
3. Thermal discharge plumes from the existing and expansion units at the OCPP site will typically not overlap and, even during infrequent occurrences of overlap, the balanced indigenous community will be protected.
4. There have been no changes in the aquatic community which would preclude reliance on the results of the OCPP Type I Demonstration
5. The changes to the Lake Michigan fish community that have occurred during the past 50 years have occurred on a lakewide basis.
6. The impact on representative important species will be negligible.
7. The conclusions reached in studies conducted at the OCPP site are consistent with assessments undertaken at other power plants on Lake Michigan.

## Regulatory Decision and Conclusions

On March 30, 2005, the WDNR issued the WPDES permit that authorizes discharges from the OCPP existing and expansion units. Details of the regulatory decision were documented in the WPDES permit Fact Sheet [15]. Additional information about the WDNR decision was provided in their Response to Comments document [16]. The WDNR explained in the fact sheet that the Company submittals provided the necessary evidence in support of its request for alternate thermal effluent limitation. The WDNR included thermal discharge effluent limitations for all of the cooling water outfalls expressed in units MBTU/hr. The existing cooling water outfalls for OCPP Units 5 and 6 are limited to a daily average heat addition of 1,500 MBTU/hr. Existing outfalls for Units 7 and 8 are limited to 1,700 MBTU/hr. The limit for the expansion units combined cooling water outfall was set at 6,200 MBTU/hr.

In reaching its permit decision, the WDNR stated that the scientific evidence presented to the Department supports the conclusion that the thermal discharges from the OCPP will "…assure the protection and propagation of a balanced, indigenous population of shellfish, fish and wildlife…" in and on Lake Michigan [16].

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2. Baird and Associates. 2003. *Thermal Discharge Analysis: Oak Creek Power Plant and Proposed Elm Road Generating Station.* Report by Baird and Associates to We Energies, Milwaukee, Wisconsin.
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16. Wisconsin Department of Natural Resources. 2005. *Response to Comments on Draft WPDES Permit and Water Loss Approval Application for the Wisconsin Electric Power Company OCER Power Plant.* Madison, Wisconsin.

# 24

# EFFECTS OF IMPINGMENT AT COLBERT FOSSIL PLANT ON THE FISH COMMUNITY IN PICKWICK RESERVOIR

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Tennessee Valley Authority, Knoxville, Tennessee

## Introduction

Colbert Fossil Plant (COF) is located on the south shore of Pickwick Reservoir at Tennessee River Kilometer (TRK) 394 (Tennessee River Mile [TRM] 245) (Figure 24-1). Four units began operation in 1955 and a fifth unit was added in 1963 increasing total generating capacity to 1,396 megawatts. COF is subject to compliance with the Alabama Department of Environmental Management and the Clean Water Act (CWA).

**Figure 24-1**
**Aerial Photograph of Colbert Fossil Plant Cooling Water Intake Depicting the Skimmer wall, Condenser Cooing Water Pumps, Intake Screens and Discharge Channel in Northwest Alabama**

Section 316(a) of the CWA allows point-source discharges of heated water to exceed State water quality thermal criteria if maintenance of balanced indigenous populations (BIP) of aquatic life can be demonstrated. COF is operating under a 316(a) thermal variance that has been administratively continued with each permit renewal based on studies conducted in the mid 1970s. The National Pollutant Discharge Elimination System permit for COF requires Tennessee Valley Authority (TVA) to provide "necessary technical data and relevant information to include supplemental data collected within the life of the permit" to support the request for continuation of the Section 316(a) variance. In response to this request, TVA initiated a study to evaluate fish and benthic macroinvertebrate communities in areas immediately upstream and downstream of COF between the years 2000 and 2006. This monitoring is a part of TVA's valley-wide Vital Signs (VS) monitoring program initiated in 1990 to evaluate ecological conditions in major reservoirs [1] [2]). At the core of this monitoring effort is a multi-metric approach to data evaluation. Five environmental indicators are used: dissolved oxygen, chlorophyll, sediment quality, benthic macroinvertebrate community, and the fish community.
In the beginning, specific evaluation techniques had to be developed for each indicator. The outcome of this effort was development of multi-metric evaluation techniques for the Reservoir Fish Assemblage Index (RFAI) and the benthic community, as described below [3]. These techniques have proven successful in TVA's monitoring efforts as well as other Federal and State monitoring programs and form the basis of evaluating these monitoring results.

In addition, Section 316(b) of the CWA requires facilities to demonstrate that the Condenser Cooling Water (CCW) withdrawal is having no significant impact on the aquatic community. Impingement mortality is a component of Section 316(b) and is defined as the condition in which fish and other aquatic organisms are trapped or impinged against the intake screens. TVA conducted impingement mortality monitoring at COF from March 2005 through March 2007 to assess the effects of impingement on the aquatic community of Pickwick Reservoir. This report presents impingement data collected from the CCW intake screens during 2005-2007 with comparisons to historical data collected during 1974-1976.

### Plant Description

The intake pumping structure at COF contains twelve separate suction pits, each with a trashrack, vertical traveling screen, and condenser circulating water pump. A 50-meter (164 ft) long excavated intake basin located at the edge of Pickwick Reservoir provides CCW at a rate of 54.6 cubic meters per second (1928 cfs). A skimmer was designed and constructed in 2002 for the purpose of excluding floating debris, reducing impingement and entrainment of fish and lowering intake water temperature to minimize derating to meet thermal compliance [4]. The skimmer wall is 82.1 meters long (89.8 yds) with an opening of 2.4 meters (8 ft) between the bottom of the wall and river channel. This enables COF to withdraw cooler water from the lower stratified layers of Pickwick Reservoir.

## Methods

### Vital Signs Sample Locations

To meet NPDES permit requirements, two sample locations, one upstream and one downstream of the plant discharge channel were selected in upper Pickwick Reservoir. The COF discharge enters the Tennessee River via Cane Creek at TRK 392.7 (TRM 244). For the fish community, the upstream sample site was centered at TRK 395.5 (TRM 247), and the downstream site was centered at TRK 389.5 (TRM 242). For the benthic macroinvertebrate community sampling, transects across the full width of the reservoir were established at TRK 395.9 (TRM 246) upstream and TRK 392.7 (TRM 244) immediately downstream of the confluence of Cane Creek and the Tennessee River. TVA's VS program has four sample sites on Pickwick Reservoir Forebay TRK 333.6 (TRM 207.3), Transition TRK 370.1 (TRM 230), Inflow TRK 416.8 (TRM 259), and Embayment Bear Creek RK 13.5 (TRM 8.4); two of which (inflow and transition are relatively close to COF (Figure 24-2). The VS inflow sample site near Wilson Dam is at TRK 416.8 (TRM 259) for the fish community and TRK 407.2 (TRM 253) for the benthic macroinvertebrate community. The VS transition zone site is at TRK 370.1 (TRM 230) for both communities.

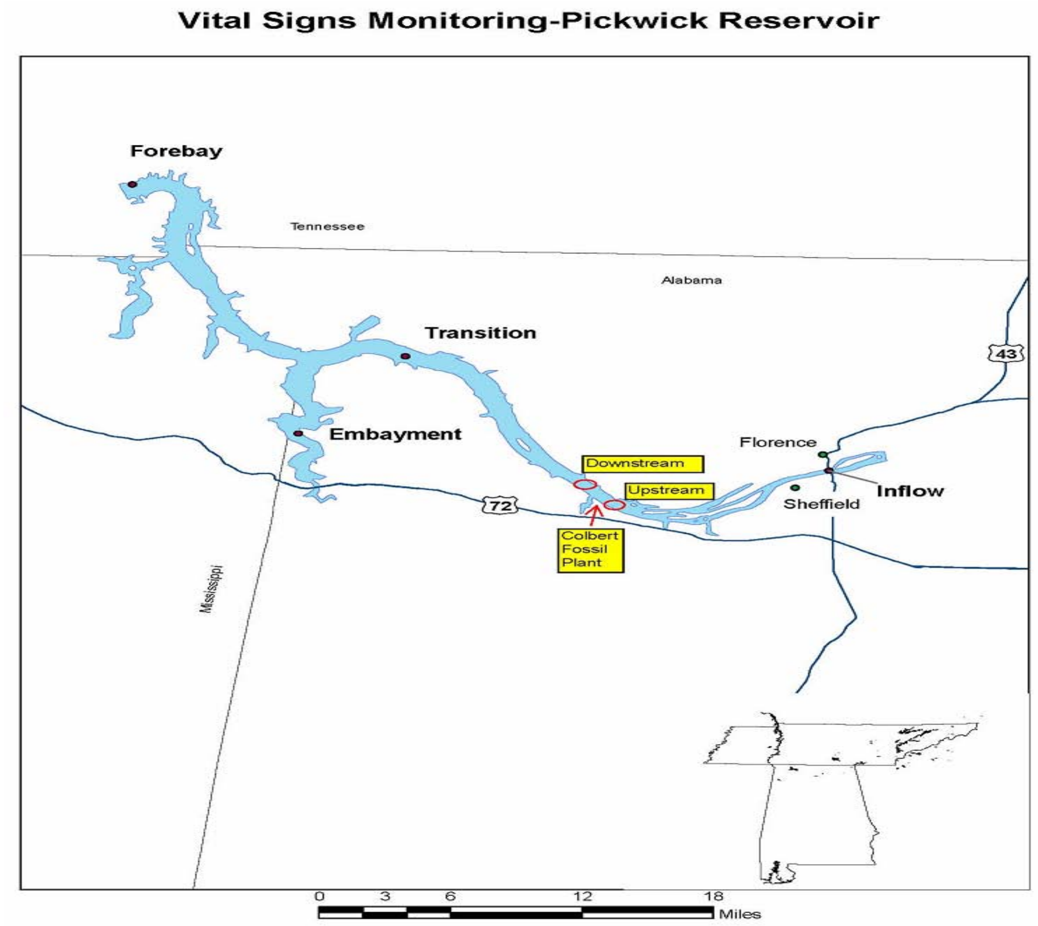

**Figure 24-2**
**Map of Vital Signs Monitoring Locations on Pickwick Reservoir**

## *Fish Community*

Fish sampling effort for upstream and downstream locations in upper Pickwick Reservoir consisted of fifteen 300-meter (328 yds) electrofishing runs (approximately 10 minutes duration each) and ten overnight experimental gill net sets (five 6.1 meter panels with mesh sizes of 2.5, 5.1, 7.6, 10.2, and 12.7 cm) per site. Recorded values for each of the 12 metrics were compared to reference conditions for transition zones of lower mainstream Tennessee River reservoirs. Assigned scores are based upon three categories hypothesized to represent relative degrees of degradation: least degraded -5; intermediate -3; and most degraded -1. These categories are based on "expected" fish community characteristics in the absence of human-induced impacts other than impoundment. Individual metric scores for a site are summed to obtain the RFAI score. Comparison of the attained RFAI score from the potential impact zone to a predetermined criterion has been suggested as a method useful in identifying presence of normal community structure and function and hence existence of BIP. For multi-metric indices, two criteria have been suggested to ensure a conservative screening of BIP. First, if an RFAI score reached 70% of the highest attainable score (adjusted upward to include sample variability), and second, if fewer than half of RFAI metrics potentially influenced by thermal discharge receive a low (1) or moderate (3) score, then normal community structure and function would be present indicating that BIP existed and hence, the heated discharge would meet screening criteria and no further evaluation would be needed. The range of RFAI scores possible is from 12 to 60. As discussed in detail below, the average variance for RFAI scores in TVA reservoirs is 6 (± 3). Therefore, any location that attains an RFAI score of 45 (42 + our upward sample variance of 3) or higher would be considered to have BIP. It must be stressed that scores below this endpoint do not necessarily reflect an adversely impacted fish community. The endpoint is used to serve as a conservative screening level, i.e., any fish community that meets these criteria is obviously not adversely impacted. RFAI scores below this level would require a more in-depth look to determine if BIP exist. An inspection of individual RFAI metric results would be an initial step to help identify if COF operation is a contributing factor. This approach is appropriate if a validated multi-metric index is being used and scoring criteria applicable to the zone of study are available.

Comparison of upstream/downstream stations can be used to identify if COF operation is adversely impacting the downstream fish community. A similar or higher RFAI score at the downstream site compared to the upstream (control) site is used as one basis for determining absence of COF operational impacts on the resident fish community. Definition of "similar" is integral to accepting the validity of these interpretations. The Quality Assurance (QA) component of VS monitoring deals with how well the RFAI scores can be repeated and is accomplished by collecting a second set of samples at 15%-20% of the sites sampled throughout the Tennessee Valley each year. Experience to date with the QA component of VS shows that comparison of RFAI index scores from 54 paired sample sets collected over the past seven years range from 0 to 18 points, the 75th percentile is 6, the 90th percentile is 12. The mean difference between these 54 paired scores is 4.6 points with 95% confidence limits of 3.4 and 5.8. Based on these results, a difference of 6 points or less is the value selected for defining "similar" scores between upstream and downstream fish communities. That is, if the downstream RFAI score is within 6 points of the upstream score, the communities will be considered similar and it will be concluded that COF has had no effect. It is important to bear in mind that differences greater than 6 points can be expected simply due to method variation (25% of the QA paired sample sets exceeded that value). When such occurs, a metric-by-metric examination will be conducted to determine what caused the difference in scores and the potential for the difference to be thermally related.

### *Benthic Macroinvertebrate Community*

Ten benthic grab samples were collected at equally spaced points along the upstream and downstream transects. A Ponar sampler was used for most samples but a Peterson sampler was used when heavier substrate was encountered. Collection and processing techniques followed standard VS procedures. Bottom sediments were washed on a 533μ screen; organisms were then picked from the screen and remaining substrate and identified in the field to Order or Family level without magnification. Benthic community results were evaluated using seven community characteristics or metrics. Results for each metric were assigned a rating of 1, 3, or 5 depending upon how they scored based on reference conditions developed for VS reservoir inflow sample sites. The ratings for the seven metrics were summed to produce a benthic score for each sample site. Potential scores ranged from 7 to 35.

A similar or higher benthic index score at the downstream site compared to the upstream site is used as basis for determining absence of impact of COF on the benthic community. The QA component of VS monitoring shows that benthic index scores from 49 paired sample sets collected over the past seven years throughout the Tennessee Valley range from 0 to 14 points; the 75th percentile is 4, the 90th percentile is 6. The mean difference between these 49 paired scores is 3.1 points with 95% confidence limits of 2.2 and 4.1. Based on these results, a difference of 4 points or less is the value selected for defining “similar” scores between upstream and downstream benthic communities. That is, if the downstream benthic score is within 4 points of the upstream score, the communities will be considered similar and it will be concluded that COF has had no effect. Once again, it is important to bear in mind that differences greater than 4 points can be expected simply due to method variation (25% of the QA paired sample sets exceeded that value). When such occurs, a metric-by-metric examination will be conducted to determine what caused the difference in scores and the potential for the difference to be thermally related.

### *Impingement Monitoring*

Weekly impingement monitoring at COF began on March 31, 2005, and continued through March 22, 2007. To simplify comparisons in this report, data from March 31, 2005 through March 23, 2006, will be referred to as Year-One, and from March 30, 2006 through March 22, 2007, as Year-Two. To collect each sample, intake screens were rotated and washed on a prearranged schedule by the plant assistant unit operator to remove all fish and debris. After 24 hours, screens were again rotated and washed with an Aquatic Monitoring and Management crew on site. Fish and debris were collected in a catch basket constructed of 9.5 mm (3/8 in) mesh at the end of the CCW discharge sluice pipe where the monitoring crew removed and processed the sample. Fish were sorted from debris, identified, separated into 25 mm (1 in) length classes, enumerated, and weighed. Data were recorded by one member of the crew and checked and verified (signed) by the other for Quality Control (QC). QA/QC procedures for impingement sampling were followed to ensure samples were comparable with historical impingement mortality data [5]. Historical impingement sampling was conducted by TVA from August 6, 1974 through March 25, 1976 [6].

### *Moribund/Dead Fish*

The majority of fish collected from a 24-hr screen wash were dead when processed. Fish which appeared to have been dead for more than 24 hours (i.e., exhibiting pale gills, cloudy eyes, fungus or partially decomposed) were not included in the sample. During winter, threadfin shad occasionally suffer die-offs and are impinged after death or in a moribund state [7, 8]. If these incidents were observed, they were documented to specify that either all, or a portion of impinged threadfin shad during the sample period were due to cold-shock and would not have been impinged otherwise. Any fish collected alive were returned to the reservoir after processing.

### *Data Analysis*

Estimates of weekly samples were extrapolated to provide estimates of total fish impinged by week and during each year of the study. In rare situations when less than a 24-hour sample occurred, data were normalized to 24-hours.

To facilitate the implementation of and compliance with the Environmental Protection Agency's (EPA) regulations for Section 316(b) of the Clean Water Act (Federal Register Vol. 69, No. 131; July 9, 2004), impingement losses of fish will be evaluated by extrapolating the losses to equivalent reductions of adult fish, or of biomass production available to predators. EPRI (Electric Power Research Institute) has identified two models for extrapolating losses of fish eggs, larvae and juveniles at intake structures to numbers or production of older fish [9]. The Equivalent Adult (EA) model quantifies entrainment and impingement losses in terms of the number of fish that would have survived to a given future age. The Production Foregone (PF) model applies to forage fish species to quantify the loss from entrainment and impingement in terms of potential available forage for consumption by predators. Requirements of the models are site-specific data on the distribution and abundance of fish populations vulnerable to entrainment and impingement TVA used these models to determine the "biological liability" of the COF CCW intake structure based on the EPA guidance developed under the suspended rule.

## Results and Conclusions

### *Fish Community*

Table 24-1 through Table 24-3 provide COF's individual metric scores and overall RFAI scores for upstream and downstream stations during 2000-2002, respectively. Figure 23-3 presents RFAI scores for all sites sampled in Pickwick Reservoir. Table 24-4 and Table 24-5 present 2005 and 2006 individual metric scores and overall RFAI results. Electrofishing and gill net samples from the initial three-year sampling period yielded RFAI scores ranging from 42 to 46 at the downstream station and from 42 to 47 at the upstream station. All RFAI observations rated in the good category. Average scores were 44.0 and 44.4 for the downstream and upstream stations, respectively. Comparable results were found in 2005, although the upstream site had the highest score to date, 49 (Table 24-4). The downstream score of 42, while still in the good category, was one of the lowest observed during the years surveyed.

**Table 24-1**
**Individual Metric Scores and the Overall Reservoir Fish Assemblage Index (RFAI) Score* for sites Upstream and Downstream of Colbert Fossil Plant in the Pickwick Reservoir during Fall, 2000**

| | | Downstream | | Upstream | |
|---|---|---|---|---|---|
| | | TRM 242 | | TRM 247 | |
| **Metric** | **Sample Gear** | **Obs** | **Score** | **Obs** | **Score** |
| A. Species richness and composition | | | | | |
| 1. Number of species | | 29 | 3 | 32 | 5 |
| 2. Number of centrarchid species | | 3 | 5 | 5 | 5 |
| 3. Number of benthic invertivores | | 8 | 5 | 6 | 3 |
| 4. Number of intolerant species | | 8 | 5 | 6 | 5 |
| 5. Percent tolerant individuals | Electrofishing | 54.7 | 0.5 | 65.4 | 0.5 |
| | Gill Netting | 10.8 | 2.5 | 13.4 | 2.5 |
| 6. Percent dominance by 1 species | Electrofishing | 45.3 | 1.5 | 40.9 | 1.5 |
| | Gill Netting | 21.1 | 1.5 | 21.2 | 1.5 |
| 7. Percent non-native species | Electrofishing | 2 | 1.5 | 0.0 | 2.5 |
| | Gill Netting | 10.3 | 0.5 | 7.8 | 0.5 |
| 8. Number of top carnivore species | | 10 | 5 | 12 | 5 |
| B. Trophic composition | | | | | |
| 9. Percent top carnivores | Electrofishing | 15.5 | 2.5 | 9.1 | 1.5 |
| | Gill Netting | 76.8 | 2.5 | 49.2 | 2.5 |
| 10. Percent omnivores | Electrofishing | 50.7 | 0.5 | 20.3 | 2.5 |
| | Gill Netting | 8.6 | 2.5 | 26.8 | 1.5 |
| C. Fish abundance and health | | | | | |
| 11. Average number per run | Electrofishing | 9.9 | 0.5 | 32.8 | 0.5 |
| | Gill Netting | 18.5 | 1.5 | 17.9 | 1.5 |
| 12. Percent anomalies | Electrofishing | 0.7 | 2.5 | 1.0 | 2.5 |
| | Gill Netting | 0.0 | 2.5 | 0.0 | 2.5 |
| RFAI Score | | | 46 | | 47 |
| | | | Good | | Good |

Scored with transition criteria
*Scores are based on updated criteria

**Table 24-2**
**Individual Metric Scores and the Overall Reservoir Fish Assemblage Index (RFAI) Score* for sites Upstream and Downstream of Colbert Fossil Plant in the Pickwick Reservoir during Fall, 2001**

| | | Downstream | | Upstream | |
|---|---|---|---|---|---|
| | | TRM 242 | | TRM 247 | |
| **Metric** | **Sample Gear** | **Obs** | **Score** | **Obs** | **Score** |
| A. Species richness and composition | | | | | |
| 1. Number of species | | 27 | 3 | 29 | 3 |
| 2. Number of centrarchid species | | 3 | 5 | 5 | 5 |
| 3. Number of benthic invertivores | | 6 | 3 | 6 | 3 |
| 4. Number of intolerant species | | 4 | 3 | 7 | 5 |
| 5. Percent tolerant individuals | Electrofishing | 43.5 | 1.5 | 52.5 | 1.5 |
| | Gill Netting | 10 | 2.5 | 13.2 | 2.5 |
| 6. Percent dominance by 1 species | Electrofishing | 30.5 | 1.5 | 24.7 | 2.5 |
| | Gill Netting | 24 | 1.5 | 18.4 | 1.5 |
| 7. Percent non-native species | Electrofishing | 0.4 | 2.5 | 0.7 | 2.5 |
| | Gill Netting | 2 | 1.5 | 5.3 | 0.5 |
| 8. Number of top carnivore species | | 9 | 5 | 11 | 5 |
| B. Trophic composition | | | | | |
| 9. Percent top carnivores | Electrofishing | 17.9 | 2.5 | 10.8 | 2.5 |
| | Gill Netting | 68 | 2.5 | 47.4 | 2.5 |
| 10. Percent omnivores | Electrofishing | 42.2 | 1.5 | 28.8 | 1.5 |
| | Gill Netting | 18 | 1.5 | 21.1 | 1.5 |
| C. Fish abundance and health | | | | | |
| 11. Average number per run | Electrofishing | 14.9 | 0.5 | 28.9 | 0.5 |
| | Gill Netting | 7.1 | 0.5 | 3.8 | 0.5 |
| 12. Percent anomalies | Electrofishing | 2.2 | 1.5 | 2.3 | 1.5 |
| | Gill Netting | 2 | 1.5 | 2.6 | 1.5 |
| RFAI Score | | | 42 | | 44 |
| | | | Good | | Good |

Scored with transition criteria
*Scores are based on updated criteria

**Table 24-3**
**Individual Metric Scores and the Overall Reservoir Fish Assemblage Index (RFAI) Score* for sites Upstream and Downstream of Colbert Fossil Plant in the Pickwick Reservoir during Fall, 2002**

| | | **Downstream** | | **Upstream** | |
|---|---|---|---|---|---|
| | | **TRM 242** | | **TRM 247** | |
| **Metric** | **Sample Gear** | **Obs** | **Score** | **Obs** | **Score** |
| A. Species richness and composition | | | | | |
| 1. Number of species | | 27 | 3 | 27 | 3 |
| 2. Number of centrarchid species | | 5 | 5 | 5 | 5 |
| 3. Number of benthic invertivores | | 6 | 3 | 6 | 3 |
| 4. Number of intolerant species | | 6 | 5 | 6 | 3 |
| 5. Percent tolerant individuals | Electrofishing | 57.8 | 0.5 | 58.8 | 0.5 |
| | Gill Netting | 9.9 | 2.5 | 5.8 | 2.5 |
| 6. Percent dominance by 1 species | Electrofishing | 37 | 1.5 | 37.7 | 1.5 |
| | Gill Netting | 27.5 | 1.5 | 21.7 | 1.5 |
| 7. Percent non-native species | Electrofishing | 1.3 | 1.5 | 0 | 2.5 |
| | Gill Netting | 2.2 | 0.5 | 4.3 | 0.5 |
| 8. Number of top carnivore species | | 10 | 5 | 9 | 5 |
| B. Trophic composition | | | | | |
| 9. Percent top carnivores | Electrofishing | 16.9 | 2.5 | 10.8 | 2.5 |
| | Gill Netting | 80.2 | 2.5 | 44.9 | 2.5 |
| 10. Percent omnivores | Electrofishing | 40.3 | 1.5 | 40.7 | 1.5 |
| | Gill Netting | 15.4 | 2.5 | 20.3 | 1.5 |
| C. Fish abundance and health | | | | | |
| 11. Average number per run | Electrofishing | 11 | 0.5 | 28.5 | 0.5 |
| | Gill Netting | 9.1 | 0.5 | 6.9 | 0.5 |
| 12. Percent anomalies | Electrofishing | 0 | 2.5 | 0 | 2.5 |
| | Gill Netting | 0 | 2.5 | 0 | 2.5 |
| RFAI Score | | | 44 | | 42 |
| | | | Good | | Good |

Scored with transition criteria
*Scores are based on updated criteria

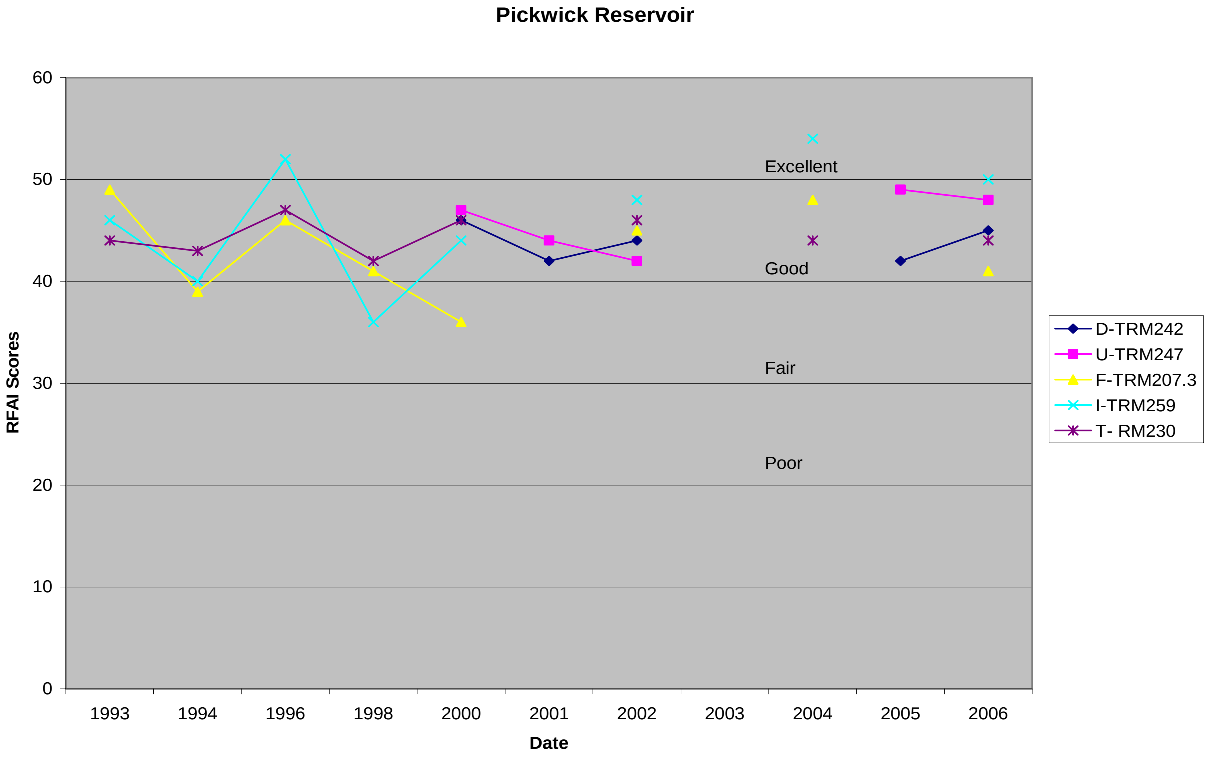

**Figure 24-3**
**Annual Pickwick Reservoir RFAI Scores for Sample years between 1993 and 2006**

**Table 24-4**
**Individual Metric Scores and the Overall Reservoir Fish Assemblage Index (RFAI) Score* for sites Upstream and Downstream of Colbert Fossil Plant in the Pickwick Reservoir during Fall, 2005**

| | | Downstream | | Upstream | |
|---|---|---|---|---|---|
| | | TRM 242 | | TRM 247 | |
| **Metric** | **Sample Gear** | **Obs** | **Score** | **Obs** | **Score** |
| A. Species richness and composition | | | | | |
| 1. Number of species | | 27 | 3 | 36 | 5 |
| 2. Number of centrarchid species | | 5 | 5 | 7 | 5 |
| 3. Number of benthic invertivores | | 6 | 3 | 8 | 5 |
| 4. Number of intolerant species | | 6 | 5 | 7 | 5 |
| 5. Percent tolerant individuals | Electrofishing | 68.7 | 0.5 | 48.2 | 1.5 |
| | Gill Netting | 5.9 | 2.5 | 9.8 | 2.5 |
| 6. Percent dominance by 1 species | Electrofishing | 47.2 | 1.5 | 22.6 | 2.5 |
| | Gill Netting | 29.4 | 1.5 | 24.6 | 1.5 |
| 7. Percent non-native species | Electrofishing | 0.5 | 2.5 | 0.1 | 2.5 |
| | Gill Netting | 0 | 2.5 | 1.6 | 1.5 |
| 8. Number of top carnivore species | | 6 | 3 | 10 | 5 |
| B. Trophic composition | | | | | |
| 9. Percent top carnivores | Electrofishing | 5.7 | 1.5 | 5.5 | 1.5 |
| | Gill Netting | 41.2 | 2.5 | 29.5 | 1.5 |
| 10. Percent omnivores | Electrofishing | 54.4 | 0.5 | 23.0 | 2.5 |
| | Gill Netting | 29.4 | 1.5 | 19.7 | 1.5 |
| C. Fish abundance and health | | | | | |
| 11. Average number per run | Electrofishing | 29.4 | 0.5 | 52.9 | 0.5 |
| | Gill Netting | 2.8 | 0.5 | 6.1 | 0.5 |
| 12. Percent anomalies | Electrofishing | 1.1 | 2.5 | 2.5 | 1.5 |
| | Gill Netting | 0 | 2.5 | 0 | 2.5 |
| RFAI | | | 42 | | 49 |
| | | | Good | | Good |

Scored with transition criteria
*Scores are based on updated criteria

**Table 24-5**
**Individual Metric Scores and the Overall Reservoir Fish Assemblage Index (RFAI) Score* for sites Upstream and Downstream of Colbert Fossil Plant in the Pickwick Reservoir during Fall, 2006**

| | | Downstream | | Upstream | |
|---|---|---|---|---|---|
| | | TRM 242 | | TRM 247 | |
| **Metric** | **Sample Gear** | **Obs** | **Score** | **Obs** | **Score** |
| A. Species richness and composition | | | | | |
| 1. Number of species | | 27 | 3 | 33 | 5 |
| 2. Number of centrarchid species | | 4 | 5 | 4 | 5 |
| 3. Number of benthic invertivores | | 6 | 3 | 8 | 5 |
| 4. Number of intolerant species | | 6 | 5 | 7 | 5 |
| 5. Percent tolerant individuals | Electrofishing | 11.4 | 2.5 | 61 | 0.5 |
| | Gill Netting | 2.5 | 2.5 | 6.3 | 2.5 |
| 6. Percent dominance by 1 species | Electrofishing | 79.6 | 0.5 | 35.4 | 1.5 |
| | Gill Netting | 31.6 | 1.5 | 17.5 | 1.5 |
| 7. Percent non-native species | Electrofishing | 0.1 | 2.5 | 0 | 2.5 |
| | Gill Netting | 2.5 | 0.5 | 3.8 | 0.5 |
| 8. Number of top carnivore species | | 8 | 5 | 11 | 5 |
| B. Trophic composition | | | | | |
| 9. Percent top carnivores | Electrofishing | 5.4 | 1.5 | 9.5 | 1.5 |
| | Gill Netting | 62 | 2.5 | 51.3 | 2.5 |
| 10. Percent omnivores | Electrofishing | 4.8 | 2.5 | 36.2 | 1.5 |
| | Gill Netting | 27.8 | 1.5 | 11.3 | 2.5 |
| C. Fish abundance and health | | | | | |
| 11. Average number per run | Electrofishing | 95.2 | 0.5 | 52.6 | 0.5 |
| | Gill Netting | 7.9 | 0.5 | 8 | 0.5 |
| 12. Percent anomalies | Electrofishing | 0.3 | 2.5 | 0.8 | 2.5 |
| | Gill Netting | 1.3 | 2.5 | 0 | 2.5 |
| RFAI | | | 45 | | 48 |
| | | | Good | | Good |

Scored with transition criteria
*Scores are based on updated criteria

Because the RFAI score difference between the upstream and downstream sites was greater than 6 points in 2005, the two sites are not considered similar and additional discussion is necessary. The overriding factor causing the higher upstream score in 2005 was the greater diversity of native species (36) present that year, which resulted in higher species richness scores than at the downstream site (Table 24-4). Metrics for the number of (native) species, number of benthic invertivores, and number of top carnivore species all received the highest rating at the upstream site, outscoring the downstream site by two points for each of these three metrics. Other metrics scoring higher upstream included percent tolerant individuals in electrofishing samples, percent dominance by one species in electrofishing samples, and percent omnivores in electrofishing samples. Conversely, three metrics scored higher at the downstream site; the number of non-native species in gill netting, percent carnivores in gill netting, and percent of fish with anomalies in electrofishing.

Electrofishing and gill netting catch rates for individual species from both sites for 2000-2002 and 2005-2006 are listed in Table 24-6 through Table 24-8 and Table 24-9 through Table 24-10, respectively. During 2005, 13 species collected at the upstream site were not found at the downstream site and four species collected at the downstream site were not encountered at the upstream site (Table 24-9). Of those found only upstream from COF, four were suckers (northern hog sucker, black buffalo, silver redhorse, and shorthead redhorse) and three were temperate basses (white bass, yellow bass, and striped bass), along with mimic shiner, flathead catfish, black crappie, sauger, and brook silverside. These species affected the higher upstream RFAI metric scores because suckers are benthic invertivores, while the temperate basses, flathead catfish, black crappie, and sauger are top carnivores. The four species found only downstream of COF included one sucker species (river redhorse), skipjack herring, emerald shiner, and yellow perch. Of the 17 species found only at one site, ten species were represented by only a single individual, indicating their relative scarcity in the vicinity of COF.

It is not possible at this time to determine that the 2005 dissimilarity in the two sites was due to COF thermal impacts. Both sites were categorized as good, and the upstream site only scored one point higher than the threshold difference of six points. The previous three years of sampling (2000-2002) indicated no adverse impacts to the fish community below the COF discharge. However, future RFAI results should be closely monitored to determine if any trend is developing between fish communities at the two sites.

Fish communities sampled in the vicinity of COF in 2006 were more similar than the previous year. RFAI scores were 48 upstream of COF and 45 downstream (Table 24-5). Thus, fish communities at both sites were considered similar and both rated good. Each of the samples from 2000 to 2002 and 2005 to 2006 reached or exceeded the 70% BIP criteria. The similarity in the upstream and downstream scores indicates that the operation of COF was not adversely affecting the quality of the fish communities in its vicinity in 2006.

**Table 24-6**
**Species Collected and Catch Per Unit Effort during Fall Electrofishing (Catch per 300-m Run and Per hour) and Gill Netting (Catch Per Night) at the Upstream and Downstream Stations of Colbert Fossil Plant, Fall 2000**

| | Downstream TRM 242 | | | Upstream TRM 247 | | |
|---|---|---|---|---|---|---|
| | Electrofishing | | Gill Netting | Electrofishing | | Gill Netting |
| Common Name | Catch Per Run | Catch Per Hour | Catch Per Net Night | Catch Per Run | Catch Per Hour | Catch Per Net Night |
| Spotted gar | 0.07 | 0.39 | | 0.07 | 0.45 | |
| Longnose gar | | | 1.10 | | | 0.10 |
| Skipjack herring | 0.13 | 0.78 | 2.60 | 0.07 | 0.45 | 1.00 |
| Gizzard shad | 4.47 | 26.07 | 0.30 | 5.73 | 39.09 | 1.00 |
| Threadfin shad | | | 0.20 | 0.13 | 0.91 | |
| Common carp | 0.07 | 0.39 | 0.10 | | | 1.00 |
| Golden shiner | | | | 0.40 | 2.73 | |
| Emerald shiner | 0.13 | 0.78 | | | | |
| Spotfin shiner | | | | 0.07 | 0.45 | |
| Bluntnose minnow | 0.07 | 0.39 | | | | |
| River carpsucker | | | | | | 0.10 |
| Northern hog sucker | | | 0.10 | | | |
| Smallmouth buffalo | 0.20 | 1.17 | 0.20 | | | 1.00 |
| Spotted sucker | 0.13 | 0.78 | | 0.07 | 0.45 | 0.40 |
| Silver redhorse | | | 0.20 | | | 0.50 |
| Shorthead redhorse | | | 0.30 | | | 0.90 |
| River redhorse | | | 0.10 | | | 0.10 |
| Black redhorse | 0.20 | 1.17 | | | | |
| Golden redhorse | | | 0.80 | 0.07 | 0.45 | 1.90 |
| Blue catfish | | | 0.50 | | | 1.10 |
| Channel catfish | 0.20 | 1.17 | 0.50 | 0.53 | 3.64 | 0.60 |
| Flathead catfish | | | 0.30 | 0.07 | 0.45 | 0.40 |
| White bass | 0.13 | 0.78 | 3.90 | | | 2.00 |
| Yellow bass | 0.40 | 2.33 | | 0.13 | 0.91 | |

**Table 24-6**
**Species Collected and Catch Per Unit Effort during Fall Electrofishing (Catch per 300-m Run and Per hour) and Gill Netting (Catch Per Night) at the Upstream and Downstream Stations of Colbert Fossil Plant, Fall 2000 (Continued)**

| | Downstream TRM 242 | | | Upstream TRM 247 | | |
|---|---|---|---|---|---|---|
| | Electrofishing | | Gill Netting | Electrofishing | | Gill Netting |
| Common Name | Catch Per Run | Catch Per Hour | Catch Per Net Night | Catch Per Run | Catch Per Hour | Catch Per Net Night |
| Striped bass | 0.13 | 0.78 | | | | |
| Hybrid striped x white bass | | | 1.80 | | | 0.40 |
| Rock bass | | | | 0.07 | 0.45 | 0.10 |
| Warmouth | | | | 0.07 | 0.45 | |
| Green sunfish | | | | 0.20 | 1.36 | |
| Bluegill | 0.33 | 1.95 | 0.10 | 13.40 | 91.36 | |
| Longear sunfish | 0.47 | 2.72 | | 5.53 | 37.73 | |
| Redear sunfish | 0.27 | 1.56 | 0.50 | 2.33 | 15.91 | 0.50 |
| Smallmouth bass | | | 0.30 | 0.07 | 0.45 | 0.20 |
| Spotted bass | 0.20 | 1.17 | 2.00 | 0.73 | 5.00 | 3.80 |
| Largemouth bass | 0.47 | 2.72 | 0.40 | 1.67 | 11.36 | 0.20 |
| Sauger | | | 1.80 | 0.13 | 0.91 | 0.50 |
| Walleye | | | | | | 0.10 |
| Freshwater drum | 1.53 | 8.95 | 0.40 | 0.33 | 2.27 | |
| Brook silverside | 0.27 | 1.56 | | | | |
| Inland silverside | | | | 0.93 | 6.36 | |
| **Totals** | **9.87** | **57.61** | **18.5** | **32.8** | **223.59** | **17.9** |
| **Number Samples** | **15** | | **10** | **15** | | **10** |
| **Number Fish** | **148** | | **185** | **492** | | **179** |
| **Number Species** | **20** | | **23** | **23** | | **23** |

**Table 24-7**
**Species Collected and Catch Per Unit Effort During Fall Electrofishing (Catch Per 300-m Run and Per Hour) and Gill Netting (Catch Per Night) at the Upstream and Downstream Stations of Colbert Fossil Plant, Fall, 2001**

| | Downstream TRM 242 | | | Upstream TRM 247 | | |
|---|---|---|---|---|---|---|
| | Electrofishing | | Gill Netting | Electrofishing | | Gill Netting |
| **Common Name** | **Catch Per Run** | **Catch Per Hour** | **Catch Per Net Night** | **Catch Per Run** | **Catch Per Hour** | **Catch Per Net Night** |
| Spotted gar | | | | 0.07 | 0.36 | |
| Longnose gar | 0.27 | 1.68 | 0.20 | 0.07 | 0.36 | |
| Skipjack herring | | | 0.40 | | | 0.30 |
| Gizzard shad | 4.53 | 28.57 | 0.20 | 6.33 | 34.67 | 0.10 |
| Threadfin shad | 0.13 | 0.84 | | | | |
| Central stoneroller | 0.07 | 0.42 | | | | |
| Common carp | | | 0.10 | 0.20 | 1.09 | 0.20 |
| Golden shiner | | | | 0.13 | 0.73 | |
| Spotfin shiner | 0.07 | 0.42 | | | | |
| Striped shiner | 0.07 | 0.42 | | | | |
| Smallmouth buffalo | 0.20 | 1.26 | 0.10 | | | |
| Black buffalo | | | | 0.07 | 0.36 | |
| Spotted sucker | 0.33 | 1.26 | | 1.20 | 6.57 | |
| Silver redhorse | | | 0.10 | | | 0.10 |
| Shorthead redhorse | | | 0.20 | | | |
| Black redhorse | | | | 0.07 | 0.36 | |
| Golden redhorse | 0.13 | 0.84 | | | | 0.30 |
| Blue catfish | | | 0.30 | | | 0.30 |
| Channel catfish | 1.47 | 9.24 | 0.20 | 1.60 | 8.76 | 0.20 |
| Flathead catfish | | | 0.10 | | | 0.10 |
| White bass | | | 1.20 | | | 0.10 |
| Yellow bass | 0.27 | 1.68 | | | | 0.10 |
| Striped bass | 0.07 | 0.42 | | | | |
| Rock bass | | | | 0.47 | 2.55 | 0.10 |

**Table 24-7**
**Species Collected and Catch Per Unit Effort During Fall Electrofishing (Catch Per 300-m Run and Per Hour) and Gill Netting (Catch Per Night) at the Upstream and Downstream Stations of Colbert Fossil Plant, Fall, 2001 (Continued)**

| | **Downstream TRM 242** | | | **Upstream TRM 247** | | |
|---|---|---|---|---|---|---|
| | **Electrofishing** | | **Gill Netting** | **Electrofishing** | | **Gill Netting** |
| **Common Name** | **Catch Per Run** | **Catch Per Hour** | **Catch Per Net Night** | **Catch Per Run** | **Catch Per Hour** | **Catch Per Net Night** |
| Warmouth | | | | | | 0.10 |
| Redbreast sunfish | | | | 0.07 | 0.36 | |
| Bluegill | 1.00 | 6.30 | | 7.13 | 39.05 | 0.20 |
| Longear sunfish | 2.13 | 13.45 | | 4.60 | 25.18 | |
| Redear sunfish | 0.87 | 5.46 | 0.10 | 1.33 | 7.30 | 0.30 |
| Smallmouth bass | 0.60 | 3.78 | | 0.53 | 2.92 | |
| Spotted bass | 1.00 | 6.30 | 1.00 | 0.73 | 4.01 | 0.70 |
| Largemouth bass | 0.47 | 2.94 | | 1.27 | 6.93 | |
| Logperch | 0.40 | 2.52 | | 1.27 | 6.93 | |
| Sauger | | | 0.50 | | | 0.40 |
| Freshwater drum | 0.40 | 2.52 | 0.30 | 0.20 | 1.09 | 0.20 |
| Brook silverside | | | | 0.07 | 0.36 | |
| Inland silverside | 0.40 | 2.52 | | 1.53 | 8.39 | |
| **Totals** | **14.88** | **93.68** | **5.00** | **28.94** | **158.33** | **3.80** |
| **Number Samples** | **15** | | **10** | **15** | | **10** |
| **Number Fish** | **223** | | **50** | **434** | | **38** |
| **Number Species** | **21** | | **15** | **21** | | **17** |

**Table 24-8**
**Species Collected and Catch Per Unit Effort During Fall Electrofishing (Catch Per 300-m Run and Per Hour) and Gill Netting (Catch Per Night) at the Upstream and Downstream Stations of Colbert Fossil Plant, Fall 2002**

| | **Downstream TRM 242** | | | **Upstream TRM 247** | | |
|---|---|---|---|---|---|---|
| | **Electrofishing** | | **Gill Netting** | **Electrofishing** | | **Gill Netting** |
| **Common Name** | **Catch Per Run** | **Catch Per Hour** | **Catch Per Net Night** | **Catch Per Run** | **Catch Per Hour** | **Catch Per Net Night** |
| Spotted gar | | | | 0.20 | 1.32 | |
| Longnose gar | 0.27 | 2.07 | 0.70 | | | 0.20 |
| Skipjack herring | | | 2.50 | | | |
| Gizzard shad | 3.80 | 29.53 | 0.10 | 10.73 | 70.93 | |
| Threadfin shad | 1.80 | 13.99 | | | | |
| Largescale stoneroller | | | | 0.07 | 0.44 | |
| Common carp | 0.13 | 1.04 | 0.10 | | | 0.20 |
| Spotfin shiner | | | | 0.07 | 0.44 | |
| Smallmouth buffalo | | | 0.10 | 0.60 | 3.96 | 0.20 |
| Spotted sucker | 0.13 | 1.04 | | | | 0.20 |
| Silver redhorse | | | 0.10 | | | 0.10 |
| Shorthead redhorse | | | 0.20 | | | 0.40 |
| Black redhorse | | | | | | 0.20 |
| Golden redhorse | 0.07 | 0.52 | | 0.13 | 0.88 | 0.80 |
| Blue catfish | | | 0.40 | | | 0.20 |
| Channel catfish | 0.20 | 1.55 | 0.70 | 0.27 | 1.76 | 0.80 |
| Flathead catfish | | | 0.50 | | | 0.50 |
| White bass | | | 0.40 | 0.20 | 1.32 | |
| Yellow bass | 0.13 | 1.04 | 0.10 | 0.13 | 0.88 | 0.20 |
| Striped bass | | | 0.10 | | | |
| hybrid striped x white bass | | | | | | 0.10 |
| Rock bass | | | 0.10 | | | |
| Warmouth | 0.07 | 0.52 | | | | |

**Table 24-8**
**Species Collected and Catch Per Unit Effort During Fall Electrofishing (Catch Per 300-m Run and Per Hour) and Gill Netting (Catch Per Night) at the Upstream and Downstream Stations of Colbert Fossil Plant, Fall 2002 (Continued)**

| | **Downstream TRM 242** | | | **Upstream TRM 247** | | |
|---|---|---|---|---|---|---|
| | **Electrofishing** | | **Gill Netting** | **Electrofishing** | | **Gill Netting** |
| **Common Name** | **Catch Per Run** | **Catch Per Hour** | **Catch Per Net Night** | **Catch Per Run** | **Catch Per Hour** | **Catch Per Net Night** |
| Redbreast sunfish | | | | 0.07 | 0.44 | |
| Green sunfish | 0.07 | 0.52 | | 0.07 | 0.44 | |
| Bluegill | 0.93 | 7.25 | | 4.33 | 28.63 | |
| Longear sunfish | 0.60 | 4.66 | | 0.73 | 4.85 | |
| Redear sunfish | 0.27 | 2.07 | | 0.60 | 3.96 | 0.50 |
| Smallmouth bass | 0.07 | 0.52 | 0.10 | 0.13 | 0.88 | 0.40 |
| Spotted bass | 0.53 | 4.15 | 2.40 | 0.93 | 6.17 | 1.50 |
| Largemouth bass | 0.73 | 5.70 | | 1.47 | 9.69 | |
| Logperch | 0.07 | 0.52 | | | | |
| Sauger | | | 0.40 | | | 0.20 |
| Freshwater drum | 0.20 | 1.55 | 0.10 | 0.13 | 0.88 | 0.20 |
| Inland silverside | 0.20 | 1.55 | | 7.60 | 50.22 | |
| **Totals** | **10.27** | **79.79** | **9.1** | **28.46** | **188.09** | **6.9** |
| **Number Samples** | **15** | | **10** | **15** | | **10** |
| **Number Fish** | **154** | | **91** | **427** | | **69** |
| **Number Species** | **19** | | **18** | **19** | | **18** |

**Table 24-9**
**Species Collected and Catch Per Unit Effort During Fall Electrofishing (Catch per 300-m Run and Per Hour) and Gill Netting (Catch Per Night) at the Upstream and Downstream Station**

| | Downstream TRM 242 | | | Upstream TRM 247 | | |
|---|---|---|---|---|---|---|
| | Electrofishing | | Gill Netting | Electrofishing | | Gill Netting |
| Common Name | Catch Per Run | Catch Per Hour | Catch Per Net Night | Catch Per Run | Catch Per Hour | Catch Per Net Night |
| Spotted gar | 0.07 | 0.42 | | 0.33 | 2.02 | |
| Longnose gar | | | 0.10 | | | 0.50 |
| Skipjack herring | 0.07 | 0.42 | 0.10 | | | |
| Gizzard shad | 11.67 | 73.84 | | 11.33 | 68.83 | |
| Threadfin shad | 0.53 | 3.38 | | 11.93 | 72.47 | |
| Common carp | 0.07 | 0.42 | | | | 0.10 |
| Emerald shiner | 0.20 | 1.27 | | | | |
| Spotfin shiner | 2.07 | 13.08 | | 2.13 | 12.96 | |
| Mimic shiner | | | | 0.27 | 1.62 | |
| Bluntnose minnow | 1.13 | 7.17 | | 0.20 | 1.21 | |
| Bullhead minnow | 0.27 | 1.69 | | 0.33 | 2.02 | |
| Northern hog sucker | | | | 0.07 | 0.40 | |
| Smallmouth buffalo | 0.13 | 0.84 | | | | 0.10 |
| Black buffalo | | | | 0.13 | 0.81 | |
| Spotted sucker | 0.60 | 3.80 | 0.10 | 0.20 | 1.21 | |
| Silver redhorse | | | | 0.07 | 0.40 | 0.50 |
| Shorthead redhorse | | | | 0.07 | 0.40 | 1.50 |
| River redhorse | | | 0.10 | | | |
| Black redhorse | 0.20 | 1.27 | | 0.13 | 0.81 | |
| Golden redhorse | | | 0.30 | 0.20 | 1.21 | 0.60 |
| Blue catfish | | | 0.30 | | | 0.40 |
| Channel catfish | 0.47 | 2.95 | 0.20 | 0.47 | 2.83 | 0.60 |
| Flathead catfish | | | | | | 0.50 |

**Table 24-9**
**Species Collected and Catch Per Unit Effort During Fall Electrofishing (Catch per 300-m Run and Per Hour) and Gill Netting (Catch Per Night) at the Upstream and Downstream Station (Continued)**

| | Downstream TRM 242 | | | Upstream TRM 247 | | |
|---|---|---|---|---|---|---|
| | Electrofishing | | Gill Netting | Electrofishing | | Gill Netting |
| **Common Name** | **Catch Per Run** | **Catch Per Hour** | **Catch Per Net Night** | **Catch Per Run** | **Catch Per Hour** | **Catch Per Net Night** |
| White bass | | | | | | 0.10 |
| Yellow bass | | | | 0.20 | 1.21 | 0.10 |
| Striped bass | | | | 0.07 | 0.40 | |
| Warmouth | 0.07 | 0.42 | | 0.13 | 0.81 | |
| Redbreast sunfish | | | | 0.27 | 1.62 | |
| Green sunfish | 0.07 | 0.42 | | 0.40 | 2.43 | |
| Bluegill | 1.40 | 8.86 | | 9.27 | 56.28 | |
| Longear sunfish | 1.87 | 11.81 | | 6.47 | 39.27 | |
| Redear sunfish | 0.60 | 3.80 | | 2.93 | 17.81 | 0.40 |
| Smallmouth bass | 0.20 | 1.27 | | 0.13 | 0.81 | 0.20 |
| Spotted bass | 0.47 | 2.95 | 0.50 | 0.33 | 2.02 | 0.20 |
| Largemouth bass | 0.60 | 3.80 | | 1.87 | 11.34 | |
| Black crappie | | | | | | 0.10 |
| Yellow perch | 0.07 | 0.42 | | | | |
| Logperch | 0.07 | 0.42 | | 0.40 | 2.43 | |
| Sauger | | | | | | 0.10 |
| Freshwater drum | 0.47 | 2.95 | | 0.47 | 2.83 | 0.10 |
| Brook silverside | | | | 0.13 | 0.81 | |
| Inland silverside | 1.40 | 8.86 | | 1.93 | 11.74 | |
| **Total** | **24.77** | **156.53** | **1.70** | **52.86** | **321.01** | **6.10** |
| **Number Samples** | **15** | | **10** | **15** | | **10** |
| **Number Collected** | **371** | | **17** | **793** | | **61** |
| **Species Collected** | **25** | | **8** | **30** | | **17** |

**Table 24-10**
**Species Collected and Catch Per Unit Effort During Fall Electrofishing (Catch Per 300-m Run and Per Hour) and Gill Netting (Catch Per Night) at the Upstream and Downstream Stations of Colbert Fossil Plant, Fall 2006**

| | Downstream TRM 242 | | | Upstream TRM 247 | | |
|---|---|---|---|---|---|---|
| | Electrofishing | | Gill Netting | Electrofishing | | Gill Netting |
| Common Name | Catch Per Run | Catch Per Hour | Catch Per Net Night | Catch Per Run | Catch Per Hour | Catch Per Net Night |
| Spotted gar | 0.07 | 0.39 | | 0.20 | 1.18 | |
| Skipjack herring | 1.27 | 7.42 | 2.50 | | | 1.30 |
| Gizzard shad | 3.60 | 21.09 | | 18.60 | 109.84 | 0.10 |
| Threadfin shad | 75.80 | 444.14 | | 10.33 | 61.02 | |
| Common carp | | | 0.10 | | | 0.30 |
| Emerald shiner | | | | 0.07 | 0.39 | |
| Spotfin shiner | 3.00 | 17.58 | | 0.40 | 2.36 | |
| Striped shiner | 0.07 | 0.39 | | | | |
| Bullhead minnow | | | | 0.20 | 1.18 | |
| Smallmouth buffalo | | | 0.20 | 0.13 | 0.79 | 0.10 |
| Black buffalo | 0.07 | 0.39 | 0.20 | 0.13 | 0.79 | 0.10 |
| Spotted sucker | 0.80 | 4.69 | 0.10 | 0.80 | 4.72 | 0.10 |
| Silver redhorse | | | | | | 0.20 |
| Shorthead redhorse | 0.07 | 0.39 | 0.10 | | | 0.50 |
| River redhorse | 0.20 | 1.17 | | | | 0.30 |
| Black redhorse | 0.20 | 1.17 | 0.10 | 0.20 | 1.18 | 0.30 |
| Golden redhorse | | | | 0.07 | 0.39 | 0.60 |
| Blue catfish | | | 0.70 | | | 0.10 |
| Channel catfish | 0.87 | 5.08 | 1.00 | 0.20 | 1.18 | 0.20 |
| Flathead catfish | | | | | | 0.20 |
| Inland silverside | 2.13 | 12.50 | | 3.07 | 18.11 | |
| White bass | 0.13 | 0.78 | 0.30 | | | 0.10 |
| Yellow bass | | | 1.20 | 0.47 | 2.76 | 0.20 |
| Striped bass | | | 0.10 | | | |

**Table 24-10**
**Species Collected and Catch Per Unit Effort During Fall Electrofishing (Catch Per 300-m Run and Per Hour) and Gill Netting (Catch Per Night) at the Upstream and Downstream Stations of Colbert Fossil Plant, Fall 2006 (Continued)**

| | Downstream TRM 242 | | | Upstream TRM 247 | | |
|---|---|---|---|---|---|---|
| | Electrofishing | | Gill Netting | Electrofishing | | Gill Netting |
| Common Name | Catch Per Run | Catch Per Hour | Catch Per Net Night | Catch Per Run | Catch Per Hour | Catch Per Net Night |
| Rock bass | | | | 0.07 | 0.39 | |
| Green sunfish | 0.33 | 1.95 | | 1.67 | 9.84 | |
| Bluegill | 1.00 | 5.86 | 0.10 | 7.67 | 45.28 | 0.10 |
| Longear sunfish | 1.07 | 6.25 | 0.10 | 1.47 | 8.66 | 0.20 |
| Redear sunfish | 0.60 | 3.52 | | 2.40 | 14.17 | 0.30 |
| hybrid sunfish | | | 0.10 | | | |
| Smallmouth bass | 0.40 | 2.34 | | 0.27 | 1.57 | 1.40 |
| Spotted bass | 0.27 | 1.56 | 0.30 | 0.27 | 1.57 | 0.30 |
| Largemouth bass | 2.87 | 16.80 | | 3.73 | 22.05 | |
| Yellow perch | 0.07 | 0.39 | | | | |
| Logperch | 0.13 | 0.78 | | 0.07 | 0.39 | |
| Sauger | 0.13 | 0.78 | 0.50 | | | 0.50 |
| Freshwater drum | 0.07 | 0.39 | 0.20 | 0.13 | 0.79 | 0.50 |
| **Total** | **95.22** | **557.80** | **7.9** | **52.6** | **310.6** | **8.0** |
| **Number Samples** | **15** | | **10** | **15** | | **10** |
| **Number Collected** | **1428** | | **79** | **789** | | **80** |
| **Species Collected** | **25** | | **18** | **24** | | **24** |

RFAI scores obtained from VS monitoring sites located 24.1 river kilometers (15 mi) upstream and 22.5 river kilometers (14 mi) downstream of the COF discharge, since 1993 revealed similar fish communities (Table 24-11). Average (1993-2006) RFAI scores for the upstream and downstream sites were within one point (46.3 and 44.5, respectively). These scores met the adjusted 70% criteria for designation as BIP and were within the six point acceptable variation. These data also indicate that the COF discharge is not adversely impacting the broader, and apparently stable, fish community of upper Pickwick Reservoir.

**Table 24-11**
**Summary of RFAI Scores Collected from 1993 through 2006 as Part of the Vital Signs Monitoring Program at Stations (TRM 259) Upstream and Downstream (TRM 230) of Colbert Fossil Plant, Pickwick Reservoir**

| | | Year | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Site** | **Location** | **1993** | **1994** | **1996** | **1998** | **2000** | **2002** | **2004** | **2006** | **Avg** |
| Upstream | TRM 259 | 46 | 40 | 52 | 36 | 44 | 48 | 54 | 50 | 46.3 |
| Downstream | TRM 230 | 44 | 43 | 47 | 42 | 46 | 46 | 44 | 44 | 44.5 |

### Benthic Macroinvertebrate Community

Table 24-16 provide results and ratings for each metric as well as the overall benthic index score for upstream/downstream monitoring sites sampled in 2000-2002 and 2005-2006, respectively. Table 24-17 summarizes density by taxon at both collection sites; 2000-2002 and 2005-2006 taxa are presented in Table 24-18. During the first three-year sampling period, benthic indices consistently rated better in the downstream sample than the upstream sample. While downstream samples rated in the good category, upstream samples only rated in the fair category. In 2005, the downstream sample declined into the fair category, but the upstream site index also declined and scored four points below the downstream index. Due to the consistently higher index values at the site downstream from the COF discharge, benthic invertebrate monitoring indicates that COF is not adversely impacting the benthic community of Pickwick Reservoir.

**Table 24-12**
**Individual Metric Ratings and the Overall Benthic Community index Score for Upstream (TRM 246) and Downstream (244) Sites near Colbert Fossil Plant, Pickwick Reservoir, November 2000**

| | TRM 244 | | TRM 246 | |
|---|---|---|---|---|
| **Metric** | **Obs** | **Rating** | **Obs** | **Rating** |
| 1. Average number of taxa | 6.3 | 5 | 4.7 | 3 |
| 2. Proportion of samples with long-lived organisms | 0.9 | 5 | 1.0 | 5 |
| 3. Average number of EPT taxa | 0.3 | 1 | 0.2 | 1 |
| 4. Average proportion of oligochaete individuals | 2.88 | 5 | 3.65 | 5 |
| 5. Average proportion of total abundance comprised by the two most abundant taxa | 74.3 | 5 | 80.1 | 3 |
| 6. Average density excluding chironomids and oligochaetes | 395.9 | 1 | 232.3 | 1 |
| 7. Zero-samples – proportion of samples containing no organisms | 0 | 5 | 0 | 5 |
| **Benthic Index Score** | | **27** | | **23** |
| | | **Good** | | **Fair** |

Scored with inflow criteria

**Table 24-13**
**Individual Metric Ratings and the Overall Benthic Community Index Score for Upstream (TRM 246) and Downstream (TRM 244) Sites near Colbert Fossil Plant, Pickwick Reservoir, November 2001**

| | TRM 244 | | TRM 246 | |
|---|---|---|---|---|
| **Metric** | **Obs** | **Rating** | **Obs** | **Rating** |
| 1. Average number of taxa | 4.8 | 3 | 3.7 | 3 |
| 2. Proportion of samples with long-lived organisms | 0.9 | 5 | 0.6 | 3 |
| 3. Average number of EPT taxa | 0.4 | 3 | 0.5 | 3 |
| 4. Average proportion of oligochaete individuals | 6.1 | 5 | 1.4 | 5 |
| 5. Average proportion of total abundance comprised by the two most abundant taxa | 79.8 | 3 | 83.0 | 3 |
| 6. Average density excluding chironomids and oligochaetes | 383.3 | 1 | 160.0 | 1 |
| 7. Zero-samples – proportion of samples containing no organisms | 0 | 5 | 0 | 5 |
| **Benthic Index Score** | | **25** | | **23** |
| | | **Good** | | **Fair** |

Scored with inflow criteria

**Table 24-14**
**Individual Metric Ratings and the Overall Benthic Community Index Score for Upstream (246) and Downstream (244) Sites near Colbert Fossil Plant, Pickwick Reservoir, November 2002**

| | TRM 244 | | TRM 246 | |
|---|---|---|---|---|
| **Metric** | **Obs** | **Rating** | **Obs** | **Rating** |
| 1. Average number of taxa | 4.8 | 3 | 3.7 | 3 |
| 2. Proportion of samples with long-lived organisms | 0.9 | 5 | 0.6 | 3 |
| 3. Average number of EPT taxa | 0.4 | 3 | 0.5 | 3 |
| 4. Average proportion of oligochaete individuals | 6.1 | 5 | 1.4 | 5 |
| 5. Average proportion of total abundance comprised by the two most abundant taxa | 79.8 | 3 | 83.0 | 3 |
| 6. Average density excluding chironomids and oligochaetes | 383.3 | 1 | 160.0 | 1 |
| 7. Zero-samples – proportion of samples containing no organisms | 0 | 5 | 0 | 5 |
| **Benthic Index Score** | | **25** | | **23** |
| | | **Good** | | **Fair** |

Scored with inflow criteria

**Table 24-15**
**Individual Metric Ratings and the Overall Benthic Community Index Score for Upstream (246) and Downstream (244) Sites near Colbert Fossil Plant, Pickwick Reservoir, November 2005**

| | TRM 244 | | TRM 246 | |
|---|---|---|---|---|
| **Metric** | **Obs** | **Rating** | **Obs** | **Rating** |
| 1. Average number of taxa | 4.3 | 3 | 2.9 | 3 |
| 2. Proportion of samples with long-lived organisms | 0.8 | 5 | 0.6 | 3 |
| 3. Average number of EPT taxa | 0.3 | 1 | 0 | 1 |
| 4. Average proportion of oligochaete individuals | 0.9 | 5 | 1.8 | 5 |
| 5. Average proportion of total abundance comprised by the two most abundant taxa | 84.3 | 3 | 96.1 | 1 |
| 6. Average density excluding chironomids and oligochaetes | 198.3 | 1 | 175.0 | 1 |
| 7. Zero-samples – proportion of samples containing no organisms | 0 | 5 | 0 | 5 |
| **Benthic Index Score** | | **23** | | **19** |
| | | **Fair** | | **Fair** |

Scored with inflow criteria

**Table 24-16**
**Individual Metric Ratings and the Overall Benthic Community Index Score for Upstream (246) and Downstream (244) Sites near Colbert Fossil Plant, Pickwick Reservoir, October 2006**

| | TRM 244 | | TRM 246 | |
|---|---|---|---|---|
| **Metric** | **Obs** | **Rating** | **Obs** | **Rating** |
| 1. Average number of taxa | 8.0 | 5 | 6.3 | 5 |
| 2. Proportion of samples with long-lived organisms | 1.0 | 5 | 0.8 | 5 |
| 3. Average number of EPT taxa | 0.3 | 1 | 0.5 | 3 |
| 4. Average proportion of oligochaete individuals | 2.0 | 5 | 5.5 | 5 |
| 5. Average proportion of total abundance comprised by the two most abundant taxa | 58.5 | 5 | 68.7 | 5 |
| 6. Average density excluding chironomids and oligochaetes | 515.0 | 1 | 363.3 | 1 |
| 7. Zero-samples – proportion of samples containing no organisms | 0 | 5 | 0 | 5 |
| **Benthic Index Score** | | **27** | | **29** |
| | | **Good** | | **Good** |

Scored with inflow criteria

**Table 24-17**
**Average Mean Density Per Square Meter of Benthic Taxa Collected at Upstream (246) and Downstream (244) Sites near Colbert Fossil Plant, Pickwick Reservoir, November 2000-2002**

| | 2000 | | 2001 | | 2002 | |
|---|---|---|---|---|---|---|
| **Taxa** | **TRM 244** | **TRM 246** | **TRM 244** | **TRM 246** | **TRM 244** | **TRM 246** |
| Tubellaria | | | | | | |
| Tricladida | | | | | | |
| Planariidae | 75 | | 3 | 5 | 1 | |
| Oligochaeta | | | | | | |
| Oligochaetes | 19 | 4 | 25 | 5 | 38 | |
| Hirudinea | 7 | 3 | 3 | 7 | 3 | 2 |
| Crustacea | | | | | | |
| Amphipoda | | | 7 | 3 | 8 | |
| Insecta | | | | | | |
| Ephemeroptera | | | | | | |
| Mayflies | | | 2 | 7 | | |
| Ephemeridae | | | | | | |
| Hexagenia (<=10mm) | 10 | | 17 | | 35 | |
| Hexagenia (>10mm) | 23 | | 10 | | 10 | |
| Odonata | | | | | | |
| Anisoptera | 1 | 11 | | | | |
| Zygoptera | | | | | 17 | |
| Trichoptera | | | | | | |
| Caddisflies | | 3 | | | 1 | |
| Plecoptera | | | | | | |
| Stoneflies | | | | 3 | | |
| Diptera | | | | | | |
| Chironomidae | | | | | | |
| Chironomids | 11 | 22 | 3 | 2 | 5 | 2 |
| Gastropoda | | | | | | |
| Snails | 43 | 36 | 38 | 13 | 34 | 33 |

**Table 24-17**
**Average Mean Density Per Square Meter of Benthic Taxa Collected at Upstream (246) and Downstream (244) Sites near Colbert Fossil Plant, Pickwick Reservoir, November 2000-2002 (Continued)**

| | **2000** | | **2001** | | **2002** | |
|---|---|---|---|---|---|---|
| **Taxa** | **TRM 244** | **TRM 246** | **TRM 244** | **TRM 246** | **TRM 244** | **TRM 246** |
| Bivalvia | | | | | | |
| Unionoida | | | | | | |
| Unionidae | | | | | | |
| Mussels | 26 | 35 | 28 | 22 | 17 | 22 |
| Veneroida | | | | | | |
| Corbiculidae | | | | | | |
| Corbicula (<=10mm) | 147 | 122 | 187 | 98 | 66 | 68 |
| Corbicula (>10mm) | 30 | 5 | 13 | 2 | | |
| Sphaeriidae | | | | | | |
| Fingernail clams | 30 | 19 | 30 | | 30 | 2 |
| Dreissenidae | | | | | | |
| Dreissena polymorpha | 3 | . | | | | |
| **Number of samples** | **10** | **10** | **10** | **10** | **10** | **10** |
| **Sum** | **425** | **258** | **367** | **167** | **263** | **128** |
| **Sum of area sampled** | **0.9** | **0.7** | **0.6** | **0.6** | **0.8** | **0.6** |

**Table 24-18**
**Average Mean Density Per Square Meter of Benthic Taxa collected at Upstream (TRM 246) and Downstream (244) Sites near Colbert fossil Plant, Pickwick Reservoir, November 2005 and October 2006**

| | 2000 | | 2001 | | 2002 | |
|---|---|---|---|---|---|---|
| **Taxa** | **TRM 244** | **TRM 246** | **TRM 244** | **TRM 246** | **TRM 244** | **TRM 246** |
| Tubellaria | | | | | | |
| Tricladida | | | | | | |
| Planariidae | | | 72 | 50 | | |
| Oligochaeta | | | | | | |
| Oligochaetes | 5 | 3 | 10 | 13 | | |
| Hirudinea | | 2 | 40 | 25 | | |
| Crustacea | | | | | | |
| Amphipoda | 13 | | 52 | 28 | | |
| Isopoda | 5 | 5 | | | | |
| Insecta | | | | | | |
| Ephemeroptera | | | | | | |
| Mayflies | 2 | | | 13 | | |
| Ephemeridae | | | | | | |
| Hexagenia (<=10mm) | 3 | | | | | |
| Hexagenia (>10mm) | 3 | | 5 | | | |
| Odonata | | | | | | |
| Anisoptera | 3 | 2 | 2 | | | |
| Zygoptera | | | | | | |
| Trichoptera | | | | | | |
| Caddisflies | | | 3 | | | |
| Plecoptera | | | | | | |
| Stoneflies | | | | | | |
| Diptera | | | | | | |
| Chironomidae | | | | | | |
| Chironomids | 38 | 3 | 15 | 5 | | |

**Table 24-18**
**Average Mean Density Per Square Meter of Benthic Taxa collected at Upstream (TRM 246) and Downstream (244) Sites near Colbert fossil Plant, Pickwick Reservoir, November 2005 and October 2006 (Continued)**

| | 2000 | | 2001 | | 2002 | |
|---|---|---|---|---|---|---|
| **Taxa** | **TRM 244** | **TRM 246** | **TRM 244** | **TRM 246** | **TRM 244** | **TRM 246** |
| Gastropoda | | | | | | |
| Snails | 17 | 23 | 91 | 45 | | |
| Bivalvia | | | | | | |
| Unionoida | | | | | | |
| Unionidae | | | | | | |
| Mussels | 12 | 5 | 18 | 8 | | |
| Veneroida | | | | | | |
| Corbiculidae | | | | | | |
| Corbicula (<=10mm) | 117 | 135 | 42 | 70 | | |
| Corbicula (>10mm) | 10 | 3 | 12 | 3 | | |
| Sphaeriidae | | | | | | |
| Fingernail clams | 13 | | 178 | 120 | | |
| Dreissenidae | | | | | | |
| Dreissena polymorpha | | | | 3 | | |
| **Number of samples** | **10** | **10** | **10** | **10** | | |
| **Sum** | **242** | **182** | **540** | **383** | | |
| **Sum of area sampled** | **0.6** | **0.6** | **0.6** | **0.6** | | |

Lower average number of species at the upstream site and a lower proportion of total organisms comprised by the two most abundant taxa at the downstream site in 2000 accounted for the four point higher score at the downstream station. A higher proportion of samples with long-lived organisms at the downstream site accounted for the two point variation in scores in 2001. The proportion of total abundance comprised by the two most abundant taxa and the average numbers of Ephemeroptera, Plecoptera and Trichoptera (EPT) taxa were better at the downstream site in 2002, accounting for the six point difference from the upstream sample. In 2005, metrics for the percentage of long-lived organisms and the percentage of two most abundant taxa were each scored two points better downstream of the COF discharge than above. Table 24-19 provides benthic index scores from VS monitoring at the inflow (TRM 253) and transition (TRM 230) zone sites from 1994 to 2006. The transition zone sample site is of sufficient distance downstream 22.5 km (14 mi) that results would not be expected to reflect plant effects. The relatively high scores at this site indicate that a healthy benthic macroinvertebrate community is present.

Based on these results, it appears that COF operation has not had an adverse environmental impact on the benthic macroinvertebrate community immediately downstream of the plant.

**Table 24-19**
**Recent (1994-2006) Benthic Index Scores Collected as Part of the Vital Signs Monitoring Program at Inflow (Upstream) and Transition Zone (Downstream) on Pickwick Reservoir**

| | | Year | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Site** | **Location** | **1994** | **1996** | **1998** | **2000** | **2002** | **2004** | **2006** | **Avg** |
| Upstream | TRM 253 | 25 | 21 | 23 | 25 | 25 | 31 | 27 | 25.3 |
| Downstream | TRM 230 | 31 | 33 | 31 | 21 | 25 | 31 | 29 | 28.7 |

## *Impingement Mortality Monitoring*

During Year-One and Year-Two of impingement monitoring, 6,022 and 33,528 fish were collected from 104 weekly screen-wash samples (Table 24-20 and Figure 24-4). Table 24-21 presents estimated total number of fish impinged by species for both Year-One and Year-Two. Threadfin shad comprised 87% of the total fish collected followed by gizzard shad (5%), bluegill (4%), freshwater drum (2%), and skipjack herring and channel catfish at 1% each (Table 24-21). Thirty-seven and 28 species were collected in Year-One and Year-Two, respectively (Table 24-20). Estimated total numbers of fish impinged and percent by month for both years are presented in Table 24-22. The estimated annual impingement extrapolated from weekly samples was 42,154 during Year-One and 234,696 during Year-Two (Table 24-23). In Year-One, peak impingement occurred from January through March. However, in Year-Two peak impingement occurred from October through December (Figure 24-4). The proportion of total fish impinged from January through March of Year-One was 48%, while in Year-Two from October through December the proportion of total fish impinged was 72% (Table 24-22). Plotted daily (24-hour average) ambient intake water temperatures for COF during each of the two years sampled appear to be generally correlated with peak impingement as previously reported by numerous studies (Figure 24-5) [7, 8, 10, 11]. Table 24-5 also presents average COF intake temperatures from 1986 through 2006 for comparison. Winter temperatures during both Year-One and Year-Two, dropped below the average on several occasions during December through March, but these did not appear to coincide with specific peaks in impingement.

Threadfin and/or gizzard shad typically comprise over 90% of fish impinged on cooling-water intake screens of thermal power stations in the Southeast U. S. [10]. A recent study by Fost indicated that cold-stressed threadfin and gizzard shad can be classified as either *impaired* or *moribund* [12]. Impaired shad could recover if environmental conditions improved and would therefore not die if not impinged. Moribund fish on the other hand, are assumed to not be able to recover and die regardless of impingement. Fost’s data indicated that threadfin shad began to exhibit reduced or impaired swimming performance at 7.5°C (45.5°F). Winter temperatures during both years of monitoring at COF didn’t fall below the Fost threshold therefore no correlations were noted with peak fish impingement (Figure 24-4 and Figure 24-5).

**Table 24-20**
**List of Fish Species by Family, Scientific and common Name Including Numbers Collected in Impingement Samples during 2005-2007 at TVA's Colbert Fossil Plant**

| Family | Scientific Name | Common Name | Total Number Impinged | |
|---|---|---|---|---|
| | | | Year-One | Year-Two |
| **Amiidae** | *Amia Calva* | Bowfin | 2 | 0 |
| **Clupeidae** | *Dorosoma cepedianum* | Gizzard shad | 1012 | 842 |
| | *Dorosoma petenense* | Threadfin shad | 3267 | 31126 |
| | *Alosa chrysochloris* | Skipjack herring | 77 | 421 |
| **Cyprinidae** | *Cyprinella spiloptera* | Spotfin shiner | 1 | 0 |
| | *Pimephales promelas* | Fathead minnow | 1 | 1 |
| | *Pimephales notatus* | Bluntnose minnow | 3 | 0 |
| | *Notemigonus crysoleucas* | Golden shiner | 0 | 8 |
| | *Notropis atherinoides* | Emerald shiner | 4 | 0 |
| **Catostomidae** | *Catostomus commersonnii* | White sucker | 1 | 0 |
| | *Minytrema melanops* | Spotted sucker | 4 | 2 |
| | *Hypentelium nigricans* | Northern Hog sucker | 2 | 0 |
| | *Carpiodes carpio* | River carpsucker | 1 | 1 |
| | *Moxostoma erythrurum* | Golden redhorse | 2 | 0 |
| **Ictaluridae** | *Ictalurus punctatus* | Channel catfish | 169 | 31 |
| | *Ictalurus furcatus* | Blue catfish | 58 | 79 |
| | *Pylodictis olivaris* | Flathead catfish | 7 | 17 |
| **Atherinopsidae** | *Labidesthes sicculus* | Brook silverside | 1 | 0 |
| **Belonidae** | *Strongylura marina* | Atlantic needlefish | 0 | 2 |
| **Cottidae** | *Cottus carolinae* | Banded sculpin | 1 | 0 |

**Table 24-20**
**List of Fish Species by Family, Scientific and common Name Including Numbers Collected in Impingement Samples during 2005-2007 at TVA's Colbert Fossil Plant (Continued)**

| Family | Scientific Name | Common Name | Total Number Impinged | |
|---|---|---|---|---|
| | | | Year-One | Year-Two |
| **Moronidae** | *Morone chrysops* | White bass | 35 | 4 |
| | *Morone mississippiensis* | Yellow bass | 67 | 20 |
| | *Morone saxatilis* | Striped bass | 1 | 0 |
| | *M. chrysops* x *M. saxatilis* | Hybrid striped bass | 3 | 0 |
| **Centrarchidae** | *Micropterus salmoides* | Largemouth bass | 5 | 8 |
| | *Micropterus dolomieu* | Smallmouth bass | 28 | 34 |
| | *Micropterus punctulatus* | Spotted bass | 8 | 0 |
| | *Lepomis cyanellus* | Green sunfish | 0 | 5 |
| | *Lepomis megalotis* | Longear sunfish | 71 | 19 |
| | *Lepomis gulosus* | Warmouth | 4 | 0 |
| | *Lepomis macrochirus* | Bluegill | 792 | 609 |
| | *Lepomis humilis* | Orangespotted sunfish | 2 | 0 |
| | *Lepomis microlophus* | Redear sunfish | 7 | 3 |
| | *Pomoxis annularis* | White crappie | 3 | 0 |
| | *Ambloplites rupestris* | Rock bass | 5 | 0 |
| **Percidae** | *Sander canadense* | Sauger | 1 | 2 |
| | *Percina caprodes* | Logperch | 15 | 15 |
| **Sciaenidae** | *Aplodinotus grunniens* | Freshwater drum | 362 | 279 |
| | **Total Number of Fish** | | **6,022** | **33,528** |
| | **Number of Sample Days** | | **52** | **52** |
| | **Total Number of Species** | | **37** | **28** |

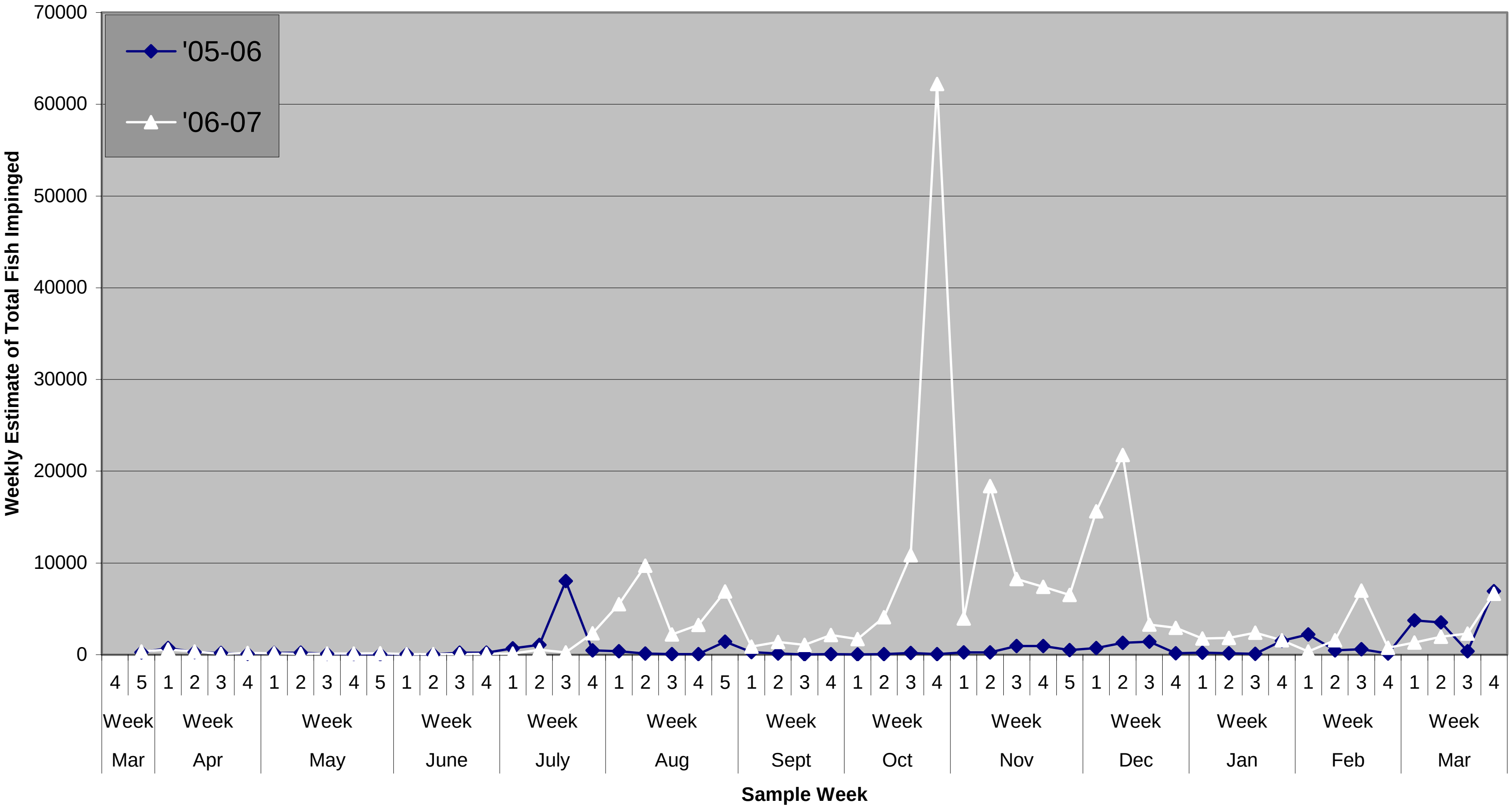

**Figure 24-4**
**Estimated Annual Numbers, Biomass, and Percent Composition of Fish Impinged by Species at Colbert Fossil Plant during 2005-2007**

**Table 24-21**
**Estimated Annual Numbers, Biomass, and Percent Composition of Fish Impinged by Species at Colbert Fossil Plant during 2005-2007**

| | Estimated Number | | | Estimated Biomass (g) | | | Percent Composition by Number |
|---|---|---|---|---|---|---|---|
| **Species** | **Year 1** | **Year 2** | **Average** | **Year 1** | **Year 2** | **Average** | |
| Threadfin shad | 22,869 | 217,882 | 120,376 | 136,451 | 757,281 | 446,866 | 87 |
| Gizzard shad | 7,084 | 5,894 | 6,489 | 89,901 | 285,957 | 187,929 | 5 |
| Bluegill | 5,544 | 4,263 | 4,904 | 30,779 | 32,270 | 31,525 | 4 |
| Freshwater drum | 2,534 | 1,953 | 2,244 | 346,521 | 135,604 | 241,063 | 2 |
| Skipjack herring | 539 | 2,947 | 1,743 | 17,703 | 47,768 | 32,736 | 1 |
| Channel catfish | 1,183 | 217 | 700 | 94,444 | 24,612 | 59,528 | 1 |
| Blue catfish | 406 | 553 | 480 | 32,767 | 81,319 | 57,043 | T |
| Longear sunfish | 497 | 133 | 315 | 11,361 | 7,742 | 9,552 | T |
| Yellow bass | 469 | 140 | 305 | 14,700 | 10,794 | 12,747 | T |
| Smallmouth bass | 196 | 238 | 217 | 5,684 | 9,296 | 7,490 | T |
| White bass | 245 | 28 | 137 | 18,158 | 8,008 | 13,083 | T |
| Logperch | 105 | 105 | 105 | 1,582 | 1,120 | 1,351 | T |
| Flathead catfish | 49 | 119 | 84 | 3,990 | 26,292 | 15,141 | T |
| Largemouth bass | 35 | 56 | 46 | 4,669 | 6,846 | 5,758 | T |
| Redear sunfish | 49 | 21 | 35 | 4,200 | 1,491 | 2,846 | T |
| Golden shiner | 0 | 56 | 28 | 0 | 546 | 273 | T |
| Spotted bass | 56 | 0 | 28 | 378 | 0 | 189 | T |
| Spotted sucker | 28 | 14 | 21 | 8,498 | 11,214 | 9,856 | T |
| Green sunfish | 0 | 35 | 18 | 0 | 126 | 63 | T |
| Rock bass | 35 | 0 | 18 | 1,498 | 0 | 749 | T |
| Emerald shiner | 28 | 0 | 14 | 217 | 0 | 109 | T |
| Warmouth | 28 | 0 | 14 | 350 | 0 | 175 | T |
| Bluntnose minnow | 21 | 0 | 11 | 70 | 0 | 35 | T |
| Hybrid striped bass | 21 | 0 | 11 | 2,212 | 0 | 1,106 | T |
| Sauger | 7 | 14 | 11 | 3,990 | 4,354 | 4,172 | T |
| White crappie | 21 | 0 | **11** | 8,120 | 0 | **4,060** | **T** |

**Table 24-21**
**Estimated Annual Numbers, Biomass, and Percent Composition of Fish Impinged by Species at Colbert Fossil Plant during 2005-2007 (Continued)**

| | Estimated Number | | | Estimated Biomass (g) | | | Percent Composition by Number |
|---|---|---|---|---|---|---|---|
| **Species** | **Year 1** | **Year 2** | **Average** | **Year 1** | **Year 2** | **Average** | |
| Atlantic needlefish | 0 | 14 | **7** | 0 | 1,337 | **669** | **T** |
| Bowfin | 14 | 0 | **7** | 15,008 | 0 | **7,504** | **T** |
| Fathead minnow | 7 | 7 | **7** | 56 | 14 | **35** | **T** |
| Golden redhorse | 14 | 0 | **7** | 13,160 | 0 | **6,580** | **T** |
| Northern hog sucker | 14 | 0 | **7** | 140 | 0 | **70** | **T** |
| Orangespotted sunfish | 14 | 0 | **7** | 56 | 0 | **28** | **T** |
| River carpsucker | 7 | 7 | **7** | 42 | 252 | **147** | **T** |
| Banded sculpin | 7 | 0 | **4** | 126 | 0 | **63** | **T** |
| Brook silverside | 7 | 0 | **4** | 14 | 0 | **7** | **T** |
| Spotfin shiner | 7 | 0 | **4** | 42 | 0 | **21** | **T** |
| Striped bass | 7 | 0 | **4** | 9,730 | 0 | **4,865** | **T** |
| White sucker | 7 | 0 | **4** | 546 | 0 | **273** | **T** |

**Table 24-22**
**Numbers of Fish Impinged at Colbert Fossil Plant by Month and Percent of Annual Total during 2004-2005, 2005-2006, and for Both Years Combined**

| Month | Total Number of Fish Impinged 2004-2005 (Year 1) | Percent of Annual Total | Total Number of Fish Impinged (Year 2) | Percent of Annual Total | Years 1 and 2 Combined | Percent of Two-year Total |
|---|---|---|---|---|---|---|
| Jan | 286 | 5 | 1,079 | 3 | 1,365 | 3 |
| Feb | 482 | 8 | 1,384 | 4 | 1,866 | 5 |
| Mar | 2116 | 35 | 1,788 | 5 | 3,904 | 10 |
| Apr | 186 | 3 | 125 | 0 | 311 | 1 |
| May | 82 | 1 | 51 | 0 | 133 | 0 |
| Jun | 82 | 1 | 63 | 0 | 145 | 0 |
| Jul | 1468 | 24 | 464 | 1 | 1,932 | 5 |
| Aug | 85 | 1 | 3940 | 12 | 4,025 | 10 |
| Sep | 269 | 4 | 786 | 2 | 1,055 | 3 |
| Oct | 50 | 1 | 11,260 | 34 | 11,310 | 29 |
| Nov | 334 | 6 | 6354 | 19 | 6,688 | 17 |
| Dec | 582 | 10 | 6,234 | 19 | 6,816 | 17 |
| | | | | | | |
| Total | 6,022 | | 33,528 | | 39,550 | |

**Table 24-23**
**Total Numbers of Fish Estimated Impinged by Year at Colbert Fossil Plant including Biological Liability Following Application of Equivalent Adult and Production Foregone Models**

| | 1974-1975 | 1975-1976 | 2005-2006 | 2006-2007 |
|---|---|---|---|---|
| Extrapolated Annual Number Impinged | 325,696 | 1,259,923 | 42,154 | 234,696 |
| Number Liable for after EA & PF Reduction | 39,765 | 67,901 | 3,246 | 9,035 |

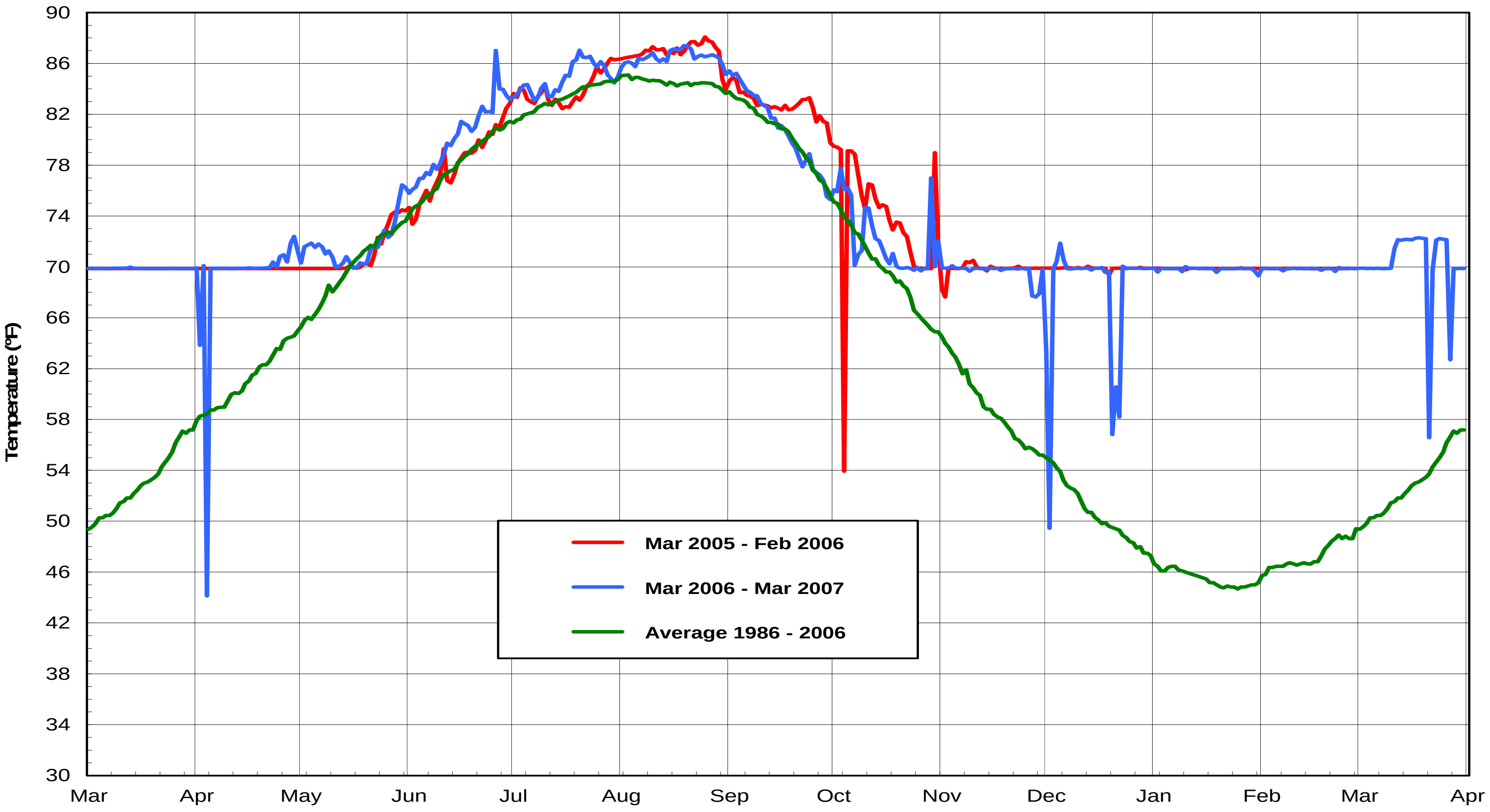

**Figure 24-5**
**Ambient Daily (24-hr avg) Water Temperature at Colbert Fossil Plant Intake during Historical (1986-2006) and Recent (2005-2007) Impingement Monitoring**

Application of the EA and PF models to the total numbers estimated impinged resulted in reduced numbers of fish (Table 24-23) which would have been expected to survive to either harvestable (EA) size/age or to provide forage (PF). This reduced number is considered the "biological liability" resulting from plant CCW impingement. The numbers of fish representing COF's biological liability for Year-One and Year-Two were 3,246 and 9,035 respectively (Table 24-23).

### *Comparison with Historical Data*

Estimated impingement from historical sampling from 1974 through 1976, including the extrapolated annual totals for number of fish impinged and the numbers estimated after EA and PF reduction are presented in Table 24-23. A comparison to the current estimated annual impingement data resulted in an 83% reduction from the average historical data collected during 1974 through 1976. Threadfin shad dominance was consistent with percentages ranging from 54% to 98%, except during 1975-1976 when gizzard shad were the dominant species impinged. The extrapolated annual totals of fish for 1974-1975 and 1975-1976 were 325,696 and 1,259,923 respectively (Table 24-23 and Figure 24-6). Table 24-24 presents the percent composition by number and biological liability of major species impinged during 1974-1976 and 2005-2007.

### *Skimmer Wall Benefits*

The benefits derived from installation of the skimmer wall in 2002 were a significant reduction of debris collected on the CCW trashracks and traveling screens, no net loss of generation capacity due to debris buildup at the CCW structure and reduced average intake water temperatures of approximately 0.14°C (0.25°F) due to exclusion of the upper stratified layer of the Tennessee River. An additional expected benefit of excluding the upper layer of water from Pickwick Reservoir was the significant reduction of fish impingement from the impingement baseline established in the mid-1970s. These benefits have improved COF generating efficiency with cooler water and cleaner condensers and save approximately 20 million dollars over 25 years of operation. Capital cost of designing and building the skimmer wall was 1.4 million dollars.

Skimmer wall installation reduced fish impingement but had no effect to the aquatic community in the vicinity of COF. Threadfin and gizzard shad are the primary forage species in the Tennessee River and are capable of sustaining high mortality without affecting the survival of the species. These prolific species seldom live more than three years and are capable of spawning during the first year of life. Power plant impingement mortality has not impacted the structure and function of the threadfin and gizzard shad population in the Tennessee River. In addition, fish and benthic macroinvertebrate community index scores rated good at both the upstream and downstream stations with no discernable impacts to the aquatic community's structure and function. Therefore, COF thermal discharges as well as the CCW intake have not adversely impacted the fish and benthic communities of Pickwick Reservoir.

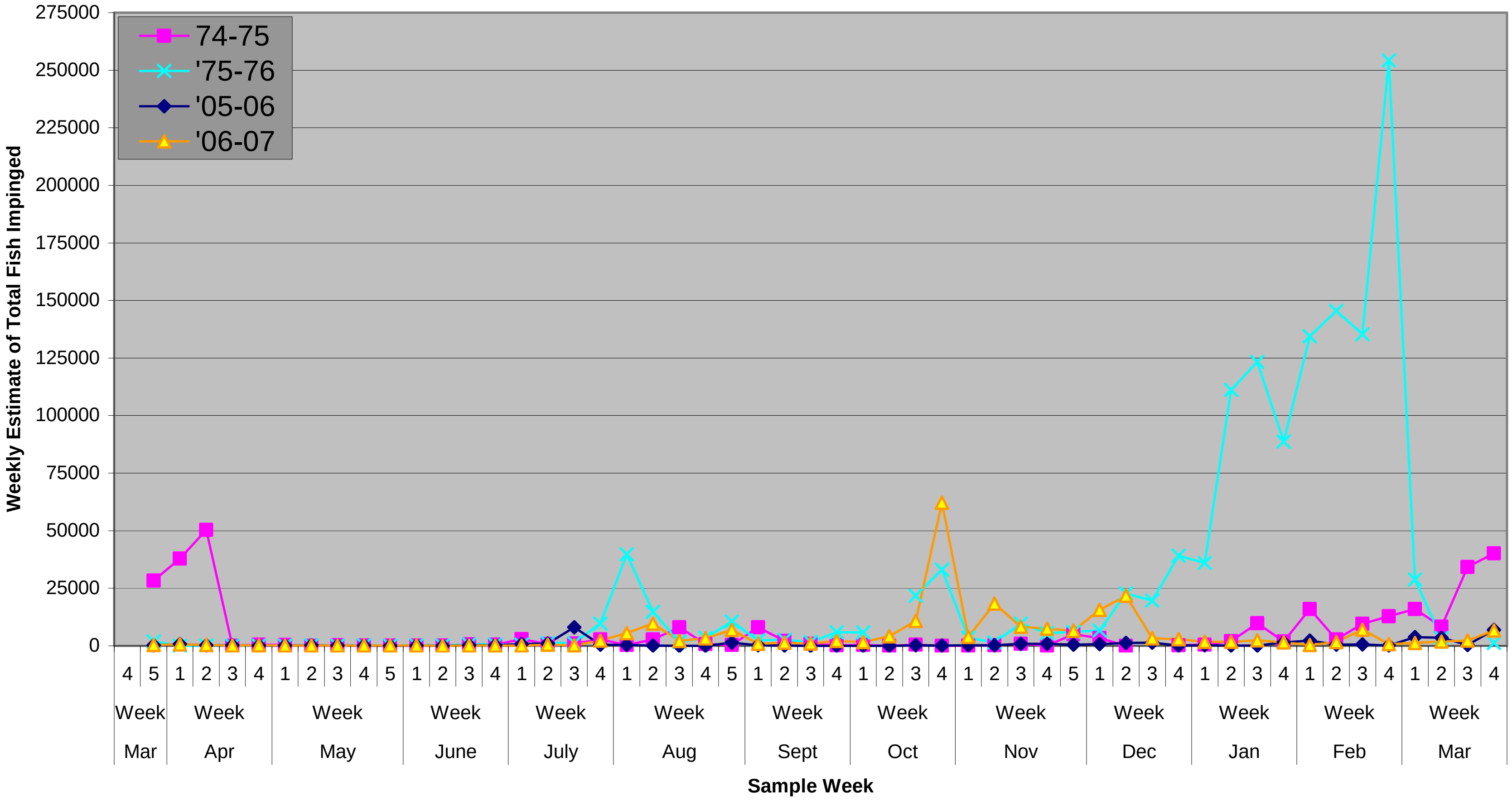

**Figure 24-6**
**Comparison of Estimated Weekly Fish Impingement at TVA's Colbert Fossil Plant during Historical and Recent Monitoring Periods**

**Table 24-24**
**Percent Composition (By Number and after EA and PF Models Applied) of Major Species of Fish Impinged at TVA's Colbert Fossil Plant during 1974-1976 and 2005-2007**

| | **1974-1975** | | **1975-1976** | | **2005-2006** | | **2006-2007** | |
|---|---|---|---|---|---|---|---|---|
| **Species Composition** | **% by Number** | **% after PA and EF** | **% by Number** | **% after PA and EF** | **% by Number** | **% after PA and EF** | **% by Number** | **% after PA and EF** |
| Threadfin shad | 83 | 72 | 19 | 19 | 54 | 29 | 93 | 84 |
| Freshwater drum | 5 | 7 | T | T | 6 | 11 | 1 | 2 |
| Skipjack herring | 5 | 4 | 1 | 1 | 1 | 1 | 1 | 1 |
| Gizzard shad | 2 | 2 | 79 | 77 | 17 | 9 | 3 | 2 |
| Yellow/white bass | T | T | T | T | 2 | 7 | 0 | 1 |
| Channel & Blue catfish | T | T | T | T | 4 | 9 | 0 | 1 |
| Sunfish | T | T | T | T | 14 | 22 | 2 | 4 |
| Striped bass | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 0 |
| Smallmouth bass | T | T | T | T | 0 | 3 | 0 | 1 |
| Logperch | T | T | T | T | 0 | 1 | 0 | 0 |
| White crappie | T | T | T | T | 0 | 1 | 0 | 0 |
| Sauger | T | T | T | T | 0 | 1 | 0 | 0 |
| Largemouth bass | T | T | T | T | 0 | 1 | 0 | 0 |
| **Total** | **95** | **85** | **99** | **97** | **99** | **97** | **100** | **97** |

**T = Trace < one percent**

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# 25

# NEW COOLING WATER DISCHARGE GUIDELINES IN THE NETHERLANDS

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## Abstract

In this paper we present the main results of a field study on the effects of cooling water discharge on fish in the outlet area of the Claus Power Plant in the Netherlands during the summer of 2006. The project was initiated by the Governmental working group MEETPOL (Monitoring Ecological Effects of Thermal Pollution, by the Centre for Water Management), which has the aim to develop a protocol to investigate the effects of cooling water discharge with respect to the new cooling water discharge guidelines in the Netherlands. The project was performed by KEMA and VisAdvies at the Claus power station at the river Meuse, near Maasbracht (the Netherlands) from May till September 2006. The aim of this study was to investigate the behavioural changes of fish during cooling water discharge when exposed to the cooling water plume. The hypothesis is that fish will actively avoid the discharged heated cooling water when the temperature of this water is higher than the comfort temperature of the fish.

The study took place in the outlet harbor of the Claus Power Plant, located near the river Meuse in the Netherlands. The cooling water is discharged into this outlet harbor and from here the water flows back into the river Meuse. Monitoring of temperature was achieved by installing Vemco Minilogs sensors at three depths in the river upstream of the power plant, directly in the outlet harbor and downstream in the river. Behaviour of fish in the outlet harbor was monitored by fixed location survey using split beam sonar (Simrad) and 3D hydro-acoustic surveys (HTI). Fish populations were sampled by means of conventional sampling using a bottom trawl and electro fishing equipment.

The heating by the Claus power station (difference between inlet temperature and the temperature at the weir in the outlet harbor) was maximal 10,0ºC and average 3,2 ± 1,6ºC during the study period. In the outlet harbor, a clear influence by meteorological conditions is present during the day. Depending on cooling water availability and river temperature, cooling takes place by once-through cooling or cooling towers. Discharge of cooling water by once-through cooling predominantly occurs during the night. In the outlet harbor (~1 km in length), the cooling water cools down before it flows back into the river Meuse. After discharge in the river, the plume remains at the right bank. During the study period, no significant heating of the river has been observed due to operation of the Claus power station. The temperature downstream in the river Meuse remains below ~28ºC and is similar to the temperature at the inlet. Based on the observation of fish, three behavioural strategies are distinguished: 1) a group of fish that shortly after marking, several hours to a few days, leaves the area and do not return, 2) a group that after a longer or shorter period, hours to days, leaves the area but visits the outlet harbor regularly, hours to days, and 3) a group of fish that is present in the outlet harbor permanently. It is noticed that when tested for presence and absence of individual fish in relation to temperature, no clear relations are found.

The study, which investigated fish populations and movement in relation to water temperature in the outlet area, provided insight into the effect of cooling water discharge during warm summers. According to the results and experiences gained during the project, recommendations are developed that can be used for application of the new cooling water regulations and for determining and designing further research.

## Introduction

To protect the environment from thermal pollution, the Dutch water authorities (Rijkswaterstaat) defined standards in 1976, which limited the permitted discharge and temperature of discharged water. During the last extreme warm summers, problems with heat discharge occurred more frequently, leading to critical situations with shortage in electricity supply due to surface water temperatures > 30ºC. Especially in the summer of 2003, conflicts arose between violating standards and the risk of economical damage due to problems with electricity production. Rijkswaterstaat gave out special consents to exceed the standards in order to warrant the national energy supply. The hot summer scenarios increased the need for new regulations for heat discharges. After the summer of 2003, new cooling water standards, including a new systematic to evaluate heat discharges, have been defined by the Dutch Commission for Integral Water Management (CIW) [1, 2]. By the new approach in these new guidelines, Rijkswaterstaat claims that a better judgment can be made for each individual situation and that the environment is as well as, or even better protected than by the former regulations.

From literature studies on the effect of heat discharges on the aquatic environment and 3D-modeling studies of heat distribution, three test criteria have been derived: withdrawal, mixing zone and heat discharge. Discussions in the Netherlands, following particularly hot summers such as 2003, have led to an understanding that stratification is to be encouraged rather than rapid vertical mixing. This is based on the hypothesis that fish can actively avoid a cooling water plume when the fish detects a clear thermocline.

Maximum heating of the water system (after full mixing) is ΔT 3°C, to a maximum of 28°C for cyprinid waters, 25°C for shellfish waters and 21,5°C for salmonid waters. Instead of the temperature limit (maximum of 30°C end of pipe), the criteria of mixing zone has been introduced. The mixing zone is the part of the water system (in the vicinity of the point of discharge), that due to the discharge of heat is brought to a temperature of ≥30°C and is bounded by the spatial 30°C-isotherm (fresh waters) (see Figure 25-1) or the 25°C-isotherm (marine waters). The new regulatory regime requires that no more than 25% of the cross-sectional area in the receiving surface water does not exceed a temperature of >30ºC. The 25% threshold was the result of political negotiation rather than being science based, but it is hypothesized that this will leave 'ecological space' for fish, *i.e.* where the water is cold enough for fish to migrate along the cooling water plume. In extremely hot summers, in the exceptional ones with high background temperatures (> 25°C), the temperature at the border of the mixing zone is allowed to be 32ºC during one continuous period of maximal one week during July and August. If this approach leads to problems with its practical implementation, the administrator can make a reasoned deviation.

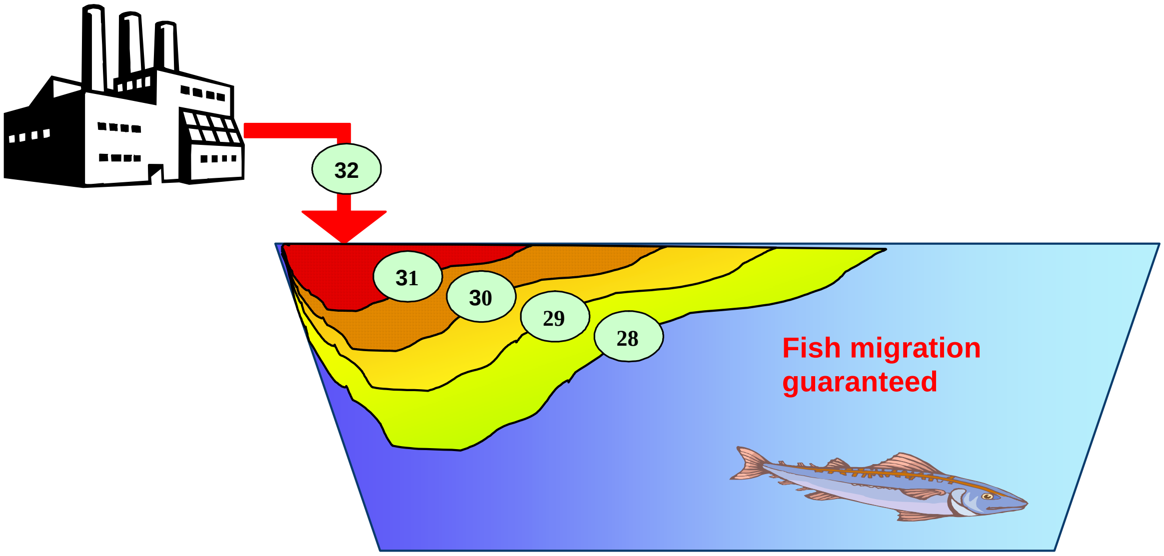

**Figure 25-1**
**Cross Section of a Water Body: 3D Modeling. The Shaded Area Represents the Area (Mixing Zone) Bounded by the Spatial 30°C-Isotherm (fresh waters) that is not Allowed to be >25% of the Total Cross Section of the Receiving Water System**

## *Project Goals*

Studying the effects of cooling water discharge on fish is necessary to investigate the effects on the ecosystem. To do this however, a study of several years would be needed. This particular study aimed to investigate the behaviour of fish when exposed to a sudden increase of the environmental temperature, i.e. when confronted with a cooling water plume. The hypothesis is that fish will actively avoid the cooling water plume when the temperature of this water is higher than the comfort temperature of the fish. For the study it was preferred to perform the monitoring during a discharge with a temperature of >30°C at the border of the mixing zone.

From the results it is evaluated whether discharge with a high temperature has a direct effect on fish. For this, the following research questions where formulated:

- What is the temperature development within the study are: is there a total increase of temperature along the total water column, or is there a clear stratification due to the cooling water plume?
- What is the inter-dependence between the temperature development in the area and operation of the power station (once-through cooling or cooling tower operation)?
- Which fish species are present?
- What is the condition of the species observed?
- What is the density fish in the area?
- Is there a specific biotope in the area?
- What fish movement take place in the area (effects of the cooling water discharge on population and individual level, day-night rhythm, seasonal effects)?

This paper presents the main results obtained during the study [3]. The project was initiated by the Governmental working group MEETPOL (Monitoring Ecological Effects of Thermal Pollution). MEETPOL has the aim to develop a protocol to investigate the effects of cooling water discharge, especially in times of high atmospheric temperatures and/or times of aridity, with respect to the new cooling water discharge guidelines in the Netherlands. The project was performed by KEMA and VisAdvies at the Claus power station at the river Meuse, near Maasbracht (the Netherlands) from May–September 2006.

## Study Area and Location

### The River Meuse

The River Meuse originates in France, runs through Belgium and Luxembourg, enters the Netherlands at Eijsden and drains into the North Sea at the Haringvliet (Figure 25-2). Total length is 935 km, including 300 km in the Dutch section. Total head is 409 m. Most water originates in the Ardennen area of Belgium and France.

Because of low soil porosity in the catchment area of the river Meuse, rainwater drains rapidly into the river. Hence river level increases quickly after heavy rains, while during dry periods water input is very limited. To provide some insight in the discharge dynamics of the river Meuse, table 1-1 presents historical discharges of the river Meuse, measured at location Borgharen in the period 1975 – 2004. Mean discharge at Borgharen, 50 km upstream from Maasbracht, is 250 $m^3/s$, peaking around January and reaching a minimum around July. Mean summer flow is 160 $m^3/s$. The sight depth is inversely proportional to water flow and varies from 20 to 130 cm. Water temperature varies from 2 to 25°C, with a mean of ~15°C.

**Table 25-1**
**Historical Discharge Values for the River Meuse at Borgharen. Data is Based on Average 24-hour Values ($m^3/s$) over the Period 1975 – 2004**

| | River Discharge ($m^3/s$) | | | | |
|---|---|---|---|---|---|
| | **Average** | **Absolute Maximum** | **Absolute Minimum** | **Average Maximum** | **Average Minimum** |
| January | 499 | 2702.0 | 48.0 | 590 | 393 |
| February | 469 | 2466.0 | 32.0 | 540 | 374 |
| March | 401 | 1815.0 | 47.0 | 465 | 358 |
| April | 295 | 1673.0 | 21.0 | 410 | 218 |
| May | 166 | 991.0 | 11.0 | 219 | 137 |
| June | 111 | 748.0 | 1.0 | 159 | 87 |
| July | 98 | 2000.0 | 1.0 | 141 | 74 |
| August | 52 | 604.0 | 1.0 | 68 | 38 |
| September | 56 | 694.6 | 1.0 | 78 | 41 |
| October | 111 | 1044.8 | <1.0 | 159 | 57 |
| November | 210 | 1759.8 | 2.0 | 269 | 152 |
| December | 385 | 2959.0 | 8.0 | 512 | 258 |

Figure 25-2 shows the discharge of the river Meuse during the study period of May 18 – September 12, 2006, measured at Borgharen (upstream the study area). During the second half of May an increase of the discharge occurred. After this, the discharge remained very low, on average <235 $m^3/s$. The consequence was that during the day, cooling mostly took place by operation of the cooling towers. During the night the cooling water system was mostly operated by once-through operation.

### The Claus Power Station

The Claus power station, owned and operated by Essent Energy BV, is located at the river Meuse, near Maasbracht in the Netherlands (Figure 25-3). It has 2 units of each 640 MWe ($\Delta T = 8K$) and a total cooling water flow of 50 $m^3/s$ (once-through, each unit maximum 25 $m^3/s$) or 5 $m^3/s$ when using its two cooling towers. The cooling water is withdrawn from an inlet harbor with open connection to the river Meuse. Whether cooling is operated once-through or by cooling towers depends on the discharge of the river Meuse and the (expected) maximum temperature of the discharge of 30°C and maximum increase of 3°C of the river. When the cooling water capacity of the river is too low and/or when the discharge drops below 235 $m^3/s$, the cooling towers are put into operation. The blow-down water from the cooling water is discharged into the inlet harbor.

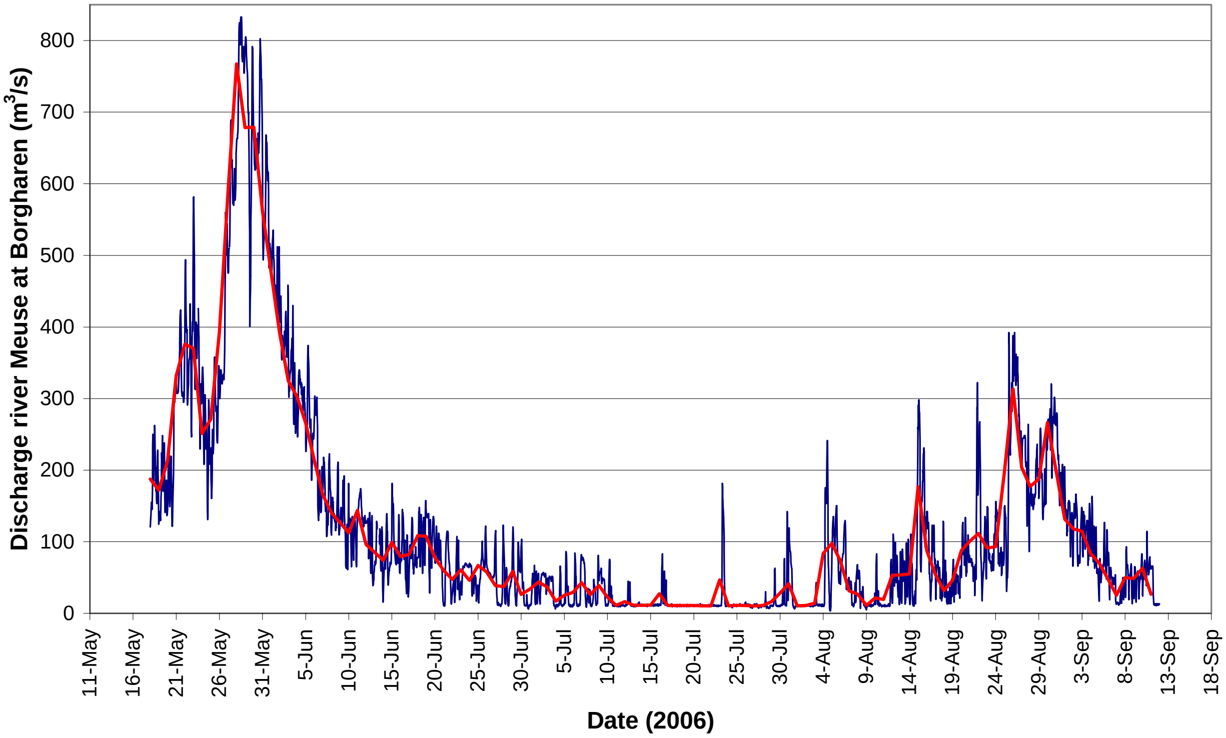

**Figure 25-2**
**Discharge on an Hourly Basis ($m^3/s$) of the River Meuse (Blue Line) and the 24-hour Average Values (Red Line), Measured at Location Borgharen During the Study Period of May 18 – September 12, 2006**

During once-through cooling (Figure 25-4) the cooling water is discharged through an outlet channel (~1.2 km long), via an overflow (weir for oxygenation of the water) into the outlet harbor, which is in open connection with the river Meuse. The outlet harbor has a length of about 1 km and has a depth of 7–9 m at the mouth and 16–20 near the discharge point. The mouth of the harbor, where the water flows into the river, is regarded as the real point of discharge with respect to the cooling water regulation. Hence, the outlet harbor is regarded as part of the cooling water circuit.

## *Fish Species in the Study Area*

In 2005 a monitoring was performed to investigate the abundance of species in the outlet harbor [4]. In total 17 species were found: Ide, Chub, Perch, Pumpkinseed, Roach, Gudgeon, Dace, Stone loach, Bream, Pike perch, White bream, Ruffe, Eel, Asp, Carp, Stickleback and Bullhead. From ecological information on the river Meuse water system it is known that 33 species are potentially may occur in the area. It was found in a desk study [5] that the outlet harbor has limited conditions to act as a spawning and nursery area for fish. Only 8 species of the total of 33 species that can occur in this area may find here habitat for spawning and for 10 species nursery possibilities are present. Some species are thought to be able to have or develop stable populations in the outlet harbor, which are mainly small species with a limited habitat, e.g.

**Figure 25-3**
**Map of the Netherlands. The Location of the Claus Power Station is Indicated in Red**

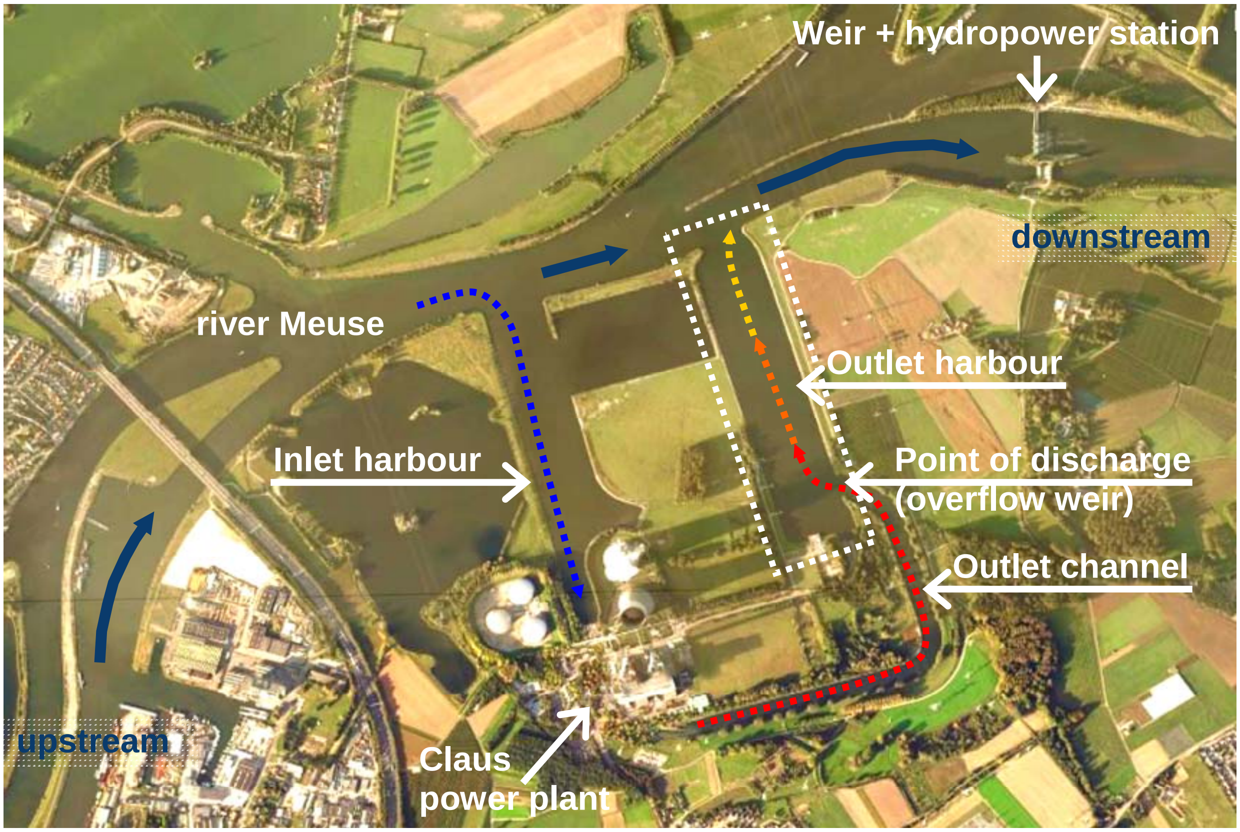

**Figure 25-4**
**Study Area (Indicated by the White Dotted Line) and Location of the Claus Power Station at the River Meuse. The Light Blue/Red/Orange/Yellow Dotted Line Indicates the Cooling Water Flow. The Dark Blue Arrows Indicate River Flow**

Pumpkinseed and Bullhead. Other, larger species are thought not to be permanently present in the area but using the outlet harbor only for foraging, spawning and nursing. As it is directly located to the river, the outlet harbor also functions as a refuge area where the fish will find shelter during periods of high river discharge. As there are higher temperatures in the outlet harbor due to the discharge of cooling water, some species may also find here a place to winter.

## Study Approach and Methods

The study aimed at providing the best possible insight in the fish stock present in the area and changes therein under influence of the cooling water discharge. Because the natural dynamics of the fish stock in the outlet harbor is not known, a continuous monitoring was chosen. Any changes in species composition and abundance that are found can be related to the temperature development in the outlet harbor. The following monitoring techniques have been applied:

- Monitoring temperature by means of Vemco Minilogs
- Conventional fish stock sampling by means of electro fishing and bottom trawl
- Fixed location survey by means of sonar (Simrad split beam)
- Hydro-acoustic telemetry (HTI model 291 system).

It was decided to perform the study within the outlet harbor (Figure 25-4), as the river dynamics and fish migration activity of tagged fish makes it very uncertain whether the tagged fish would remain in the vicinity of the hydrophones. Also, it was expected that within the outlet harbor the best situation is present to create a clear cooling water plume. However, due to river conditions the power station was not always cooled by means of once-through cooling. Hence it was not possible to discharge according to the exemption rule in the guidelines and have a discharge >30ºC to a maximum of 32ºC at the border of the mixing zone, i.e. cooling water plume. This would have been the preferred ‘worst-case’ condition under which the hypothesis could be tested.

## *Monitoring Water Temperature*

Monitoring of temperature in the outlet area was done by means of Vemco Minilogs sensors, recording the temperature at logging intervals of 30 minutes. At each location the temperature was monitored at three depths: at the bottom, at mid-depth and at the surface (-10 cm). To do so, the sensors where attached to a line that was fixated between a weight at the bottom and a buoy at the water surface (Figure 25-5).

The sensors where installed at in total 13 strategic locations within the study area (Figure 25-5). The locations indicated with red circles are those of which the results in this paper are presented.

## *Monitoring Fish Populations and Behaviour*

### Conventional Fish Monitoring

Fish populations were sampled by means of conventional sampling using a bottom trawl and electro fishing. In order to obtain proper insight in the fish stock, at least three samplings where performed, at the start, in the middle and at the end of the study period. The banks of the outlet harbor where fish by means of electro-fishing during the afternoon and evening. During the night the bottom trawl was used.

### Sonar: Fixed Location Survey

The split beam sonar provides a 3D-image of the fish in the water column. This enables analyses of the biomass, swimming direction and length distribution of the fish. As the system does not identify species, information on species was derived from the conventional fish monitoring. Two systems have been located in the direct vicinity of the cooling water discharge point in the outlet harbor. The real-time monitoring provided information on the actual fish density and fish movements at population level, among others in relation to the temperature development in the outlet harbor. Because this monitoring was started relatively early in the season, fish abundance and movements in a ‘normal’ situation could be compared with those during more extreme situations during warmer periods.

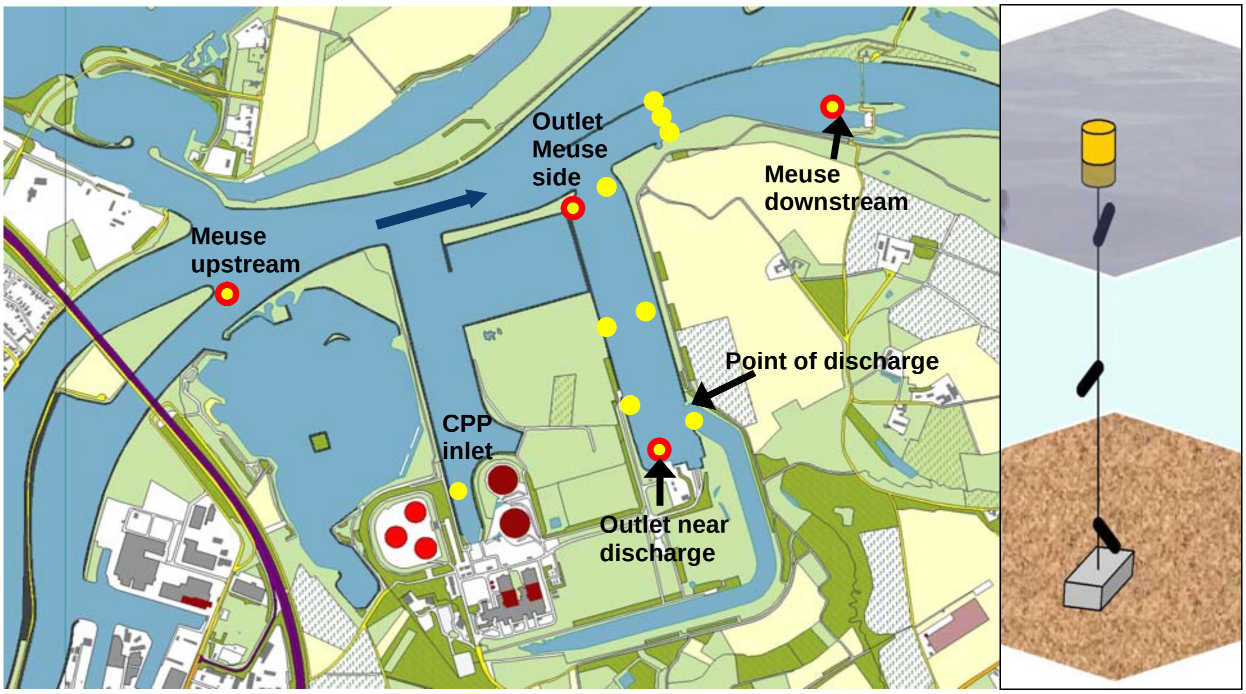

**Figure 25-5**
**Overview of the Locations of the Vemco Minilogs in the Study Area. On the Right Side a Schematic view of the fixation of the Vemco Minilogs**

## Hydro-Acoustic Telemetry

Behaviour of fish was monitored by means of 3D hydro-acoustic surveys (HTI). The acoustic tags (Model 795G), have a length of 25 mm and a diameter of 11 mm with a weight of 2,4 g (in water). At an ambient temperature of 25ºC the tags have a life span of 24 days, depending on the settings (pulse duration and frequency). The hydrophones where located directly in front of the cooling water discharge point in the outlet harbor, covering an area of ~300 x 300 m from bottom to surface (Figure 25-6).

It was planned to apply the acoustic tags for three species, Ide, Bream and Pike perch, 25 specimens per species. These species differ in temperature preference, Ide prefers lower temperature, Pike perch higher temperatures and Bream is rather indifferent. Because the number of specimens per species was found to be too low, it was chosen to tag other species as well.

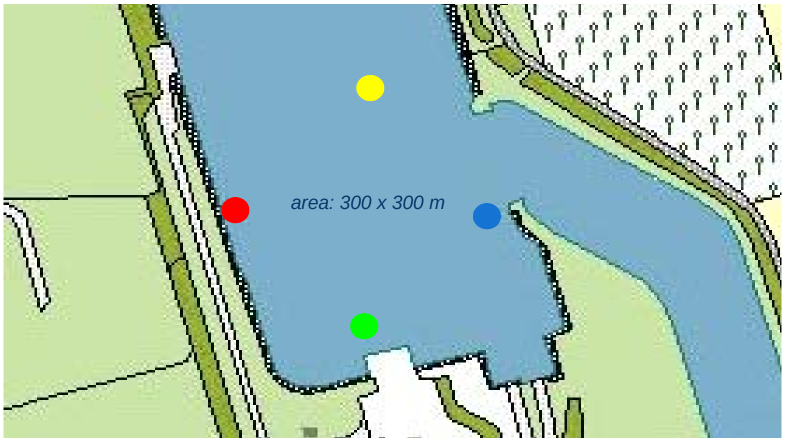

**Figure 25-6**
**Location of the Hydrophones in Front of the Cooling Water Discharge Point**

## Results

### *Temperature Monitoring*

#### Meteorological Conditions During The Study Period

The year 2006 was a relatively hot year, with 2 official heat waves. Figure 25-7 shows the atmospheric temperature and sun influx during the project period. The development of the surface water temperature in the river Meuse (Figure 25-7), as well as the inlet harbor and the outlet harbor (not shown in Figure 25-7), follow the same trend as the atmospheric temperature and the sun influx. This is observed in both the relative temperature at any time, as well as in day-night rhythm. The influence of meteorological conditions on water temperature was especially clear in the inlet and outlet harbors. During the night there is no sun influx and temperatures decrease, so there is logically less heating of the surface water. It was expected that there would be differences due to differences in operation of the cooling water system, i.e. once-through cooling or cooling tower operation. However, these differences were not very distinct. An explanation of the clear influence of the inlet and outlet harbor could be that the residence time, i.e. water flow, within these harbors is low compared to the water velocity in the river Meuse itself. Especially during cooling tower operation when only ~5 $m^3/s$ is withdrawn.

#### Monitoring Water Temperature

During the study period it occurred only a few times that both units of the Claus power station where operated at once-through cooling at the same time. Under the meteorological conditions and power station operation (which is directly depended on river discharge and water temperature), no clear cooling water plume (including a clear thermocline) occurred in the outlet harbor. However, a clear vertical temperature gradient was observed. Figure 25-7 shows a computed view on the temperature on this gradient. This temperature gradient is likely caused by both the cooling water discharge as well as by the meteorological conditions. The temperature development (increase) is found at all water levels, probably due to the low water flow through the outlet harbor. The hypothesis that fish actively avoids a cooling water plume could therefore not directly be tested.

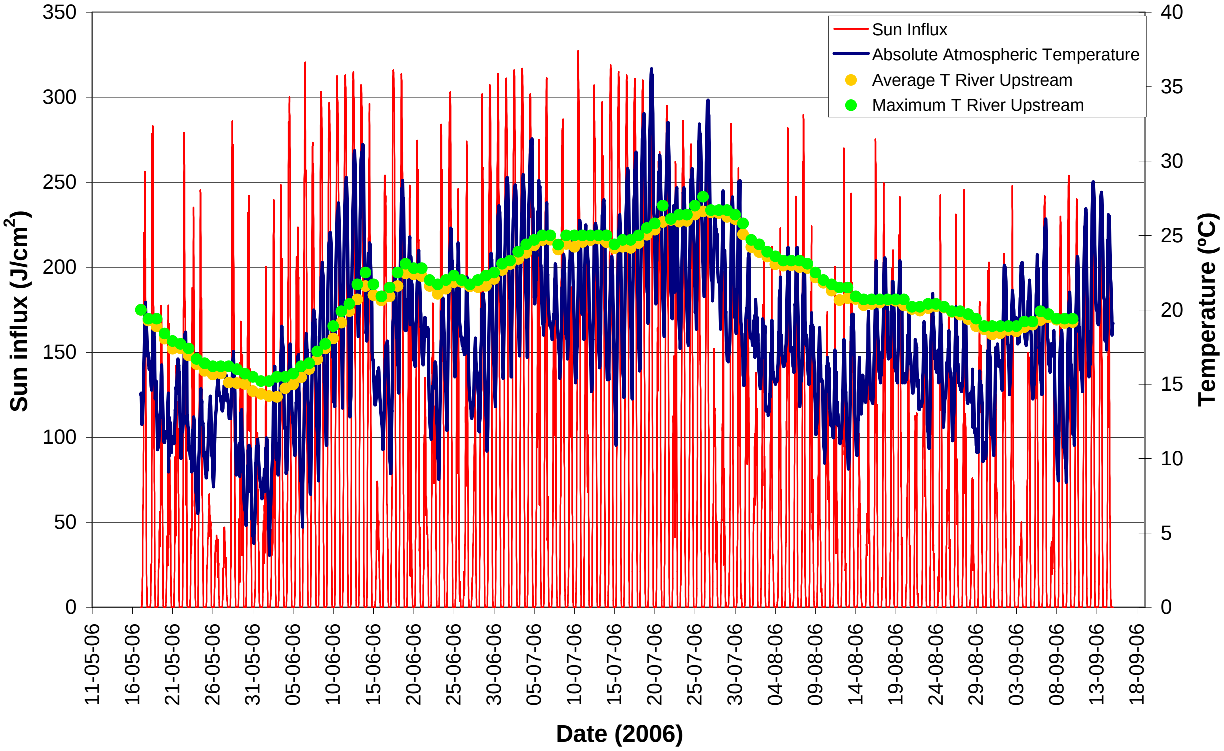

**Figure 25-7**
**Atmospheric Temperature (°C) (Blue Line) and Sun Influx (J/cm$^2$) (Red Line) during the Project Period (°C) (Source KNMI). The Maximum (Green Dots) and Daily Average (Yellow Dots) Temperature of the River Meuse Upstream are Indicated**

The heating of cooling water (ΔT as difference between the inlet temperature and the temperature measured at the cooling water discharge point in the outlet harbor) by the Claus power station was maximal 10,0ºC and average 3,2 ± 1,6ºC during the entire study period. Discharge of cooling water by once-through cooling mainly occurred during the night. However, the temperature of the outlet harbor was predominantly lower during the night than during the day. This observation is an indication that during the day there is a clear influence of the meteorological conditions (air temperature and sun influx) on the water temperature in the outlet harbor.

The water temperature decreases from the point of discharge to the mouth of the outlet harbor where the harbor discharges into the river Meuse (see Figure 25-8 through Figure 25-11). So the discharge cooling water has cooled down before it is discharged into the river Meuse. At the river Meuse, the cooling water remains predominantly at the right side of the river.

At the river Meuse no significant increase of water temperature, measured as daily average, was observed. The absolute maximum temperature was < 30ºC at the water surface and the maximum temperature as daily average was ~28ºC. This temperature resembles the temperature measured at the inlet of the Claus power station. Ranges in ΔT (as difference between $T_{upstream}$ and $T_{downstream}$ as daily average values) where 0 – 3,59ºC at the surface and 0 – 1,34ºC at the bottom. Also at the river it was found that meteorological conditions had a clear influence on the surface water temperature.

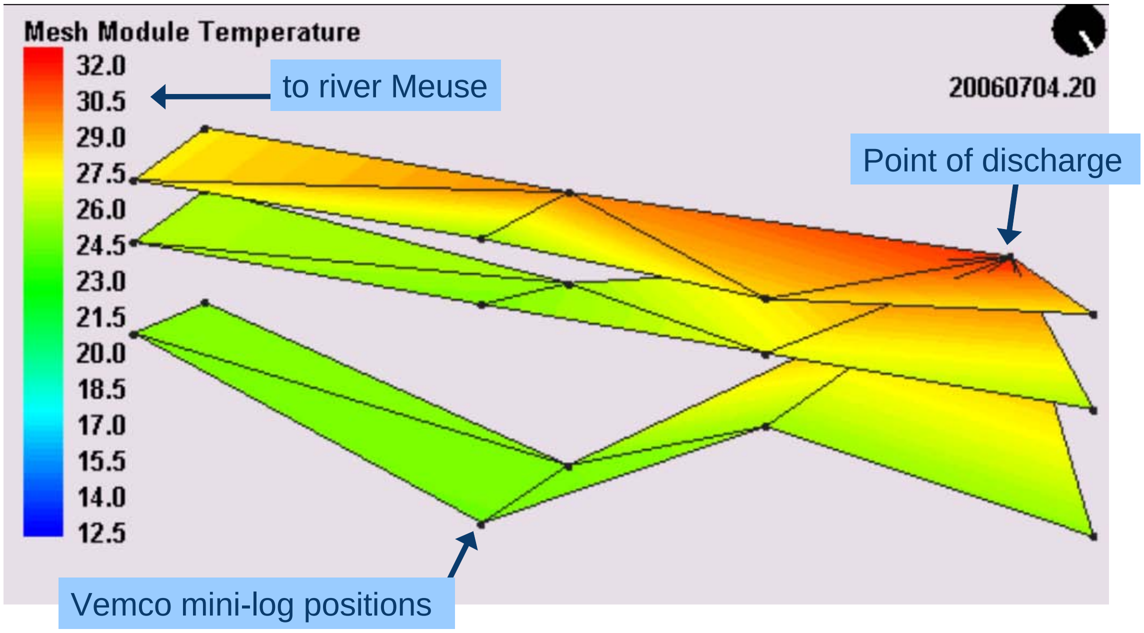

**Figure 25-8**
**Computed Drawing of the Temperature Gradient (Three Depths) in the Outlet Harbor**

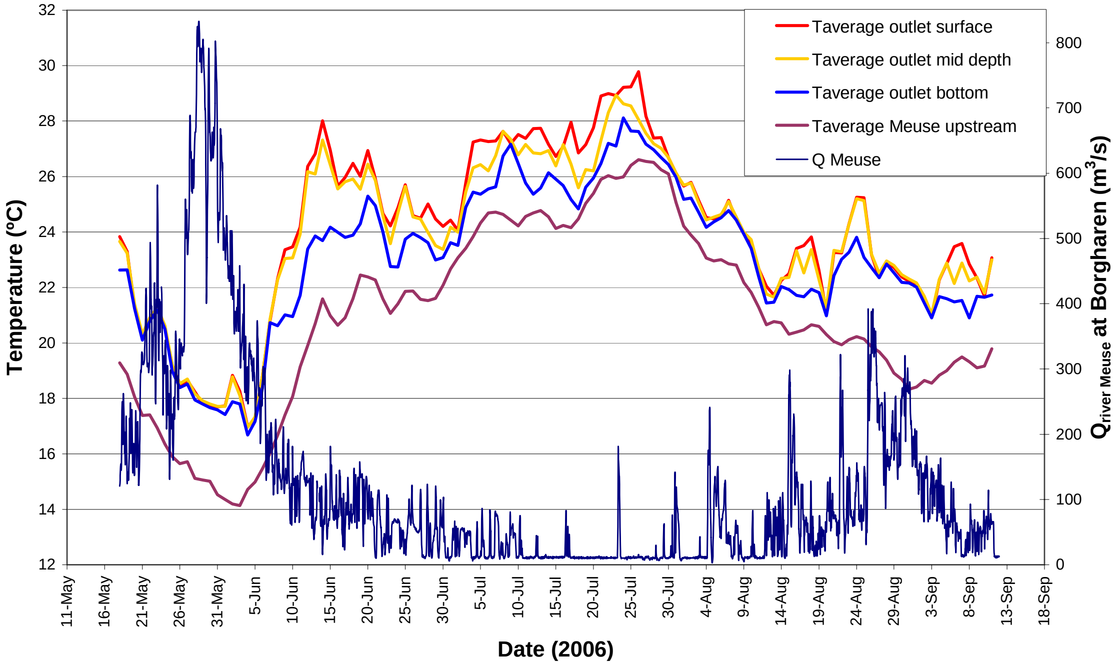

**Figure 25-9**
**Temperature Development (as daily average) Near the Point of Discharge in the Outlet Harbor, Measured at the Bottom, Mid-Depth and at the Surface (-10 cm)**

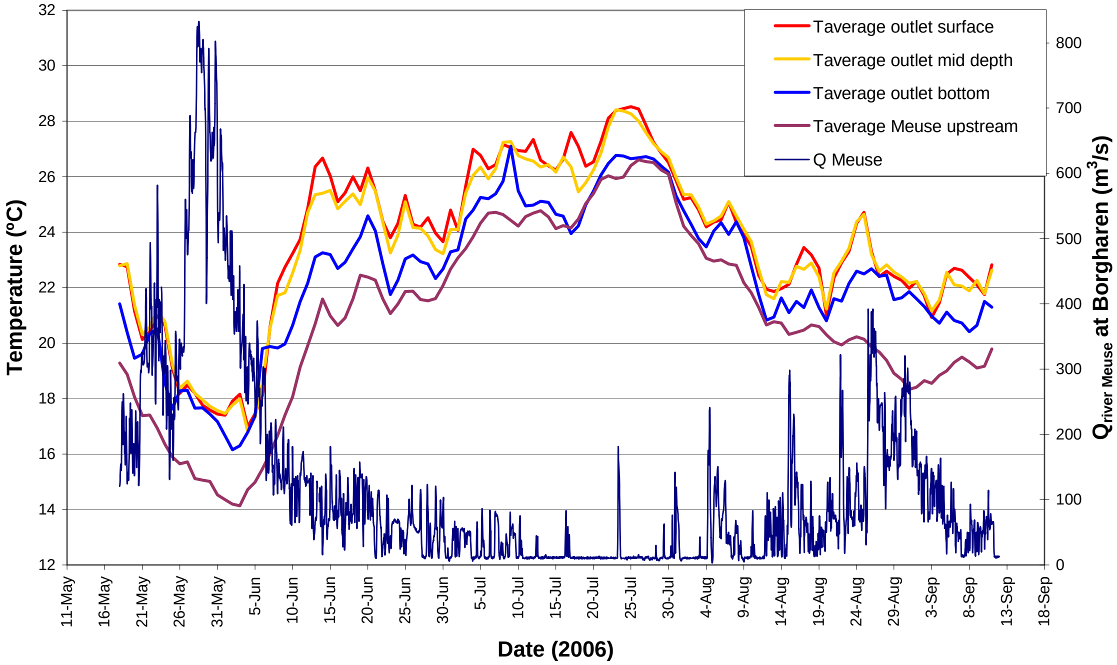

**Figure 25-10**
**Temperature Development (as daily average) Near the Mouth of the Outlet Harbor Close to the River Meuse, Measured at the Bottom, Mid-Depth and at the Surface (-10 cm)**

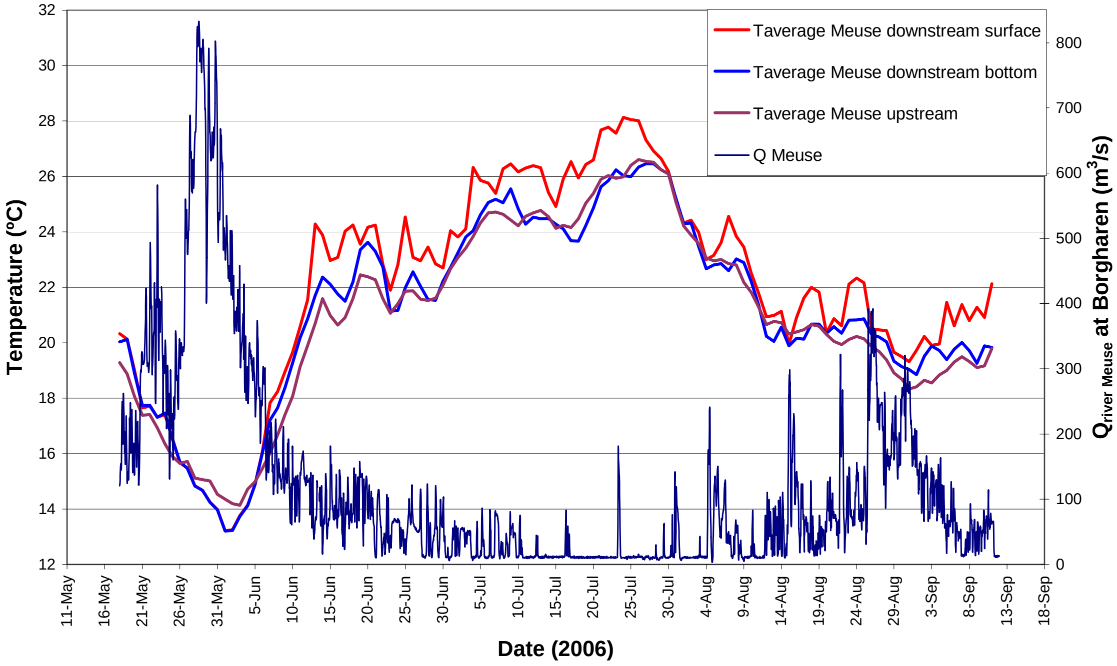

**Figure 25-11**
**Temperature Development (as daily average) Downstream in the River Meuse, Measured at the Bottom and at the Surface (-10 cm)**

## *Fish Stock Monitoring*

### Conventional Fish Monitoring

By both the sonar and fish stock samplings a major increase in juveniles was observed during the second half of June. The contribution of fish >15 cm in the catches was highest during the first fish samplings at the end of May (22%). During the following samplings this contribution decreases to 2% at the end of June and 3% at the end of July. Also in absolute numbers the portion of larger fish is lowest in June and mainly in July. This is in accordance with the observations by the sonar.

During the samplings the presence of a Pumpkinseed population (occurrence of different length classes, i.e. age classes) in the outlet harbor was observed. Also, the number of hybrids, probably hybridization between Bream and Roach, is very high. Both observations are likely related to the higher temperatures within the outlet harbor throughout the year. Pumpkinseed prefers higher temperatures and would probably not survive during the cold winter period. Also, hybridization between Roach and Bream can occur when the spawning periods overlap due to local higher temperatures. The observations in this study do not provide clear evidence for this, but it seems likely to happen.

The fish species found in the outlet harbor are very similar to the species in the river Meuse that are generally always observed during the yearly National Water Quality Monitoring Program (MWTL) over the years 1995–2002 [6,7,8]. Typical riverine species are hardly observed in the outlet harbor, probably because proper habitat is lacking. However, this could also be an effect of the higher temperature in the outlet harbor, as in general riverine fish species prefer lower temperatures.

### Sonar: Fixed Location Survey

The sonar showed a significant day-night rhythm for fish >15cm. For fish <15 cm only a slight, not significant day-night rhythm was found. This rhythm might be related to temperature, as during the night the water temperature in the outlet harbor is often several deg. C. lower then during the day. The sonar observations also showed a negative correlation between the number of fish >15 cm and the 24-hour average water temperatures during the study period: during periods of higher temperature the number of fish >15 cm is smaller (Figure 25-12). This might indicate that larger fish actively avoids higher temperatures.

## Table 25-2
## Overview of the Fish Species Found During the Fish Monitoring in the Outlet Harbor

| | **Electro Fisheries** | | | | | | | | | **Bottom Trawl** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **May 30** | | | **June 27** | | | **July 25** | | | **May 30** | | | **June 27** | | | **July 25** | | |
| | **Length** | | **n** | **Length** | | **n** | **Length** | | **n** | **Length** | | **n** | **Length** | | **n** | **Length** | | **n** |
| | **min** | **max** | | **min** | **max** | | **min** | **max** | | **min** | **max** | | **min** | **max** | | **min** | **max** | |
| Asp | 5 | 13 | 4 | 3 | 15 | 24 | 6 | 22 | 25 | 11 | 83 | 2 | | | | | | |
| Bleak | | | | | | | | | | 7 | 7 | 1 | | | | | | |
| Bream | 3 | 3 | 2 | | | | | | | 9 | 52 | 110 | 12 | 42 | 41 | 25 | 48 | 21 |
| Bullhead | 7 | 7 | 1 | | | | | | | | | | 82 | 82 | 1 | 43 | 43 | 1 |
| Chub | 5 | 51 | 4 | 51 | 51 | 1 | | | | | | | | | | | | |
| Crucian carp | | | | | | | 16 | 16 | 1 | | | | | | | | | |
| Eel | | | | 23 | 53 | 5 | 29 | 45 | 3 | 55 | 81 | 3 | | | | | | |
| Gudgeon | | | | | | | 6 | 8 | 4 | | | | | | | | | |
| Hybrid | | | | | | | | | | 23 | 23 | 1 | | | | | | |
| Ide | 4 | 50 | 4 | 6 | 6 | 1 | 6 | 12 | 81 | | | | | | | | | |
| Nose carp | | | | 4 | 6 | 5 | 6 | 6 | 1 | | | | | | | | | |
| Perch | | | | 13 | 13 | 2 | 5 | 13 | 5 | | | | | | | 44 | 44 | 1 |
| Pike | | | | 23 | 23 | 1 | | | | | | | | | | | | |
| Pike perch | 4 | 4 | 1 | 4 | 9 | 3 | | | | 3 | 81 | 32 | 3 | 49 | 1556 | 5 | 81 | 333 |
| Pumpkinseed | 7 | 15 | 6 | 7 | 10 | 6 | | | | | | | | | | | | |
| Roach | 3 | 3 | 2 | 3 | 12 | 54 | 5 | 11 | 212 | 7 | 14 | 24 | 3 | 5 | 332 | 5 | 8 | 222 |
| Rudd | | | | | | | 9 | 12 | 2 | | | | | | | | | |
| Ruffe | | | | | | | | | | | | | | | | 9 | 9 | 2 |
| Stone loach | 8 | 8 | 1 | 4 | 9 | 6 | 8 | 8 | 1 | | | | | | | | | |
| Tench | 6 | 6 | 1 | 8 | 8 | 1 | | | | | | | | | | | | |
| White bream | | | | | | | | | | 20 | 20 | 1 | 36 | 36 | 1 | | | |
| **Total** | | | **26** | | | **109** | | | **335** | | | **174** | | | **1931** | | | **580** |

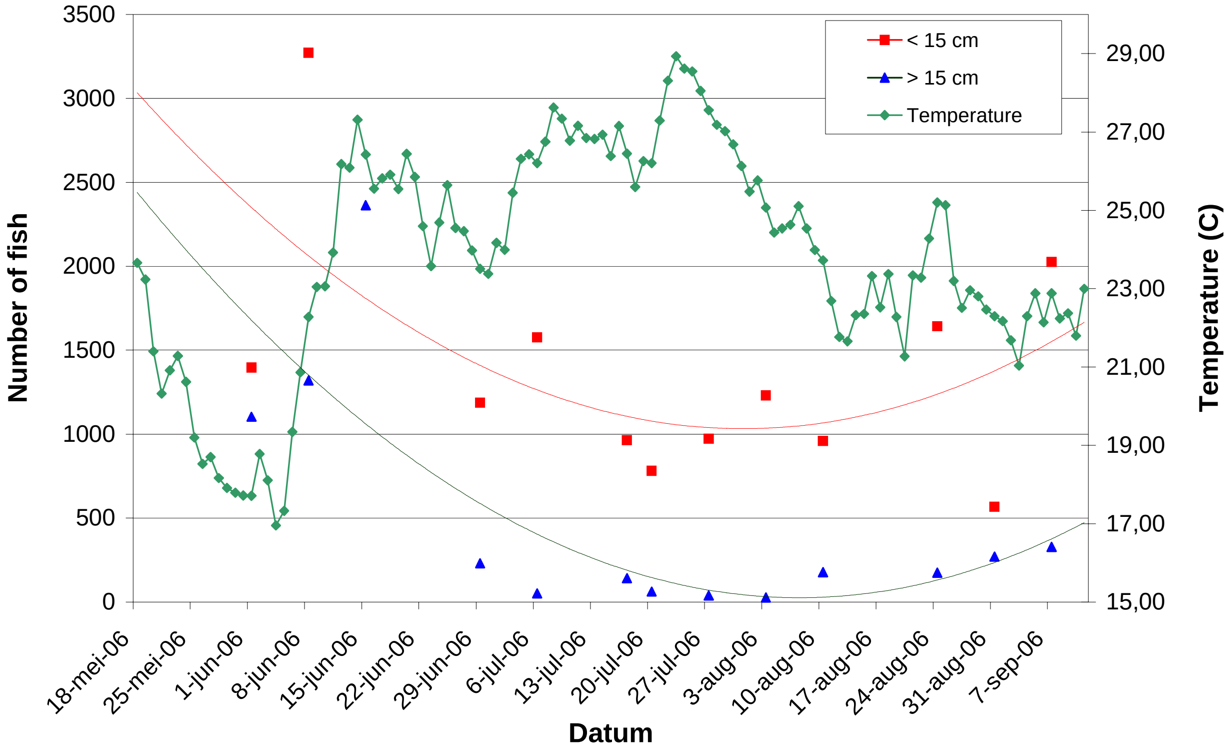

**Figure 25-12**
**Sonar Observations (n Fish) in Relation To Temperature**

## Hydro Acoustic Telemetry

During the project, the tagging of fish for the hydro acoustic survey took place at three moments. On June 28 group 1 (21 specimens) was tagged and released. A July 26 and 27 group 2 (23 specimens) and at August 28 group 3 (24 specimens) were tagged and released. Based on the observation that the individual reaction of the fish between these three groups are different, three behavioural strategies are distinguished. The characteristics of the reactions after tagging and release in the outlet harbor are:

- Group 1: relatively short presence (2 stayers/10 out within hrs – days)
- Group 2: relatively short, but regularly return (4 stayers/12 out within hrs – days, but return)
- Group 3: constantly (10 stayers/5 out for short period)

The temperatures during tagging and release were (as daily average temperature): 24°C at June 28; 27°C at July 26 and 27 and 21°C at August 28). The different reactions of each group could be an indication that their behaviour is related to the temperature in the outlet harbor. However, when tested individual fish, no relation was found between the absence or presence of individuals and temperature. Group 1 and 2 have been released during highest temperatures, but no significant relation between abundance and temperature was found. However, some fish are always present at high temperatures and a number of fish show to be indifferent to increased temperatures at all.

## Discussion and Conclusions

This study was the very first project in the Netherlands in which the effect of the discharge of heated cooling water on fish was investigated in the field. The former regulation was fully based on knowledge from literature, studies in laboratories and the idea that the discharge of cooling water is extremely harmful to aquatic ecology. The discharge of cooling water was limited by a maximum end-of-pipe temperature of 30ºC. Also, the discharged cooling water should fully mix with the receiving water to a maximum ΔT of 3ºC. However, in the past no large scale fish kills related to cooling water discharge were recorded. Only on two occasions an effect was observed, but these occurred in situations of a closed cooling circuit in small canal with no water circulation. The effect was indirect and caused by too low oxygen levels.

The new CW regulations are based on the assumption that fish is able to actively avoid the heated cooling water when the temperature of this water is higher than the comfort temperature of the fish. Heated cooling water that is discharged in such a way that stratification occurs, will 'float' on top of the cooler receiving water, i.e. form a plume, and spread along the surface and relatively quick dissipate heat to the atmosphere. The warmer the cooling water, the better it is possible to have such a stratified discharge and clear cooling water plume. 3D-modeling studies and field measurements confirm this. It is thereby thought that when limits are provided for the cooling water plume, i.e. mixing zone, ecological space for fish to take refuge or migrate through along the plume, is safeguarded. The aim of this study was to investigate this assumption in the field by observation of behavioral changes of fish during cooling water discharge, when confronted with a (sudden) increase in temperature due to a cooling water plume.

The hypothesis could however not be tested directly. During the field study it has only occurred a few times that both units of the Claus power station where operated in once-through cooling simultaneously during the day, but only for a short period. Because of these circumstances it was not possible to distinguish a cooling water plume with a corresponding distinct temperature gradient (thermocline). However, a clear vertical temperature gradient was found.

The summer of 2006 was a very warm period with low river discharge and the hottest July-month in 300 years, with two official heat waves, from June 30–July 6 (with maximum temperature of 32ºC) and from July 15–July 30(with maximum temperature of 35.7ºC). It was found that the temperature in the outlet harbor is markedly influenced by meteorological conditions. The temperature development (trends in increasing and decreasing temperature) occurred at all depths, during both day and night.

Before the discharged cooling water reaches the river Meuse, it has already cooled down within the outlet harbor. Overall the residence time of cooling water in the outlet harbor is relatively long. After flowing back into the river Meuse, the heated water remains predominantly at the right side of the river. During the study period, no significant increase (i.e. ΔT > 3°C as stated in the cooling water guidelines) of the river temperature due to the cooling water discharge has been observed. The absolute maximum temperature was < 30ºC at the water surface and the maximum temperature as daily average was ~28°C. This temperature resembles the temperature measured at the inlet of the Claus power station.

The fish samplings have shown that there is no specific biotope in outlet harbor which is adjusted to increased temperatures, although it was observed that there is a population of Pumpkinseed present in the outlet harbor, as well as hybrids. This could be an indication that an increased temperature in the outlet harbor does have some effect on fish, *i.e.* a warmer area where Pumpkinseed can survive during the winter and overlap of spawning periods between different species. Overall there is a group of indifferent species that is always present and a group of species that changes in time and is only present in small numbers (guest and opportunistic species such as Asp and Wels). A clear relation with temperature and the abundance of species has not been found.

It is concluded that higher temperatures are accompanied by less fish > 15 cm, which could be an indication of active avoidance of higher temperatures in the outlet harbor by larger fish. However, no clear relation between fish abundance, condition of fish and temperature in the outlet harbor has been found, which could be an indication of adaptation to temperature. Also, no individual reaction to a thermocline or sudden increased temperature was observed as these circumstances did not occur during the project. However, based on the observations by the hydro acoustic survey, several behavioral strategies by groups of fish have been distinguished in relation to temperature. However, it is also noticed that when it is tested on the presence and absence of individual fish in relation to temperature, no clear relations are found. Occurrence of hybrids, exotic species and fluctuations in biomass have been observed frequently. Presence of hybrids and exotic species are probably related to higher temperatures and subsequent overlap of breeding seasons.

## Acknowledgements

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# 26

# ADVANCES IN THERMAL PLUME MODELING

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## Introduction

Thermal plume modeling refers to the delineation of velocities and temperatures near heated water discharges usually associated with electric power plants that utilize once-through cooling. Major advances in thermal plume modeling came during the late 1960s through the early 1980s with the construction of numerous plants located at sites on the coast, Great Lakes and large rivers. With the decrease in the number of new plants using once-through cooling, model development work slowed, and as a result, many of the technical challenges that faced modelers twenty years ago, are still with us. Nonetheless, a number of modeling advances have taken place; this paper describes some of them.

## Types of Models

As illustrated in Figure 26-1, most thermal plume models can be divided into three types. 1) 3-D far field (and complete field) models compute time-dependent temperatures and velocities in three dimensions over a prescribed domain, which is usually discretized using either a finite difference or a finite element grid. A complete field model simulates conditions over the entire domain, while a far field model omits the near field, and must be coupled with a near field model (discussed in more detail below). 2) 1-D near field (initial mixing) jet/plume models integrate the fluxes of mass, momentum and thermal energy over the plume cross-section, then use 1-D numerical techniques to compute values of velocity, temperature and width/depth along the plume centerline. An assumption self-similarity allows plume details to be resolved in the coordinate directions normal to the plume centerline. 3) 0-D near field (initial mixing) models provide simple correlations of plume properties (e.g., minimum dilution, maximum plume depth) as a function of discharge and ambient conditions.

### *3D Numerical Models*

A nice summary of numerical models used for thermal plume calculations was provided as part of the First Thermal Ecology and Regulation Workshop conference [1]. Such models have become more commonplace in recent years due to increased computation speed. In addition, improved field instrumentation, such as acoustic Doppler current profilers (ADCPs) and wireless data loggers, have made it easier to provide data for model input and validation.

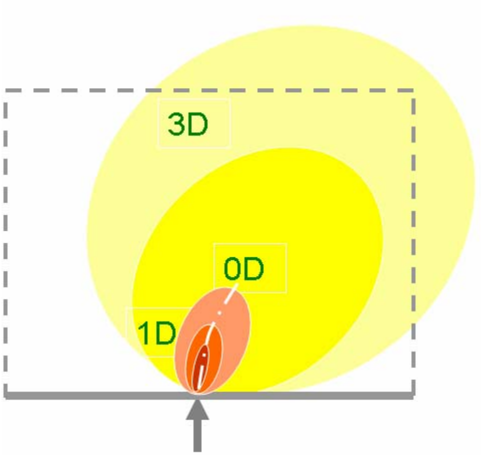


**Figure 26-1**
**Types of Models**

One of the continuous challenges for numerical plume models is specifying open boundary conditions. This is most difficult for coastal or large lake sites where the size of the water body exceeds the model domain, requiring that a substantial fraction of the domain boundary be ‘open’. What temperatures do you specify on an open boundary when the tide reverses and brings back water that is warmer than ambient due to previously discharged waste heat? This situation is usually treated in an ad hoc manner, e.g., by assigning the boundary temperature during incoming tide to be a time-varying weighted average of the last computed boundary temperature during outgoing tide and an ‘ambient temperature’, with the weighting depending on the elapsed time since the tidal reversal.

Another challenge is how to represent the near field. The magnitude of the problem depends on the amount of initial mixing: if the discharge gets high dilution as a result of high discharge momentum, it is important to represent this near field mixing properly, in order that the downstream far field temperatures will be correct. In principle this requires a highly resolved numerical grid. Grid resolution can be achieved by using variable grid sizes, as is common in finite element grids, or by nesting a highly resolved inner grid inside a more coarsely resolved outer grid. However, to truly resolve the jet entrainment that is responsible for mixing requires grid sizes of less than the jet width/depth, which could mean grid sizes of a few tens of centimeters, compared with model domains that may be a few tens of kilometers—a factor of five orders of magnitude! In practice, complete field models are sometimes ‘calibrated’ by adjustment of grid sizes or ambient diffusion coefficients, which serve as surrogates for entrainment. This is the approach used in the example of Boston’s wastewater outfall described below. An alternative is to couple the far field model with a near field model, as describe in a later section.

## *Boston’s Outfall*

As an example of the calibration of a complete field model, we use Boston’s wastewater outfall. Marine wastewater discharges are similar to thermal discharges in that both are positively buoyant, though the former are usually more buoyant as a result of larger density differences and smaller effluent flow rates.

Boston now discharges its wastewater into Massachusetts Bay through a 9 mile long tunnel which terminates in 53 risers that each discharge effluent into about 30 m of water through a diffuser head containing 8 ports. Figure 26-2 shows predicted rise height and dilution under summer (thermally stratified) conditions as predicted by a near field model (EPA's ULINE model) [2] and a far field model (ECOMsi) [3]. Reasonable agreement was obtained despite the fact that the lateral plume dimension (taken as 10% of the water depth, or about 3m) was 2-3 orders of magnitude smaller than the typical far field grid size of order 1000m.

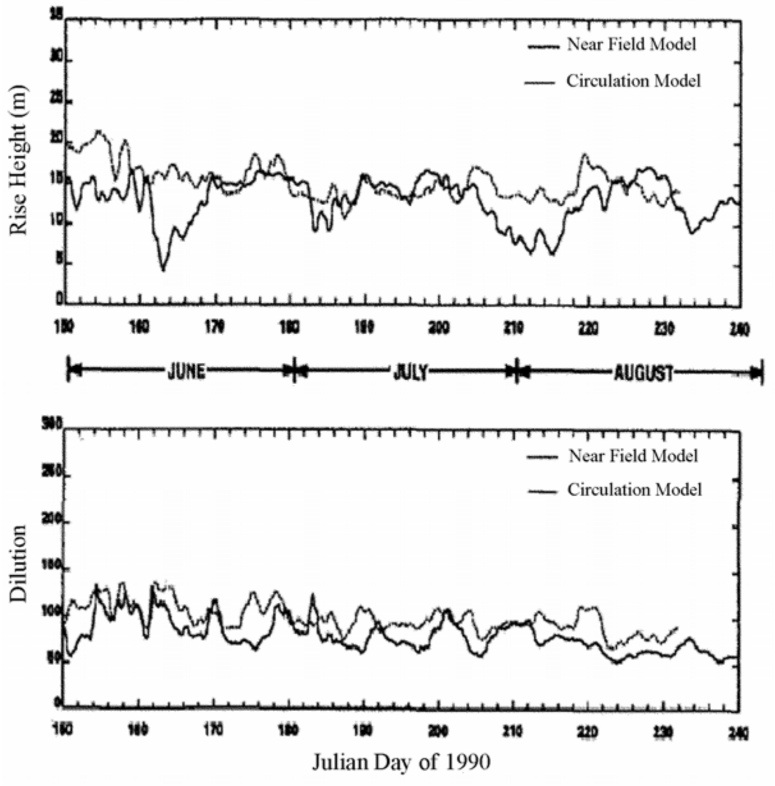


**Figure 26-2**
**Near Field and Far Field (Circulation) Model Simulations of Rise Height and Dilution of Boston's Wastewater Effluent Plume [3]**

How can this be? It turns out that the plume rise height and dilution predicted by ECOMsi are strong functions of horizontal and vertical grid sizes, and horizontal and vertical diffusivities (Figure 26-3). By judicious choice of these parameters, one can generate the correct mixing, but it is not by properly simulating entrainment [4]. (Note that the predicted rise height improves as grid spacing gets *larger* rather than smaller.) Other factors which can contribute to good agreement, particularly for submerged buoyant discharges, include 1) the fact that dilution is controlled not only by jet entrainment, but also by density exchange flow, a far field process that can be resolved by reasonably small *vertical* grid cells, 2) the forgiving relationship between trap height and dilution (if a model over-predicts the rate of dilution, it will tend to under-predict rise height, which will give the plume less height over which to entrain, leading to less dilution), and 3) the fact that ambient density profiles tend to be two-layered causing the plume to become trapped at the base of the pycnocline, regardless of the degree of mixing [4]. While in this example a complete field model was able to adequately reproduce initial mixing, with the help of appropriate adjustment of model parameters, one is not always so lucky!

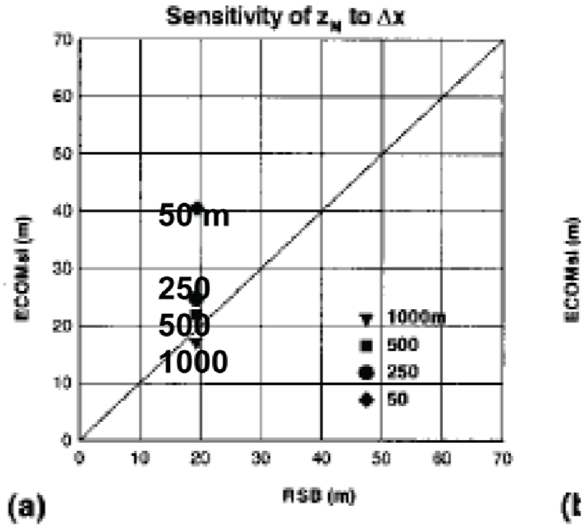


**Figure 26-3**
**Comparison of Plume Rise Heights Predicted with a Near Field Model (RSP) and a Far Field Model (ECOMsi) using Varying Grid Sizes [4]**

### *1D and 0D Initial Mixing Models*

A number of initial mixing models are now in use including CORMIX, VISJET, VISUAL PLUMES and RSB [5-8]. Many of these have been developed for related applications such as wastewater or dredged material disposal, but can be used for thermal discharges.

While the basic physics underlying these models has not changed much, model accuracy has improved as the result of improved laboratory data, made possible by modern instrumentation such as laser induced fluorescence (LIF) to measure dye concentrations, and particle image velocimetry (PIV), acoustic Doppler velocimetry (ADV) and Laser Doppler velocimetry (LDV) to measure velocities [9]. Indeed over the past two decades, many of the classical laboratory experiments that have provided data for model calibration have been re-run to yield more precise model coefficients.

Perhaps the most common near field model is CORMIX, which is based on a jet classification scheme that allows the model to analyze thermal plumes using the most appropriate module. Their most recent scheme, as applied to surface jets, is illustrated in the top portion of Figure 26-4 [5]. The bottom portion shows LIF images of laboratory plumes typifying the four principles plume classes. The data for classification continues to improve, but there are still many cases that don't fit any particular module, e.g., sites characterized by irregular topography or bathymetry.

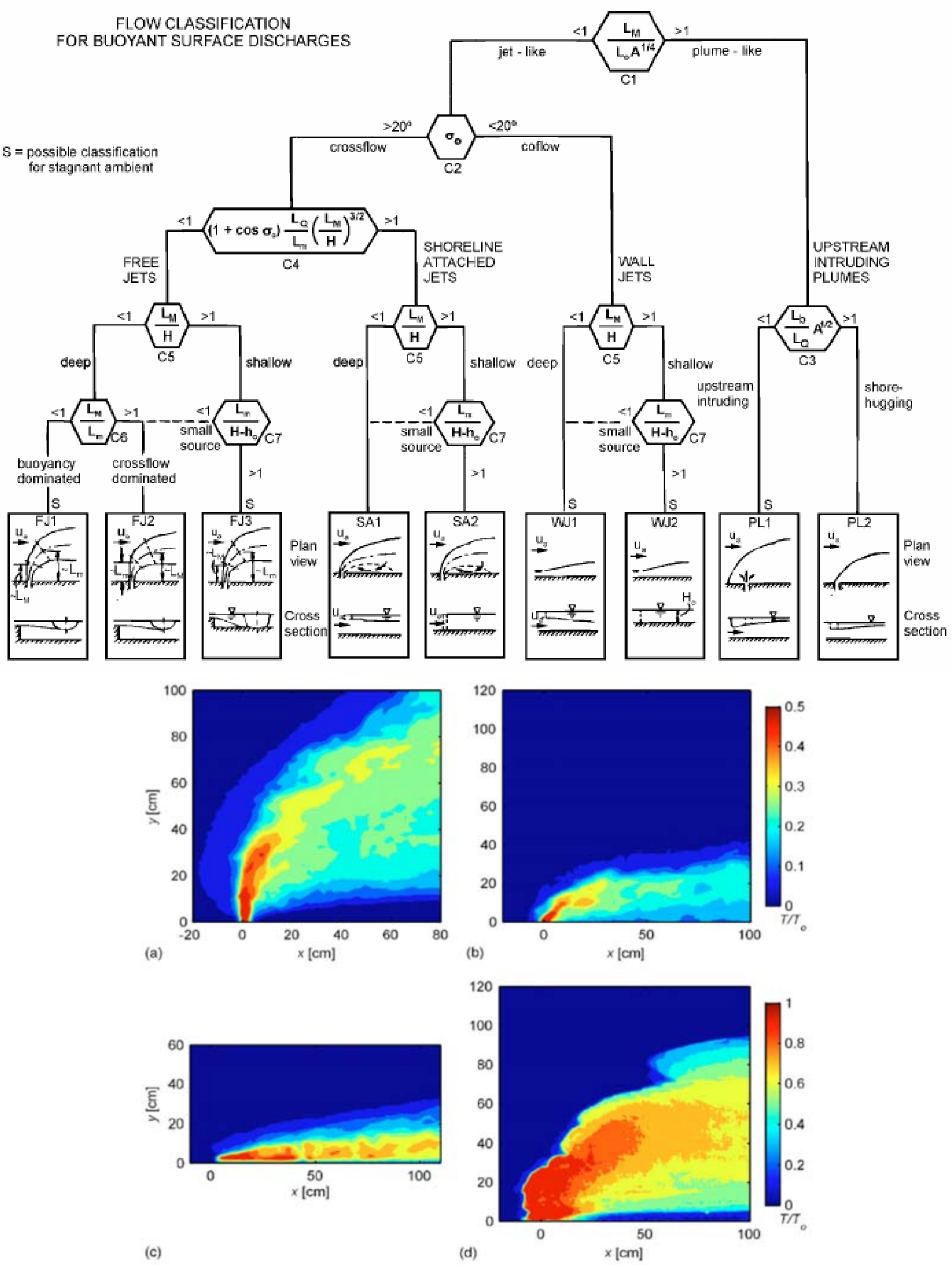


**Figure 26-4**
**The CORMIX Classification System with Application To Surface Jets (top). Images Illustrate Principal Classes: (a) Free Jets, (b) Bottom Attached Jets, (c) wall Jets, and (d) Upstream Intruding Plumes [5]**

Another basic challenge with 1D integral models is that they rely on the assumption of self-similarity, which breaks down for surface discharges. A dimensionless number which describes the relative important of plume momentum to buoyancy is called the densimetric Froude number, F, and a local value of F can be shown to decrease along the centerline of a surface discharge plume, indicating that buoyancy is becoming more important as the distance from the outfall increases [10]. In the absence of an ambient current to remove the heat, the temperature will simply build up as indicated in the thermal image from the Pilgrim Nuclear Power Station shown in Figure 26-5. This phenomenon has been well known, but most models that rely on the notion of self-similarity must provide a ‘fix up’ to account for re-entrainment of previously discharged water. The only true alternative is to use a complete field model with high resolution in the near field which can become expensive.

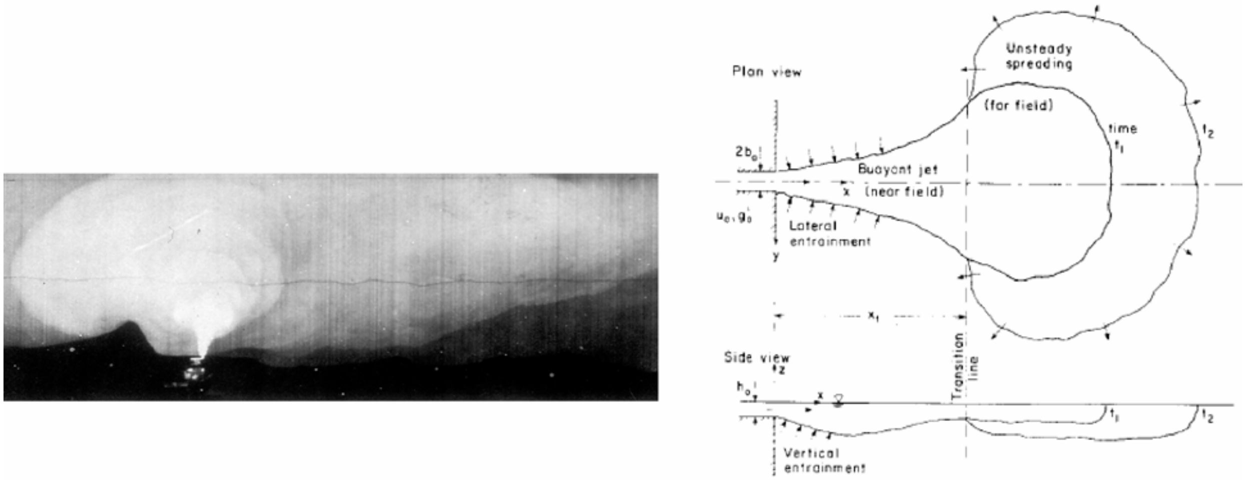


**Figure 26-5**
**Thermal Image of Surface Discharge in A Quiescent Ambient (Left) and Depiction of Time-Varying Heat Build-Up after [10]**

## Coupling Near and Far Field Models

One of the significant efforts in thermal plume modeling has been the attempt to couple near and far field models, the basic motivation, of course, being the dramatic range in spatial scales. There are several basic approaches: 1) direct simulation using ‘calibrated’ complete field models as discussed above, 2) use of separate near and far field models, 3) use of hybrid (Eulerian-Lagrangian) models, and 4) distributing sources/sinks within a numerical model.

### *Separate Near and Far Field Models*

Near field models implicitly assume that the discharge is mixing with clean (unheated) ambient water, but reversing tidal currents, wind, or simply stagnant ambient currents, may have caused previously discharged water to have returned to the discharge site, leading to background temperature build-up. As illustrated in the following example, this can be treated, in principle, by first running a far field model to determine the background temperature, and then running the near field model which is assumed to entrain water of the previously computed background temperature. Of course care must be taken to not ‘double account’ heat sources.

## Salem Station

Figure 26-6 shows an example of the use of separate near and far field models in a study of the Salem Station on the Delaware River in New Jersey [11]. CORMIX was used to analyze mixing from the submerged diffuser discharge, and the finite element package RMA10/11 [12] was used to simulate far field mixing in the Delaware River. Because the trajectories of the two models did not quite ‘match’, a transition region was developed to provide a smooth transition in temperature and trajectory.

Another issue tackled in this application was the computation of ambient temperature. One of the objectives in the thermal plume analysis was to determine the size of various mixing zones, defined by the length, area or volume over which the plume temperature exceeds the ambient temperature. But in a tidal river, with excursions of several miles in either direction, how do you measure ambient? The process entailed using meteorological data to compute thermal fluxes from a well mixed ambient water body, representing the Delaware River. Unknowns in this procedure included an average water depth, which affects the thermal response of the water body, and a temperature offset, which were both calibrated against field data collected nearby. The ambient temperature model could then be combined with the near and far field models, and run with historical time series of meteorological data, to determine the probabilities that certain temperatures thresholds would be exceeded.

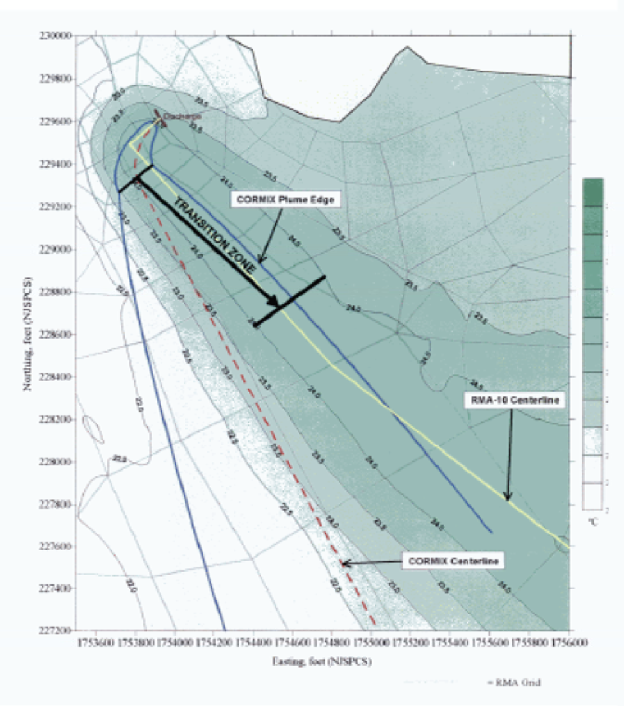


**Figure 26-6**
**Matching Near and Far Field Model Predictions at the Salem Station**

## Hybrid Models

A second way to interface near and far field processes is to use ‘numerical particles’ to extend near field calculations into the far field. Figure 26-7 shows an application where the results of a submerged near field plume are extended using particles introduced at the water surface after plume surfacing [13]. Simulated concentrations (not shown) were in good agreement with laboratory measurements. A related approach uses Gaussian puffs to model transport in the intermediate field between near and far fields [14]. The puffs are advected by the numerically computed ambient current, and allowed to diffuse in accordance with a user-specified relative diffusion relationship, until such time as their size is sufficient to allow their concentrations to be projected onto a numerical grid. Numerical simulations suggest that such hybrid techniques can be more accurate than pure Eulerian models, and more computationally efficient than pure Lagrangian models [15].

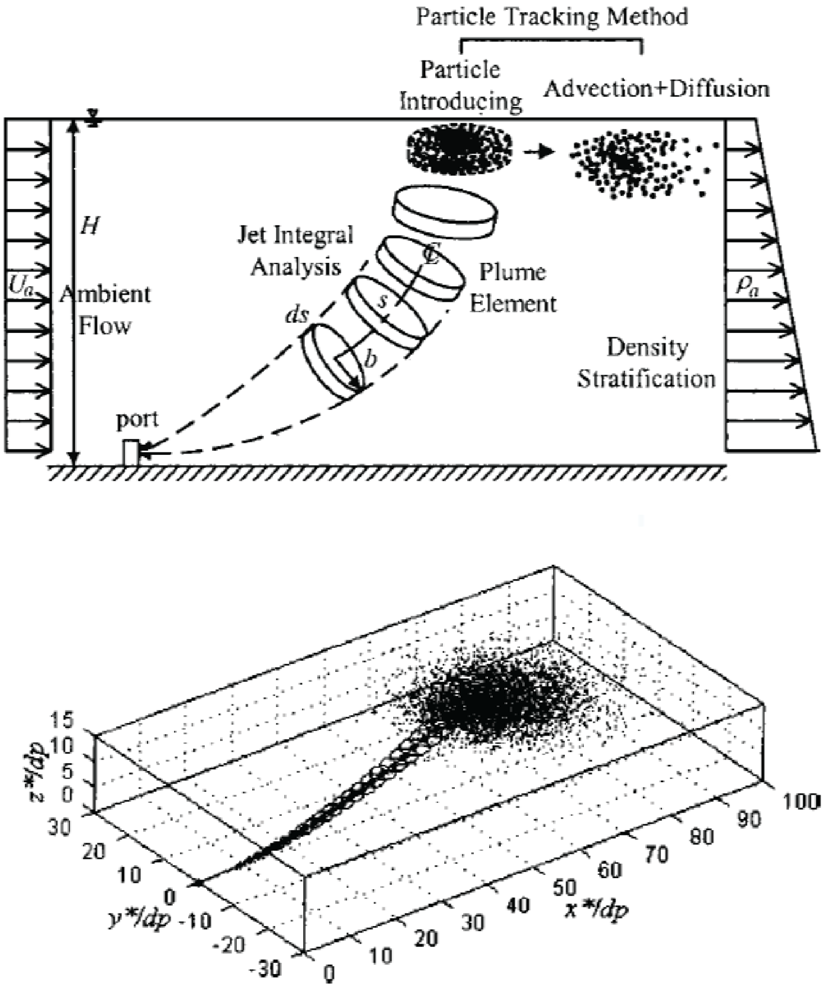
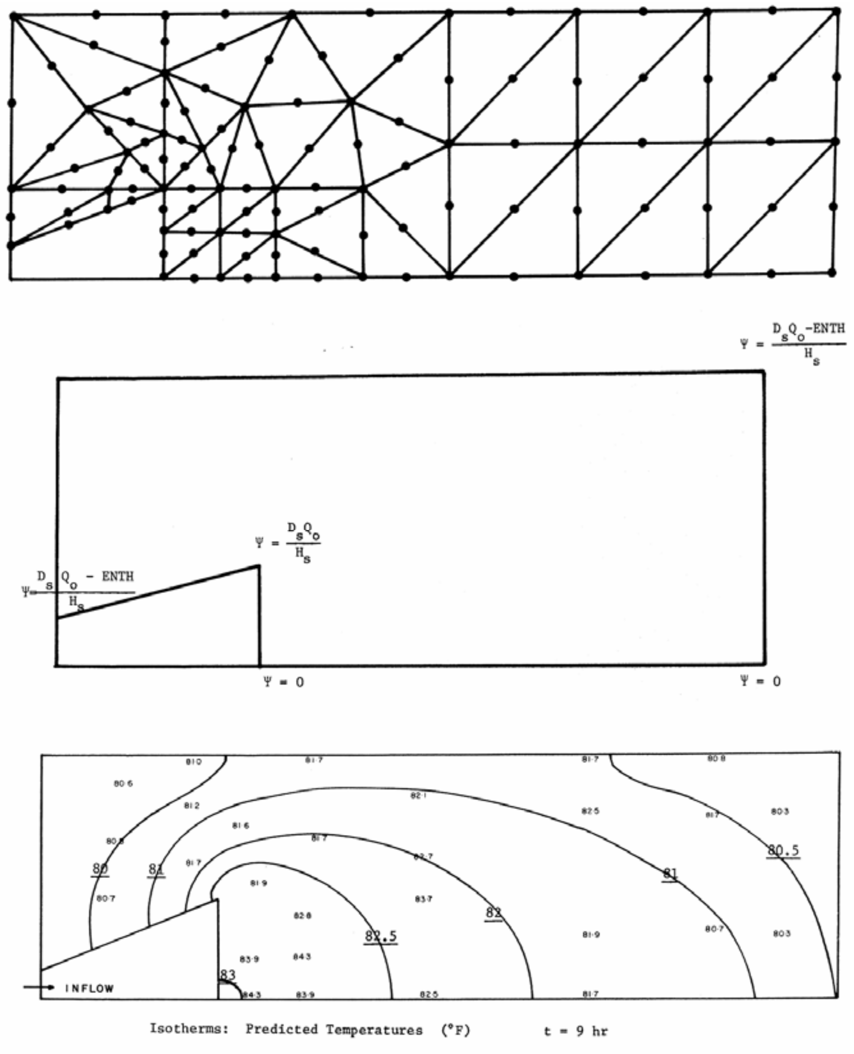


**Figure 26-7**
**Use of Numerical Particles in Hybrid Model [13]**

### Distributed Source and Sink

A third approach employs a far field model with the near field ‘carved out’. A near field model is used to generate a distributed entrainment sink and the mixed plume source, along the boundary between near and far fields. An early application of this methodology simulated the steady state circulation and thermal patterns in the surface layer of a stratified cooling pond as shown in Figure 26-8 [16]. In this 2-D application, the authors used a finite element circulation model based on a stream function formulation. A similar approach has been used to simulate the intermediate field for thermal discharges from coastal electric power stations [17]. The procedure worked adequately for steady conditions, but was not well-suited for tidal conditions when many of the nodes needed to change from source to sink or vice versa. Recently a similar procedure was used to simulate wastewater plumes from a submerged discharge, as illustrated in Figure 26-9 [18].



Isotherms: Predicted Temperatures (°F) t = 9 hr

**Figure 26-8**
**Use of Distributed Entrainment Source and Sink in A Model of the Surface Layer of A Stratified Cooling Pond [16]**

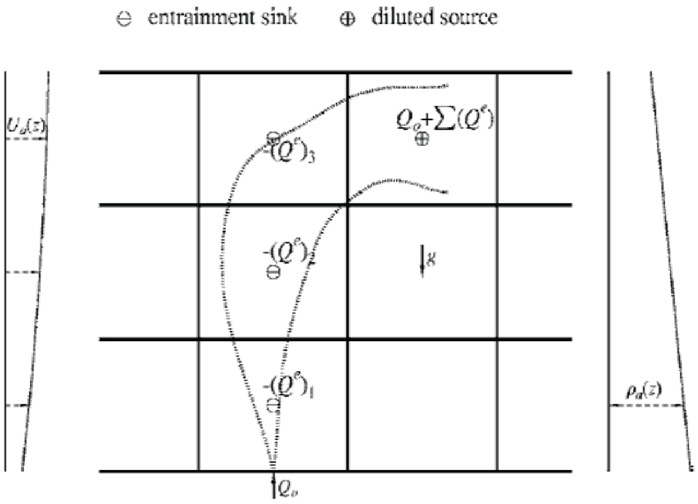


**Figure 26-9**
**Use of Distributed Entrainment Source and Sink in A Model of A Submerged Buoyant Plume [18]**

## New Challenges and Applications

In the 1960s-1980s, most applications involved large power plants discharging heated water to large receiving waters in relative isolation, and the focus of thermal modeling was largely on identifying ways to reduce temperatures through mixing. Several factors are conspiring to make at least some recent applications more complex.

### *Trade-Off between 316(a) and (b)*

Entrainment and impingement at plant intakes can be mitigated by reducing condenser water flows, e.g., by using variable speed pumps or fewer pumps. For approximately the same amount of power generation, this means that discharge velocities are reduced and discharge temperatures are increased, resulting in lower values of the densimetric Froude number, discussed above. For a surface discharge, in particular, this means less energetic mixing, resulting in generally smaller plumes with larger temperatures (more induced stratification), at least near the source. From the thermal impact standpoint, there is debate as to whether this approach (which induces strong stratification) is better than using high momentum to induce more mixing, and the answer is likely to be quite site-specific. However, the nature of the thermal plume will be different and, from the discussion above, the one which generates more stratification is often the more difficult one to model.

### *Co-Located Outfalls*

A number of facilities discharge water whose buoyancy differs from ambient. Table 26-1 summarizes some of these, along with a qualitative assignment of the magnitude and sign of their buoyancy.

**Table 26-1**
**Relative Buoyancy of Different Discharge Types**

| Discharge Type | Relative Buoyancy |
|---|---|
| Thermal | Moderately buoyant |
| Wastewater | Strongly buoyant |
| Desalination | Highly negatively buoyant |
| LNG | Moderately negatively buoyant |

As described by Hogan and Taft, in this volume, there are a number of reasons why it makes sense to consider co-locating such facilities. However, co-locating outfalls results in a discharge with a more complex buoyancy composition, and factors such as double diffusion between salt and heat may come into play.

### *Multiple Water Quality Constituents*

In addition to concerns over thermal impacts to aquatic life, temperature is an important water quality parameter because it affects reaction rates, the solubility of dissolved gases (such as oxygen), etc. Mixing induced by the discharge itself can also affect water quality in ways that might be positive or negative. An example is the Mirant Kendall Power Station located on the Charles River Basin between Boston and Cambridge, and described by Bulleit in this volume. To help reduce temperatures associated with re-powering, the company proposed using a bottom diffuser to discharge a portion of their condenser cooling water in order to provide greater mixing than would be possible using only the existing surface discharge. The bottom diffuser would also help mix salty anoxic water that resides at the bottom of the Basin as a result of salt water intrusion from the downstream dam. The extra mixing might also serve to stir up bottom sediments and associated phosphorous, thus possibly exacerbating algal blooms; on the other hand, the higher benthic oxygen levels could serve to bind the phosphorous to the bottom sediments, sequestering it from the overlying waters. The case is currently before the Environmental Appeals Board in Washington DC, but the point here is that the water quality issues are complicated and involve far more than ‘simple’ thermal plume modeling.

### *Combining Model Predictions and Real Time Monitoring*

As the ability to collect field data improves, it will be possible to use these data to improve thermal plume modeling. A potential example is remote sensing. For example, Mixzon (the company that maintains the model CORMIX) has piloted a small thermal imaging system, launched from a tethered blimp, which can be used to map temperatures in the near field of a plume [19]. With appropriate ground truth, such measurements can potentially be used to calibrate model mixing parameters allowing better prediction of the size of mixing zones.

## Summary

The major advances in thermal plume modeling came during the late 1960s to early 1980s, and hence many of the technical challenges that faced modelers twenty years ago, are still with us today. However, there have been many evolutionary improvements which include:

1. Increased computer speed has made 3D far (and complete) field models much more accessible for routine use.
2. In part due to related applications such as wastewater discharge, and dredged material disposal, near field models have become more user-friendly in regards to their interfaces, the extent of their calibration, the utility of their output, and their documentation.
3. While there is still work to be done, significant efforts are underway to advance the coupling of near and far field models.

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# 27

# CO-LOCATING POWER PLANTS WITH DESALINATION AND LNG FACILITIES: MAXIMIZING WATER USE WHILE ADDRESSING 316(A) AND 316(B) ISSUES

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## Introduction

The U.S. Census Bureau projects a 40% increase in the world's population over the next 40 years [1]. Additionally, the Intergovernmental Panel on Climate Change projects a continuation of the current global warming trend into the indefinite future [2]. These projections indicate that an increased demand for water resources by a growing population will likely be exacerbated by a decreased supply of water due to global warming. Given these projections, water has the potential to become one of the world's most limiting natural resources. Efforts to make efficient use of the water resources currently available are, therefore, critical.

The agricultural sector is the largest water-user globally, accounting for approximately 70% of all water withdrawals. The industrial and municipal sectors account for approximately 20% and 10% of all water withdrawals, respectively [3]. However, a significant discrepancy in the distribution of water resources exists regionally. Developing regions of the world such as Africa, the Near East, Asia, and Latin American commit between 70 and 90% of their water resources to agriculture. Conversely, in industrialized regions such as North America and Europe, the vast majority (between 45 and 50%) of water is withdrawn by the industrial sector. Therefore, efficient use of water by the industrial sector in developed regions is vital.

There is relatively little net consumption of water in the industrial sector. The majority of water is withdrawn for cooling purposes by electric power generation facilities and is ultimately discharged back to the source waterbody (albeit at a higher temperature). This effluent represents excess raw material that is available for reuse by other industries. Through the strategic coupling of industrial intakes and discharges, there is potential to minimize water withdrawal in the industrial sector by reusing one facility's effluent as another facility's intake source. Industries compatible with this type of intake and withdrawal approach can often be sited in close proximity to each other. This co-location of compatible water-use industries offers a number of potential benefits to each of the participating facilities. Two emerging industries that stand to potentially benefit from co-location with power plants are the liquid natural gas (LNG) and desalination industries. The characterization of the types of intakes and discharges associated with power generation, LNG, and desalination facilities are shown in Figure 27-1.

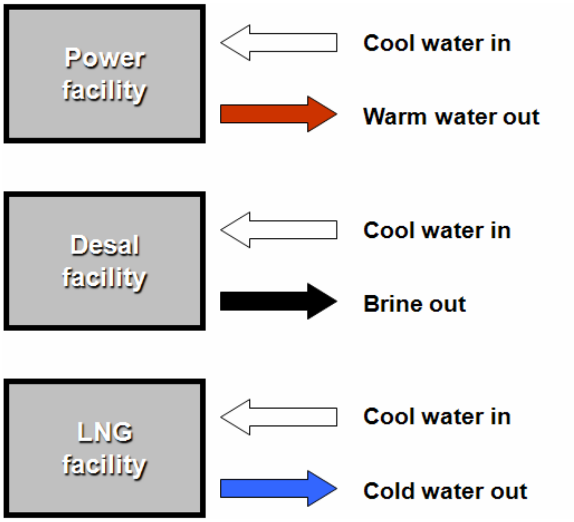

**Figure 27-1**
**Characterization of the Types of Intakes and Discharges at Power Generation, Liquid Natural Gas (LNG), and Desalination Facilities**

Early efforts to co-locate compatible industries sought to recapture waste heat energy in power plant effluents. Principal among the benefits of co-location, at its inception, was the cost savings associated with the reduction of energy input. Though cost savings is still a strong advantage of co-location, the principal focus has shifted more towards the responsible use and conservation of natural resources. In particular, the minimization of adverse impacts on aquatic life in the vicinity of water intake structures has become extremely important.

There are a number of potential operational and economic benefits associated with the co-location of LNG and desalination facilities with power plants. These include the potential to:

- Minimize environmental impacts on aquatic organisms by making use of existing, state-of-the-art fish protection technologies at power plant intakes,
- Minimize capital costs by making use of existing intake and discharge infrastructure at power plants,
- Limit industry's encroachment on land use,
- Streamline intake and discharge permitting for both facilities,
- Minimize operational, testing, monitoring, and maintenance costs of intake and discharge structures, and
- Create a dedicated electricity customer for the power facility at which it is located

Among the benefits listed above, the prevention of additional adverse impacts on aquatic organisms is arguably the most important advantage of co-location. Since power plants comprise the largest U.S. water user-group in the industrial sector [4], the protection of aquatic life has been a major concern in the regulation of these facilities. Fish protection technologies at power plants have undergone significant research and development to ensure that the approach taken to minimize adverse environmental impacts represents the best technology available. Technologies designed to meet these standards, therefore, typically represent the state-of-the-art in fish protection. Co-located facilities sharing intake structures with power plants stand to benefit greatly from the use of these existing fish protection technologies.

Cooling water intake structures (CWIS) at power facilities are required to meet strict environmental standards in regards to the impingement and entrainment of aquatic organisms. The Environmental Protection Agency's (EPA) Clean Water Act Section 316(b) required that "the location, design, construction, and capacity of a CWIS reflect the "best technology available" (BTA) for minimizing adverse environmental impacts (AEI)." Some of the most promising technologies designed to meet these standards include narrow-slot wedgewire screens, fine-mesh traveling water screens, and aquatic filter barriers (Figure 27-2). Each of these particular intake technologies has been shown to be highly protective of early life stages of fish. Through a combination of fine screening (0.5 mm) and low through-screen approach velocities (≤ 0.5 ft/s), most life stages of fishes are able to avoid both entrainment through and impingement on these intake technologies.

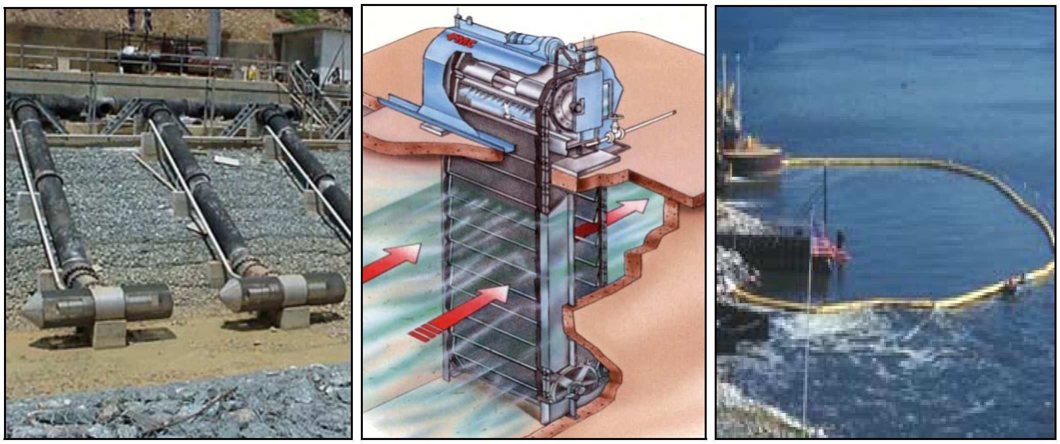

**Figure 27-2**
**Some of the Most Protective Intake Technologies at Industrial Water Intakes. From Left to Right: Narrow Slot Wedgewire Screens (Courtesy Johnson Screens), Traveling Water Screen (Courtesy Siemens), and Aquatic Filter Barrier (courtesy Gunderboom, Inc.)**

Section 316(a) of the CWA also mandates that the thermal component of the heated effluent discharged from a power facility be regulated "to assure the protection and propagation of a balanced, indigenous population of shellfish, fish, and wildlife in and on the body of water into which the discharge is to be made." Co-location affords the opportunity to minimize the thermal footprint of power facilities by making use of the waste heat produced in the cooling process.

The capital cost of an intake structure is also an important consideration in determining the feasibility of constructing LNG or desalination facilities. It is estimated that capital costs for the construction of a desalination intake, for example, can account for up to 20% of the total capital construction costs of the facility [5]. Since the ultimate objective of desalination and LNG facilities is to produce the most environmentally-friendly product at the lowest possible cost, co-location can be a great benefit. In addition, the costs associated with the operation and maintenance, permitting, and monitoring of the intake structure can be shared in a co-location scheme.

## Co-Location of LNG Facilities with Power Plants

Demand for LNG has increased in recent years due to the decreasing costs of production and LNG's subsequent competitiveness in the energy marketplace. Technological advances in the processing and transport of LNG, in conjunction with the evolution of an increased desire to diversify energy portfolios, have spurred the growth of the LNG market [6].

LNG is the liquid storage phase of natural gas. The liquid phase takes up approximately 1/600th the volume of the gas phase and is therefore more cost-effective to transport over long distances [6]. Prior to entering a distribution system, LNG is regasified through the addition of heat. Regasification is achieved in either submerged combustion vaporizers (SCVs) or in open rack vaporizers (ORVs). A SCV relies on the combustion of natural gas to supply the heat needed for vaporization, while an ORV relies on a large volume of seawater to supply the heat needed for vaporization. The majority of LNG regasification is done with seawater via ORVs [7]. For this reason, LNG regasification facilities making use of ORV lend themselves well to being co-located with coastal power plants. Adverse environmental impacts associated with a co-located LNG facility are decreased on both the intake and discharge sides. On the intake side, the LNG facility benefits from the state-of-the-art fish protection technologies at the power facility's CWIS. On the discharge side, the refrigerated LNG acts as a heat sink for the heated effluent from the power facility, thereby reducing the absolute temperature change between intake and discharge (delta T) in each facility.

Key considerations for the operation of LNG ORV facilities are analogous to those faced by the electric power industry. Namely, LNG ORV facilities are obliged to minimize adverse environmental impacts associated with operation of their intakes (316(b) issues) and discharges (316 (a) issues). It would therefore be an operational benefit for an LNG ORV facility to share a common intake with another facility that is concerned with same environmental impacts. LNG facilities are also concerned with having adequate access to a source of heating water and with having an acceptable effluent dilution and discharge scheme. Co-locating an LNG facility with a power facility would satisfy each of these requirements.

Figure 27-3 illustrates the general intake and discharge scheme of an LNG facility co-located with a power facility. LNG facilities typically require smaller volumes of water than that required by power facilities for cooling purposes. For example, an LNG facility may require up to 175 million gallons per day (mgd), while an average sized power facility may require three times that amount for cooling purposes. For that reason, the LNG facility would only make use of a portion of the heated effluent as its intake source. The remaining heated effluent from the power facility is then available to mix with the cooled effluent from the LNG facility upstream of the common discharge structure. This efficient water circulation scheme allows the intake and discharge for two distinct facilities to occur within a single intake and one discharge structure.

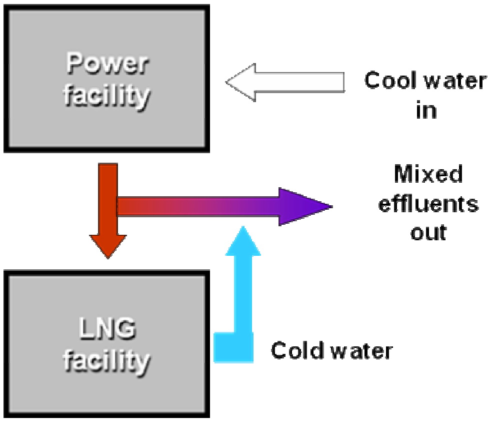

**Figure 27-3**
**Characterization of an LNG Facility Co-Located with a Power Facility**

## Co-Location of Desalination Facilities with Power Plants

Desalination of seawater and brackish water has become extremely important to the water supply portfolio of many countries. As water resources become more limiting, desalination offers a viable option for meeting the world's growing demand for potable water. For many years, cost was the limiting factor in the development of the desalination industry. Recent technological advances in materials and processes have spurred the recent growth of the desalination industry. The additional cost saving measures made available through the co-location of desalination facilities with power facilities would help ensure that the growing demand for potable water can realistically be met in the future.

Some critical considerations in locating and constructing a desalination facility include: the availability of a high quality, abundant water source; the adequate protection of aquatic organisms at the intake (316 (b) issues); the presence of an acceptable brine dilution and discharge scheme (316 (a) issues), and adequate access to a reliable power supply. Co-locating a desalination facility with a power facility satisfies each of these requirements.

There are two principal desalination processes. Thermal processes, such as multistage flash distillation (MSF) and other distillation techniques, rely on heat to convert feedwater to steam which is then condensed. Membrane processes, such as reverse osmosis (RO), rely on pressure to force feedwater through a semi-permeable membrane leaving salts behind. While both types of desalination processes require significant energy input, thermal technologies are often less viable due to their greater energy requirement. The use of pre-heated water as the intake source for a desalination facility can potentially decrease energy costs by between 5 and 10% [8].

Figure 27-4 illustrates the general intake and discharge scheme of a desalination facility co-located with a power facility. Desalination facilities typically require smaller volumes of water than that required by power facilities for cooling purposes. For example, a large desalination facility may require up to 100 mgd, while an average sized power facility may require four to five times that amount for cooling purposes. For that reason, the desalination facility only makes use of a portion of the heated effluent as its intake source. The remaining heated effluent from the power facility is then available to mix with the concentrated brine from the desalination facility at the common discharge structure. This efficient water circulation scheme allows the intakes and discharges of two distinct facilities to occur within a single intake and discharge structure.

Co-located desalination facilities benefit on both the intake and discharge side. On the intake side, the desalination facility benefits from the state-of-the-art fish protection technologies at the power facility's CWIS. On the discharge side, the concentrated brine effluent from the desalination facility can be efficiently mixed and discharged with the effluent from the power facility. In addition, since the volume of brine being discharged from a desalination facility is typically small in relation to the amount of effluent from the power facility, the brine is significantly diluted before discharge to the environment.

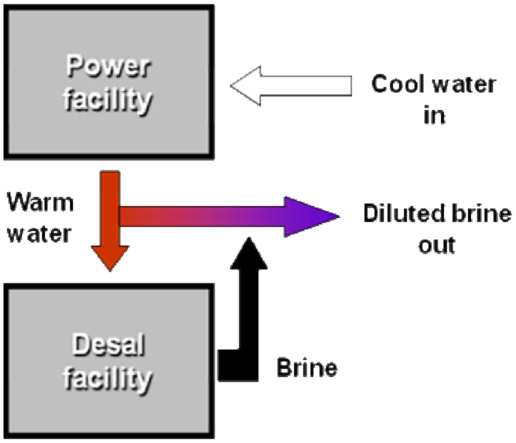

**Figure 27-4**
**Characterization of a Desalination Facility Co-located with a Power Facility.**

## Case Study: Big Bend Station, Tampa Electric Company

The following description of the desalination facility co-located at the Big Bend Station was presented at the American Desalination Association conference in 2000 [9].

In the 1970s, the State of Florida identified a need for additional potable water in the Tampa Bay area. Therefore, the West Coast Regional Water Supply Authority (presently Tampa Bay Water) was established in 1974 to ensure a source of water for its member governments. Additional demand for water had been met through increased pumping of groundwater sources. In the early 1990s, however, the Southwest Florida Water Management District (SWFWMD) initiated a series of efforts to minimize the adverse environmental effects associated with excess groundwater withdrawals. In addition, the SWFWMD developed a planning document to identify future needs and sources in a 16 county area including the region supplied by Tampa Bay Water.

Seawater desalination was identified as the most promising long-term alternative to water shortages in the Tamp Bay area. In 1992, SWFWMD and the Electric Power Research Institute (EPRI) began a feasibility study to investigate the co-location of desalination plants with coastal power plants that utilize large quantities of seawater for cooling. The studies focused on determining acute and chronic toxicity levels of desalination concentrate under different dilution scenarios and also included evaluation of various hydrodynamic models to establish mixing zones for concentrate disposal. Results of these studies indicated that, with proper design, seawater desalination concentrate discharge could be managed to meet environmental requirements.

Encouraged by the results of these studies, Tampa Bay Water (TBW), in late 1996, initiated a procurement process to select a developer to design, build, own, operate and transfer (DBOOT) a 20-50 mgd seawater desalination plant. Siting of the new desalination facility was begun by examining land use maps and aerial photos of the Gulf and Tampa Bay coastline to identify areas that should be excluded from further consideration due to incompatible land use. For example, much of the coastline in this region had already been developed for recreational, residential, or commercial use and therefore, land and access to the marine environment was limited. In addition, ecologically sensitive areas were excluded from further consideration. As a result of this preliminary screening, focus was paid to coastal sites where power plants were located in the region. In particular, power facilities that utilized large quantities of seawater for cooling and that could support the addition of a 20-50 mgd seawater desalination plant were targeted. Early in the process, it was determined that the development of a new dual-purpose power/desalination facility would not be a preferable alternative to developing a desalination facility at an existing power plant site, since substantially more development time would be required to permit a new power generation facility with all the associated potential environmental impacts on air quality, water quality, noise, land use, etc..

Having established that the new desalination facility should be co-located with an existing power facility, a review of the various desalination technologies was undertaken to determine which process would provide the most economical alternative with minimal impact to the environment at existing sites. It was decided that RO was the best process for this facility because of the lower capital and operating costs. The cost of water from RO plants decreases as salinity decreases, whereas the cost of water from thermal plants does not change appreciably with salinity variations. Since salinity varied considerably by season (between 15 and low 30's ppt), RO was favored. Additional advantages associated with RO technology included no increase in thermal loading to the discharge or increased emissions to the atmosphere.

When selecting the site for this seawater desalination facility, several factors were considered to assure that the facility could be constructed and operated in a manner that was compatible with protecting the environment. The major factors considered included:

- Compatibility of the facility with existing land uses in the vicinity of the site
- Accessibility to a sufficient supply of source water with minimal disruption to the biota of the source water body
- Ability of the site to accommodate disposal of the concentrate in an environmentally acceptable manner
- Provisions for minimizing potential effects of chemical additives for operation and maintenance of the facility
- Minimization of impacts to air quality
- Evaluation of potential effects associated with routing a new pipeline to deliver product water to TBW's distribution system
- Accessibility of a power source for production of potable water

Close examinations of the surrounding environment in the vicinity of each site and of the power plants design and operating history were conducted. As a result, it was determined that the Tampa Electric Company's Big Bend Station site was an ideal location to co-locate a 20-50 mgd seawater desalination plant.

The Big Bend Station consists of four base-load coal fired generating units totaling 1823 megawatts (MW). The plant is cooled by withdrawing water from Tampa Bay through an intake canal and circulating the flow through the plant for release back to the Bay via a discharge canal (Figure 27-5). Each unit requires approximately 350 mgd of cooling water with four units totaling about 1,400 mgd. Since the station is a base-load facility, all four units operate the majority of the time assuring that high levels of flow are available on a continuous basis. An examination of plant records indicated that at least three units are in operation over 90% of the time and four units are operating about 80% of the time. It is rare that only one unit is operating alone, occurring less than 0.3% of the time. It is assumed that at least one unit would have to be operated in order for the desalination plant to be operational.

The desalination plant uses RO technology and is sized to produce 25 mgd on average with a maximum production capability of approximately 29 mgd. The main source water for the plant is drawn from the discharge side of the power plant cooling water system (Figure 27-5). To produce 25 mgd of high quality potable water (100mg/l chloride), 44 mgd of seawater are conveyed via a 54-inch diameter pipeline to the desalination site where it is pretreated to remove suspended solids. The filtered seawater is then passed on to the RO facility which passes the seawater through a two-pass system to produce 25 mgd of freshwater and 19 mgd of concentrate. The freshwater is conveyed to TBW's distribution system through 15 miles of buried 42-inch diameter pipeline along existing Tampa Electric Company transmission line rights of way. The 19 mgd of concentrate is conveyed back to the discharge side of the power plant through a 30-inch diameter pipeline where it is blended with the remaining 1,350 mgd of cooling water prior to release into the discharge canal. The highly diluted concentrate is then discharged into the canal and further diluted in the Bay.

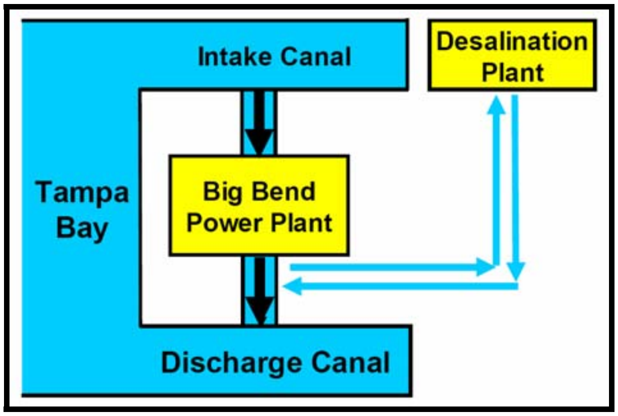

**Figure 27-5**
**Schematic of the Desalination Facility Co-Located with the Big Bend Station**

There are a number of key factors associated with the successful co-location of the TBW desalination plant at the Big Bend Station. First, it was compatible with existing land use. The Big Bend Station site is a 1,100-acre industrial zoned site; the desalination facility occupies only about 8.5 acres of previously unused property on the northeast corner of the site.

Second, the existing intake could supply all of the water needed via an existing CWIS with state-of-the-art fish protection technologies. The screenwells of Units 3 and 4 incorporate 0.5-mm fine-mesh traveling water screens with a fish return system to meet 316(b) requirements. Utilizing the existing intake structure provided a significant benefit in terms of avoiding the cost of a new intake while minimizing environmental impacts.

Next, brine disposal was achievable using the existing discharge structure with minimal incremental environmental impact. With four units running, the dilution ratio is 70:1. With only one unit operating, a dilution ratio of 18:1 is achieved, well beyond the regulatory agency recommended ratios of 3:1 to 6:1. With four-units in operation, the increase in salinity in the discharge canal is less than 0.5 ppt, or less than 1.5% above the intake water to the power plant. With only one unit in operation, the increase is about 1.5 ppt, or 6% above intake salinities. The slight increase in salinity at the point of discharge was determined to be well within the natural range of salinities throughout Tampa Bay resulting in minimal environmental impact.

A key advantage of the Big Bend site is that it provided easy access to the water distribution system of the Tampa Bay area. By locating the pipeline within existing rights of way, disruption to local residences and businesses and sensitive natural habitats was minimized. It was estimated that less than 10 acres of wetlands were affected during construction; the impacts were temporary since the area where the pipeline was buried was re-vegetated with indigenous material.

Finally, there was adequate access to a reliable power supply since the desalination facility was located adjacent to the power generating station. Conversely, the Big Bend Station benefited from having a dedicated base-load customer in the TBW desalination facility.

Due to begin production in 2002, the project experienced economic difficulties combined with operational problems (mainly biofouling). After $29 million worth of repair and remediation work, the facility is expected to be fully operational by 2008. The projected cost for water produced at this facility is still considered inexpensive in the context of desalinated water [10].

This case study has illustrated a number of important points. Co-location often represents a better alternative to constructing new intake and discharge structures for new industrial facilities. Most importantly, co-location of compatible industrial facilities has been shown to substantially reduce adverse environmental impacts associated with the siting, construction and operation of new intake and discharge structures. Additionally, co-location can offer substantial cost savings over the capital investment, permitting, monitoring, operation, and maintenance costs associated with constructing new intake and discharge structures. As seen in the case of TBW's co-located desalination facility at the Big Bend Station, co-location also creates a symbiotic relationship in which each facility involved derives benefit, whether environmental or economic. As demands for water and energy increase, driving the growth of the desalination and LNG industries, the need for new facilities will continue to increase. Careful consideration of the alternatives will likely reveal that co-location represents an intelligent use of the world's limited resources.

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# 28

# ECOLOGY ISSUES/TECHNOLOGY RESPONSES

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## Abstract

This paper reviews recent advances in power plant cooling technology, many of which address aqueous discharge, intake and consumption issues simultaneously. These include dry and hybrid cooling, water recovery options, advanced recycle/reuse concepts and approaches for the use of non-fresh waters. All of these technologies achieve the objectives of minimizing aquatic environmental concerns but do so at a price of higher cost and lowered plant efficiency and capacity.

## Introduction

On October 2–3, 2007, the Second Thermal Ecology and Regulation Workshop was held at the headquarters of the Tri-State Generation and Transmission Association in Westminster, Colorado. The intent of the program was to explore new issues which had emerged since the first Workshop held in 2003. Among the many issues are recent and expected advances in cooling system technology which affect the effects of power generation on the aquatic environment. This paper addresses those technologies.

The interactions between power generation plants and the aquatic environment include not only thermal discharges, which was the primary focus of this Workshop, but also chemical discharges and the effects of the withdrawal of water into the plant and the consumption of water by plant processes. For all plants using Rankine steam cycles for all or a portion of the power generation, power plant cooling is the major use of water [1]. The discussion in this paper is restricted to power plant cooling.

“Power plant cooling” in this context refers to the rejection of the heat released by the condensation of the turbine exhaust steam in a Rankine power cycle to the environment. Other cooling requirements, commonly referred to collectively as “auxiliary cooling”, include, for example, such items as lube oil cooling, generator cooling and transformer cooling. The auxiliary cooling load is small compared to the main condenser cooling load, typically about 5% and can either be handled in a separate cooler or be integrated into the main plant cooling system. It will not be considered further in this discussion.

The remainder of the paper will briefly describe the important types of plant cooling systems, compare them on the bases of not only environmental impacts but also cost and impact on plant efficiency and capacity. In addition, a number of technology options currently under development for improving the performance and mitigating the environmental effects will be described.

## Power Plant Cooling Systems

Power plant cooling systems are commonly one of four types. These are:

- Once-through cooling
- Closed-cycle wet cooling
- Dry cooling
- Hybrid (wet/dry) cooling

Choosing among these alternative cooling systems involves a number of tradeoffs of system cost, operation and maintenance (O&M) requirements, effect on plant efficiency and capacity, water requirements (both withdrawal and consumption) and a variety of environmental issues including wastewater discharge, drift, noise, aesthetics and visible atmospheric plumes. Additionally, the choice of cooling system can affect site selection flexibility and overall plant cost by, for example, allowing the location of a plant close to low cost fuel resources which may be in areas of very limited water supply.

### *Once-Through Cooling*

In once-through systems, cooling water is withdrawn from a natural waterbody, passed through the tubes of a steam condenser and returned to the waterbody. The system is shown schematically in Figure 28-1.

Once-through cooling was the common form of cooling at thermal-electric power plants until around the 1970s because of its simplicity, low capital and operating cost and high plant efficiency. Its use on new plants has been limited or prohibited in recent decades. Environmental regulations [2] on thermal discharges, intake losses from entrainment and impingement and in-stream flow maintenance requirements have led to the almost exclusive use of closed-cycle cooling of the wet, dry or hybrid type. Nonetheless, at the present time, nearly 50% of the Nation's installed generating capacity is operating on once-through cooling.

### *Closed-Cycle Wet Cooling*

Closed-cycle (or recirculating) wet cooling systems are similar to once-through cooling in that the steam is condensed in a water-cooled, shell-and-tube steam condenser, but differ in that the heated cooling water is not returned to the environment but is conveyed to a cooling component, typically a wet cooling tower (other options include cooling ponds, spray enhanced ponds, spray canals, etc.) where it is cooled and then recirculated to the condenser. A typical closed-cycle wet cooling system is shown schematically in Figure 28-2. A photograph of a large, mechanical-draft, counterflow wet cooling tower is shown in Figure 28-3.

Hot water from the condenser is pumped to the top of the tower. From there it flows down through the tower fill where it is brought into intimate contact with ambient air. The cooling is accomplished by the evaporation of a small fraction (approximately 1 to 2%) of the water. The cold water falls into a cold water collection basin beneath the fill from which it is recirculated back to the condenser inlet.

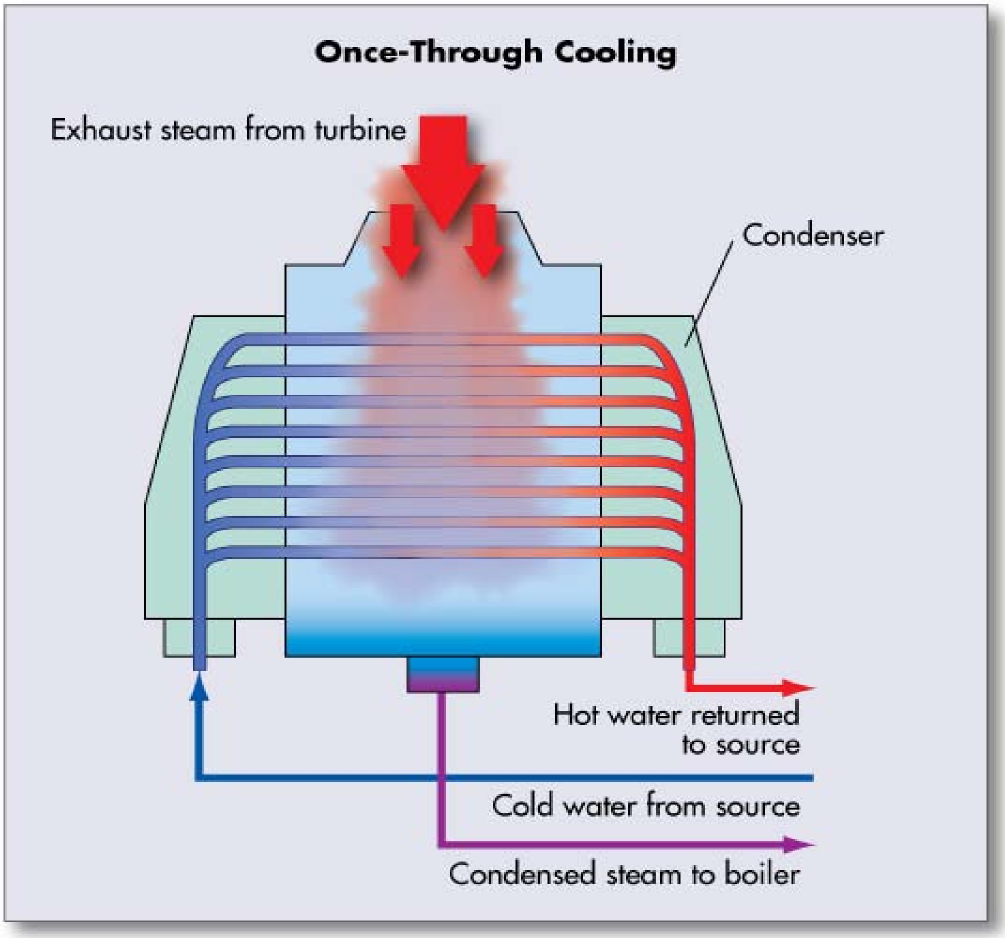


**Figure 28-1**
**Once Through Cooling System Schematic**

Some portion of the circulating water flow is discharged as “blowdown” from the system back to the environment in order to control the build-up of suspended and dissolved solids brought into the cooling system with the make-up water. A very small amount of water (typically less than 0.001% of the circulating water flow) is entrained in the exiting air as “drift”. Make-up water must be withdrawn from the environment and added to the recirculating water loop to replace the water lost as evaporation, blowdown and drift. The amount of make-up required is a strong function of the amount of blowdown required to maintain acceptable levels of dissolved solids for control of scaling, fouling and corrosion.

Closed-cycle wet cooling has been the design of choice for most PC plants brought on line in the last 30 years. It substantially reduces the withdrawal rate and the thermal discharge and offers siting flexibility for power generation away from rivers and large natural water bodies.

## *Dry Cooling*

Dry cooling systems reject the heat of condensation directly to the atmosphere. Steam from the turbine exhaust is ducted directly to an air-cooled condenser as shown conceptually in Figure 28-4 and in a more detailed schematic in Figure 28-5.

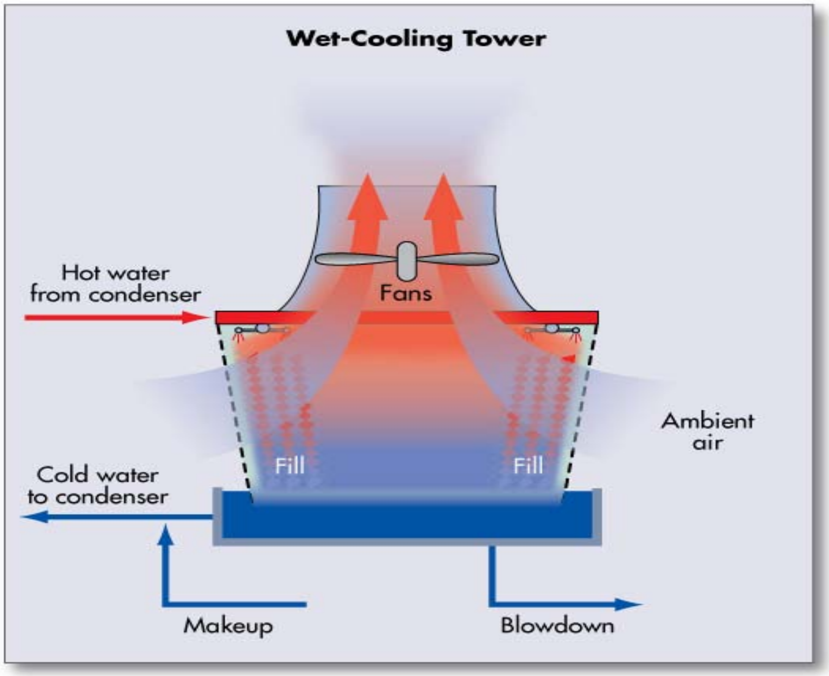


**Figure 28-2**
**Closed-Cycle Wet Cooling System Schematic (Shown with a Mechanical Draft, Cross-Flow Wet Cooling Tower)**

**Figure 28-3**
**32 Cell, Mechanical-Draft, Counterflow Wet Cooling Tower**

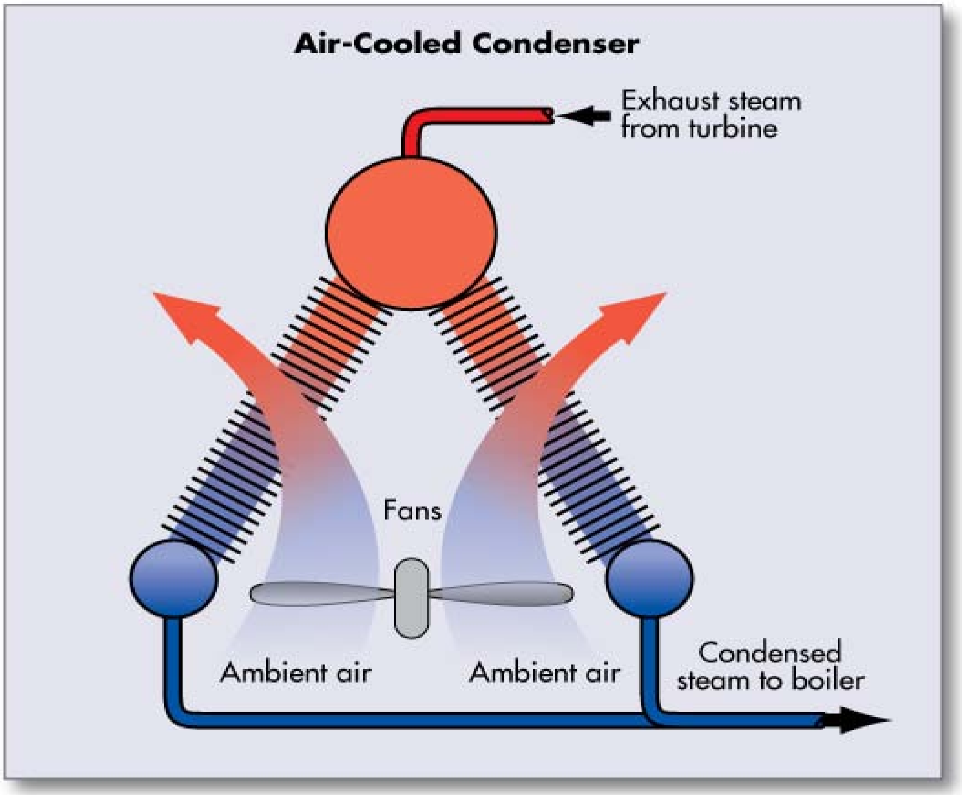


**Figure 28-4**
**Dry Cooling Schematic (Shown as "Direct" Dry Cooling with a Forced-Draft Air-Cooled Condenser)**

The condenser consists of a modular arrangement of cells, each in the general shape of an A-frame structure. The sloping sides are arrays of finned tube bundles. An axial flow fan, in the floor of the cell draws air from the environment below the cell and forces it up and out across the finned tubes. The steam flows from a horizontal steam duct at the apex of the A-frame downward into the finned tubes where it condenses and drains down to a condensate line at the bottom of each side of the cell. The condensate is then returned to the boiler feedwater loop.

## Current Status and Practice

The first use of dry cooling in the U.S. was in the late 1960s at the Black Hills station near Gillette, Wyoming, motivated by the presence of abundant cheap coal in a region with very limited water supply. Since then, while the use of dry cooling has become more common with more than 75 plants, it still represents a small fraction of currently installed capacity. It is noteworthy, however, that many of the installations are not, as might be expected, in arid regions but are in parts of the country with normally abundant rainfall and water supply. The use of dry cooling is these areas has been motivated by concerns over plumes and drift from wet cooling systems but more commonly by increasing sensitivity to minimizing water consumption and reducing withdrawals from natural water bodies wherever they may be.

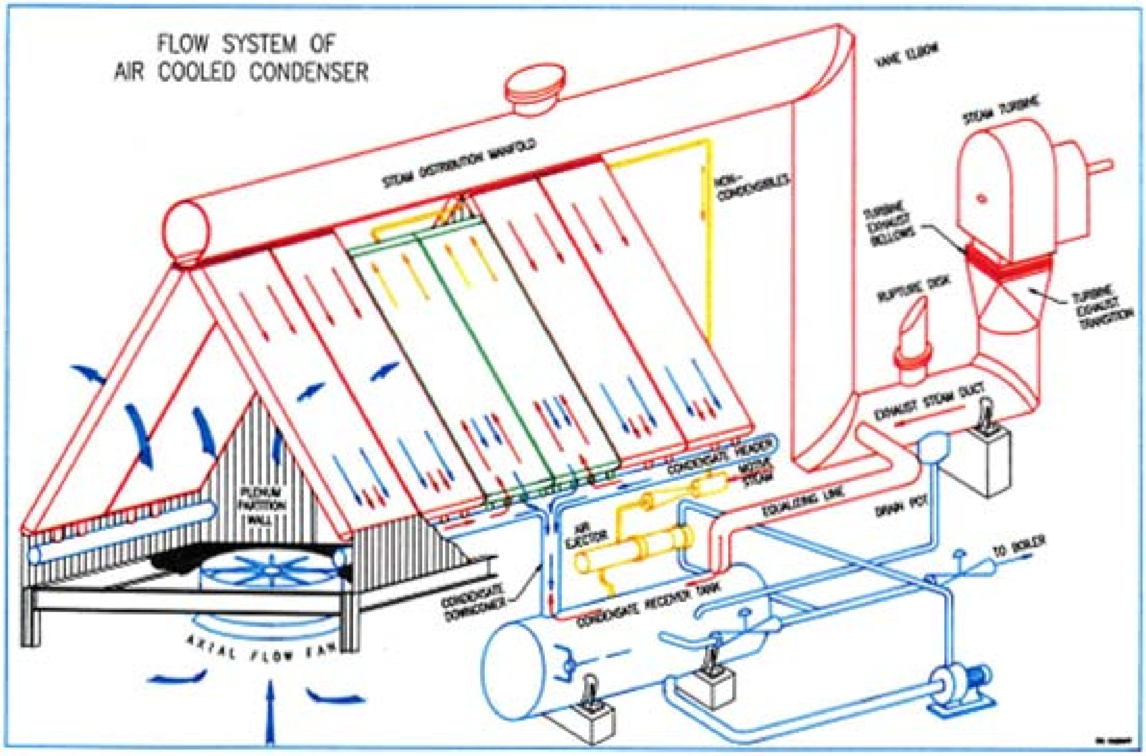


**Figure 28-5**
**Schematic of Air-Cooled Condenser (Courtesy of SPX Cooling Technologies, Inc.)**

## *Hybrid Cooling*

Hybrid cooling systems are intended to exploit the virtues of both the wet and dry systems. In these systems, both air-cooled and wet cooling equipment are available for handling the plant heat load as conditions dictate.

Two types of hybrid cooling exist. The first is intended primarily for purpose of abating visible plumes from wet cooling towers; the second, primarily for water conservation.

Plume abatement towers employ a small amount of dry cooling to heat the tower exhaust plume above saturation during those cold, high-humidity periods of daytime operation when a wet cooling tower plume is likely to be visible. From the standpoint of interaction with the aquatic environment, they are essentially identical to wet cooling systems and will not be considered further in this discussion.

### Hybrid, Water-Conservation Towers

Hybrid systems designed specifically for water conservation have received increasing interest in recent years although to date only a few are installed on U.S. power plants. They are intended to reduce the amount of water required for power plant cooling by using dry cooling during the cooler periods of the year and supplementing the dry capability with wet cooling during hotter periods when dry cooling systems cannot maintain as low a turbine exhaust pressure as is desired.

The earliest system of this type in the U.S. consisted of a conventional shell-and-tube steam condenser from which the hot cooling water was cooled in a dry/wet integrated tower. The water passed first through an air-cooled heat exchanger and then discharged into a wet cooling tower. During cold periods, when the dry section could carry a larger faction of the heat load portions of the wet tower cold be by passed until all dry operation was achieved. A photograph of a tower of this design is shown in Figure 28-6.

**Figure 28-6**
**Photograph of Integrated Hybrid (Dry/Wet) Tower**

The more commonly considered approach in recent years is that shown in Figure 28-7 in which the dry and wet portions are separate parallel systems. The steam flow is split between an air-cooled condenser and a surface (shell and tube) condenser coupled with a mechanical-draft wet cooling tower. A photograph of a small hybrid system under construction is shown in Figure 28-8.

## Comparison of Cooling Systems

A comparison of those cooling system characteristics most relevant to effects on the aquatic environment is summarized in Table 28-1.

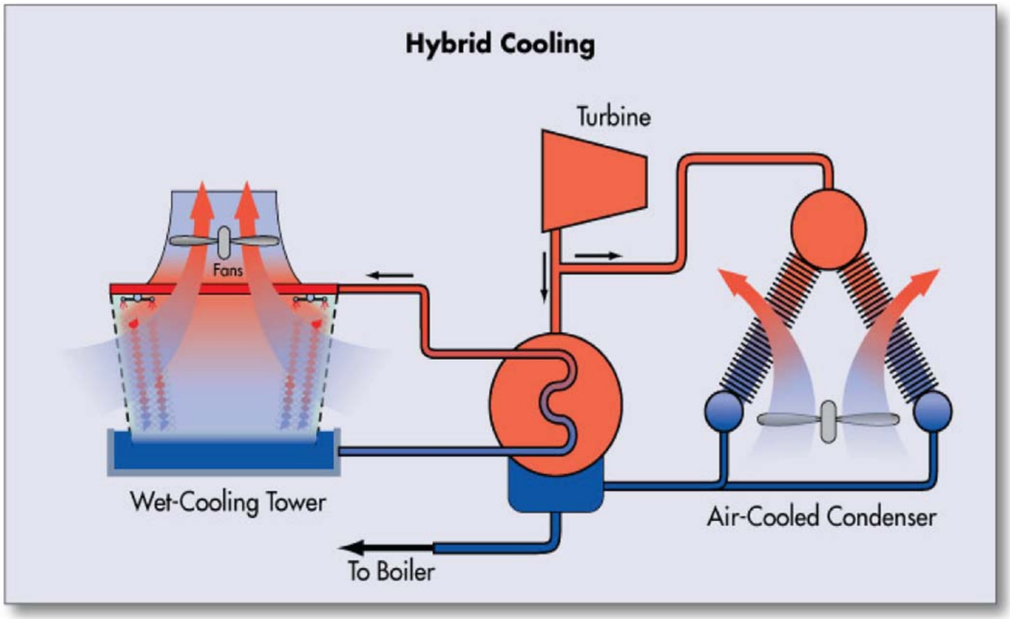


**Figure 28-7**
**Hybrid Cooling (Shown with Parallel Wet and Dry Loops Using an Air-Cooled Condenser and a Mechanical Draft Wet Cooling Tower)**

**Figure 28-8**
**Hybrid Water-Conservation Cooling System (shown with a 10 Cell Air-Cooled Condenser and a 2 Cell Wet Cooling Tower)**

**Table 28-1**
**Cooling System Comparisons**

| System/Environment Interactions | | | | | |
|---|---|---|---|---|---|
| System | Withdrawal | Consumption | Discharge | Temperature | Quality |
| | gallons/MWh | gallons/MWh | gallons/MWh | F | |
| Once-through | 30,000 | ??? | ~30,000 | Source + ~20 F | Source; chlorine residual |
| Closed cycle, wet | 1,800 to 750 | ~ 600 | 1,200 to 150 | Wet bulb + ~ 10 F | Source x 1.5 to x 10 |
| Closed-cycle, dry | Nil | Nil | Nil | Not applicable | Not applicable |
| Closed-cycle, hybrid (1) | 150 to 1,440 | ~ 120 to ~480 | 30 to 960 | Wet bulb + ~ 10 F | Source x 1.5 to x 10 |

(1) Amounts are annual average; vary seasonally from 0 to close to all wet systems

## *Intake Effects*

The withdrawal of water from natural water bodies can result in the impingement and entrainment of aquatic organisms. These effects are roughly proportional to the amount of water withdrawn. Once-through cooling has by far the highest withdrawal rate. Wet or hybrid cooling systems typically reduce the withdrawal requirements by 97 to 98% compared to once-through systems. For recirculating wet systems using seawater of highly saline brackish water as make-up, the blowdown rate must be increased to keep the cycles of concentration below ~1.5 to x2, resulting in withdrawal requirements which are unusually high for recirculating systems. But still constitute only about 5 to 6% of the withdrawal for once-through cooling. Hybrid systems are normally designed to conserve from 20% to 80% of the water required for recirculated wet cooling. The annual average withdrawal rates are reduced proportionally. However, two items are noteworthy.

1. The withdrawal ate, at times of high water usage, may rise to essentially the same as an all-wet system.
2. During much of the year, the withdrawal rate will be very small or zero. The seasonal effects on aquatic populations will depend on the coincidence of critical periods in the life stages of local fish species and the seasonal variation in ambient temperature which drives the amount of cooling (and hence withdrawal) provided by the wet portion of the hybrid system.

Dry cooling requires no water for power plant cooling. In comparison to wet, or hybrid, systems which already reduce withdrawal by factors of x20 to x50 compared to once-though cooling, the further reductions might be considered marginal.

## *Water Consumption*

Recirculating wet systems, while substantially reducing the withdrawal rates, cool by evaporation and, hence, consume as much as 80 to 90% of the water they withdraw. Once-through cooling on the other hand withdraws large amounts but returns essentially all of what is withdrawn. However, the discharge of large quantities of heated water to the receiving waterbody undoubtedly increases the local surface temperature and, as a result, the evaporation rate to the atmosphere. Calculation of the increased consumption from once-through cooling has been a long-standing difficult problem. The comparison of interest is with the well-established rate from recirculating cooling systems. Estimates have ranged from “negligible” to “approximately 75% of wet cooling”. Actual amounts will be highly site-dependent, varying with water current, water depth, discharge location, wind patterns, cloud cover, foliage cover and other characteristics.

Hybrid systems further reduce the consumption below that of recirculating wet systems in an amount roughly proportional to the annual reduction in wet system use. Dry systems obviously reduce the effect to zero.

### Thermal Discharge

Thermal discharges are the greatest for once-through cooling. The full cooling water flow is returned to the natural receiving waterbody at a temperature ranging from less than 20ºF to as much as 30°F above the source water temperature depending on plant and condenser design. By comparison, water is returned to the receiving waterbody from a recirculating wet system in much smaller amounts and typically at lower temperatures.

The blowdown flow ranges from 0.5% to 4% of the once-through cooling return flow. If the blowdown is taken from the cold side of the cooling system (i.e., from the cold water basin of the cooling tower), the temperature would be the ambient wet bulb temperature plus the tower "approach" temperature which might range from 8ºF to over 15ºF depending on tower type and design. At the hottest time of the year, the atmospheric wet bulb temperature can be les than, approximately equal to or greater than the local waterbody temperature depending on local climatology, waterbody characteristics and the presence of upstream heated discharges. In any case, the increased heat load on the receiving water proportional to the discharge flow times the temperature difference between the discharge and the receiving water will be, in all cases, significantly lower than that from a comparable once-though cooling system. As before, hybrid systems reduce the thermal discharge proportionally to their wet system utilization and dry cooling eliminates it entirely.

### Chemical Discharge

The presence of pollutants in aqueous discharges is regulated under the National Pollutant Discharge Elimination System (NPDES) for point source discharges to surface waters and, in some cases, under state protection plans for discharges to the oceans, bays or estuaries. In this context, the differences between once-through cooling and recirculated wet cooling can be important.

For once-though cooling, the discharge composition is the same as that of the water originally withdrawn with the possible exception of some chlorine (or other biofouling oxidant) residual. However, recirculated wet systems concentrate the constituents in the source water prior to blowdown and are thereby sometimes prohibit from discharging back to the source waterbody without treatment. Furthermore, the operation of the condenser and cooling tower on the recycled, concentrated cooling water may require the addition of some treatment chemicals to control scaling and corrosion, necessitating some treatment prior to discharge.

## Cost-Performance Comparisons

The choice of cooling system has an important effect on the cost and performance of a power plant. As a general rule, once-through cooling is the least costly and provides the highest plant efficiency and capacity. Among the recirculating systems, closed-cycle wet cooling has the lowest cost and provides the best performance. Dry cooling is normally the most expensive and has the largest adverse effect on plant efficiency and capacity particularly during the hottest hours of the year. This is an important consideration in cases where the hottest days coincide with peak electrical demand and highest power prices.

Hybrid systems can vary widely in cost, their effect on plant performance and their water consumption depending on the selected design point. The most important characteristic is the amount of water the hybrid system uses compared to the amount required for an all wet system. Again, as a general rule, they are significantly more expensive that all wet systems. They can often be less expensive than all dry systems unless they are constrained to use very small amounts of water. Their primary benefits are the ability to reduce the annual water withdrawal requirements to levels even less than closed-cycle wet cooling without the potentially severe hot day penalties often associated with all dry systems.

It should be recognized that many site- and plant- specific circumstances can alter the general conclusions given above. Careful system optimizations and comparative analyses taking into consideration particular site, plant and project characteristics are necessary to arrival at a meaningful comparison for each situation. A detailed discussion of the comparative costs and performance of wet vs. dry cooling is provided in a recent EPRI report [3]. The discussion of hybrid systems in that report is limited and qualitative. Some representative comparisons of cost and hot day performance penalty are given in Figure 28-9 and Figure 28-10.

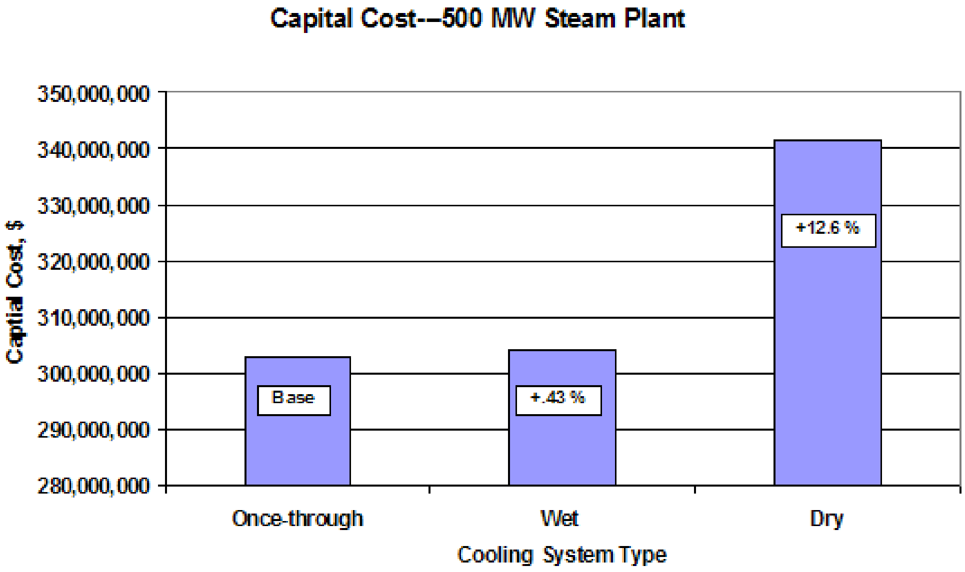


**Figure 28-9**
**Cost Comparison of Plant Costs with Various Cooling Systems**

## Advanced Technologies

The systems, as described in the previous sections, are essentially mature, proven technologies with well established performance characteristics. A number of cooling system improvements are currently being researched and developed which have the potential of maintaining or improving the environmental benefits of the recirculated wet, dry and hybrid systems while reducing the cost and performance penalties associated with them.

For wet systems, two of these approaches are the recovery of water from the exit plume of a wet cooling tower and the demonstration of a heat rejection unit capable of operating more effectively than conventional cooling towers on low quality make-up.

For dry systems, three approaches currently under investigation are spray enhancement of ACC performance, the design of improved air-side surfaces for the finned-tube condenser bundles and the mitigation of the deleterious effects of wind on ACC performance.

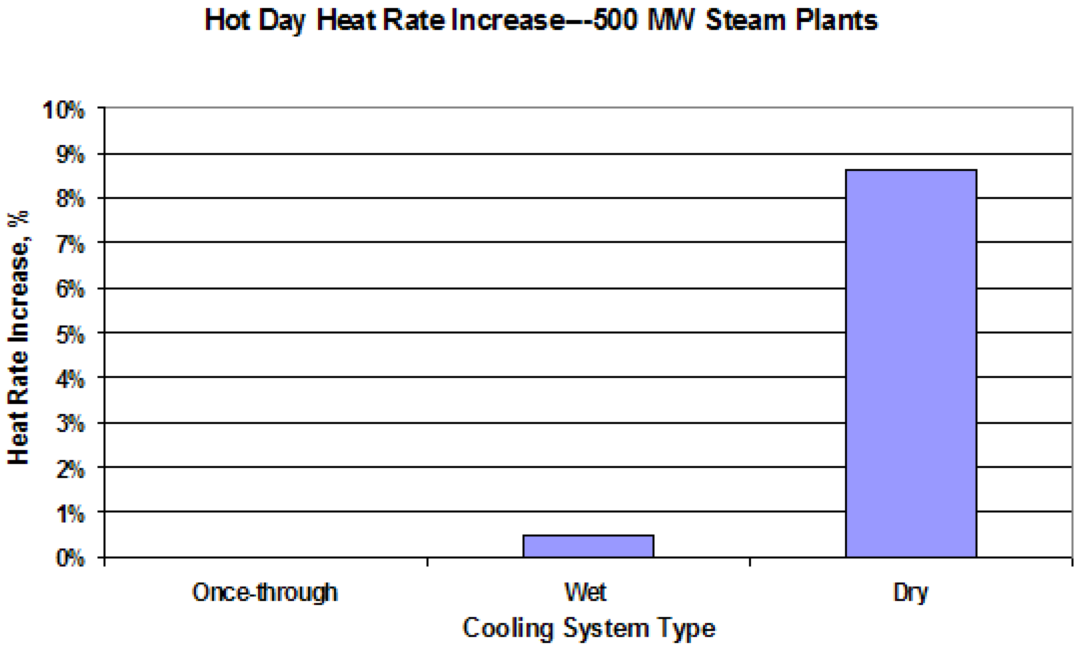


**Figure 28-10**
**Comparison of Hot Day Heat Rate Penalties with Various Cooling Systems**

### *Wet Cooling—Water Recovery from Tower Plumes*

The major portion of the water consumed at power plants with closed-cycle wet cooling is that which is evaporated in the cooling tower. For a large, coal-fired, zero liquid discharge (ZLD) plant in the Southwestern U.S., 86% of the water taken into the plant is evaporated into the atmosphere in the cooling tower plume.

With this in mind, the concept of condensing and recovery of some portion of the vapor in the plume is being investigated by the U. S. Department of Energy, SPX Cooling Technologies, Inc. (SPX) and Public Service New Mexico (PSNM). The approach, proposed and lab-tested by SPX in called an Air-to-air® cooling tower shown schematically in Figure 28-11. The warm saturated plume leaving the tower fill section is drawn through one side of a plate-plate heat exchanger. Fresh cool atmospheric air is drawn through the other side (alternate passages) of the heat exchanger cooling the plume. Water vapor in the plume condenses on the plate surfaces and drains back into the hot water distribution deck of the cooling tower. Alternatively, since the condensed water from the plume is has a much lower level of dissolved solids that the tower circulating water, consideration can be given to collecting it separately for recycling to other applications.

Tests, scheduled to begin in 2008, will be conducted on a full-size, single cell now being erected on the end of the Unit 4 cooling tower at the San Juan Generating Station (SJGS). Preliminary indications from analysis and small-scale laboratory tests suggest that between 15 and 30% of the moisture in the plume can be recovered depending on the climate conditions at the site [4].

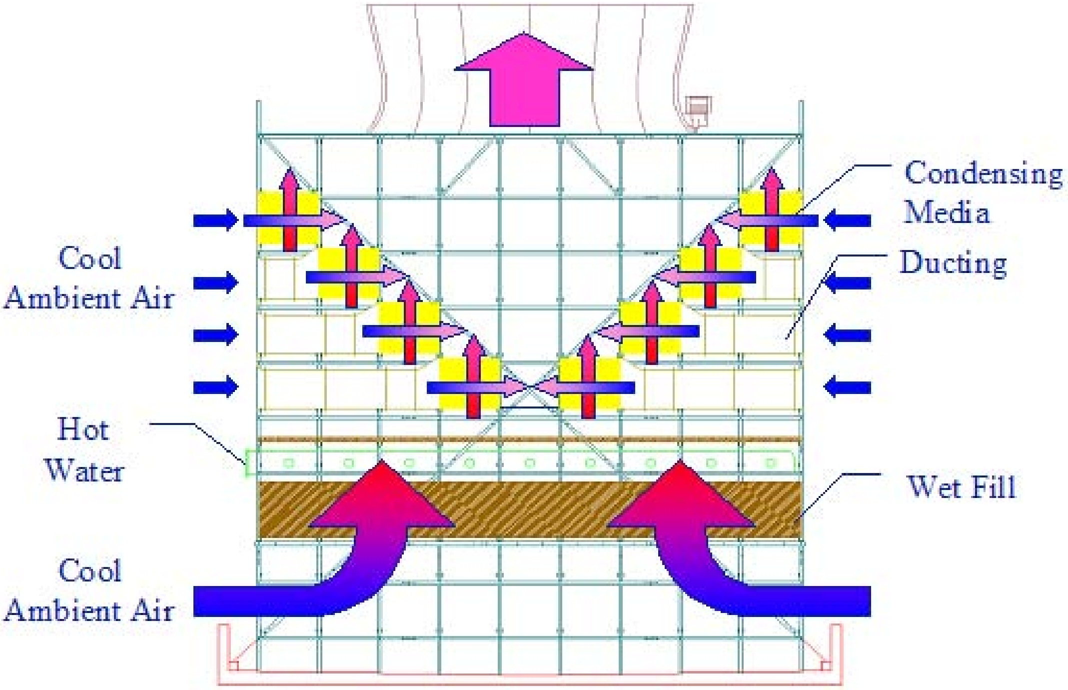
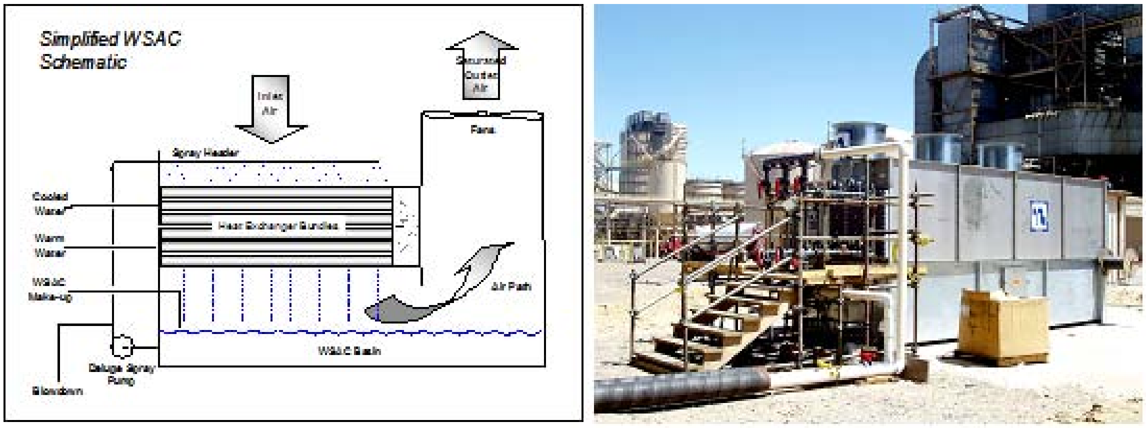


**Figure 28-11**
**Air-to-air Cooling Tower (Courtesy of SPX Cooling Technology, Inc.)**

### *Wet Cooling—Improved Equipment for the Use of Degraded Make-Up Water*

An alternative to the use of water from natural sources, be it fresh or saline surface water or groundwater, is the use of degraded or reclaimed water such as treated municipal discharge water, produced water from oil and gas drilling operations, mine drainage water or agricultural run-off. To date the most common alternative water use in power plants is reclaimed municipal treated discharge. A recent report [5] lists over 75 instances of power plant use of reclaimed municipal water. The technology for this is mature and reliable.

For other alternative water sources, pre- or sidestream treatment may be required to control fouling or scaling from the concentration of suspended or dissolved solids in the make-up water. An approach which may facilitate the use of reclaimed water with high material content and high scaling potential is the wet-surface air cooler (WSAC) [6]. The technology has been in commercial use for many yeas in diverse applications including a full-scale cooling system at the MassPower 240 MW plant in Massachusetts [7]. Its use on high TDS make-up water has been pilot tested on a sidestream from the SJGS Unit 3 cooling tower. The results of that test are reported in detail by EPRI [8]. A schematic of the WSAC unit and operation and a photograph of the pilot test facility are shown in Figure 28-12. As shown, it is operating as a heat exchanger and is cooling hot water from the Unit 3 cooling system. It can operate also as a steam condenser with the steam condensing inside the tubes.



**WSAC Schematic**

**WSAC Pilot Unit---San Juan Generating Station; New Mexico**

**Figure 28-12**
**WSAC**

The tests at SJGS were conducted on a small (3 x $10^6$ Btu/hr.; 260 gpm) pilot unit shown in Figure 28-12. The cooling spray was drawn from the cold water basin of the Unit 3 tower which operates at an average of 7 cycles of concentration on San Juan River make-up. Therefore, the TDS of the make-up to the WSAC ranged from 2,400 to 3,000 mg/l. Over the twenty week test period, the cycles of concentration in the WSAC itself average x 4.4 giving an effective cycle of concentration based on fresh make-up from the river of approximated x 30.

During the test period, the thermal performance of the WSAC did not degrade. Specifically,

- The tube exterior surfaces appeared visually clean with no apparent mineral deposits or biofouling film.
- Heat transfer rates were maintained throughout the tests based on a steady temperature range of the hot water flow through the tubes.

However, although the heat transfer surfaces remained clean, the buildup of mineral scale and suspended mater in the “non-heat transfer” areas of the unit was severe. Suspended solids levels (TSS) greatly exceeded cooling system standards. Solids management and control must be addressed in further development efforts in order for this technology to be practically applicable with make-up water of this type.

### *Dry Cooling—Spray Enhancement of ACC performance*

Dry cooling of electric power plants is being used with increasing frequency in the United States and around the world. One concern is that air-cooled systems can impose a limitation on plant output during the hottest hours of the year, when power demand is at its peak. An approach to mitigating this concern is the use of a small amount of water for a limited period to enhance ACC performance at this critical time.

This approach can be implemented by cooling the inlet air with water sprayed into the inlet air stream. Spray enhancement has the benefit of being a low capital cost system which can be easily installed on existing ACC's. Its perceived disadvantages are the relatively inefficient use of the spray water and potential corrosion damage or scaling of the finned surfaces of the ACC.

Field tests of spray enhancement at Crockett Co-Generation in Crockett, California [9] and at Reliant's Bighorn Power Plant in Primm, Nevada [10] were undertaken to develop design and operating guidelines which would address the two primary issues—water use inefficiency from "rainback" out of the spray zone and potential scaling and corrosion to the finned tube bundles.

The tests at Crockett were conducted with arrays of a large number of small (~ 0.1 gpm/nozzle) nozzles as shown in Figure 28-13. The results showed a reasonably consistent performance illustrated in Figure 28-14. It should be noted that the correlation is dimensional and cannot be confidently applied to ACC's of different sizes or to operation at significantly different atmospheric conditions.

The tests at Bighorn were conducted with fewer, larger (~ 5 gpm/nozzle) nozzles and under hotter, dryer conditions as shown in Figure 28-15.

Results suggest general design criteria of:

- Spray rate: 15 gpm/cell
- Nozzle arrangement: 4 radial flow nozzles 5 feet below fan inlet
- Nozzle pressure: 350 psig
- Water treatment: Reverse osmosis

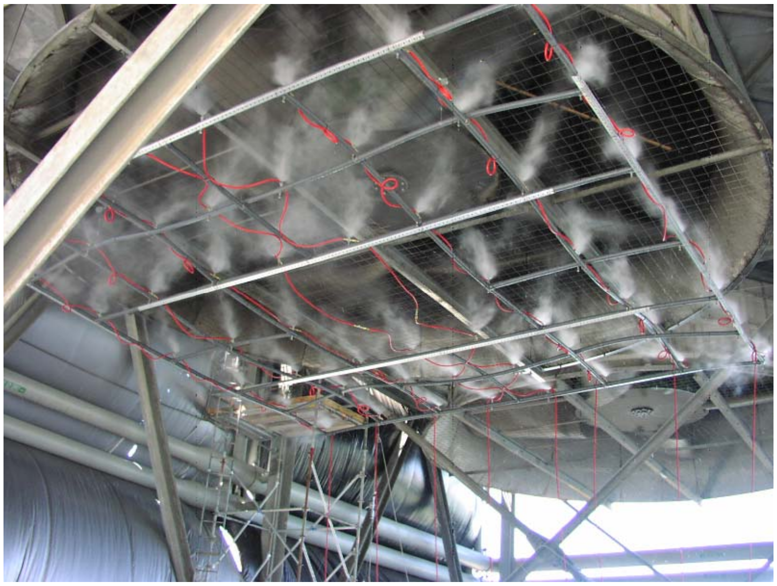


**Figure 28-13**
**Spray Enhancement under ACC Fans at Crockett**

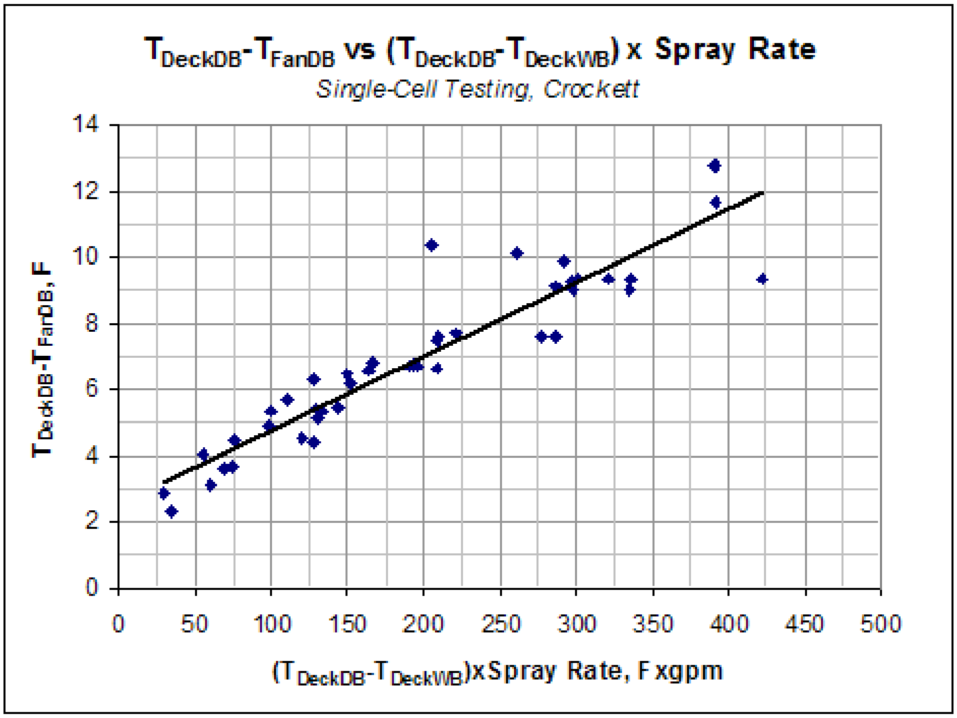


**Figure 28-14**
**Correlation of Spray Enhancement Performance Data from Crockett Tests**

**Figure 28-15**
**Spray Nozzle Arrangement at Bighorn Power Plant**

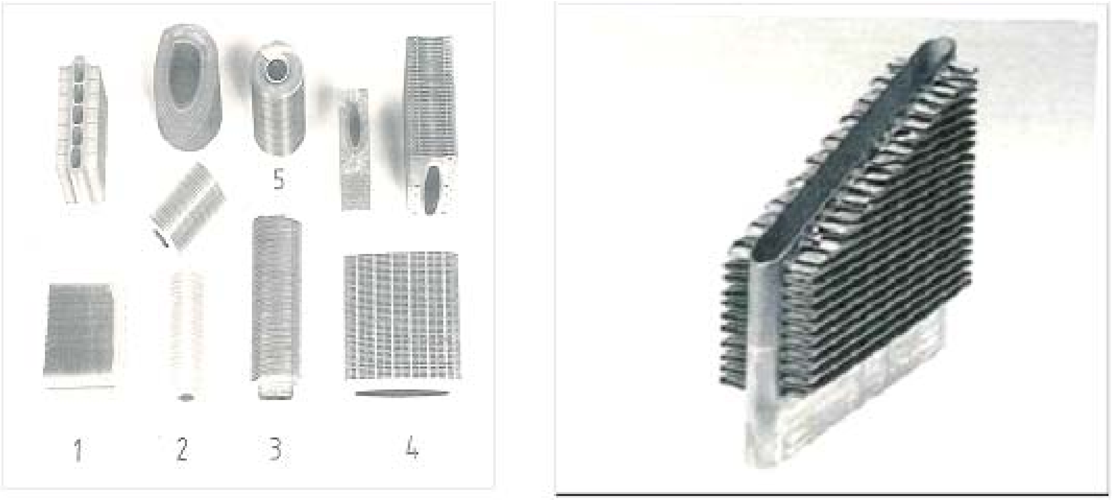
Practical considerations of rainback and unit wetting will likely limit the cooling effect for typical ACC designs to no more than 5 F. This is sufficient to significantly reduce the load reduction during the hottest 200 to 300 hours of the year in locations in the Southwestern U.S..

Additional development work should be pursued before a practical system can be applied with confidence. Specifically,

1. Opportunities should be sought to work with plants who wish to try spray enhancement, to encourage them to follow the design recommendations in this report and to observe full scale operation over an extended time.
2. Variations on the approach taken in these tests should be explored. For example, the use of a larger number of smaller nozzles mounted inside the cells has been recommended by an ACC vendor as a preferred approach.
3. A systematic comparison of the cost/benefits of spray enhancement with those of a supplementary wet cooling tower should be made for both new unit and retrofit situations.

### *Dry Cooling—Improved Air-Side Surfaces*

The most important element in determining the performance of air-cooled condensers is the characteristic of the finned tube bundles where the heat is transferred from the condensing steam to the air. A number of extended surface designs have been used over the years. Figure 28-16 [11] shows a variety of geometries. The most commonly used on modern installations in the U.S is the SRC or (single row condenser) shown on the right in Figure 28-16. Here aluminum fins are bonded to a flattened externally aluminized or aluminum clad steel tube forming a tube that replaces two or three rows of round or elliptical tubes. The steam side geometry is particularly effective for draining the condensate and avoiding vapor blockage or potential freezing in cold climates.



**Historical evolution** **Single row condenser–today**

**Figure 28-16**
**Evolution of Extended Surface Condensing Tubes**

The wavy fin has good characteristics of high heat transfer coefficients and acceptable pressure drop. Further advances will undoubtedly come from research on innovative fin geometries.

## *Dry Cooling—Mitigation of Wind Effects on ACC Performance*

It is well known that the performance of air-cooled condensers can be adversely affected by wind [12]. This is illustrated in Figure 28-17 for an ACC in operation on a plant in the Southwestern U.S. At an ambient temperature of 100°F, the turbine exhaust pressure at wind in the range of 12 to greater than 20 mph is approximately 1.5 in Hga higher than at low wind conditions, with a resultant reduction in steam turbine output of the order of 10%.

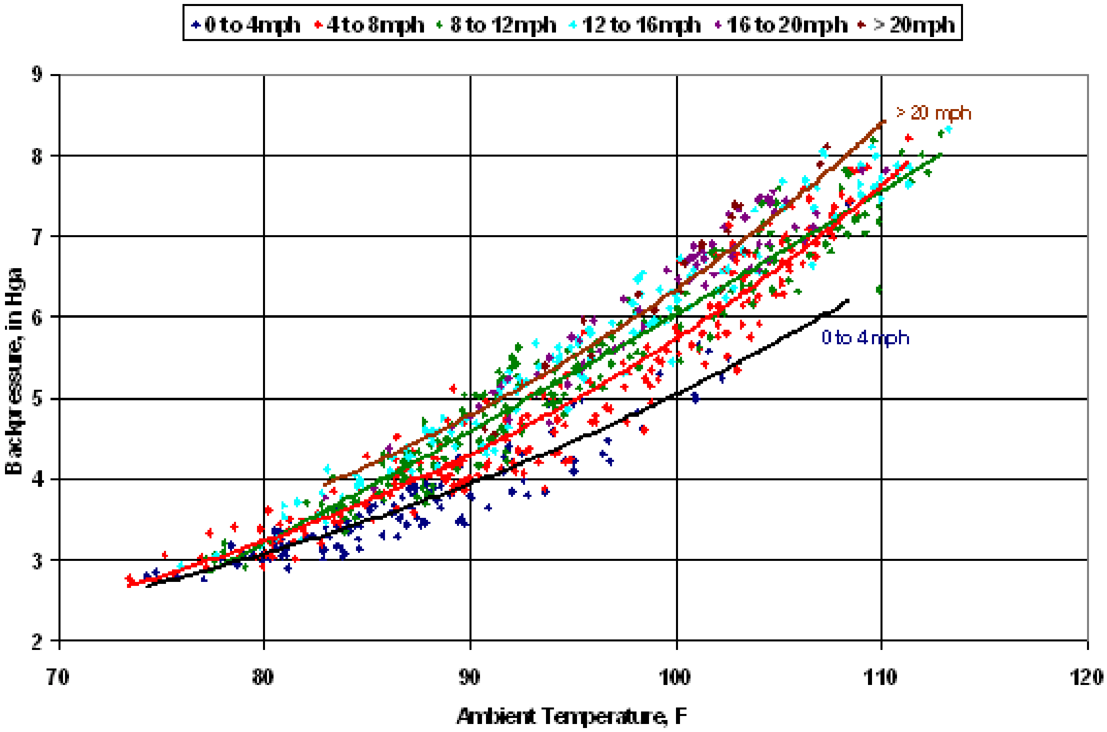


**Figure 28-17**
**Recirculation**

The generally accepted hypotheses are that the negative effect of wind on ACC performance is attributable to two major causes, namely:

- Recirculation of heated plume air into the ACC inlet air stream
- Degradation of the fan performance and reduced air flow to some cells.

Figure 28-18 shows the nature of severe recirculation. This normally occurs in edge and corner cells in the downwind portion of an ACC. Fan performance degradation on the other hand normally occurs in upwind cells close to the perimeter. The combined effect can degrade the performance of several cells in different areas of the ACC with the overall performance effect illustrated in Figure 28-17.

**Figure 28-18**
**Recirculation**

Extensive tests were conducted on five full-scale ACC's in 2005(EPRI/CEC Wind study report) and more detailed measurements were made on one of the units in the summer of 2007. Analysis of the data is still in progress, but it is believed that the effect on fan performance is the more important of the mechanisms. Figure 28-19 shows the fall off of the inlet air flow to a perimeter cell on the south end of an ACC when the wind comes predominantly form the South.

Several studies are underway around the world to combine field data, computational fluid dynamic modeling and wind tunnel testing to develop quantitative, generalizable correlations of wind performance that will usable for the design of wind screens or other features to mitigate the deleterious effect of wind on ACC performance.

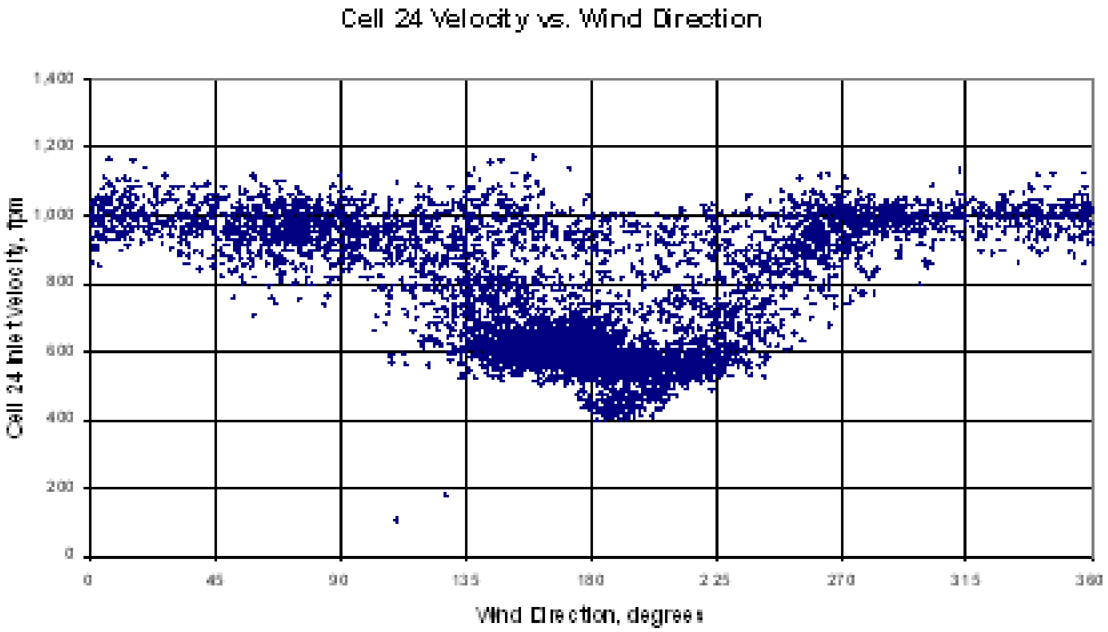


**Figure 28-19**
**Effect of Wind on Fan Performance (from [13])**

## Conclusions

The effect of thermo-electric power generation on the aquatic environment is primarily influenced by the choice of the power plant cooling system. Four primary types of cooling system are commonly used: once-through cooling, closed-cycle wet cooling, dry cooling and hybrid (wet/dry) cooling. The important environmental effects are thermal discharge, intake losses, chemical discharges and water consumption.

Once-through cooling, while once the system of choice at nearly all plants, is now almost never used for new plants. Of the closed-cycle systems, the all-wet system withdraws and consumes the most water but is the least costly and most efficient. Dry cooling eliminates nearly all interactions with the aquatic environment but is the most costly and has the largest adverse impact on plant efficiency and capacity. Hybrid systems are normally intermediate in cost and performance between wet and dry systems, but to date have been rarely used in the U.S.

A number of technological advances are to be expected which will further reduce the environmental impacts of wet systems and further reduce the cost of the dry systems. These include approaches such as water recovery from wet cooling tower plumes, heat rejection equipment that can more effectively use reclaimed water in place of fresh water, improved heat exchanger surfaces of dry cooled equipment, enhancement of air-cooled condenser performance using inlet air sprays and reducing the adverse effects of wind on air-cooled condenser performance.

## References

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2. *Water Use for Electric Power Generation*. EPRI, Palo Alto, CA: In press (2007).
3. U.S. Clean Water Act; Sections 316(a) and 316(b).
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11. Inlet Air Spray Cooling Enhancement for Air-Cooled Condensers, California Energy Commission. Sacramento, CA: In press (2006).
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13. *Air-Cooled Condenser Design, Specification, and Operation Guidelines*. EPRI, Palo Alto, CA: 2005. 1007688.
14. Effect of Wind on the Performance of Air-Cooled Condensers, California Energy Commission. Sacramento, CA. In press (2007).

# A
# WORKSHOP AGENDA

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## Final Workshop Agenda

**The Second Thermal Ecology and Regulation Workshop**
**October 2-3, 2007**
**Located at Tri-State Generation and Transmission Association Headquarters**
**1100 West 116th Avenue**

### DAY 1 OCTOBER 2, 2007

| | |
|---|---|
| **Registration and Continental Breakfast** | 7:00 - 8:00 |
| **Moderator for Sessions I & II: Chantell Johnson, Tri-State** | |
| **I. Introductions and Workshop Overview - Bob Goldstein, EPRI** | 8:00 - 8:10 |
| Keynote Speaker: Sixty Years of Trying to Set Temperature Criteria and Standards to Protect Aquatic Life - **Chuck Coutant, ORNL (Retired)** | 8:10 - 8:30 |
| **II. Perspectives on 316(a)** | |
| USEPA perspectives on the 316(a) program: past to present - **Deborah Nagle, EPA** | 8:30 - 9:00 |
| Overview of thermal paradigms associated with 316(a): Are they valid today? - **Steve Jinks, ASA Analysis & Communication, Inc.** | 9:00 - 9:20 |
| New Thermal Metrics and Permit Implementation by States and Regions - **Kristy Bulleit, Hunton & Williams** | 9:20 - 9:40 |
| Discussion for session II | 9:40 -10:00 |
| **Morning Break** | 10:00 - 10:20 |
| **Moderator for Session III: Chuck Coutant** | |
| **III. Water Quality, Thermal Standards and Protection of Aquatic Life** | |
| Narrative temperature standards in Colorado: Why they remained narratives and associated policy decisions - **Lareina Wall, GEI Consultants** | 10:20 - 10:40 |
| Temperature criteria development for the Ohio River: Lessions learned - **Erich Emery, ORSANCO** | 10:40 - 11:00 |

| | |
|---|---|
| Towards developments for scientifically-based implementation of the European Water Framework Directive (WFD, 2000) as regard to fish communities, thermal fluctuations and implications for power generation thermal releases - **Yves Souchon, CEMAGREF and Cecile Delattre, EDF R&D** | 11:00 - 11:20 |
| Development of Proposed Thermal Water Quality Rules in Wisconsin - **Mike Wenholz, Wisconsin Department of Natural Resources** | 11:20 - 11:40 |
| Discussion for Session III | 11:40 - 12:00 |
| **Lunch** | 12:00 - 1:00 |
| **Moderator for Session IV: Ron Lewis, Duke Energy** | |
| **IV. Thermal Response Characterization** | |
| Challenges with moderizing a temperature criteria derivation methodology: the Fish Temperature Modeling System (FTMS) - **Chris Yoder, Midwest Biodiversity Institute** | 1:00 - 1:20 |
| Laboratory vs. Field Thermal Tolerances: A Review and Mechanisms Explaining Thermal Tolerance Plasticity - **Rob Reash, American Electric Power** | 1:20 - 1:40 |
| Sensitivity of early life stages of freshwater mussels to a range of common and extreme water temperatures - **Tamara Pandolfo, North Carolina State University** | 1:40 - 2:00 |
| Thermal Stress and Recovery in Fish Exposed Intermittently to Near-lethal Temperatures - **Mark Bevelhimer, ORNL** | 2:00 - 2:20 |
| Modeling to demonstrate thermal impacts on benthic algae and mussel metabolism in Great Lakes - **John Schafer, Great Lakes WATER Institute** | 2:20 - 2:40 |
| **Afternoon Break** | 2:40 - 2:55 |
| Telemetry and other tools for evaluating the impacts of thermal discharges on fishes - **Tim Brush, Normandeau Associates** | 2:55 - 3:15 |
| A Methodology for Evaluating Effects of Power Plant Heat Load on Biota - **Tom Englert, HDR\|LMS** | 3:15 - 3:35 |
| Discussion for Session IV | 3:35 - 3:55 |
| **Moderator for Session V: Bill Mills, Tetra Tech** | |
| **V. Poster Session** | 3:55 - 4:45 |
| Estimation of Forced Evaporation from Power Plants that use once-through cooling systems - **Bill Mills, Tetra Tech** | |

Use of field data to support or refute laboratory-derived thermal tolerance values - **Greg Seegert, EA Engineering**

eTherm: A web-based resource document on 316(a)-related issues - **Christine Lew, Tetra Tech**

Utilization of Aerial Thermal Imaging in a Regional Water Quality Monitoring Program - **Mark Hess, Ocean Imaging**

Viability of temporary cooling towers to comply with thermal discharge regulations - **Patrick Williams, Aggreko**

Establishing alternative criteria for thermal shock - **John Young, ASA Analysis & Communication, Inc.**

New regulations on the discharge of heated water in the Netherlands - **Maarten Bruijs, KEMA**

Application of 3D numerical model THREETOX to the prediction of cooling water transport and mixing - **Maarten Bruijs, KEMA**

## DAY 2: OCTOBER 3, 2007

| | |
|---|---|
| **Breakfast** | 7:30 - 8:30 |
| **Moderator for Session VI:** **David Michaud, We Energies** | |
| **VI. Case Studies** | |
| Defining Hydrothermal Limits for Merrimack Station that are Protective of the Balanced Indigenous Populations of Fish in the Merrimack River, New Hampshire - **Mark Hutchins, Normandeau Associates** | 8:30 - 8:50 |
| Dissolved Oxygen Enhancement for Cooling Water Discharge – Can It Be Done? Is It Necessary? - **Sharon Good, Tampa Electric Company** | 8:50 - 9:10 |
| Thermal effects at several Ohio River power plants - **Greg Seegert, EA Engineering** | 9:10 - 9:30 |
| Thermal Load, Dissolved Oxygen, and Assimilative Capacity; Is 316(a) Becoming Irrelevant? – The Georgia Power Experience - **Terry Cheek, Geosyntec and Bill Evans, Georgia Power** | 9:30 - 9:50 |
| FLOW MANAGEMENT - Keeping a 316(b) solution from becoming a 316(a) problem - **Bill Dey, ASA Analysis & Communication, Inc.** | 9:50 - 10:10 |
| **Morning Break** | 10:10 - 10:30 |
| Elm Road Story - interplay between 316(a) and 316(b) - **Dave Lee, We Energies** | 10:30 - 10:50 |

| | |
|---|---|
| Effects Of Colbert Fossil Plant On The Fish Community In Pickwick Reservoir - **Dennis Baxter, TVA** | 10:50 - 11:10 |
| Monitoring ecological effects thermal pollution by means of telemetry - **Maarten Bruijs, KEMA** | 11:10 - 11:30 |
| Thermal discharges - The New Zealand experience - **Jacques Boubee, National Institute of Water & Atmospheric Research Ltd.** | 11:30 - 11:50 |
| Discussion for Session VI | 11:50 - 12:10 |
| **Lunch** | 12:10 - 1:10 |
| **Moderator for Session VII: Doug Dixon, EPRI** | |
| **VII. Emerging Issues and Technologies** | |
| Advances in Thermal Plume Modeling - **E. Eric Adams, MIT** | 1:10 - 1:30 |
| Thermal Issues and a Hybrid Cooling Technology in Siting North Anna Unit 3 - **Judson White and John Waddill, Dominion** | 1:30 - 1:50 |
| Co-locating Power Plants with Desalination and LNG facilities: Maximizing Water Use While Addressing 316(a) and 316(b) Issues - **Tim Hogan, Alden** | 1:50 - 2:10 |
| Recent advances in cooling technology and relevant research questions as they apply to thermal discharge issues - **John Maulbetsch , Maulbetsch Consulting** | 2:10 - 2:30 |
| Discussion for Session VII | 2:30 - 2:50 |
| **Workshop Closure - Bob Goldstein, EPRI**<br>Identification and summarization of issues | 2:50 - 3:20 |

# B

# REGISTRANTS FOR THE SECOND THERMAL ECOLOGY AND REGULATION WORKSHOP

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