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Ronald G. King , Greg Seegert , Joe Vondruska , Elgin S. Perry & Douglas A. Dixon

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[Article]

Factors Influencing Impingement at 15 Ohio River Power Plants

RONALD G. KING,* GREG SEEGERT, AND JOE VONDRUSKA
EA Engineering, Science, and Technology, Inc., 444 Lake Cook Road, Suite 18, Deerfield, Illinois 60015, USA

ELGIN S. PERRY
2000 Kings Landing Road, Huntingtown, Maryland 20639, USA

DOUGLAS A. DIXON
Electric Power Research Institute, 3420 Hillview Avenue, Palo Alto, California 94304, USA

Abstract.—Impingement abundance monitoring was conducted at 15 Ohio River power plants as part of the Ohio River Ecological Research Program. Impingement rates were compared with environmental, power plant design, and operational factors that varied within and among the power plants, including water temperature, river flow and stage, change in flow and stage during the sampling events, volume of cooling water pumped, design pumping capacity, approach velocity, location of the intakes along the river, intake type, and intake configuration. The study demonstrated similarities in species composition, size distributions, and seasonal patterns over nearly 1,400 river kilometers of the Ohio River, results that were consistent with studies conducted nearly 30 years earlier. Dramatic annual differences in impingement rates during the 2-year study indicated that impingement is largely a function of the recruitment levels of juvenile gizzard shad *Dorosoma cepedianum*, threadfin shad *D. petenense*, and freshwater drum *Aplodinotus grunniens*, measures that fluctuate widely in the Ohio River based on long-term monitoring data and unpredictably based on current knowledge of the impingement process. The study also showed that most physical variables had little or no effect on impingement rates. Water temperature was identified through multiple regression analyses as the most important physical variable, with impingement tending to increase during the winter. Actual pumping rate during sampling events—the only factor evaluated that is under the direct control of the participating power plants—was one of the least important factors affecting impingement rates.

The use of surface waters as cooling water at conventional power plants results in the impingement of aquatic organisms at cooling water intake structures (intakes) that are screened to limit the size of particles passing through condenser systems. Impingement studies conducted in the 1970s and 1980s were in response to section 316(b) of the Clean Water Act (CWA; CWA 1972), which required that "the location, design, construction, and capacity of cooling water intake structures reflect the best technology available [BTA] for minimizing adverse environmental impact." Rules implementing section 316(b) were challenged after passage of the CWA, and in 1979 the U.S. Environmental Protection Agency (EPA) withdrew implementing regulations. In the absence of regulations, permitting authorities relied on impact assessments, regulatory decisions, EPA administrative findings, and resource management objectives to assess compliance on a case-by-case basis (Dey et al. 2000). In lieu of implementing regulations, the EPA and state administrators generally reissued discharge permits when studies demonstrated that impingement losses did not represent an adverse impact to the fish community. Historical impingement studies at power plants along the Ohio River followed the national trend in that discharge permits issued by the five states (West Virginia, Ohio, Kentucky, Indiana, and Illinois) within our study reach typically required 1- or 2-year studies to estimate impingement losses (EPRI 2009a).

In 1995, EPA entered into a consent decree that established a timetable for issuing rules that required installation of BTA at power plant intakes. In July 2004, EPA issued final regulations that established requirements for intakes at existing power plants (U.S. Office of the Federal Register 2004: EPA Phase II Rule). This rule was subsequently vacated and remanded in part by the U.S. Court of Appeals for the Second Circuit in January 2007 (U.S. Office of the Federal Register 2007). Though remanded, the BTA requirement of section 316(b) remains intact; therefore, we believe the results from this study will be useful for evaluating BTA alternatives for reducing impingement impacts at existing intakes in the future when regulations are re-established.

The Phase II Rule allowed use of historical data to

* Corresponding author: rking@eaest.com

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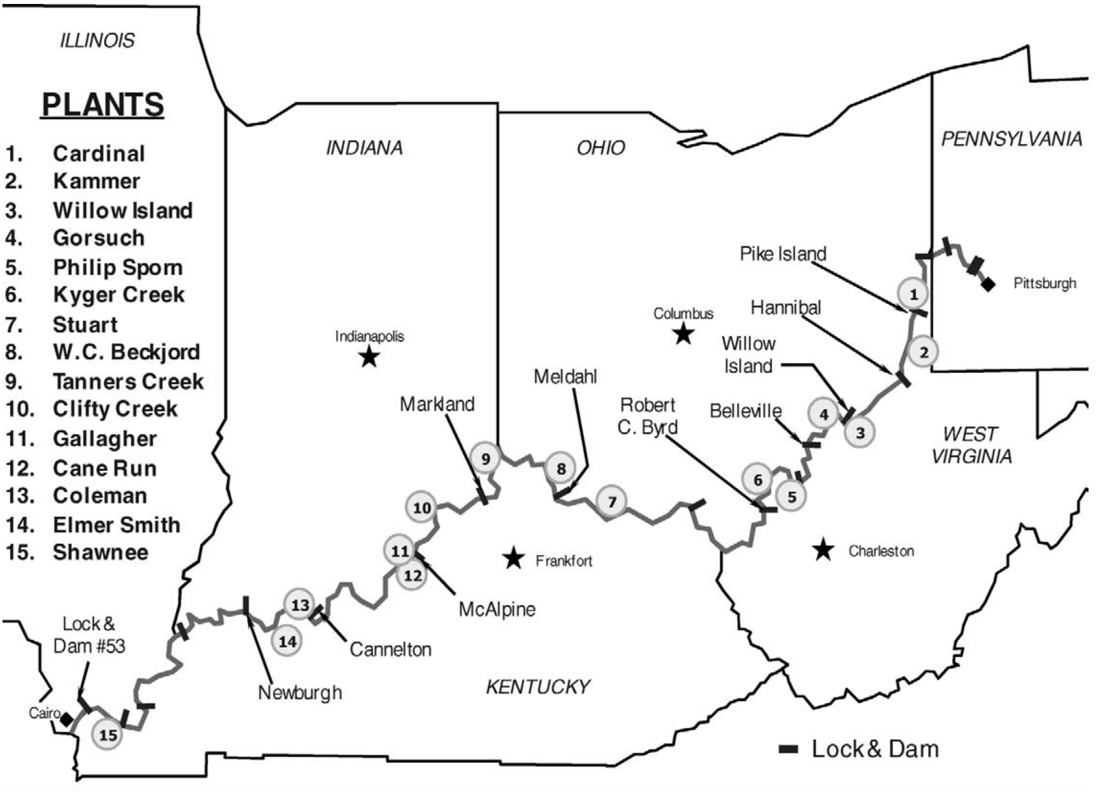

FIGURE 1.—Location of the 15 power plants participating in the Ohio River Ecological Research Program impingement monitoring study, June 2005–June 2007.

estimate current impingement losses; however, evaluation of previous impingement studies at power plants along the Ohio River led to a decision to collect new impingement data as part of the Ohio River Ecological Research Program (ORERP). The ORERP is the largest collaborative power plant research program in the world and has an objective of providing quantitative and qualitative fisheries data from the Ohio River to support assessment of the effects of power plant operation on the river's aquatic community. This collaborative effort afforded the opportunity to assess factors potentially influencing impingement at the intakes of 15 power plants located over almost the entire length of the Ohio River (Figure 1). The power plants in the study were subject to the Phase II Rule and volunteered to participate in the ORERP study. They represent nearly 70% of the power plants on the Ohio River with once-through cooling and are therefore subject to section 316(b) and portions of the remanded rule.

The 2-year study evaluated environmental, power plant design, and operational factors that potentially influence impingement rates. Environmental factors included water temperature and hydrological data from the Ohio River. Water temperatures directly affect swimming capabilities of fish, and low winter temperatures are known to result in morbidity among clupeid fishes (Loar et al. 1978; White et al. 1986). Hydrological factors, such as river flow, stage, and changes in river flow and stage during sampling events, potentially influence fish behavior and movements that determine distribution patterns near power plant intakes. Water temperature and hydrological factors probably exert a combined influence on the susceptibility of fish to impingement. The design and operational factors that were evaluated were volume of cooling water pumped during sampling events, design flow, design approach velocities at the intakes, intake locations along the river, intake configurations (e.g., submerged or surface), and position of the intakes on the riverbank (shoreline or recessed canals).

The scope of impingement studies conducted after passage of the CWA in 1972 varied widely among EPA regions and states. There was little coordinated effort to standardize studies, and differences in sampling frequency, duration, and data analysis make it difficult to use historical results to evaluate factors influencing impingement. Consequently, those early studies did not allow the causal analyses that were applied in the ORERP study as presented herein. Our study provided data collected in a coordinated manner at multiple power plants on the same river system. Previous evaluations of impingement at multiple power plants in different water bodies include a study of 16 power plants in Michigan (Benda and Houtcooper 1977) and an analysis of impingement data from 32 power plants in the southeastern USA (Loar et al. 1978). Although both studies evaluated factors influencing impingement rates, there were variables that limited their analysis. The data analyzed in the Michigan study were collected during the same 1-year period but the 16 intakes were on very different systems, including the Great Lakes, other inland lakes, and rivers, whereas the ORERP study included only Ohio River power plants. Factors influencing impingement at the Michigan power plants were not specifically identified except that impingement rates at adjacent units were directly related to pumping capacity. Rates varied seasonally and on a diel basis, but those trends were not related to causal factors, such as water temperature or intake approach velocities.

Loar et al. (1978) analyzed impingement data from 32 power plants in the southeastern USA that represented intakes in a 15-state region to evaluate factors influencing impingement. The precision of that analysis was limited because data were collected from numerous river basins over an extended number of years. Furthermore, water quality data and pumping rates were not typically recorded concurrently with the impingement sampling events. Their analysis focused on threadfin shad *Dorosoma petenense*, which accounted for 90% of the fish impinged at the power plants included in their study. Water temperature below 10°C was identified as the dominant factor influencing impingement of threadfin shad and it was suggested that abundance of fish in the source water was also a primary factor. Although impingement rates have been assumed to be directly related to velocities near intakes (Boreman 1977), a direct relationship was not found between clupeid impingement and theoretical maximum intake velocities (Loar et al. 1978).

More recently, Saalfeld (2006) evaluated factors influencing impingement at five Alabama power plants with intakes located on rivers in three physiographic regions. The study examined the influence of environmental (dissolved oxygen, water temperature, specific conductance, turbidity, river discharge, river stage, and change in water level during sampling) and operational (number of screens operating, debris loading, cooling water flow, intake velocity, and hydraulic zone of influence [HZI]) variables. Saalfeld (2006) used correlation and stepwise regression analyses similar to those used in our study and showed that water temperature, dissolved oxygen, the size of the HZI, river discharge, and time of year were the best predictors of impingement rates when the five plants were grouped. Contradictory results occurred at the individual intakes for several of the variables that were correlated inversely or directly with impingement rates depending on the intake. Impingement rates were consistently correlated directly with the size of the HZI, with the lowest rates at the intake associated with the smallest zone and the highest rates at the intake associated with the largest zone.

The ORERP study provided the data needed to examine potential causal relationships of impingement and variables that potentially influence impingement rates. The data were collected over a 2-year period in a consistent and coordinated manner that yielded a sample size large enough for statistical testing. Using that large sample size, impingement rates of six common fish taxa were evaluated relative to environmental, design, and operational factors that have been inferred from earlier studies as potentially influencing impingement or that were presumed to be contributing factors as noted in the EPA Phase II Rule.

Methods

Power plant characteristics.—The power plants sampled during the ORERP study are located along the Ohio River and extend from river kilometer (rkm) 124 near Brilliant, Ohio, downstream to rkm 1,522 at Paducah, Kentucky (Figure 1). The intakes and screening systems at all 15 power plants are typical for the power industry, including fixed bar-racks (spaced approximately 10 cm apart) at the screen house entrances to exclude large debris (e.g., logs) and conventional vertical traveling-band screens in the intake screen houses. The linked bands of screens are typically about 3 m wide by about 1 m deep, with total heights ranging from 15 to 25 m depending on water depth and screen house elevations. The vertical traveling screens at the participating power plants do not provide fish protection features, such as fish collection buckets, low-pressure screen washes, or fish return systems. Mesh size for all screens was 9.5 mm. The linked screens are periodically rotated to remove accumulated debris, including impinged fish, using high-pressure backwashes. Normally, screen rotation is done either automatically based on pressure differential readings made on either side of the screens or manually at the beginning of work shifts. For this study,

TABLE 1.—Selected characteristics of 15 Ohio River power plants studied during the Ohio River Ecological Research Project impingement study, 2005–2007 (rkm = river kilometer).

Plant name	rkm	Design flow (m^3/min)	Generating capacity (MW)	Design approach velocity (m/s)	Number of generating units	Intake location	Intake configuration	River bank position
Cardinal	124	3,077	1,830	0.4	3	Canal	Submerged	Outside bank
Kammer	179	1,817	630	0.2	3	Canal	Submerged	Inside bank
Willow Island	257	606	243	0.4	3	Shoreline	Submerged	Straight channel
Gorsuch	283	963	213		3	Shoreline	Surface	Straight channel
Philip Sporn	389	2,729	1,050	0.5	5	Shoreline	Submerged	Straight channel
Kyger Creek	418	3,142	1,085	0.5	5	Canal	Submerged	Straight channel
J. M. Stuart	653	2,503	1,830	0.3	4	Shoreline	Surface	Straight channel
W. C. Beckjord	729	1,938	1,186	1.0	6	Shoreline	Surface	Straight channel
Tanners Creek	795	2,801	995	0.3	4	Shoreline	Submerged	Straight channel
Clifty Creek	901	3,770	1,306	0.8	6	Canal	Submerged	Outside bend
Gallagher	982	1,167	637	0.5	4	Shoreline	Surface	Straight channel
Cane Run	993	1,379	550	1.2	3	Shoreline	Submerged	Straight channel
Coleman	1,165	938	455		1	Shoreline	Submerged	Straight channel
Elmer Smith	1,215	803	445	1.5	2	Shoreline		Outside bend
Shawnee	1,522	3,962	1,750	0.2	10	Canal	Submerged	Straight channel

however, the screens were rotated continuously or frequently (e.g., every 1–2 h) to facilitate sample processing. Removed debris and fish are sluiced back to the river downstream from the intakes.

The power plants represent a range of generating and cooling water capacities, with various intake types and configurations (Table 1). The number of generating units at each power plant ranged from 1 to 10 units, with generating capacities ranging from 213 to 1,830 MW and design pumping capacities ranging from 606 to 3,962 m^3/min. The power plants withdrew cooling water from submerged or surface intakes that were recessed from the riverbank (intake canals and forebays) or were flush with the shoreline. Five of the intakes were recessed intakes with canals (about 15–100 m long × about 25–75 m wide), and 10 intakes were flush with the shoreline (Table 1). Most of the power plants had submerged intakes, but four had surface intakes. The majority of intakes were located along straight segments of the river; only one intake was located on an inside bend, and three power plants had intakes located on outside bends (Table 1).

Sampling schedule.—Sampling was conducted under a survey design based on seasonal results from historical impingement data for the Ohio River (EPRI 2009a). A "model-based estimation" survey design (Rao 2003) allowed prediction of impingement estimates using data outside of the target population of a single power plant and therefore allowed a lower frequency of sampling than has historically been employed for impingement studies at existing facilities (EPRI 2004). Intakes at the participating power plants were sampled 20–45 times during the 2-year study. Two power plants were sampled 20 times during the first year of the study, and the other 13 power plants were sampled 37–45 times over a 2-year period from June 2005 through June 2007. Each plant was sampled once every 4 weeks from late January to mid-July (a period when historical impingement rates were lowest) and every 2 weeks from late July to mid-January.

Sampling.—Impingement sampling events represented 24-h collections from each intake screen. Sampling locations depended on the screen wash configurations. If all screens were washed into a common sluiceway, sampling was conducted with a single collection basket placed in the sluiceway downstream from the last screen. In cases where there were separate spray wash sluiceways, each sluiceway was monitored separately, following either a concurrent or an alternating sampling scheme.

Collection devices.—Two types of collection baskets were used to collect impinged organisms: "in-line" and "end-of-pipe" baskets fitted with the same or slightly smaller screening than the 9.5-mm mesh used for the traveling screens at each intake. The in-line collection baskets were fabricated to fit in the return sluiceways so that the screen wash, debris, and all impinged fish passed through the baskets. In-line baskets were open at the upstream (receiving) end of the basket and were usually open on the top, while the sides, bottom, and downstream ends were screened. Due to their smaller size, the in-line collection baskets were easier to deploy than were the larger end-of-pipe baskets but filled rapidly during periods of high fish or debris loading, which could cause the basket to overflow, potentially resulting in sample loss. Sample loss was minimized by frequent visual monitoring when necessary. When required by screen loads, sampling duration was prorated based on the time necessary to remove and clean the collection baskets.

The end-of-pipe collection baskets were positioned at the end of the screen wash return so that its size was only constrained by the strength of the frame used to suspend it and the device used to lift it. Because of their larger size, end-of-pipe baskets were less prone to overflowing and therefore required less monitoring and held more fish and larger debris loads than did the in-line baskets.

Sample collection.—Traveling screens were rotated and washed immediately prior to the start of each 24-h sampling event. At a minimum, the screens were rotated 12 and 24 h after sampling was initiated. Frequent rotation of the screens was preferred because it allowed a more accurate determination of the initial condition of impinged organisms; therefore, at most of the power plants, screens were operated continuously or at least regularly (e.g., every 1–2 h) during each 24-h sampling period. Accumulated material was removed from the collection basket as needed to prevent the collection basket from overflowing.

Sample processing.—Material accumulated in the collection baskets was sorted as quickly as possible, both during sampling and at the conclusion of each sampling event. Unless the number of fish encountered was high, impinged fish were sorted from the debris and placed in buckets filled with ambient river water to allow a more accurate determination of each fish's condition. Fish exhibiting signs of life (e.g., swimming or with opercular movements) were classified as "alive." Best professional judgment was applied to determine the condition of impinged organisms other than those classified as alive. Impinged fish that appeared to have recently died were classified as "fresh-dead." Fresh-dead fish typically had gill filaments that were still red or slightly faded but had not been bleached white. Fish that had gill filaments bleached white or that were visibly diseased, covered in fungus, bloated, or beginning to decompose were classified as "long-dead." The distinction between fresh-dead and long-dead specimens was relatively easy to discern during warm weather but more difficult during the winter, when low water temperatures delayed decomposition. Consistent with the Phase II Rule, only fish classified as alive or fresh-dead were considered to have been impinged during a given sampling event.

Impinged fish were typically identified to species, whereas shellfish were only identified as crayfish (Cambaridae) or mussels (Unionidae). All organisms were counted and the condition of each was recorded. For each species or taxa collected during each sampling event, up to 25 individuals of each life stage (e.g., age-0 and age-1 fish) and life condition (i.e., fish classified as dive or fresh-dead) were individually weighed to the nearest gram, and their total lengths (TLs) were measured to the nearest millimeter. Additional specimens were counted and weighed as a batch. Juvenile fish were placed into two life stages, age 0 and age 1, based on size distributions. Age-0 fish, which were spawned between June–December 2005 and June–December 2006, were classified as age-1 fish in January following the year in which they were spawned.

Statistical analyses.—Impingement rates of six commonly impinged taxa (gizzard shad *Dorosoma cepedianum*, channel catfish *Ictalurus punctatus*, temperate basses *Morone* spp., sauger *Sander canadensis*, bluegill *Lepomis macrochirus*, and freshwater drum *Aplodinotus grunniens*) were compared with two sets of independent variables that potentially influenced impingement at the 15 power plants. Physical variables included in the analyses that varied over time within a given power plant were termed "within"-plant variables. These within-plant variables were water temperature, volume of cooling water used during sampling events (termed total shift volume), river flow and stage, and change in river flow and stage during each sampling event. Total shift volumes, which were reported by the power plant operators, were based on the number of pumps operating and pump ratings. River flow and stage data were obtained from the U.S. Geological Survey or U.S. Army Corps of Engineers gauges located nearest to each power plant. The change in river flow and stage represents the difference between daily means for the start and end dates of each 24-h sampling event.

The second set of independent variables represents intake characteristics that varied "among" plants (Table 1). These among-plant variables were rkm, plant capacity (as generation and pumping capacity), intake location (canal or shoreline), intake configuration (surface or submerged), and intake position (straight channel, inside river bend, or outside river bend).

Linear models in the Statistical Analysis System (SAS; SAS 1999), including linear regression, multiple linear regression, analysis of variance (ANOVA), and analysis of covariance (ANCOVA), were used to assess both sets of independent variables collectively by power plant and with power plants pooled to determine which variables were the best predictors of impingement rates of the six commonly impinged fish taxa. Several methods were used to ensure that the large differences in impingement rates among power plants and between study years did not confound the assessments of the within-plant independent variables. When computing correlations, the study year effect was removed by use of partial correlation and the power plant effect was removed by analyzing the power plants individually. In the regression analyses, the power plant and study year effects were included in the model as class variables. The estimated error residuals of the impingement rates in this study were skewed to the right, a pattern that is characteristic of data following a lognormal distribution. Thus, the impingement rate data were $\log_e$ transformed for these analyses.

The first step of the within-plant analysis was to compute pairwise correlation coefficients among the independent variables to address how the within-plant variables related to each other. These pairwise correlations were needed because although multivariate tools, such as stepwise regression, identify the strongest associations between dependent and independent variables, they do not integrate technical understanding to identify cases where perhaps the second-best independent variable has a stronger scientific basis for prediction than the first variable. It was important to identify such cases to formulate which independent variables are important predictors of impingement. Two independent variables are likely to “compete” in a predictive model when they are strongly associated. To assess multicollinearity among independent variables, product-moment partial correlations (CORR procedure in SAS) with the study year effect removed were computed for each power plant. Variables were considered collinear if coefficients were equal to or greater than 0.50.

The second analysis of the within-plant variables assessed the relationship of the dependent variables (i.e., impingement rates of the six common taxa) with each independent variable individually through product-moment partial correlations (CORR procedure in SAS; study year was removed) to address how the independent variables related individually to the dependent variables. A third analysis assessed the relationship of the dependent variables to the independent variables collectively for each power plant. The final step of the analysis for the within-plant variables addressed whether the effects of the independent variables were consistent among the 15 power plants.

The combined information among power plants was evaluated by multivariate relationships for all power plants using a general linear model (GLM; SAS 1999). Two class variables, power plant and study year, were forced to enter the model first, and a stepwise procedure was used to select important predictors from among the remaining within-plant independent variables. In regression analysis, it is possible that two collinear variables are equally good predictors of the response; however, in the stepwise procedure only one variable is selected, while the others are essentially redundant information. Additional analysis of the within-plant variables identified collinear variables that were not selected by the stepwise process.

A multivariate analysis between among-plant variables and impingement rates was also conducted to determine whether intake location (rkm), power plant size (as measured by pumping rate and generating capacity), design approach velocity, intake location, intake configuration, and intake position on the riverbank were associated with impingement rates. These independent variables have one value or level for each power plant and thus only vary among power plants. A stepwise procedure similar to that applied to the within-plant variables was used to select the best among-plant variable (or variables) for predicting impingement rates of the six commonly impinged fish taxa. The selection criterion was the largest F-ratio. The MIXED procedure in SAS was used to fit the two levels (between- and within-plant levels) of the model. The coefficient of determination (r^2) was used for analysis of the within-plant variables but is not defined for MIXED models and is therefore not reported.

For the among-plant analysis, the study year variable was forced to enter the model first to block impingement rates by year. Blocking was necessary because the abundance of age-0 fish, which dominated the impingement collections, varied by two to three orders of magnitude between years. The two power plants (Gorsuch and J. M. Stuart plants) with only 1 year of data were excluded from the among-plant analysis to maintain balanced and complete blocks. Replicating the power plants in blocks increased the sample size and improved the power of detecting the importance of the among-plant variables.

The model measured the effect of each among-plant variable. If the variable was continuous (e.g., rkm, generating capacity, and design approach velocity), a negative or positive slope was derived. For the three class (categorical) variables (intake location, intake configuration, and intake position), the least-squares means for each level are reported to show how the levels compare. Because log-transformed data are used, the direction of the difference in slope is of primary interest rather than the absolute slope, whereas the class variables associated with the higher least-squares means have higher impingement rates.

Results

Species Composition

The 550 sampling events conducted during the 2-year ORERP impingement study yielded a total of 2.9 million fish (Tables 2, 3) and shellfish; among these, 82 species of fish were represented. Shellfish taxa included crayfish, which were collected at all intakes in low numbers, and unionid mussels, which were collected in low numbers at 5 of the 15 power plants. The 82 fish species impinged during the study

TABLE 2.—Summary of fishes (by family) impinged at 15 Ohio River power plants during the Ohio River Ecological Research Program impingement study, June 2005 to June 2007.

Family	Common name	Number of species	Percentage of total number collected	Percentage of total weight collected
Petromyzontidae	Lampreys	1	<0.00	<0.00
Acipenseridae	Sturgeons	1	<0.00	<0.00
Polyodontidae	Paddlefishes	1	<0.00	0.05
Lepisosteidae	Gars	2	<0.00	0.11
Amiidae	Bowfins	1	<0.00	0.01
Hiodontidae	Mooneyes	2	0.01	0.07
Clupeidae	Herrings	3	94.4	88.97
Cyprinidae	Carps and minnows	16	0.04	0.20
Catostomidae	Suckers	13	0.06	0.43
Characidae	Characins	1	<0.00	<0.00
Ictaluridae	North American catfishes	8	0.32	0.58
Esocidae	Pikes	1	<0.00	<0.00
Aphredoderidae	Pirate perches	1	<0.00	<0.00
Atherinopsidae	New World silversides	2	<0.00	<0.00
Belonidae	Needlefishes	1	<0.00	<0.00
Moronidae	Temperate basses	4	0.30	1.16
Centrarchidae	Sunfishes	14	0.15	0.24
Percidae	Perches	9	0.09	1.51
Sciaenidae	Drums and croakers	1	4.54	6.61
Total		82	100.00	100.00

represented 19 families, with 52 species from four families: Cyprinidae (16), Catostomidae (13), Centrarchidae (14), and Percidae (9; Table 2). Many species known to occur in the Ohio River were not collected. Long-term monitoring of the river has yielded at least 130 species during the ORERP (EPRI 2009b), and 159 species had been reported from the river by the late 1980s (Pearson and Pearson 1989). Despite the number of species represented by the four species-rich families, none of the species in those families accounted for more than 0.2% of the fish or more than 1.5% of the biomass collected during the study (Table 2). Instead, three herring species and one species of drum dominated both the total number (98.9%) and total biomass (95.6%) collected during the study. The most commonly impinged species were threadfin shad (69.7%), gizzard shad (23.7%), freshwater drum (4.5%), and skipjack herring (1.1%), which collectively accounted for 99% of the total (Table 3). Although the threadfin shad was the most commonly impinged species, it was confined almost exclusively to the Shawnee Power Plant, the downstream-most power plant in the study. The same four species accounted for nearly 96% of the total biomass collected. All other taxa accounted for less than 1.0% of the total biomass except saugers, which accounted for 1.4% of the total biomass (Table 3).

Gizzard shad and freshwater drum were the two most abundant species at all power plants except the Shawnee Power Plant, where threadfin shad accounted for 92% of the total number collected. Collectively, the two shad species and freshwater drum accounted for 90–99% of

TABLE 3.—Relative abundance of fish taxa commonly collected at 15 Ohio River power plants during the Ohio River Ecological Research Program impingement study, June 2005 to June 2007.

Species or taxon	Number	Percent by number	Weight (kg)	Percent by weight
Threadfin shad *Dorosoma petenense*	2,023,504	69.7	10,392.0	60.2
Gizzard shad *Dorosoma cepedianum*	686,797	23.7	4,725.3	27.4
Freshwater drum *Aplodinotus grunniens*	131,779	4.5	1,140.9	6.6
Skipjack herring *Alosa chrysochloris*	30,426	1.0	235.3	1.4
Channel catfish *Ictalurus punctatus*	5,709	0.2	62.4	0.4
Yellow bass *Morone mississippiensis*	3,852	0.1	46.9	0.3
Bluegill *Lepomis macrochirus*	3,394	0.1	19.1	0.1
Blue catfish *Ictalurus furcatus*	3,075	0.1	28.7	0.2
Temperate basses *Morone* spp.	2,674	0.1	10.8	0.1
Sauger *Sander canadensis*	2,469	0.1	247.8	1.4
White bass *Morone chrysops*	1,779	0.1	136.9	0.8
Subtotal	2,895,457	99.8	17,046.1	98.8
Other taxa	6,934	0.2	210.3	1.2
Total	2,902,391	100.0	17,256.4	100.0

TABLE 4.—Size distributions of fishes commonly impinged at 15 Ohio River power plants during the Ohio River Ecological Research Program impingement study, June 2005 to June 2007.

Species	Number or percentage	Length (mm) interval			Total
		<100	100–149	>149	
Skipjack herring	Number	1,653	1,320	207	3,180
	%	52.0	41.4	6.6	100.0
Gizzard shad	Number	11,882	6,321	3,227	21,430
	%	55.3	29.5	14.9	99.7
Threadfin shad	Number	1,900	248	48	2,196
	%	86.5	11.4	2.1	100.0
Blue catfish	Number	1,122	368	67	1,557
	%	72.1	23.6	4.3	100.0
Channel catfish	Number	2,186	658	319	3,163
	%	69.1	20.8	10.1	100.0
Yellow bass	Number	337	202	198	737
	%	45.7	27.5	26.8	100.0
Unidentified *Morone* spp.	Number	1,236	71	3	1,310
	%	94.4	5.4	0.2	100.0
Bluegill	Number	1,452	114	29	1,595
	%	90.9	7.2	1.9	100.0
Sauger	Number	8	248	1,160	1,416
	%	0.6	17.5	81.9	100.0
Freshwater drum	Number	9,078	4,042	1,334	14,454
	%	62.8	28.0	9.2	100.0
Total	Number	30,584	13,592	6,592	51,038
	%	60.5	26.6	12.9	100.0

the fish and shellfish collected at each of the 15 power plants. Six other species and *Morone* spp. were frequently impinged but collectively accounted for only 0.8% of the total number collected during the 2-year study (Table 3). *Morone* spp. represent age-0 temperate bass species and their hybrids that were generally too small (<100 mm TL) for positive field identification.

Federally protected fish species were not impinged at any of the 15 power plants during the 2-year study. Eighteen species listed by at least one of the five states bordering the study reach (Ohio, West Virginia, Kentucky, Indiana, and Illinois) were impinged, typically in low numbers and at only a few of the power plants.

Size Distributions

The majority of fish impinged during the study were small, typically age-0 and age-1 fish of species common in the Ohio River or adults of smaller species, such as the emerald shiner *Notropis atherinoides*. Commonly impinged species were typically represented by several consecutive 10-mm size-classes, but most fish were less than 150 mm TL (Table 4). The majority of impinged fish represented age-0 and age-1 fish from the 2005 and 2006 year-classes, which were most susceptible to impingement. Although impinged saugers were larger than the other commonly impinged species, the majority (68%) of them were also from the 2005 and 2006 year-classes. Saugers between 100 and 250 mm TL represented primarily fast-growing age-0 or age-1 fish (Schell 1995).

Seasonal length frequency distributions of threadfin shad, gizzard shad, and freshwater drum for all power plants combined demonstrate recruitment of age-0 fish to the impingement samples in the summer and fall and as age-1 fish after December (Table 5). Threadfin shad distributions, which consist almost entirely of fish impinged at the Shawnee Power Plant (the downstream-most plant), show that age-0 fish were impinged in the summer, exhibited seasonal growth in the fall, were impinged through the winter as age-1 fish, and then were impinged in lower numbers in the spring. Gizzard shad and freshwater drum exhibited similar trends, but because they were larger than threadfin shad both species were represented by a wider range of size-classes during all seasons. The study was completed in June 2007 before age-0 fish from the 2007 year-class reached impingeable lengths.

Seasonal and Annual Trends

Seasonal impingement rates during the first year of the study averaged higher during the summer, fall, or winter season at 14 of the 15 power plants and higher in the spring at one plant (Tanners Creek Power Plant; Table 6). Higher seasonal rates were associated with age-0 or age-1 gizzard shad at all power plants except at the Shawnee Power Plant, where threadfin shad had the highest rates of impingement. Mean impingement rates of gizzard shad during the first year were highest

TABLE 5.—Seasonal length frequency distributions (%) for three fish species commonly impinged at 15 power plants along the Ohio River during the Ohio River Ecological Research Program impingement study, June 2005 to June 2007.

	2005			2006			2007	
Size-class (mm)	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring
Threadfin shad								
30–39	1.9							
40–49	8.9				3.6			
50–59	16.2	2.2			1.8	0.5		
60–69	26.5	6.7			10.7	3.3		
70–79	14.6	28.0	11.0	13.6	19.6	19.9	11.3	
80–89	26.8	38.7	45.0	40.9	39.3	45.5	60.0	60.9
90–99	4.3	16.9	17.1	31.8	14.3	12.4	18.4	31.0
100–109	0.3	3.5	6.6	4.5	7.1	4.1	2.5	4.6
110–119	0.3	1.2	9.0	4.5		2.4	1.9	1.1
120–129	0.3	2.0	6.2		1.8	2.9	0.6	1.1
130–139		0.5	1.2		1.8	3.3	2.2	1.1
140–149			0.2			1.0	0.9	
>149		0.3	3.7	4.7		4.7	2.1	
Sample size	370	403	498	44	56	418	320	87
Gizzard shad								
30–39	0.2							
40–49	2.0	<0.1				<0.1		
50–59	17.9	1.0	0.1		4.9	4.1	0.9	
60–69	22.6	1.7	0.5	0.1	18.2	12.9	2.4	
70–79	21.5	6.3	8.6	0.8	14.1	19.5	16.9	0.6
80–89	20.4	21.2	9.0	4.3	10.2	13.8	11.2	3.2
90–99	10.1	26.8	27.1	11.0	7.1	5.8	7.9	9.0
100–109	2.4	21.5	24.5	18.6	4.6	4.1	5.8	16.1
110–119	0.4	8.5	9.0	18.9	4.1	3.7	4.2	9.0
120–129	0.1	2.1	3.6	12.1	1.9	3.0	2.7	5.8
130–139	0.1	0.9	2.3	8.1	6.8	2.9	4.1	4.8
140–149		0.8	1.9	5.4	3.6	3.3	5.7	3.5
>149	2.3	9.2	13.4	20.7	24.5	26.9	38.2	48.0
Sample size	3,231	5,690	6,026	1,267	411	3,611	884	310
Freshwater drum								
30–39	0.2	<0.1			1.1	0.1		
40–49	2.8	0.2			9.2	0.9		
50–59	18.5	0.9	<0.1		31.8	6.3	0.3	
60–69	28.8	1.7	0.3	0.2	27.4	16.0	1.8	
70–79	20.2	8.5	5.0	1.0	11.2	21.7	7.1	2.6
80–89	13.7	21.4	19.8	8.5	3.3	12.6	12.4	0.9
90–99	6.6	23.0	27.0	19.4	0.6	8.1	11.1	3.3
100–109	3.6	22.3	21.2	20.1	1.1	7.4	8.2	4.7
110–119	2.3	11.0	12.1	17.4	1.4	5.2	11.9	4.7
120–129	0.7	4.9	5.1	7.3	0.8	3.8	9.0	5.1
130–139	0.6	1.5	1.6	3.2	1.2	1.3	4.0	6.0
140–149	0.3	0.5	0.9	1.8	2.4	0.7	2.4	8.1
>149	1.7	4.1	7.0	21.1	8.5	15.9	31.8	64.6
Sample size	3,256	2,934	3,609	866	660	2,525	379	235

during the summer at four power plants, during the fall at four power plants, during the winter at five power plants, and during the spring at two power plants (Table 7). Seasonal impingement rates of freshwater drum during the first year followed trends similar to those for gizzard shad, with higher mean rates occurring in the summer at five power plants, in the fall at five power plants, in the winter at four power plants, and in the spring at one power plant (Table 8). The highest mean seasonal rates for both gizzard shad and freshwater drum occurred during the same season at 9 of the 15 power plants.

Impingement rates were much lower during the second year, when mean total rates were highest during the fall at 10 of the 13 power plants sampled, during the summer at one power plant, and during the winter at two power plants (Table 6). Overall, the second-year impingement rates averaged 81% lower than rates during the first year; impingement rates at seven power plants averaged 95–99% lower during the second year than during the first year (Table 6). As seen in the first year, seasonal differences in impingement rates during the second year reflect primarily seasonal impingement of gizzard shad (Table 7) and freshwater drum (Table 8).

TABLE 6.—Total mean impingement rates (number/1,000 m^3) by season at 15 power plants along the Ohio River, 2005–2007. Seasonal high means are in bold text for the first (June 2005 to June 2006) and second (June 2006 to June 2007) study years of the Ohio River Ecological Research Program.

	June 2005 to June 2006				June 2006 to June 2007			
Power plant	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring
Cardinal	0.619	1.133	**3.519**	0.018	0.009	**0.039**	0.027	0.004
Kammer	**0.286**	0.172	0.254	0.003	0.004	**0.007**	0.003	<0.001
Willow Island	0.338	1.014	**4.306**	0.017	0.033	0.048	**0.083**	0.002
Gorsuch	**6.485**	3.790	4.289	0.155				
Philip Sporn	0.198	**0.341**	0.075	0.002	0.002	**0.023**	0.005	0.002
Kyger Creek	**6.476**	0.664	0.143	0.027	0.038	**0.198**	0.003	0.004
J. M. Stuart	0.418	0.703	**1.433**	1.043				
W. C. Beckjord	**0.664**	0.114	0.198	0.290	0.030	**0.133**	0.011	0.013
Tanners Creek	0.238	0.146	0.113	**0.490**	**0.040**	0.035	0.026	0.010
Clifty Creek	1.171	**1.485**	0.384	0.846	0.012	**0.697**	0.012	0.010
Gallagher	0.139	0.071	**0.192**	0.002	0.002	**0.009**	0.000	0.001
Cane Run	**0.080**	0.009	0.018	0.014	0.014	**0.111**	0.005	0.000
Coleman	0.348	**3.932**	2.336	0.304	0.018	**1.884**	0.026	0.012
Elmer Smith	1.189	**11.153**	0.671	0.092	0.027	**0.636**	0.015	0.028
Shawnee	0.470	**49.408**	16.640	2.435	0.173	1.063	**23.885**	0.088
Mean	1.275	**4.942**	2.305	2.383	0.031	0.375	1.854	0.015

Factors Influencing Impingement: Within-Plant Variables

Water temperature was selected by the GLM as the most important independent within-plant variable ($P <$ 0.05) associated with impingement rates of gizzard shad, *Morone* spp., and saugers during the 2-year study (Table 9). The negative coefficients for gizzard shad and saugers show that those impingement rates increased as water temperatures decreased, which is consistent with the general seasonal impingement pattern observed for the two species. In the case of *Morone* spp., the positive coefficient indicates that impingement rates were highest in the summer, when age-0 *Morone* spp. were most common in the impingement samples. Water temperature was not selected as an important variable affecting impingement rates of channel catfish, bluegills, or freshwater drum (Table 9). At the plant level, water temperature was not significantly correlated with impingement rates of the six common taxa at 4 of the 15 power plants but was correlated with rates of one or more taxa at the remaining 11 power plants (Table 10). The most correlations with water temperature were at the Gorsuch Power Plant, where impingement rates of channel catfish, bluegills, saugers, and freshwater drum were all inversely correlated with water temperature.

TABLE 7.—Mean gizzard shad impingement rates (number/1,000 m^3) by season at 15 power plants along the Ohio River during the Ohio River Ecological Research Program impingement study, 2005–2007. Sampling was not conducted at the Gorsuch or Stuart plant during the June 2006–June 2007 study period. Zero (0) indicates that gizzard shad were not collected during that season. Seasonally high means are in bold text for the first (June 2005 to June 2006) and second (June 2006 to June 2007) years of the study.

	June 2005 to June 2006				June 2006 to June 2007			
Power plant	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring
Cardinal	0.479	1.096	**3.457**	0.009	0.003	**0.033**	0.024	0.002
Kammer	0.242	0.131	**0.244**	0	<0.001	**0.005**	0.002	0
Willow Island	0.029	0.533	**1.577**	0	0	0.022	**0.028**	0
Gorsuch	**6.401**	3.557	3.963	0.064				
Philip Sporn	0.068	**0.312**	0.043	0.001	<0.001	**0.003**	0.002	0.002
Kyger Creek	**6.427**	0.370	0.087	0.014	0.005	**0.156**	0.002	0.002
J. M. Stuart	0.061	0.437	**1.027**	0.705				
W. C. Beckjord	**0.230**	0.052	0.103	0.108	0.002	**0.032**	0.003	0.002
Tanners Creek	0.158	0.077	0.054	**0.439**	0.006	0.020	**0.022**	0.004
Clifty Creek	1.034	**1.299**	0.240	0.821	0.003	**0.484**	0.008	0.008
Gallagher	0.126	0.053	**0.145**	0.001	0	**0.006**	0	0
Cane Run	**0.042**	0.005	0.002	0.011	<0.001	**0.003**	0.002	0
Coleman	0.064	**1.674**	1.614	0.255	0	**0.223**	0.002	0.002
Elmer Smith	0.894	**10.883**	0.386	0.046	<0.001	**0.086**	0.004	0
Shawnee	0.279	1.588	1.547	**1.597**	0.011	0.204	**0.218**	0.018

TABLE 8.—Mean seasonal impingement rates (number/1,000 m^3) of freshwater drum at 15 power plants along the Ohio River during the Ohio River Ecological Research Program impingement study, 2005–2007. Sampling was not conducted at the Gorsuch or Stuart plant during the June 2006 to June 2007 study period. Zero (0) indicates that freshwater drum were not collected during that season. Seasonally high means are in bold text for the first (June 2005 to June 2006) and second (June 2006 to June 2007) years of the study.

Power plant	June 2005 to June 2006				June 2006 to June 2007			
	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring
Cardinal	**0.111**	0.027	0.054	0.007	**0.004**	0.003	<0.001	<0.001
Kammer	0.022	**0.034**	0.009	<0.001	0.001	<0.001	0	<0.001
Willow Island	0.262	0.446	**2.337**	0.006	**0.025**	0.006	0.017	0
Gorsuch	0.033	0.203	**0.276**	0.047				
Philip Sporn	**0.110**	0.027	0.009	<0.001	0.001	**0.014**	0.001	0
Kyger Creek	0.024	**0.264**	0.049	0.002	**0.030**	0.024	<0.001	<0.001
J. M. Stuart	0.268	0.240	**0.383**	0.316				
W. C. Beckjord	**0.398**	0.052	0.054	0.167	0.022	**0.074**	0.001	0.002
Tanners Creek	**0.059**	0.056	0.048	0.040	**0.025**	0.010	0.001	0.002
Clifty Creek	0.051	**0.163**	0.130	0.019	0.004	**0.151**	0.001	0.002
Gallagher	0.005	0.002	**0.045**	0	**0.002**	**0.002**	0	<0.001
Cane Run	**0.022**	0.002	0.013	0.002	0.012	**0.104**	0.002	0
Coleman	0.217	**2.132**	0.654	0.035	0.005	**1.316**	0.009	0.005
Elmer Smith	0.218	**0.227**	0.163	0.028	0.008	**0.404**	0.004	0.002
Shawnee	0.133	0.093	0.250	**0.734**	0.136	**0.410**	0.028	0.019

Of the six common taxa, sauger impingement rates were correlated with water temperature at more power plants (seven) than were the other taxa. In all cases, the correlation coefficients were negative, indicating that sauger impingement rates increased when water temperatures declined. Although water temperature was selected as the best predictor for three taxa, water temperature was collinear with river stage, river flow, and total shift volume at many of the power plants (Table 11), making it difficult to separate the contributions of each of those variables.

Hydrological variables were selected as significant factors affecting impingement rates of channel catfish, bluegills, and freshwater drum, with river flow exhibiting direct relationships and river stage exhibiting inverse relationships with impingement rates (Table 9). The river flow relationships were significant ($P < 0.05$) for all three species, whereas the river stage relationships were significant for channel catfish and freshwater drum. Changes in the hydrological variables during the sampling events (delta river flow and delta river stage) had little apparent effect on impingement rates. Delta river flow was not selected by the stepwise procedures for any of the six taxa considered, and although delta river stage was selected for four taxa, that relationship was significant only for channel catfish (Table 9).

Total shift volume, a within-plant variable describing the amount of water used during each sampling event, was not selected by the stepwise procedure as an important factor influencing impingement rates for any of the six taxa tested (Table 9); however, at the plant level, total shift volume was a significant variable at 5 of the 15 power plants (Table 12). There were no significant correlations between total shift volume and impingement rates of *Morone* spp. at any of the 15 power plants. Impingement rates of gizzard shad, bluegills, saugers, and freshwater drum were each correlated with total shift volume at only one power plant (Table 12). Channel catfish impingement rates were most frequently correlated (three power plants) with total shift volume (Table 12). Overall, total shift volume was a significant factor in 7 of the 90 cases compared for the six common taxa, and in two of those seven cases there was an inverse relationship.

Two class variables, power plant and study year, accounted for the majority of variability during the 2-year study, as indicated by the "step 0" r^2 values from the regression analyses (Table 9). The r^2 values for impingement rates of the six taxa considered ranged from 0.11 for bluegills to 0.31 for gizzard shad. Power plant and study year accounted for 82–90% of the variability, whereas the physical variables selected as the best predictors of impingement rates accounted for 10% (gizzard shad) to 18% (*Morone* spp.) of the variability. In addition, the overall effect of the selected within-plant variables (water temperature, river flow, river stage, and delta river stage) was not consistent among power plants. For example, the relationship between impingement rates of gizzard shad and water temperature had significant ($P < 0.05$) negative coefficients at four power plants, whereas rates at 11 power plants had nonsignificant coefficients (Table 10). Similarly, the significant inverse relationship between sauger impingement rates and water temperature occurred at 7 of the 15 power plants (Table 10). Thus, although water temperature was the best

TABLE 9.—Summary of multiple regression analyses between impingement rates of six fish taxa and within-plant independent variables monitored at 15 Ohio River power plants during the Ohio River Ecological Research program study, 2005–2007. Significant *P*-values are shown in bold text.

Taxon and step	Model variable	Coefficient	*P*	r^2
Gizzard shad				
0	Power plant			0.3114
	Study year			
1	Water temperature	−0.0081	**0.0000**	0.3403
2	Delta river stage	−0.0590	0.1012	0.3438
	Water temperature	−0.0081	**0.0000**	
Channel catfish				
0	Power plant			0.1857
	Study year			
1	River flow	0.0002	**0.0002**	0.2075
2	River stage	−0.0025	0.0519	0.2135
	River flow	0.0003	**0.0004**	
3	Delta river stage	−0.0084	**0.0480**	0.2197
	River stage	−0.0030	**0.0224**	
	River flow	0.0003	**0.0001**	
White bass + unidentified *Morone* spp.				
0	Power plant			0.1900
	Study year			
1	Water temperature	0.0004	**0.0000**	0.2167
2	Water temperature	0.0006	**0.0000**	0.2313
	River flow	0.0001	**0.0022**	
Bluegill				
0	Power plant			0.1140
	Study year			
1	River flow	0.0001	**0.0338**	0.1220
2	River stage	−0.0023	0.0510	0.1286
	River flow	0.0002	**0.0057**	
Sauger				
0	Power plant			0.1864
	Study year			
1	Water temperature	−0.0002	**0.0008**	0.2047
2	Delta river stage	0.0019	0.1435	0.2081
	Water temperature	−0.0002	**0.0007**	
Freshwater drum				
0	Power plant			0.2440
	Study year			
1	River flow	0.0010	**0.0000**	0.2685
2	River stage	−0.0114	0.0978	0.2725
	River flow	0.0017	**0.0004**	
3	Delta river stage	−0.0416	0.0693	0.2773
	River stage	−0.0138	**0.0488**	
	River flow	0.0018	**0.0001**	

predictor for some taxa, when the power plants were pooled temperature was not a good predictor at every plant. Similar inconsistencies occurred for the other physical variables selected by the stepwise procedures.

At the power plant level, river flow was a significant variable at one to seven power plants depending on species. Bluegill impingement rates were directly correlated ($P < 0.05$) with river flow at 7 of the 15 power plants, and channel catfish rates were directly correlated to river flow at four power plants (Table 13). Although the relationships between river flow and impingement rates were typically direct, there was a significant ($P < 0.05$) inverse relationship between river flow and channel catfish impingement rates at the Tanners Creek Power Plant (Table 13).

For all taxa except gizzard shad, river stage was a significant variable at one to four power plants (Table 14). Of the hydrological factors selected by the stepwise procedure, delta river stage was the least selected variable. There was no correlation between delta river stage and *Morone* spp. impingement rates (Table 15). Impingement rates of gizzard shad, bluegills, saugers, and freshwater drum were correlated with delta river stage at one or two power plants. Impingement rates of channel catfish were correlated with delta river stage at four power plants. Overall, impingement rates of channel catfish and bluegills were the most influenced by the three hydrological factors selected by the stepwise procedure. Those factors had the least apparent influence on the impingement rates of gizzard shad and *Morone* spp.

TABLE 10.—Results of partial correlations between impingement rates of six common fish taxa and water temperatures at 15 Ohio River power plants with the study year effect removed, June 2005 to June 2007 (rkm = river kilometer). Simple correlations are shown for the Gorsuch and Stuart power plants, which were only sampled during the first year of the 2-year study. Upper value is the correlation coefficient; lower value is the *p*-value. Correlation coefficients in bold text are statistically significant ($P < 0.05$).

Power plant	rkm	Gizzard shad	Channel catfish	*Morone* spp.	Bluegill	Sauger	Freshwater drum
Cardinal	124	−0.30	−0.10	0.28	−0.10	−0.08	0.06
		0.0852	0.5614	0.0978	0.5656	0.6378	0.7168
Kammer	170	0.03	0.31	**0.50**	**−0.33**	−0.03	−0.02
		0.8759	0.0611	**0.0017**	**0.0429**	0.8730	0.9139
Willow Island	257	**−0.60**	−0.31	0.32	−0.27	0.23	−0.27
		0.0001	0.0551	0.0540	0.1032	0.1720	0.0973
Gorsuch	283	−0.28	**−0.59**	0.27	**−0.58**	**−0.58**	**−0.59**
		0.2346	**0.0060**	0.2519	**0.0077**	**0.0072**	**0.0057**
Philip Sporn	389	−0.02	−0.10	**0.38**	−0.13	**−0.33**	0.26
		0.8882	0.5430	**0.0184**	0.4383	**0.0426**	0.1177
Kyger Creek	418	0.18	−0.09	0.20	−0.17	**−0.16**	−0.21
		0.2897	0.6012	0.2198	0.3121	**0.3374**	0.2167
J. M. Stuart	653	**−0.84**	−0.14	0.37	−0.30	**−0.55**	−0.36
		0.0000	0.5526	0.1039	0.1967	**0.0126**	0.1156
W. C. Beckjord	729	−0.27	−0.05	−0.17	0.08	**−0.45**	0.00
		0.0763	0.7535	0.2841	0.6162	**0.0023**	0.9784
Tanners Creek	795	−0.03	**0.37**	0.01	0.01	**−0.35**	0.06
		0.8654	**0.0209**	0.9370	0.9602	**0.0278**	0.6972
Clifty Creek	901	−0.16	−0.05	−0.31	0.03	0.25	−0.25
		0.3569	0.7735	0.0653	0.8569	0.1491	0.1398
Gallagher	982	0.02	−0.14	0.34	−0.12	0.18	−0.10
		0.9082	0.4516	0.0613	0.5124	0.3332	0.6013
Cane Run	993	0.25	**0.35**	0.12	0.11	−0.26	0.13
		0.1380	**0.0371**	0.4756	0.5208	0.1282	0.4390
Coleman	1,165	**−0.42**	−0.09	0.14	−0.08	**−0.33**	−0.29
		0.0085	0.5712	0.4040	0.6353	**0.0438**	0.796
Elmer Smith	1,215	−0.02	−0.26	0.22	−0.24	0.07	−0.05
		0.9109	0.1087	0.1812	0.1429	0.6583	0.7459
Shawnee	1,522	**−0.53**	0.16	−0.20	−0.01	0.24	−0.15
		0.0021	0.4034	0.2915	0.9588	0.2011	0.4246

Factors Influencing Impingement: Among-Plant Variables

Seven among-plant variables were evaluated as potential predictors of impingement rates of the six common taxa considered. These variables were plant location (i.e., rkm), plant capacity (both as design flow and generating capacity), design approach velocity, intake location (canal or shoreline locations), intake

TABLE 11.—Results of partial correlations between water temperature and other physical variables (defined in Methods) monitored at 15 Ohio River power plants with study year effect removed, June 2005 to June 2007 (rkm = river kilometer). Simple correlations are shown for the Gorsuch and Stuart power plants, which were only sampled during the first year of the 2-year study. Correlation coefficients shown in bold text are greater than or equal to 0.5.

Power plant	rkm	Delta river flow	Delta river stage	River stage	River flow	Total shift volume
Cardinal	124	−0.13	0.27	0.37	**−0.59**	0.15
Kammer	170	0.12	0.29	−0.26	**−0.51**	0.07
Willow Island	257	0.03	0.04	**0.51**	**−0.68**	0.47
Gorsuch	283	−0.01	0.07	**−0.61**	**−0.73**	0.33
Philip Sporn	389	−0.11	−0.02	**−0.56**	**−0.62**	0.05
Kyger Creek	418	0.28	0.23	−0.14	**−0.50**	0.38
J. M. Stuart	653	−0.16	−0.25	−0.33	**−0.63**	0.41
W. C. Beckjord	729	−0.14	−0.14	−0.48	**−0.55**	**0.58**
Tanners Creek	795	−0.07	−0.03	**−0.57**	**−0.66**	**0.55**
Clifty Creek	901	0.04	0.05	**−0.59**	**−0.60**	**0.51**
Gallagher	982	−0.25	−0.22	**−0.74**	**−0.72**	**0.65**
Cane Run	993	−0.09	0.09	**−0.62**	**−0.55**	**0.37**
Coleman	1,165	0.20	0.14	**−0.58**	**−0.62**	**0.67**
Elmer Smith	1,215	0.09	−0.16	−0.25	**−0.60**	**0.75**
Shawnee	1,522	−0.21	−0.28	**−0.62**	**−0.62**	**0.58**

TABLE 12.—Results of partial correlations between impingement rates of six common fish taxa and total shift volume at 15 Ohio River power plants with study year effect removed, June 2005 to June 2007 (rkm = river kilometer). Total shift volume represents cooling water use during each 24-h sampling event. Simple correlations are shown for the Gorsuch and Stuart power plants, which were only sampled during the first year of the 2-year study. Upper value is the correlation coefficient; lower value is the P-value. Correlation coefficients in bold text are statistically significant ($P < 0.05$).

Power plant	rkm	Gizzard shad	Channel catfish	*Morone* spp.	Bluegill	Sauger	Freshwater drum
Cardinal	124	−0.13	0.03	0.18	0.06	0.09	0.09
		0.4597	0.8863	0.2898	0.7146	0.6102	0.6172
Kammer	170	0.17	0.05	0.06	0.15	−0.28	0.14
		0.3158	0.7822	0.7235	0.3755	0.0948	0.4219
Willow Island	257	−0.07	−0.09	−0.09	0.03	0.18	−0.07
		0.6849	0.6005	0.6040	0.8463	0.2716	0.6799
Gorsuch	283	0.35	−0.39	0.14	0.05	−0.29	−0.11
		0.1321	0.0922	0.5629	0.8379	0.2102	0.6420
Philip Sporn	389	−0.03	**−0.35**	0.10	−0.01	0.11	0.02
		0.8518	**0.0320**	0.5309	0.9455	0.5186	0.9181
Kyger Creek	418	0.25	0.03	0.05	0.04	−0.30	−0.17
		0.1303	0.8612	0.7514	0.8248	0.0663	0.2951
J. M. Stuart	653	**−0.54**	−0.36	0.10	0.18	−0.29	−0.35
		0.0150	0.1159	0.6605	0.4523	0.2164	0.1326
W. C. Beckjord	729	−0.03	0.04	−0.05	0.12	−0.20	0.14
		0.8656	0.8189	0.7628	0.4395	0.2084	0.3701
Tanners Creek	795	0.20	**0.37**	0.25	−0.10	−0.07	0.17
		0.2236	**0.0220**	0.1224	0.5325	0.6630	0.2947
Clifty Creek	901	−0.22	−0.09	−0.32	−0.19	**0.37**	−0.28
		0.2070	0.6036	0.0576	0.2759	**0.0276**	0.1030
Gallagher	982	0.11	0.12	0.12	0.01	0.20	−0.07
		0.5557	0.5185	0.5337	0.9466	0.2836	0.6902
Cane Run	993	0.17	**0.45**	0.07	**0.40**	−0.01	**0.41**
		0.3285	**0.0064**	0.6761	**0.0154**	0.9559	**0.0136**
Coleman	1,165	−0.12	−0.19	0.19	0.07	−0.04	−0.14
		0.4656	0.2653	0.2521	0.6823	0.8182	0.4147
Elmer Smith	1,215	0.22	−0.12	0.15	−0.12	0.05	0.05
		0.1849	0.4620	0.3682	0.4673	0.7709	0.7533
Shawnee	1,522	−0.26	−0.11	−0.33	0.06	0.12	−0.32
		0.1599	0.5391	0.0737	0.7408	0.5084	0.0756

configuration (submerged or surface), and intake position on the riverbank (Table 16). Depending on species, the stepwise procedure selected one or more of the variables. Design approach velocity was the only variable that was not selected as an important predictor of impingement rates for at least one taxon, despite design velocities that ranged from 0.2 to 1.5 m/s. Impingement rates of gizzard shad were significantly associated with study year, intake location, rkm, and intake position (Table 16). The study year effect for gizzard shad reflects substantially lower rates during the second year at most power plants (Table 7). Impingement rates of gizzard shad were generally higher at power plants with intake canals (the Cardinal, Kammer, Kyger Creek, Clifty Creek, and Shawnee plants) than for power plants with shoreline intakes. The direct relationship with rkm was relatively consistent as rates generally increased from upstream to downstream, although two upstream power plants (the Cardinal and Kyger Creek plants) had relatively high impingement rates (Table 8). The Cardinal and Kyger Creek power plants also have intake canals. Intake position on the riverbank was a secondary factor for gizzard shad impingement rates, with higher rates occurring at the Cardinal, Clifty Creek, and Elmer Smith power plant intakes that are located on outside bends of the river (Table 1). Because the Cardinal and Clifty Creek power plants also have intake canals, those rates probably reflect the combined effect of intake location and intake position on the riverbank. Higher impingement rates of gizzard shad at the Elmer Smith Power Plant probably reflect the combined effect of rkm and position on the outside bend of the river, where faster currents may be the primary factor influencing impingement at that plant.

Channel catfish impingement rates were directly associated with rkm and inversely associated with design flow. River kilometer was selected as the most important variable (Table 16), a result of higher impingement rates of channel catfish at the three downstream-most power plants (the Coleman, Elmer Smith, and Shawnee plants). Impingement rates for channel catfish were lower at all power plants upstream from the Coleman Plant except at the Willow Island Plant located at rkm 257 (Figure 2). The inverse relationship with design flow reflects higher impinge-

TABLE 13.—Results of partial correlations between impingement rates of six common fish taxa and river flow at 15 Ohio River power plants with the study year effect removed, June 2005 to June 2007 (rkm = river kilometer). Simple correlations are shown for the Gorsuch and Stuart power plants, which were only sampled during the first year of the 2-year study. Upper value is the correlation coefficient; lower value is the *P*-value. Correlation coefficients in bold text are statistically significant ($P < 0.05$).

Power plant	rkm	Gizzard shad	Channel catfish	*Morone* spp.	Bluegill	Sauger	Freshwater drum
Cardinal	124	0.26	0.16	−0.23	**0.41**	0.22	−0.02
		0.1303	0.3737	0.1889	**0.0140**	0.2057	0.9046
Kammer	170	−0.06	−0.12	−0.24	**0.44**	0.13	0.19
		0.7432	0.4809	0.1480	**0.0059**	0.4306	0.2484
Willow Island	257	**0.59**	**0.70**	−0.16	**0.54**	−0.20	**0.46**
		0.0001	**0.0000**	0.3502	**0.0005**	0.2171	**0.0036**
Gorsuch	283	0.24	**0.78**	−0.09	**0.70**	**0.87**	**0.85**
		0.3096	**0.0001**	0.6996	**0.0005**	**0.0000**	**0.0000**
Philip Sporn	389	−0.10	**0.51**	−0.23	**0.41**	0.14	−0.04
		0.5324	**0.0011**	0.1565	**0.0102**	0.3916	0.8296
Kyger Creek	418	−0.02	0.11	−0.07	0.13	0.16	0.20
		0.9026	0.4947	0.6735	0.4366	0.3363	0.2402
J. M. Stuart	653	**0.56**	0.44	−0.23	**0.69**	**0.84**	**0.46**
		0.0122	0.0582	0.3539	**0.0012**	**0.0000**	**0.0483**
W. C. Beckjord	729	0.12	0.11	0.09	−0.07	0.19	0.13
		0.4305	0.4732	0.5686	0.6405	0.2152	0.4199
Tanners Creek	795	0.00	**−0.35**	−0.01	−0.11	0.24	−0.13
		0.9763	**0.0280**	0.9638	0.5224	0.1456	0.4413
Clifty Creek	901	0.11	−0.01	0.19	−0.04	−0.12	0.31
		0.5156	0.9584	0.2701	0.8039	0.4715	0.0656
Gallagher	982	0.02	−0.06	−0.16	−0.03	−0.14	0.04
		0.9262	0.7546	0.3872	0.8665	0.4665	0.8463
Cane Run	993	−0.04	−0.28	−0.09	0.14	0.28	0.10
		0.8209	0.0923	0.6216	0.4012	0.0967	0.5578
Coleman	1,165	0.24	0.25	−0.03	0.14	0.12	0.29
		0.1406	0.1295	0.8422	0.4120	0.4601	0.0798
Elmer Smith	1,215	0.02	**0.38**	−0.07	**0.37**	−0.17	0.28
		0.9250	**0.0179**	0.6819	**0.0206**	0.2898	0.0849
Shawnee	1,522	0.10	−0.05	**0.49**	0.03	−0.22	0.07
		0.5882	0.7925	**0.0054**	0.8620	0.2332	0.7042

ment rates at two power plants (the Coleman and Elmer Smith plants) that have two of the lowest design flows among the power plants included in the study (Table 16). In contrast to gizzard shad, study year was not a significant factor influencing channel catfish impingement rates, which were similar between years except at the Coleman Power Plant (Figure 2).

Morone spp. impingement rates were significantly correlated with study year and intake configuration (Table 16). Rates were much lower during the second year, primarily reflecting lower recruitment of age-0 fish in 2006 compared with 2005 (Figure 3). *Morone* spp. impingement rates were higher at power plants with submerged intakes. Only four of the power plants have surface intakes, and two of those (the Gorsuch and J. M. Stuart plants) were excluded from the multivariate analysis because they were not sampled during the second year. However, the highest *Morone* spp. rates during the first year did occur at the Gorsuch Power Plant, and impingement rates at the J. M. Stuart Power Plant were above average (Figure 3). The other two power plants with surface intakes (the W. C. Beckjord and Gallagher plants) had relatively low mean *Morone* spp. impingement rates compared with the other power plants that had submerged intakes.

Bluegill impingement rates were inversely related to plant size (Table 16), primarily because three of the four highest rates (Figure 4) occurred at the three smallest power plants (the Willow Island, Coleman, and Elmer Smith plants). As was the case for channel catfish, study year was not a significant factor influencing impingement rates of bluegills; their rates were similar between years except at the Willow Island and Coleman power plants (Figure 4).

Sauger impingement rates were significantly associated with study year and intake configuration (Table 16). The study year effect reflects much lower sauger impingement rates at most of the 13 power plants sampled during the second year (Figure 5). The direct association of sauger impingement rates and intake configuration (i.e., surface versus submerged structures) was influenced by the fact that 10 of the power plants have submerged intakes and three of the four highest impingement rates occurred at power plants with submerged intakes (the Coleman, Clifty Creek, and Philip Sporn plants). However, the highest sauger rates occurred at the W. C. Beckjord Power Plant,

TABLE 14.—Results of partial correlations between impingement rates of six common fish taxa and river stage at 15 Ohio River power plants with the study year effect removed, June 2005 to June 2007 (rkm = river kilometer). Simple correlations are shown for the Gorsuch and Stuart power plants, which were only sampled during the first year of the 2-year study. Upper value is the correlation coefficient; lower value is the P-value. Correlation coefficients in bold text are statistically significant ($P < 0.05$).

Power plant	rkm	Gizzard shad	Channel catfish	*Morone* spp.	Bluegill	Sauger	Freshwater drum
Cardinal	124	−0.30	−0.20	−0.09	−0.04	**−0.39**	−0.21
		0.0792	0.2482	0.5922	0.7992	**0.0216**	0.2281
Kammer	170	0.01	0.00	0.00	0.19	−0.02	−0.01
		0.9563	0.9829	0.9911	0.2643	0.8992	0.9310
Willow Island	257	−0.30	**−0.37**	0.18	**−0.36**	0.13	−0.13
		0.0634	**0.0208**	0.2871	**0.0257**	0.4268	0.4413
Gorsuch	283	0.17	**0.80**	0.12	**0.61**	**0.89**	**0.83**
		0.4775	**0.0000**	0.6199	**0.0045**	**0.0000**	**0.0000**
Philip Sporn	389	−0.09	**0.55**	−0.19	**0.43**	0.09	0.01
		0.5960	**0.0003**	0.2558	**0.0071**	0.6002	0.9402
Kyger Creek	418	0.09	−0.05	0.05	−0.08	−0.02	−0.07
		0.5800	0.7758	0.7500	0.6421	0.9092	0.6977
J. M. Stuart	653	0.27	0.36	−0.14	**0.81**	**0.76**	0.30
		0.2464	0.1213	0.5644	**0.0000**	**0.0001**	0.1941
W. C. Beckjord	729	0.05	0.10	0.05	−0.08	0.10	0.06
		0.7404	0.5200	0.7700	0.5955	0.5130	0.6904
Tanners Creek	795	−0.04	**−0.39**	−0.03	−0.12	0.15	−0.18
		0.8251	**0.0145**	0.8705	0.4620	0.3744	0.2669
Clifty Creek	901	0.15	0.00	0.21	−0.02	−0.14	**0.34**
		0.3978	0.9858	0.2145	0.9262	0.4163	**0.0444**
Gallagher	982	−0.02	−0.04	−0.22	−0.08	−0.17	0.02
		0.9107	0.8484	0.2295	0.6533	**0.3622**	0.9039
Cane Run	993	−0.08	−0.14	−0.09	0.13	**0.52**	0.10
		0.6328	0.4270	0.5867	0.4454	**0.0011**	0.5492
Coleman	1,165	0.23	0.27	−0.05	0.12	0.11	0.26
		0.1640	0.1024	0.7587	0.4637	0.4974	0.1139
Elmer Smith	1,215	0.02	0.13	0.00	0.05	0.01	0.10
		0.8901	0.4470	0.9953	0.7401	0.9618	0.5264
Shawnee	1,522	0.12	0.02	**0.46**	0.11	−0.19	0.10
		0.5233	0.9235	**0.0094**	0.5491	0.3034	0.5921

which has a surface intake. Impingement of saugers probably is related more to longitudinal distribution patterns because saugers are more abundant in the middle reaches (rkm 483–805) than in the upper or lower reaches of the Ohio River (G. Seegert, EA Engineering, Science, and Technology, Inc., personal communication) even though rkm was not selected by the stepwise procedure.

Freshwater drum impingement rates were significantly associated with study year and rkm (Table 16). The study year effect resulted from much lower impingement rates at all 13 power plants sampled during the second year, especially at the Willow Island and Coleman plants (Figure 6). Even though the stepwise procedure selected rkm as an important variable, impingement rates of freshwater drum during the first year were variable over the study reach, with higher rates occurring at rkm 257, rkm 653, and rkm 1,165 (Figure 6). In the second year, when rates were much lower overall, freshwater drum rates were clearly higher at the three power plants located farthest downstream.

Study year and rkm were the most important among-plant variables (Table 16). The similarity among the majority of power plants in terms of intake location, intake configuration, and intake position on the riverbank limited the influence of those factors because of the narrow range available for analysis. The among-plant analyses were consistent with the trends observed for the within-plant analysis in that natural factors appeared to be more important than intake characteristics. Nonetheless, for total impingement rates and for some of the common taxa, intake location (canal versus shoreline), rkm, and intake position on the river channel (i.e., inside and outside bends and straight channels) had some influence on impingement rates.

Discussion

The 2-year ORERP impingement study was a collaborative effort that afforded an opportunity to examine the impingement process and potential controlling factors in a manner that traditionally has not been possible when section 316(b) compliance studies are conducted on a plant-by-plant basis. For this study, biological, environmental, and operational data were collected under consistent and controlled protocols that allowed use of multiple regression analysis of within- and among-plant independent variables to evaluate

TABLE 15.—Results of partial correlations between impingement rates of six common fish taxa and delta river stage at 15 Ohio River power plants with the study year effect removed, June 2005 to June 2007 (rkm = river kilometer). Simple correlations are shown for the Gorsuch and Stuart power plants, which were only sampled during the first year of the 2-year study. Upper value is the correlation coefficient; lower value is the *P*-value. Correlation coefficients in bold text are statistically significant ($P < 0.05$).

Power plant	rkm	Gizzard shad	Channel catfish	*Morone* spp.	Bluegill	Sauger	Freshwater drum
Cardinal	124	−0.14	−0.20	0.10	−0.10	0.16	0.01
		0.4385	0.2440	0.5702	0.5579	0.3627	0.9645
Kammer	170	−0.24	0.00	0.01	0.01	0.11	0.16
		0.1455	0.9881	0.9510	0.9571	0.5340	0.3503
Willow Island	257	−0.08	0.18	0.28	0.19	−0.28	−0.01
		0.6459	0.2889	0.0890	0.2546	0.0871	0.9426
Gorsuch	283	−0.15	0.09	−0.02	0.01	0.09	−0.04
		0.5284	0.6974	0.9395	0.9778	0.7121	0.8613
Philip Sporn	389	−0.06	0.09	−0.05	0.01	−0.06	0.15
		0.7027	0.6119	0.7860	0.9442	0.7045	0.3793
Kyger Creek	418	0.03	0.05	0.09	0.04	0.07	0.07
		0.8445	0.7744	0.6056	0.8159	0.6633	0.6608
J. M. Stuart	653	0.32	0.25	−0.11	**0.65**	**0.47**	0.09
		0.1690	0.2945	0.6499	**0.0021**	**0.0370**	0.7123
W. C. Beckjord	729	−0.04	**−0.55**	−0.02	−0.25	0.07	−0.18
		0.8089	**0.0002**	0.9115	0.1068	0.6667	0.2395
Tanners Creek	795	0.06	0.16	0.09	0.08	−0.20	0.05
		0.7121	0.3351	0.5861	0.6381	0.2144	0.7460
Clifty Creek	901	**−0.33**	−0.31	−0.13	−0.28	0.16	−0.25
		0.0471	0.0647	0.4366	0.1024	0.3512	0.1357
Gallagher	982	−0.17	**−0.47**	0.02	0.11	−0.10	−0.42
		0.3599	**0.0083**	0.9216	0.5446	0.5945	0.0177
Cane Run	993	0.09	−0.04	0.05	−0.30	−0.31	−0.29
		0.6204	0.7956	0.7507	0.0802	0.0664	0.0844
Coleman	1,165	−0.10	**−0.60**	0.00	−0.25	−0.00	**−0.39**
		0.5393	**0.0001**	0.9831	0.1321	0.9777	**0.0167**
Elmer Smith	1,215	0.02	**−0.42**	−0.01	−0.07	−0.03	**−0.50**
		0.8921	**0.0074**	0.9490	0.6683	0.8769	**0.0011**
Shawnee	1,522	0.01	−0.25	0.01	−0.05	−0.21	−0.19
		0.9675	0.1674	0.9680	0.7829	0.2559	0.3107

which variables best predicted impingement rates of six fish taxa commonly impinged at the 15 power plants.

Study year was the most important variable affecting impingement rates based on the stepwise selection process used to evaluate results from the 2-year study. The study year effect reflected an overall 80% reduction in total impingement rates between the first and second years of the study and 95–98% reductions at 7 of the 15 power plants between the first and second years. Differences in mean rates between years were the result of much lower impingement rates for gizzard shad and freshwater drum—and in the case of the Shawnee Power Plant, threadfin shad—during the second year (Table 17). Annual differences in impingement rates reflect apparent differences in the abundance of age-0 fish, as documented by annual Ohio River surveys indicating that age-0 recruitment was higher near the participating power plants in 2005 than in 2006 (EPRI 2008).

Our study showed that more than 90% of the fish collected were age-0 fish, primarily gizzard shad, threadfin shad, and freshwater drum. Gizzard shad and freshwater drum dominated impingement at 14 of the 15 power plants; threadfin shad dominated impingement at the Shawnee Power Plant, which is the most proximal plant to the Mississippi River. Other taxa commonly impinged during the study were skipjack herring, channel catfish, *Morone* spp., bluegills, and saugers. Most of the remaining 70 or so impinged species were randomly impinged in much lower numbers.

The species composition and size of impinged fish during the study were consistent with results from studies conducted more than 25 years earlier at the same power plants (TVA 1976; CG&E 1979; EA 1987) and with results from power plants located along other large rivers and at intakes in impoundments where clupeids are abundant (Loar et al. 1978). The high relative abundance of shad species is typical of impingement in the midwestern and southeastern USA and has consistently been attributed to the shads' schooling behavior, distribution in the water column, negative rheotaxic response to intake flows, and susceptibility to low winter temperatures, which impairs swimming performance and can lead to morbidity (Loar et al. 1978). In contrast to the apparent high susceptibility of shad species to impingement,

TABLE 16.—Summary of stepwise selection for the effect of among-plant variables on impingement rates of fishes commonly impinged at 13 power plants along the Ohio River, June 2005 to June 2007 (rkm = river kilometer). *P*-values in bold are statistically significant ($P < 0.05$).

Species and step	Variable	*F*	*P*	Effect 1	Effect 2	Effect 3
Gizzard shad						
1	Study year	80.97	**<0.0001**			
	Intake location	17.93	**0.0003**			
2	Study year	81.61	**<0.0001**			
	Intake location	23.17	**<0.0001**			
	rkm	9.38	**0.0057**			
3	Study year	82.88	**<0.0001**	Year 1 0.5976	Year 2 0.0783	
	Intake location	17.79	**0.0004**	Canal 0.4840	Shoreline 0.1919	
	rkm	4.52	**0.0461**	Slope 0.02773		
	Intake position	4.20	**0.0301**	Inside 0.1432	Outside 0,04989	Straight 0.3717
Channel catfish						
1	Study year	2.68	0.1151			
	rkm	17.15	**0.0004**			
2	Study year	2.67	0.1166	Year 1 mean 0.01425	Year 2 mean 0.02637	
	rkm	17.20	**0.0004**	Slope 0.005919		
	Pumping capacity	6.37	**0.0194**	Slope −0.03226		
White bass + unidentified *Morone* spp.						
1	Study year	40.02	**<0.0001**	Year 1 0.01708	Year 2 −0.00156	
	Intake configuration	4.37	0.0502	Submerged 0.01171	Surface 0.003806	
Bluegill						
1	Study year	1.54	0.2260	Year 1 mean 0.01667	Year 2 mean 0.00893	
	Generation capacity	8.75	**0.0067**	Slope −0.00002		
Sauger						
1	Study year	13.16	**0.0018**	Year 1 0.01483	Year 2 0.004755	
	Intake configuration	11.22	**0.0034**	Submerged 0.003828	Surface 0.01576	
Freshwater drum						
1	Study year	22.80	**<0.0001**	Year 1 mean 0.2876	Year 2 mean 0.1012	
	rkm	13.64	**0.0012**	Slope 0.02773		

most demersal species (e.g., sunfishes and darters) were impinged at much lower rates that probably reflect, in part, their position in the water column, association with cover, and relatively small home ranges that limit spatial movements. Although the species commonly impinged during this study represent the most abundant species in the Ohio River based on long-term monitoring (EPRI 2009b), several species

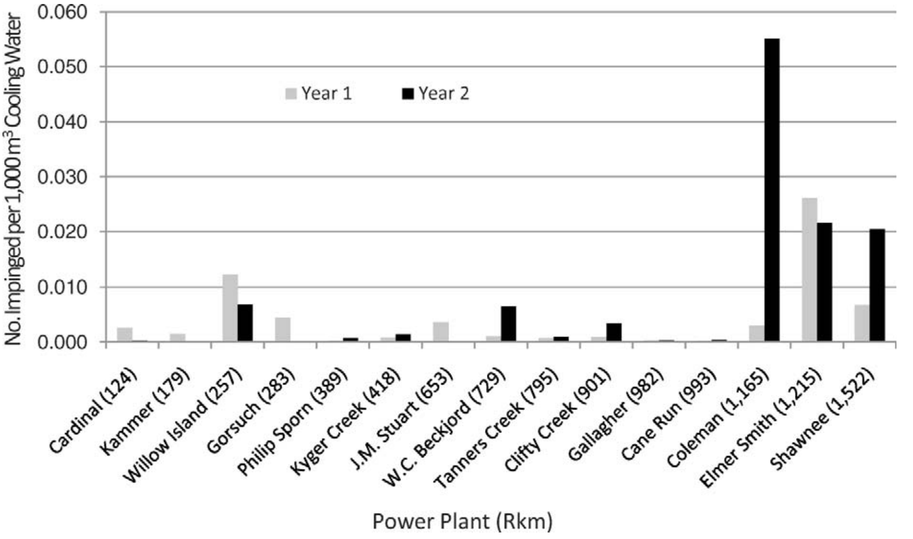

FIGURE 2.—Mean annual impingement rates of channel catfish at 15 Ohio River power plants (with river kilometer [rkm] in parentheses) during year 1 (June 2005–June 2006) and year 2 (June 2006–June 2007) of the Ohio River Ecological Research Program impingement study.

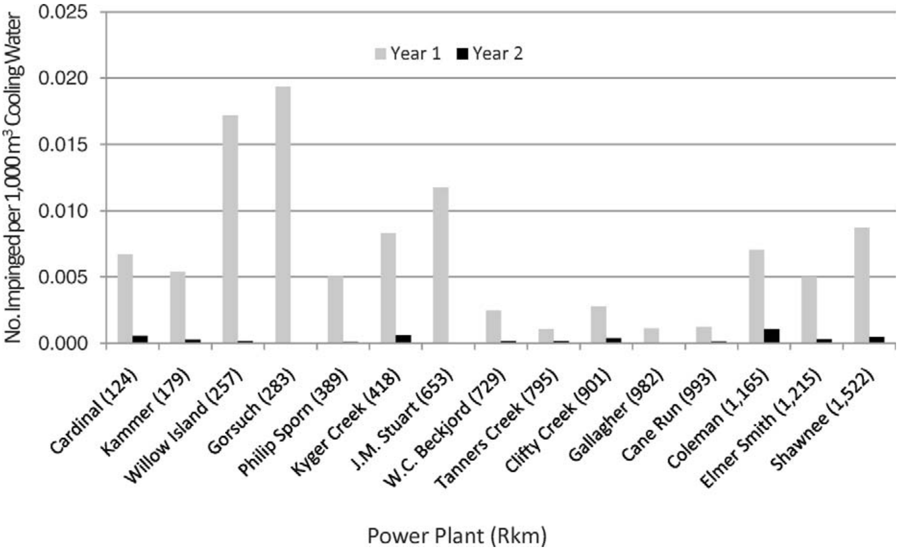

FIGURE 3.—Mean annual impingement rates of temperate basses *Morone* spp. at 15 Ohio River power plants (with river kilometer [rkm] in parentheses) during year 1 (June 2005–June 2006) and year 2 (June 2006–June 2007) of the Ohio River Ecological Research Program impingement study.

were impinged at rates lower than would be expected based on their high relative abundance in the river (e.g., emerald shiner, channel shiner *N. wickliffi*, and logperch *Percina caprodes*).

Even though gizzard shad impingement rates were inversely correlated with water temperature (Table 9), their rates peaked at some intakes when water temperature apparently was not a factor. For example,

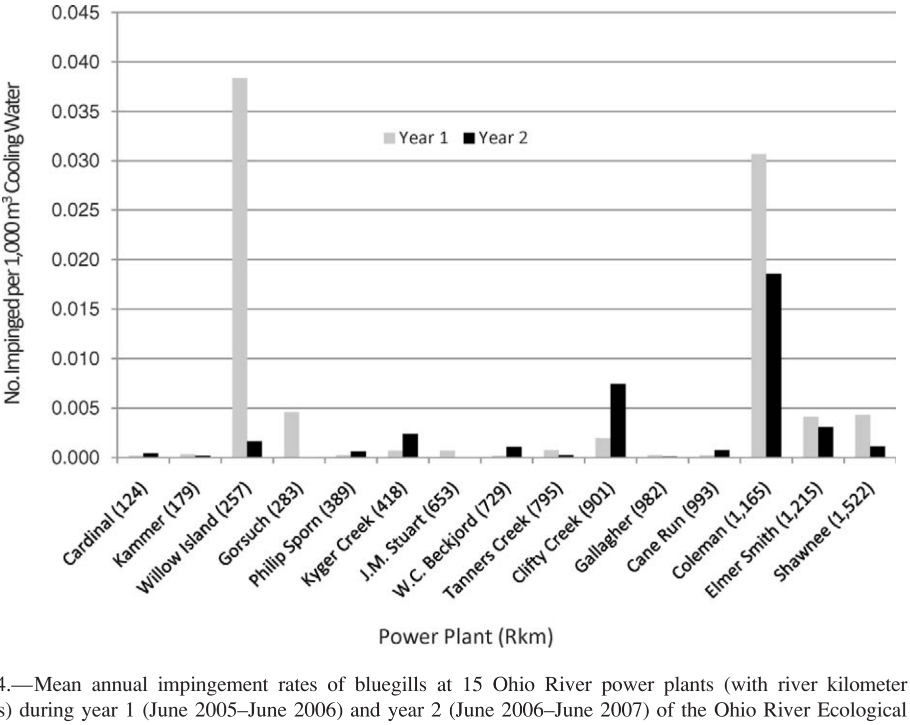

FIGURE 4.—Mean annual impingement rates of bluegills at 15 Ohio River power plants (with river kilometer [rkm] in parentheses) during year 1 (June 2005–June 2006) and year 2 (June 2006–June 2007) of the Ohio River Ecological Research Program impingement study.

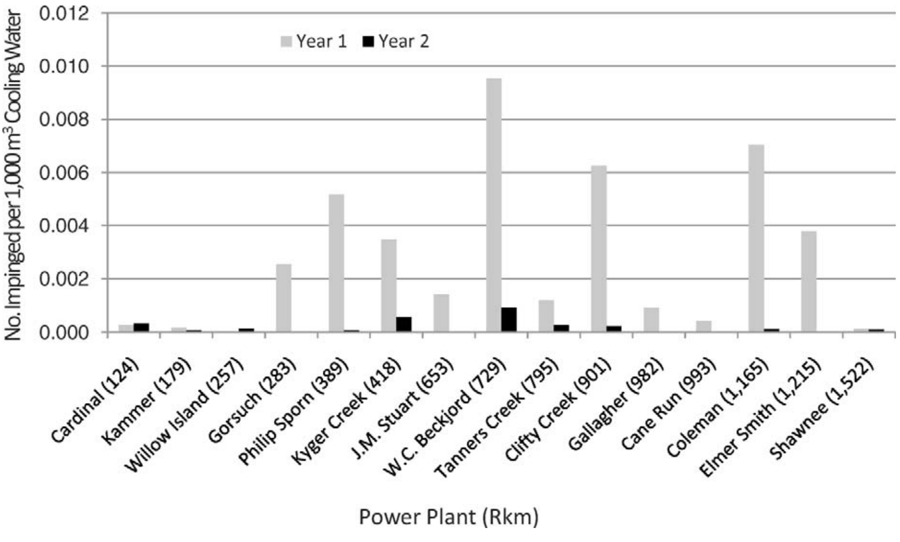

FIGURE 5.—Mean annual impingement rates of saugers at 15 Ohio River power plants (with river kilometer [rkm] in parentheses) during year 1 (June 2005–June 2006) and year 2 (June 2006–June 2007) of the Ohio River Ecological Research Program impingement study.

impingement rates at the Kyger Creek Power Plant in late August 2005 peaked at 35.2 individuals/1,000 m^3 when river flows increased about three-fold from 409 to 1,170 m^3/s (Figure 7). Although water temperatures declined from about 30°C to 27°C over a 6-week period, that gradual decline in summer temperatures would not be expected to affect the ability of gizzard shad to avoid intake approach velocities—the only within-plant variable that was not selected by the stepwise procedure. Peak summer rates at four power plants occurred earlier during the 28 August–10 September sampling period, when sampling coincided with remnants of Hurricane Katrina as it traveled up the Ohio River Valley. It is likely that increased turbidity and perhaps heavy debris loads after that major storm reduced visibility and increased approach velocities

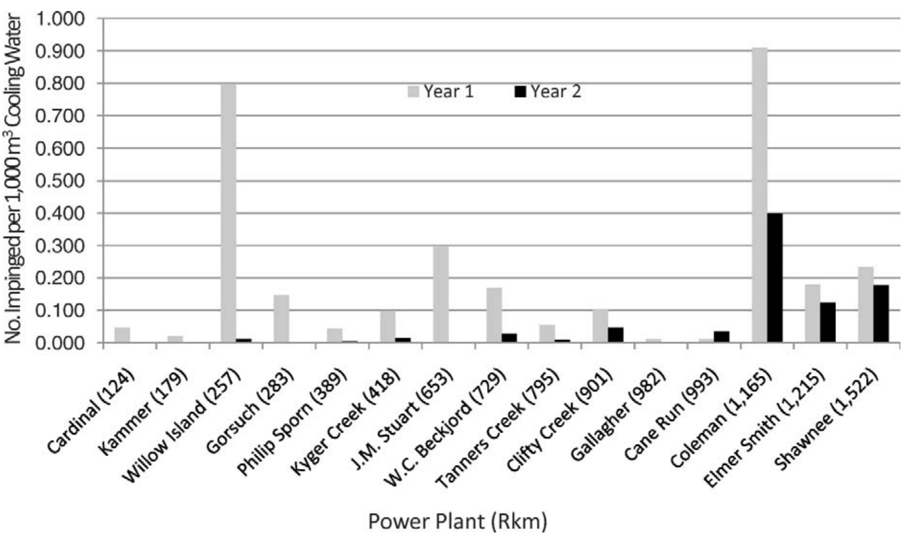

FIGURE 6.—Mean annual impingement rates of freshwater drum at 15 Ohio River power plants (with river kilometer [rkm] in parentheses) during year 1 (June 2005–June 2006) and year 2 (June 2006–June 2007) of the Ohio River Ecological Research Program impingement study.

TABLE 17.—Annual mean impingement rates (number/1,000 m^3) at 15 power plants along the Ohio River, 2005–2007. Sampling was not conducted at the Gorsuch or Stuart plant during the June 2006 to June 2007 study period. Year 1 represents data collected from mid-June 2005 to mid-June 2006; year 2 represents data collected from mid-June 2006 to mid-June 2007.

	Total		Gizzard shad		Freshwater drum	
Power plant	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
Cardinal	0.0015	2.173×10^{-5}	0.0015	1.704×10^{-5}	0.0000	2.054×10^{-6}
Kammer	0.0002	4.125×10^{-6}	0.0002	1.984×10^{-6}	0.0000	2.827×10^{-7}
Willow Island	0.0015	4.233×10^{-5}	0.0006	1.242×10^{-5}	0.0008	1.233×10^{-5}
Gorsuch	0.0042		0.0040		0.0001	
Philip Sporn	0.0002	8.984×10^{-6}	0.0001	1.645×10^{-6}	0.0000	4.703×10^{-6}
Kyger Creek	0.0022	7.041×10^{-5}	0.0021	4.902×10^{-5}	0.0001	1.476×10^{-5}
J. M. Stuart	0.0009		0.0005		0.0003	
W. C. Beckjord	0.0003	5.244×10^{-5}	0.0001	1.127×10^{-5}	0.0002	2.850×10^{-5}
Tanners Creek	0.0002	2.876×10^{-5}	0.0002	1.361×10^{-5}	0.0001	9.891×10^{-6}
Clifty Creek	0.0011	0.0002	0.0009	0.0002	0.0001	4.667×10^{-5}
Gallagher	0.0001	2.975×10^{-6}	0.0001	1.457×10^{-6}	0.0000	9.574×10^{-7}
Cane Run	0.0000	3.8136×10^{-5}	0.0000	1.532×10^{-6}	0.0000	3.474×10^{-5}
Coleman	0.0020	0.0006	0.0010	6.792×10^{-5}	0.0009	0.0004
Elmer Smith	0.0039	0.0002	0.0036	2.674×10^{-5}	0.0002	0.0001
Shawnee	0.0195	0.0070	0.0012	0.0001	0.0002	0.0003

due to the accumulation of debris on the intake trash racks, indicating an indirect effect of higher river flows. Overall, the lack of a significant association between gizzard shad impingement rates and river flow is indicated by the apparent lack of a response in rates to even greater changes in river flow during subsequent sampling events at the Kyger Creek Power Plant (Figure 7).

In contrast to the peak summer rates that were associated with higher flows, peak fall rates of gizzard shad impingement coincided with increasing river flows and declining water temperatures, two covariate variables. Fall gizzard shad impingement rates at the Cardinal Power Plant increased from 0.04 to 5.8 individuals/1,000 m^3 when river flows increased nearly five-fold and water temperatures declined by nearly 7°C (Figure 8). Similar changes in flow and water temperature occurred at the Philip Sporn Power Plant, where gizzard shad impingement rates increased from 0.006 to 1.8 individuals/1,000 m^3 (Figure 9). Fall rates

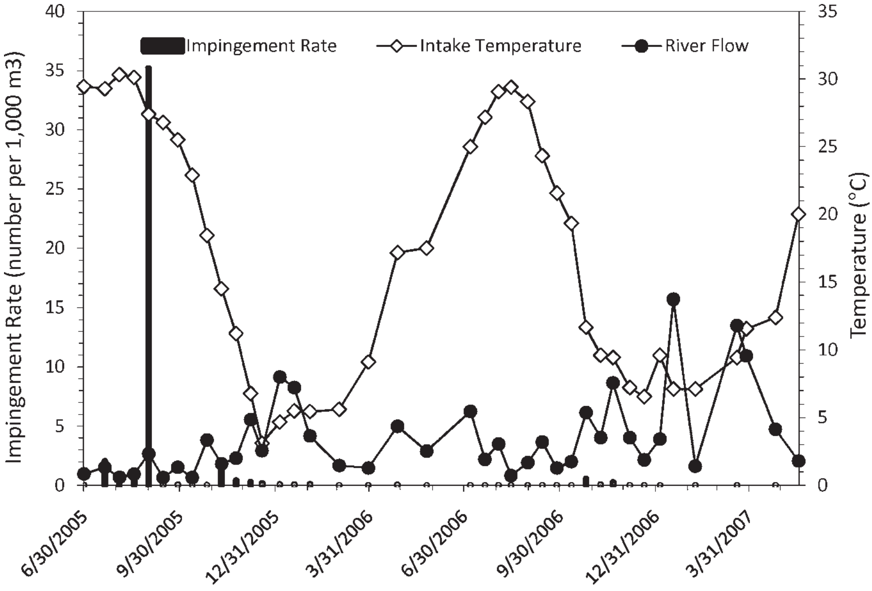

FIGURE 7.—Impingement rates of gizzard shad at the Kyger Creek Power Plant cooling water intake structure located at river kilometer 418 on the Ohio River, presented in comparison with river flows (m^3/s) and water temperatures (°C) measured during the Ohio River Ecological Research Program impingement study, June 2005–June 2007; dates are month/day/year.

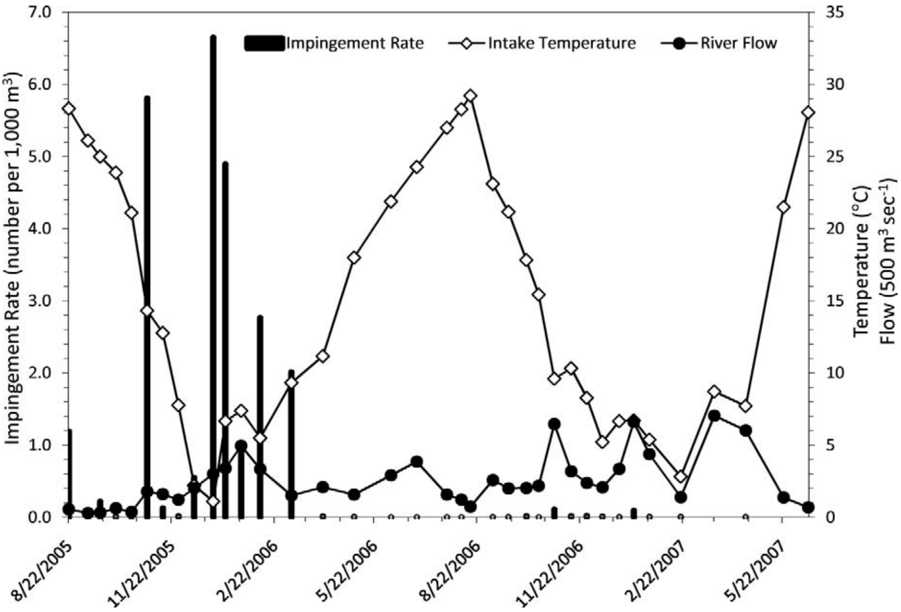

FIGURE 8.—Impingement rates of gizzard shad at the Cardinal Power Plant cooling water intake structure located at river kilometer 124 on the Ohio River, presented in comparison with river flows (m^3/s) and intake water temperatures (°C) measured during the Ohio River Ecological Research Program impingement study, June 2005–June 2007; dates are month/day/year.

at other power plants with fall peaks occurred when river flows and water temperatures were relatively stable.

Higher overall winter impingement rates were due primarily to impingement of gizzard shad at 14 of the 15 power plants and impingement of threadfin shad at the Shawnee Power Plant. The influence of low water temperatures on impingement rates was demonstrated at the Shawnee Power Plant for both shad species. The peak rate at the Shawnee Power Plant for gizzard shad occurred in late December 2005, when river flows and water temperatures were declining (Figure 10). Peak rates of threadfin shad impingement during both winter sampling periods also coincided with water temperatures that declined from 8.3°C to 5.0°C in mid-December 2005 and from 6.7°C to 3.3°C in February 2007 (Figure 11). Water temperatures at all power plants averaged below 7°C during the winter sampling events (Table 18); such temperatures probably affected the swimming performance of both shad species and were low enough to cause stress in threadfin shad (Loar et al. 1978; White et al. 1986). However, high winter impingement rates of the two shad species were not sustained even though similar winter temperatures occurred at all intakes. Despite the apparent vulnerability of the shad species to impingement during low winter temperatures, very high rates occurred infrequently, suggesting either that clupeids were outside the influence of the intakes during much of the winter or that a high percentage of the susceptible shad succumbed during the initial period of declining water temperatures.

Although peak impingement rates coincided with higher river flows at some power plants, river flows did not have a statistically significant influence on gizzard shad rates based on multiple regression analyses (Table 9). River flow did influence the impingement rates of channel catfish and freshwater drum.

Overall, impingement rates were highly variable and unpredictable, with a few events (referred to here as episodes) demonstrating disproportionately high rates. The top-four 24-h sampling events at a given plant accounted for, on average, 74% of the 2-year impingement total, and at the Shawnee Power Plant a single 24-h episodic event accounted for as much as 81% of the fish collected at that plant during the entire 2-year study. These episodes complicated the analysis of factors that influence impingement rates. To assess whether high impingement rates during an initial 24-h sampling period were representative of rates observed in the following week, an 8-d study was conducted at the Shawnee Power Plant during February 2007 (Table 19). The high impingement rate on 8 February was not sustained, as daily rates declined by 91% over the next 4 d even though water temperature (3.0–3.3°C) and cooling water use (31.7–33.0 m^3/s) were stable during

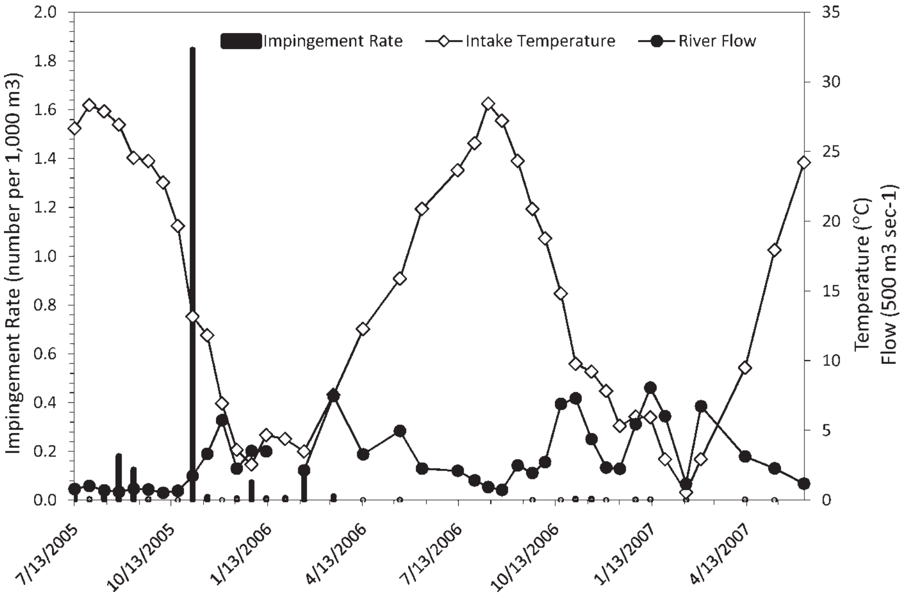

FIGURE 9.—Impingement rates of gizzard shad at the Philip Sporn Power Plant cooling water intake structure located at river kilometer 389 on the Ohio River, presented in comparison with river flows (m^3/s) and intake water temperatures (°C) measured during the Ohio River Ecological Research Program impingement study, June 2005–June 2007; dates are month/day/year.

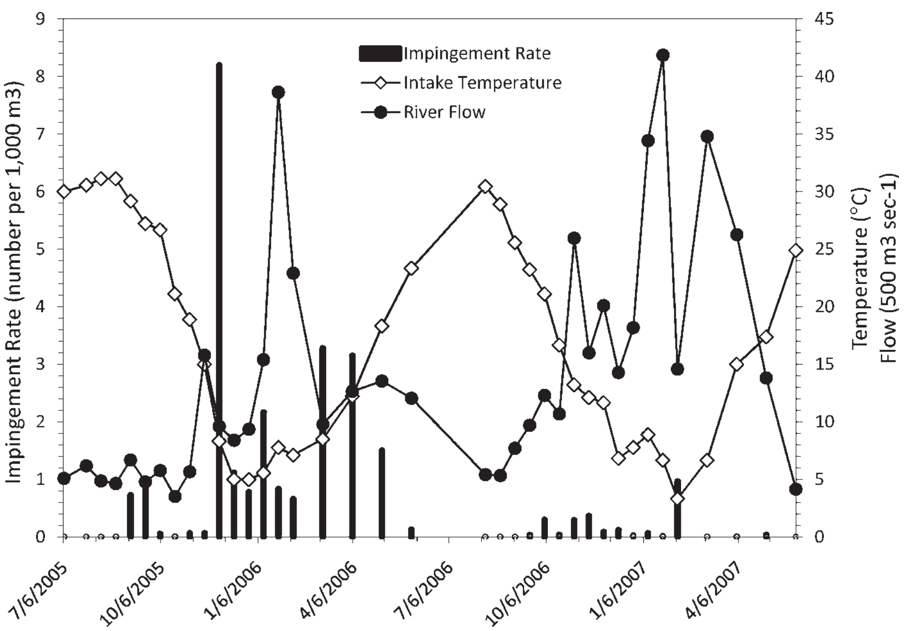

FIGURE 10.—Impingement rates of gizzard shad at the Shawnee Power Plant cooling water intake structure located at river kilometer 1,522 on the Ohio River, presented in comparison with river flows (m^3/s) and intake water temperatures (°C) measured during the Ohio River Ecological Research Program impingement study, June 2005–June 2007; dates are month/day/year.

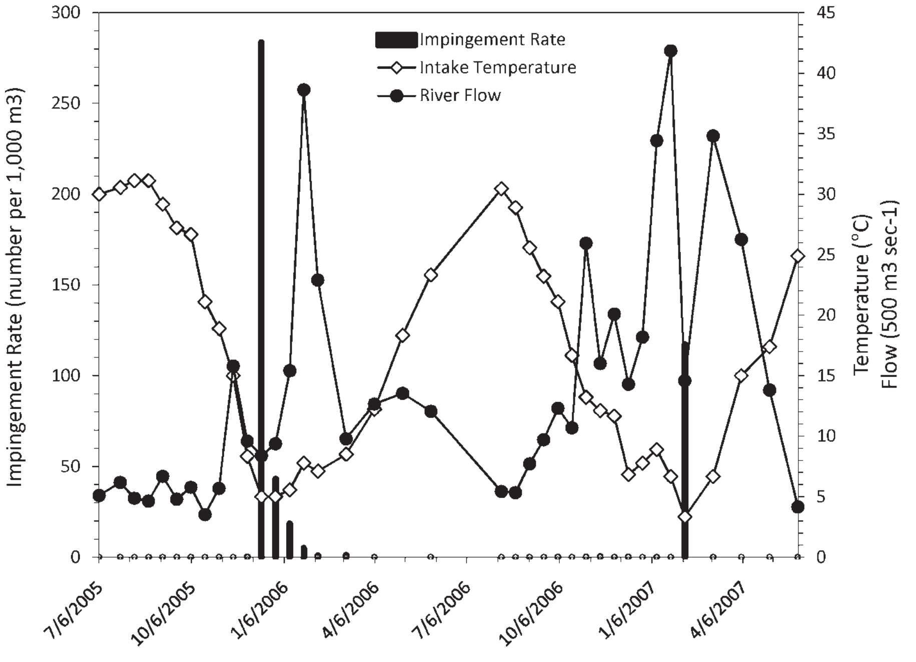

FIGURE 11.—Impingement rates of threadfin shad at the Shawnee Power Plant cooling water intake structure located at river kilometer 1,522 on the Ohio River, presented in comparison with river flows (m^3/s) and intake water temperatures (°C) measured during the Ohio River Ecological Research Program impingement study, June 2005–June 2007; dates are month/day/year.

that period. River flows did decline during the first half of the 8-d period (Table 19). Although impingement rates increased somewhat after the fourth day, total rates on the seventh day were only about one-quarter of the rate recorded for 8 February 2007. Declining impingement rates during this intensive sampling period were due primarily to lower threadfin shad impingement rates. Threadfin shad that were impinged during this period may have been moribund because water temperatures (2.8–3.3°C) were below the threshold (5°C) demonstrated to cause loss of equilibrium in threadfin shad (Griffith 1978; Loar et al. 1978). Impingement rates of threadfin shad were much lower in January 2007 (0.0163–0.1637 individuals/1,000 m^3), when water temperatures (6.7–8.9°C) were about 3–6°C warmer than in February and were above the 5°C threshold.

This study indicates that impingement at power plants along the Ohio River is largely a function of the

TABLE 18.—Mean seasonal water temperatures (°C) recorded during impingement sampling events at 15 power plants during the Ohio River Ecological Research Program impingement study, 2005–2007.

	2005–2006				2006–2007			
Power plant	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring
Cardinal	26.5	13.7	6.0	18.8	25.8	11.1	6.1	19.1
Kammer	29.3	16.1	4.3	16.4	27.3	12.4	4.3	17.1
Willow Island	27.5	13.4	3.9	18.5	25.5	12.4	4.1	17.0
Gorsuch	29.4	15.8	4.6	19.7				
Philip Sporn	26.5	13.0	4.5	18.2	25.3	11.0	3.7	17.2
Kyger Creek	28.9	16.6	4.9	17.2	27.7	13.1	8.0	14.7
J. M. Stuart	28.1	14.8	6.3	17.2				
W. C. Beckjord	28.1	15.2	5.8	19.6	28.0	13.4	5.8	15.5
Tanners Creek	28.8	15.4	5.7	19.6	27.5	12.8	5.5	18.6
Clifty Creek	28.2	16.4	5.0	17.3	27.6	13.6	5.6	18.0
Gallagher	25.7	16.9	6.1	22.1	27.4	11.1	6.5	18.8
Cane Run	27.9	17.0	5.8	17.0	27.3	13.9	4.9	16.2
Coleman	28.6	17.1	5.9	20.3	27.7	13.8	5.4	17.8
Elmer Smith	28.8	16.6	5.5	18.1	27.9	13.1	5.5	18.0
Shawnee	29.9	15.8	6.8	18.0	27.0	13.6	6.7	19.1

TABLE 19.—Impingement rates (number/1,000 m^3) during seven consecutive 24-h sampling events conducted in February 2007 at the Shawnee Power Plant during the Ohio River Ecological Research Program impingement study.

Species	8 Feb	9 Feb	10 Feb	11 Feb	12 Feb	13 Feb	14 Feb	15 Feb
Threadfin shad	90.5659	57.5423	19.6646	7.7572	6.1820	11.5575	21.9917	6.7126
Gizzard shad	0.7477	0.8452	0.4641	0.2801	0.2051	0.1592	0.1265	0.0913
Blue catfish	0.0046	1.2338	0.1860	0.0231	0.0445	0.0307	0.0407	0.0310
Skipjack herring	0.2082	0.1748	0.0608	0.1413	0.0996	0.0459	0.1143	0.0675
Freshwater drum	0.0486	0.1809	0.0256	0.0496	0.0408	0.0649	0.0743	0.0642
Yellow bass	0.1285	0.0124	0.0023	0.0263	0.0049	0.0254	0.0226	0.0182
Channel catfish	0.0004	0.0917	0.0007	0.0109	0.0091	0.0009	0.0004	0.0004
Bluegill	0.0004	0.0144	0.0100	0.0004	0.0002	0.0004	0.0100	0.0151
Other species	0.0016	0.0028	0.0137	0.0014	0.0049	0.0023	0.0096	0.0154
Total impingement	91.70575	60.09819	20.42774	8.29022	6.59109	11.88706	22.39014	7.01561
Temperature (°C)	3.3	3.3	3.2	3.3	3.3	3.2	3.0	3.0
Cooling water use ($m^3 \times 10^6$)	33.0	33.0	33.0	31.7	32.0	33.0	33.0	33.0
River flow (m^3/s)	72,916	62,014	46,227	40,989	43,095	45,095	44,528	51,961

abundance of age-0 gizzard shad and freshwater drum and, at the extreme lower river, age-0 threadfin shad. Abundance of these fishes fluctuates widely based on the long-term ORERP monitoring program (EPRI 2008) and fluctuates unpredictably based on current knowledge. The study also showed that most intake characteristics, such as volume of water pumped, design approach velocity, and intake configuration and type, had little or no effect on impingement rates of the six common fish taxa considered. Although water temperature appears to be the most important physical variable, with impingement tending to increase at low water temperatures, it may serve as a surrogate for the time required for age-0 fish to reach impingeable size except when water temperatures are very low, as was observed for threadfin shad and gizzard shad. Water temperature was collinear with several other variables, making it difficult to determine whether the impingement effect was strictly associated with water temperature, one of the collinear variables, or possibly the combined effects of all variables. However, the inverse association between impingement rates and water temperature is consistent with the effect of water temperatures on fish swimming performance, especially for both shad species, which were not only the most commonly impinged species at the Ohio River power plants but are also known to be sensitive to cold water temperatures.

The most consistent factor influencing impingement rates based on the within- and among-plant statistical analyses was study year, which reflects the dramatic differences between years in the abundance of age-0 fishes (especially gizzard shad and freshwater drum) that represent the majority of fish impinged at 14 of the 15 power plants studied. One of the least important factors identified by the multivariate analyses and the only factor under the direct control of these power plants was cooling water use as indicated by either total shift volume (which represents actual pumping rates during impingement sampling events) or design pumping capacity (the amount of water that could be pumped). The stepwise procedures failed to identify total shift volume (Table 9) or design pumping capacity (Table 16) as an important factor influencing impingement rates, and at the plant level only 7 of 90 correlations yielded significant associations (Table 12). Because the participating power plants are base-loaded facilities that operate near capacity most of the time, we examined total shift volume as a percentage of design pumping capacity to evaluate the range of pumping rates that occurred during the sampling events (Figure 12). As a group, the 15 power plants pumped at greater than 95% capacity during 22% of the sampling events and at greater than 75% capacity during about 55% of the sampling events. About 12% of the sampling events were conducted when the power plants were pumping at less than 50% capacity. Overall, the studies were conducted over a wide range of pumping capacities, especially considering the wide range of absolute pumping rates (606–3,700 m^3/min) represented by the 15 power plants (Table 1). Seasonally, pumping rates were highest in the summer (86% capacity), lower in the fall (76%) and spring (73%), and lowest (68%) in the winter, when less cooling water is required to meet discharge permit limits for discharge temperatures. The frequency of studies conducted at greater than 95% pumping capacity was highest in the summer (37%) and much lower in the other three seasons (12–18%).

The lack of significant statistical relationships between impingement rates and cooling water use and the occurrence of episodic impingement events during all but the spring season suggest that the distribution and abundance of age-0 fish were primary factors contributing to the variability of impingement rates at the Ohio River power plants. Although the multivariate analyses showed that the within-plant

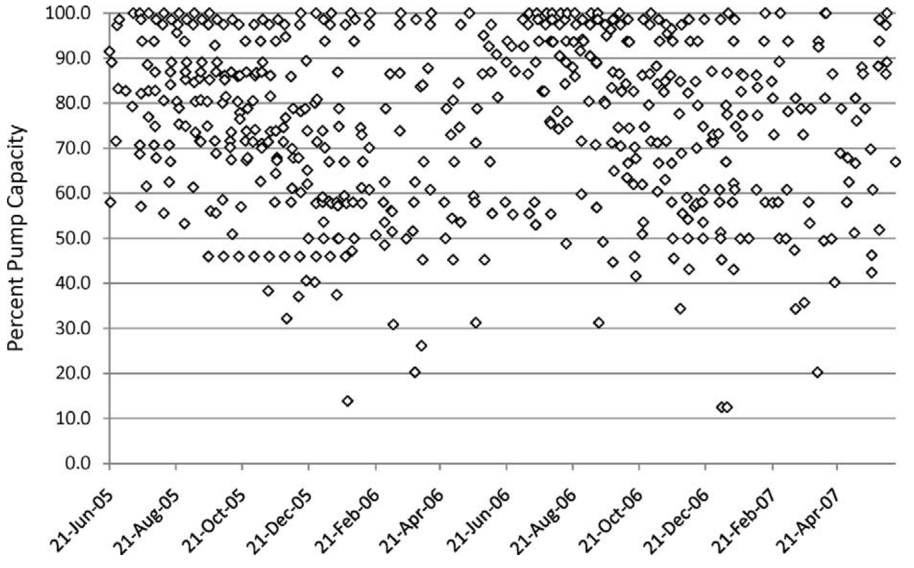

FIGURE 12.—Percentage of design pumping capacity used at 15 Ohio River power plants during sampling events of the Ohio River Ecological Research Program impingement study, June 2005–June 2007.

variables of water temperature, river flow, river stage, and delta river stage significantly influenced impingement rates, those factors accounted for a small amount of the observed variability. Likewise, the among-plant variables (e.g., rkm, intake configuration, and intake position on the riverbank) were shown to influence impingement rates, but the effect of those other factors appeared to be site-specific rather than generic. In addition, the effects of these other factors varied with the species tested.

Although the statistical analyses failed to identify a generic factor that influences the magnitude of impingement, it is possible that one or more factors exist but were not measured. The fact that impingement occurred largely as episodic events suggests the presence of some other factor (or factors). For threadfin shad, the episodic events at the Shawnee Power Plant were probably caused by water temperature declining to critically low levels. Recent studies suggest that the health of the impinged fish may also be a factor influencing impingement rates. Studies conducted by Alabama Power Company (APC) and Auburn University at APC's Barry Generating Station on Mobile Bay indicated that impinged fish have a higher incidence of weight loss, parasite load, and bacterial infections (Baker 2007). Limited studies on the Ohio River found similar results (J. Terhune, Department of Fisheries and Allied Aquaculture, Auburn University, personal communication). Thus, it appears that year-class strength, water temperatures at critical minima, and fish condition—all factors that are outside the control of individual power plants—influence impingement rates more than power plant design and operational variables.

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