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Understanding Fish Behavior, Distribution, and Survival in Thermal Effluents Using Fixed Telemetry Arrays: A Case Study of Smallmouth Bass in a Discharge Canal During Winter

STEVEN J. COOKE*
Centre for Applied Conservation Research
University of British Columbia
Vancouver, BC, Canada

CHRISTOPHER M. BUNT
JASON F. SCHREER
Department of Biology
University of Waterloo
Waterloo, Ontario, Canada

ABSTRACT / Advances in telemetry have facilitated the continuous monitoring of fish position and movement. At present, there are few examples where this approach has been applied to environmental monitoring or assessment. Here we 1) present a case study that used a fixed antenna array and continuously scanning coded receiving system to monitor the movement of radio-tagged smallmouth bass (*Micropterus dolomieu*) in a thermal discharge canal on Lake Erie during the winter of 1998/1999, and 2) evaluate the use of fixed telemetry arrays for environmental monitoring. Although the number of radiotagged bass in the canal decreased gradually over time, fish spent the majority of the winter in the canal. When in the canal, bass selected areas upstream of the tempering pumps where water was the warmest. This region was also high in habitat complexity, had adequate velocity refuges, and abundant forage. Despite residing in the thermal effluent throughout the winter, none of the fish monitored were observed to participate in reproductive activities in the canal in the Spring. Interestingly, during a biofouling chlorination pulse in May, 50% of radiotagged fish still residing in the canal left and did not return during the monitoring period. Utility infrastructure accessible to fish, including thermal effluents, should be considered as fish habitat and managed accordingly to minimize mortality and sublethal effects on resident and transient fish. Fixed telemetry arrays that permit the continuous monitoring of fish behavior as described in this paper are widely applicable to many issues in environmental management, monitoring, and conservation.

Studies investigating the ecological effects of heated effluent condenser cooling systems at power-generating stations were common in the early 1970s, but declined through the 1980s and 1990s. Collectively, these studies have contributed greatly to our understanding of the thermal biology of aquatic organisms (e.g., Crawshaw 1977, Neill 1979), as well as applied aspects of effluent monitoring and utility management (e.g., Coutant 1970, 1975). In recent years, these investigations have become more common as many of the generating stations constructed several decades ago face relicensing (Clarke 1996). In addition, the continued and increasing need for reliable power has resulted in a variety of new proposals for production infrastructure in North America, and elsewhere (Grübler 1999). Electric power utilities have also begun to place an increased focus on the conservation of aquatic biodiversity (Olmsted and Bolin 1996) while incorporating ecological principles into utility management (Temple 1996).

Since the 1970s, there have been technological advances that permit more detailed assessments of how individual fish respond to dynamic thermal regimens. Specifically, radio and ultrasonic telemetry have improved both the temporal and spatial resolution of field studies (Lucas and Baras 2000). Previously, individual fish would be located on an intermittent basis or would be followed by researchers until they had lost the signal or had been forced to abandon the tracking because of fatigue, inclement weather, or financial constraints (i.e., MacLean and others 1982). Currently, some telemetry systems are capable of monitoring the simultaneous real-time positions of numerous individuals on a continuous basis through the use of coded telemetry (Thorstad and others 2000). Coded telemetry systems permit the simultaneous monitoring of numerous fish on a single radio or ultrasonic frequency and can also

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*Author to whom correspondence should be addressed, *email:* scooke@interchange.ubc.ca

be used to minimize scan times in sequentially monitored systems (Niezgoda and others 2002). In some cases, positions can be determined in three dimensions, but aquatic environments are currently limited to ultrasonic systems and are still unrepresented in the literature. In the vicinity of generating stations, and in particular in the discharge flows, entrained air, variable velocities, and noise from station operations restrict the use of ultrasonic systems (Winter 1996).

Several recent studies using fixed radiotelemetry arrays have provided new insight into the residency patterns and movements of fish in thermal discharge canals. These studies have revealed that some individuals spend protracted periods in the zone of thermal influence of generating stations including the plume and the discharge channel (e.g., Cooke and McKinley 1999, Cooke and others 2000, McKinley and others 2000). Most discharge channels are equipped with tempering pumps to shunt ambient (cooler) water into the canal to minimize the temperature difference between the effluent and the receiving waterbody (Coutant 1970).

The purpose of this study was to elaborate on the preliminary findings of a study conducted in a thermal discharge at a thermal generating station on Lake Erie during the winter of 1997/1998 (January 7 to March 15) (Cooke and others 2000). The preliminary study documented the extended presence of fish in areas of the discharge canal that are upstream of the influence of the tempering pumps (Cooke and others 2000). These regions experienced higher and more variable thermal conditions than those downstream of the tempering pumps. Our objectives in 1998/1999 were twofold: 1) to assess the response of smallmouth bass (*Micropterus dolomieu*) to dynamic thermal conditions in a thermal effluent, and 2) to evaluate the use of fixed telemetry arrays for environmental monitoring. To this end, we installed a more comprehensive antenna array in the nontempered region to monitor movements, residency patterns, activity, and habitat selection relative to the previous study. Furthermore, we wanted to expand the monitoring period to encompass the complete winter period (December through April 31). The expanded antenna array, study objectives, and study period provide the opportunity to detail the effects of fluctuating thermal regimens in the discharge canal on smallmouth bass during the winter. This case-study approach allows us to evaluate the suitability of this technique for environmental monitoring. The unique approach, coupled with our experience in the deployment of this novel telemetry equipment, provides an opportunity to discuss its application to environmental monitoring and biological assessment. We conclude by discussing our approach and findings in the context of fish conservation strategies in thermal effluents.

Materials and Methods

Study System

The Nanticoke Thermal Generating Station (NTGS), located at 42°48' N 80°04' W, is an eight-unit, 4000 MWe (500 MWe each) coal-fired station situated on the north shore of Lake Erie. The station uses a once-through condenser cooling-water system, taking water from Lake Erie via two submerged intakes that extend approximately 550 m offshore. The maximum design cooling water flow is 154 m^3/s, of which 88 m^3/s is for condenser cooling and 66 m^3/s is for tempering of heated discharge water. The tempering pumps shunt cooler, ambient lake water into the discharge canal in an effort to reduce the difference between lake temperature and effluent temperature. The station discharges the heated effluent via a canal 550 m long, 15.25 m wide, and 9.15 m deep. The canal was blasted from bedrock, and is relatively homogeneous throughout, except for rip-rap near the mouth of the canal and a series of oil boom structures partway down the canal. NTGS operates as a peak load station, contributing power to the grid during periods of peak demand. This typically requires six- to eight- unit operation during the early morning, midday, and late afternoon periods. This “two-shifting” mode creates fluctuating effluent temperatures in the discharge canal. Additional information on operating procedures and the site are provided by Foster and Wheaton (1981) and Wiancko (1981). Public access to the study site was prohibited, permitting the installation of a permanent monitoring system.

The thermal effluent from the station is regulated by limits on the temperature increase across the station (ΔT) and maximum effluent temperature (T_{max}). To reduce the temperature differential between intake and discharge waters, normal plant operating procedure involves the operation of one thermal-tempering pump for every two cooling-water pumps in operation (Foster and Wheaton 1981). These eight tempering pumps shunt ambient intake water directly to the heated discharge stream to meet the prescribed limits. The original limits of $\Delta T = 8.3°C$ and $T_{max} = 32.2°C$ were conditionally increased to 12.5°C and 35.0°C, respectively, in 1983. This has enabled the station to limit its operation to only three or four of eight tempering pumps. Since 1983, NTGS has conducted a range of biological studies to assess the implications of reduced tempering pump operations. The primary consider-

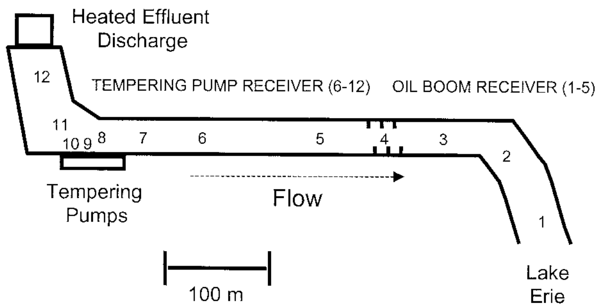

Figure 1. Overhead schematic of the thermal generating station discharge canal complex detailing the locations of the telemetry antenna array. The numbers 12 to 1 denote antennas moving from upstream to downstream for monitoring movements with coded radiotelemetry. Antennas 10, 9, 5, 4, 3, 2, and 1 were underwater, whereas antennas 12, 11, 8, 7, and 6 were aerial.

ations are the benefits of reduced water intake volume and, therefore, reduced fish entrainment and impingement (Foster and Wheaton 1981) versus the effects of an increase in temperature regimen on fish species resident in the discharge such as the smallmouth bass. During the 1999 winter season, the two most upstream tempering pumps were inoperational (Figure 1).

Environmental Monitoring

Lake temperature was measured in the station forebay, whereas the discharge temperature was measured by two fixed recorders near the head of the outflow canal, just downstream from the tempering pump discharges (Figure 1). Discharge temperature was taken as the average reading of the two recorders, even though differences > 0.1°C were rare. Both lake and discharge water temperatures were recorded hourly. We used these water temperatures for monitoring trends in activity at gross temporal scales (i.e., hourly). We also installed a temporary temperature recorder (Hobo Tidbit, Onset Inc., Bourne, MA) upstream of the tempering pumps and collected additional readings using hand-held thermometers. The generating station also recorded operating schedules expressed as net capacity factor (percent of maximum station operation).

Radiotracking

An array of antennas, configured similarly to that described in Cooke and others (2000) was used (Figure 1). This included an array of five underwater antennas in the mid to lower reaches of the canal, and an extensive grid of both aerial and underwater antennas in the upper reaches of the canal. Underwater antennas were anchored at 4-m depths and were composed of coaxial cable with 6 cm of the shielding removed. All cables used were RG58c/u and ran to central antenna switching boxes (ASP_8, Lotek Engineering Inc., Newmarket, Ontario, Canada). Two digital receivers (SRX_400, Lotek Engineering) with code discrimination software, one in the upper and one in the lower portion of the canal, continuously scanned the antenna array for fish with radiotransmitters.

Between December 11, 1998 and January 25, 1999, 29 smallmouth bass (mean ± SE: Total length = 349 ± 6 mm, Mass = 689 ± 44 g) were captured from the discharge canal, near tempering pump 1 (Figure 1) and implanted with coded radio transmitters (MCFT3em, 8.9 g in air, 11.0 mm [Diameter] × 49.0 mm [length], Lotek Engineering). Fish were held in a tank continuously supplied with outfall canal discharge water for 24 h before surgery. This period allowed swim bladders to normalize after capture in deep water (i.e., > 4 m). Detailed descriptions of surgical techniques are provided in Cooke and Bunt (2001). Briefly, each fish was anesthetized using a 60 ppm induction bath of clove oil and ethanol. After equilibrium was lost, fish were measured (total length, millimeters) and weighed (grams) before being placed ventral side up in foam padding on a surgical table. A maintenance dose (30 ppm) of anesthetic in oxygenated water continuously irrigated the gills. A 15-mm incision was made slightly lateral to the ventral midline, just posterior to the pelvic girdle. A radiotransmitter package was placed in the intraperitoneal cavity. The whip antenna exited the body through a small puncture caudal to the transmitter. The incision was closed with two independent sutures of 3/0 nonabsorbable braided silk (Ethicon Inc., Somerville, NJ) and then secured with Vetbond (3M Inc., St. Paul, MN). All operations were conducted by one of three trained individuals with equal levels of surgical experience with fish. Fish were allowed to recover in flow-through canal water for approximately 5 min before release. All fish were released at the capture location (near tempering pump 1).

During the study period, we angled extensively in the canal in an attempt to recapture previously tagged individuals to assess healing. In total, we recaptured 6 individuals, all of which revealed that the incision was healing rapidly. We also deployed videography in a parallel study (Cooke and Schreer 2002) and frequently observed radio-tagged fish interacting with nontagged conspecifics.

Assessment of Forage

To assess the relative seasonal availability of potential smallmouth bass forage, we quantified the amount of forage fish (alewife [*Alosa pseudoharengus*], emerald shiner [*Notropis atherinoides*], rainbow smelt [*Osmerus* *mordax*], and spottail shiner [*Notropis hudsonius*]) impinged on traveling screens at the condenser cooling flow intake. This serves as an approximation for estimates of the amount of forage that is entrained in the cooling system or the tempering pump intakes and is expelled into the canal where it is available as food. For 5°C temperature intervals between December 15 and April 31, we calculated both the biomass and abundance of impinged forage fish.

Data Analysis

A paired *t*-test was used to compare the mean daily water temperatures of the lake and the effluent. Telemetry data were recorded in real time and then analyzed on a daily basis for individual fish (i.e., percent of time spent in different locations). We used compositional analysis to determine whether habitat use was nonrandom, and to rank habitat use relative to availability. Analysis of variance (ANOVA) was used to evaluate monthly differences in movement rates, residency, distribution, and forage biomass and density. When significant, the conservative Tukey post hoc test was used to evaluate where differences occurred. Statistical analyses were conducted using JMPIN (V4.0, SAS Institute, Cary, NC) and were considered significant at $\propto = 0.05$.

Results

Mean daily water temperatures in the discharge canal were consistently warmer than in the lake (paired *t*-test; $P < 0.05$; mean difference 7.4 ± 2.1°C). Mean water temperatures for the period of December 1, 1998 through April 30, 1999 were 10.9 ± 0.2°C in the effluent canal and 3.5 ± 0.2°C in Lake Erie (Figure 2). Water temperatures in the lake decreased from early December, reaching lowest values in early January. Temperatures were low until March, when water temperatures began to rise steadily (Figure 2). The area upstream of the tempering pumps was always warmer than the region downstream, although the difference varied between 0.2 and 6.4°C. The station operated daily at an overall net capacity factor of 57 ± 1% during the monitoring period, with no prolonged station shutdowns (Figure 2).

Distribution of smallmouth bass in the discharge canal was consistently nonrandom throughout the study period (compositional analysis; $P < 0.05$). Smallmouth bass spent significantly more time in regions upstream of the tempering pumps than would be expected (Figure 3). In general, ~50% of the total time that smallmouth bass were tracked was spent in this region, which only accounts for ~20% of the surface area of the discharge canal. Nonrandom distribution

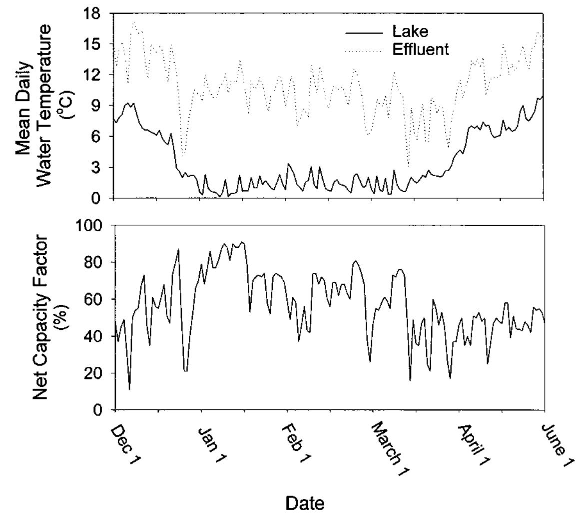

Figure 2. Daily environmental and operating conditions for the Nanticoke Thermal Generating Station from December 1, 1998 to June 1, 1999. Mean daily water temperature is plotted for both the lake and the effluent (downstream of the tempering pumps). Station operation is presented as percent of total operational capacity.

was even more evident near tempering pumps 1 and 2 (Antennas 9 and 10; Table 1). Although these two tempering pumps bays comprise less than 1% of the surface area and volume of the discharge canal, smallmouth bass spent between on average between 10 and 20% of the time that they were tracked in these finite regions. The amount of time spent upstream of the tempering pumps and within the tempering pumps were consistent across the monitoring period (ANOVA; $P > 0.05$; Figure 3). The number of fish downstream of the tempering pumps, but still in the canal decreased in April as water temperatures warmed (ANOVA; Tukey $P < 0.05$). During this time, fish tended to swim rapidly through the lower reaches of the canal and enter the lake. The percentage of time fish spent in Lake Erie increased significantly in April (ANOVA; Tukey $P < 0.05$; Figure 3). By the end of April, 19 fish had left the canal and were not observed to return during the remainder of the monitoring period. Water temperatures on the day of final fish departure were not more variable than those days where no fish departed (*t*-test, $P > 0.05$). However, because most fish departed in the spring, water temperatures on the day of departures were generally warmer than the average water temperature before departure (*t*-test, $P < 0.05$). Several other fish made movements in and out of the canal. Although fish did leave the canal, we had no evidence of any mortality based on expelled transmitters. Tracking in the effluent plume failed to locate any individuals re-

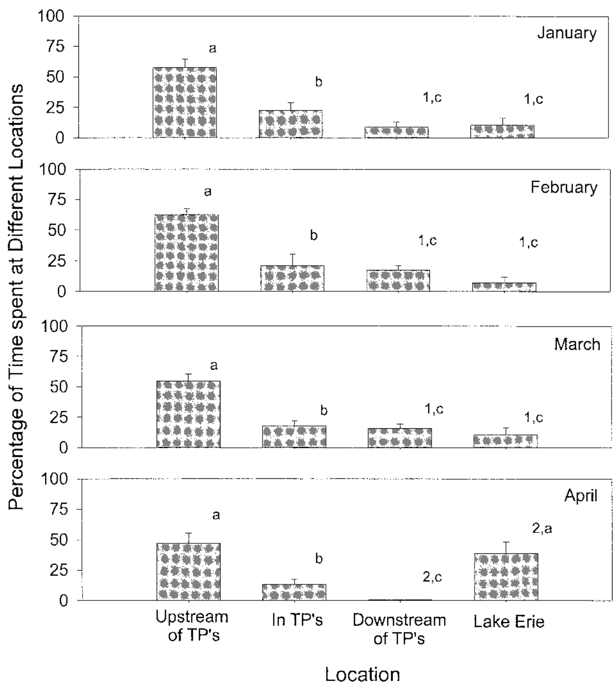

Figure 3. Mean seasonal distribution of smallmouth bass in four major regions: 1) Upstream of the tempering pumps, 2) in the tempering pumps, 3) downstream of the tempering pumps but still in the canal, and 4) in Lake Erie. Distribution is expressed as a percentage of the total time available by all fish that we monitored. Significant differences ($P < 0.05$) in distribution among locations for each month are denoted by dissimilar letters as determined by analysis of variance (ANOVA) with Tukey post hoc tests. Significant differences ($P < 0.05$) in seasonal distribution for each location are denoted by dissimilar numbers as determined by ANOVA with Tukey post hoc tests. Error bars represent the standard error of the mean.

peatedly in the same location to indicate possible mortality.

Mean monthly movement rates of fish in the canal were consistent from January through March (ANOVA; Tukey $P > 0.05$), when movement rates decreased by half for April (Tukey $P < 0.05$; Figure 4). The majority of the movements recorded in the canal were localized, with fish moving among adjacent reception cells in the region upstream of the tempering pumps (Figure 5). Although some fish made longer movements throughout the canal, those movements were less frequent and were usually associated with unidirectional movements out of the canal or brief exploratory movements below the tempering pumps (Figure 5).

Relative availability of small stunned, dead, or injured fish indicative of potential forage in the canal was highest during periods of low water temperature experienced in the winter. Both the daily impingement rates

Table 1. Summary of nonrandom space utilization in the Nanticoke Thermal General Station discharge canal[a]

Antenna number	Surface area of canal (%)	Fish locations (%)	Selection (+) and avoidance (−)
12	13.2	8.4	−
11	8.1	42.8	+
10	0.17	38.1	+
9	0.13	1.2	+
8	5.7	1.1	−
7	4.3	1.0	−
6	10.4	3.3	−
5	10.6	1.5	−
4	8.7	1.4	−
3	7.3	2.0	−
2	12.1	0.1	−
1	19.3	0.1	−

[a]Antenna numbers are arranged from the most upstream (12) to the lake (1) as outlined in Figure 1. For each reception cell, we present the percentage of total surface area covered by each of the cells and the percentage of fish locations in each of those cells. Significant differences (P < 0.05) between available space and expected fish use assuming random distribution are indicated as either selection (+) or avoidance (−) of a particular region of the canal as indicated by compositional analysis.

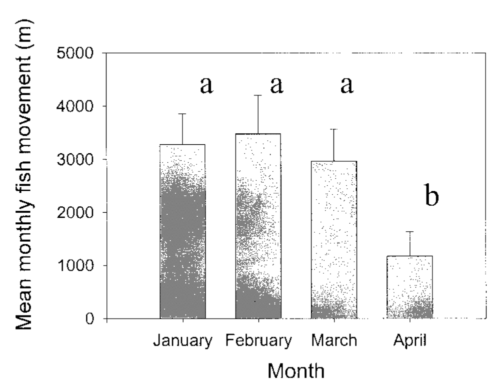

Figure 4. Mean monthly fish movement rates for those fish that were monitored while they were present in the canal. Significant differences ($P < 0.05$) in seasonal movement rates are denoted by dissimilar letters as determined by analysis of variance with Tukey post hoc tests. Error bars represent the standard error of the mean.

and daily impingement biomass were highest at water temperatures less than 5°C (ANOVA; Tukey $P < 0.05$; Figure 6). These periods coincided with some of the highest densities of predatory fish in the canal as evidenced by videographic (Cooke and Schreer 2002) and telemetric records. During these periods, prey items were observed in the water column upstream and

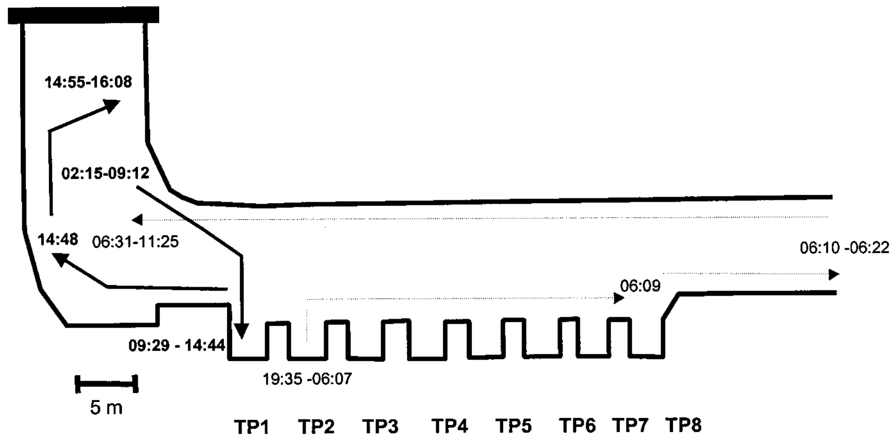

Figure 5. Example trace of two smallmouth bass exhibiting two typical behaviors. The fish indicated by the bolded solid lines exhibited typical milling behavior in the region upstream of the tempering pumps and movements between that area and the inoperational tempering pumps. The fish indicated by the dashed lines is typical of those fish that made brief forays downstream from the tempering pumps but returned upstream of the tempering pumps where they spent most of the time. Data are for two different fish on the same day in late January. Numbers presented on the figure represent times.

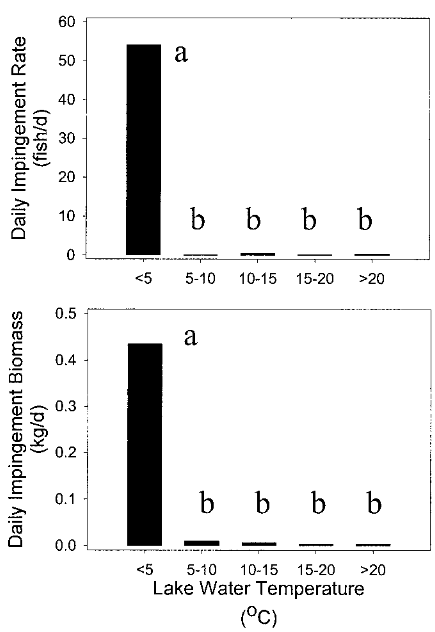

Figure 6. Mean daily impingement rate and biomass for forage fish collected on the condenser cooling loop traveling screens at 5°C lake temperature intervals. Significant differences ($P < 0.05$) in impingement rate and biomass associated with different temperature ranges are denoted by dissimilar letters as determined by analysis of variance with Tukey post hoc tests.

within the tempering pumps 1 and 2, and were also observed in the gut contents of angled fish.

Interestingly, although we conducted detailed assessments of the reproductive biology of smallmouth bass in the canal in 1999 (Cooke and others 2003), none of the male bass that constructed nests, spawned, or provided parental care were those monitored with telemetry. Also, the general lack of telemetry observations in the lower reaches suggests that none of the fish that we monitored throughout the winter and that resided in the upper reaches of the canal for extended periods actually reproduced in the canal.

We continued to monitor abundance of fish through June, but a series of chlorination events associated with biofilm removal in the condenser system coincided with a major departure of fish. Within a 1-hour period on May 10, 5 of the 10 tagged bass remaining in the canal departed and did not return during the remainder of the monitoring period. This departure rate was significantly higher than departure rates observed on any other day throughout the study. The chlorine pulse duration and concentration were not recorded. However, a similar chlorination event on June 25 that elicited loss of fish equilibrium as also observed on May 10 had total residual chlorine values that were 33 ppb downstream of the tempering pumps. Video records corroborate the finding that abundance of fish decreased dramatically during the chlorination event (Cooke and Schreer, unpublished data). This chlorination event confounded detailed analyses of seasonal or thermal patterns in fish abundance after May 10.

Discussion

Findings of Case Study

During the winter, radio telemetry showed that smallmouth bass spent the majority of their time in or above tempering pump 1, where there is no cool water input and water temperatures are the highest and most variable. Water temperature is clearly one of the most important environmental variables affecting smallmouth bass because it influences geographic range, migrations, spawning date, success of egg incubation, growth, and habitat selection (Armour 1993). Thus, with such cosmopolitan effects, there are numerous mechanisms that may explain the behavior and residency patterns observed for smallmouth bass. Cooke and others (2000) proposed two major mechanisms that may explain why fish are selecting regions upstream of the tempering pumps. The first is that preference for suitable physical structure and prey availability may override the cost of living in a thermally variable and extreme environment (e.g., Bevelhimer 1996, Cooke and others 2000). The second is that smallmouth bass may be selecting temperatures that are closer to their final preferendum (preferred water temperature of smallmouth bass is 28°C in the laboratory and 21.3°C in the field; Armour 1993), rather than the cooler conditions in the lake (Cooke and others 2000). Smallmouth bass have been observed to gradually select warmer water temperatures with more prolonged exposure, particularly in the winter (Barans and Tubb 1973).

Our data suggest that fish distributions likely reflect a combination of these two explanations. Clearly, the area in and around the tempering pumps where fish are concentrated provides ample physical structure and velocity refugia for fish (Cooke and others 2000). In addition, many prey species are killed, injured, or disoriented as they pass through the condenser cooling and tempering pumps (Kelso and Milburn 1979, Foster and Wheaton 1981), providing an abundant and easily consumed prey source, particularly during the winter. Low water temperatures in the lake during winter should result in reduced swimming capability (Fry 1971) and thus increased vulnerability of small fish to impingement. Furthermore, elevated temperatures in the canal may allow smallmouth bass to avoid going into a state of torpor or generalized inactivity at lower temperatures (Fry 1971) and provide opportunity for yearlong growth if provided with adequate food (Coble 1967). Although these fish may have an advantage during spawning because of their earlier thermal preparation and theoretically higher energy reserves, our results indicated that of the large number of smallmouth bass that reproduce in the effluent canal (71 nests in 1999; Cooke and others 2003), none of the nesting male fish in the canal were those that we had monitored with telemetry and thus overwintered in the canal. Because most of the fish we radiotagged were small relative to those that reproduce in the canal (Cooke and others 2003), perhaps bass that reside in the canal during winter secure some longer term fitness benefit through higher growth rates and thus reach maturity at younger ages. However, an alternative explanation is that fish residing in thermal effluents for protracted periods experience negative effects on gametogenesis as documented in some species (e.g., Luksiene and others 2000). At present, we have no empirical evidence to support either supposition, but a longer-term telemetry study could test those hypotheses.

Unlike studies in the winter of 1997/1998 (Cooke and others 2000) where fish never left the canal, and in fact never ventured further downstream than 375 m from the head of canal, during the 1998/1999 study, numerous radiotagged fish left the discharge canal. Although more fish left the canal in 1999, the majority of time was spent in an area that was unaffected by the tempering pumps, also similar to 1998. The expanded antenna array in 1999 allowed us to quantify the amount of time spent in the region of the inoperational tempering pumps, identified as possible fish aggregation sites in the 1998 study. In fact, fish spent an exceptionally high amount of time in this region, indicating active selection of that site and avoidance of others.

Other studies investigating the effects of thermal effluents on fish during the winter have used methods such as netting, angler surveys, scuba diving, manual telemetry tracking, acoustic surveys, and electrofishing (e.g., Minns and others 1978, Ross and Winter 1981, Shuter and others 1985). Although each of these techniques can provide important information, only telemetry studies using fixed arrays provide the opportunity to monitor long-term movements and residency of individual fish. MacLean and others (1982) also conducted a study to examine the response of smallmouth bass movement patterns to the NTGS discharge. The authors report that there was no long-term residency in the plume; however, sample sizes were small and fish were tracked primarily in the summer months and by manual tracking rather than a fixed telemetry array. Similarly, Wrenn (1976) assessed the behavior of a single smallmouth bass near a thermal effluent plume with telemetry. The fish remained in the river upstream of the discharge for 34 days before entering the heated effluent, which it traversed within 24 hours, before returning to the lake from which it was initially captured.

The departure of fish during the chlorination event is not unexpected, especially when coupled with high water temperatures. Chlorine effects are typically magnified at warm temperatures and have the potential to result in a series of sublethal disturbances and even death (Cooke and Schreer 2001). Water temperatures upstream of the pump were approaching the upper tolerance limits for smallmouth bass (Armour 1993). At these temperatures, fish tend to be hypersensitive to other stressors, particularly those that affect the already taxed cardiorespiratory system (Schreer and others 2001, Schreer and Cooke 2002). It is not possible to speculate on the fate of the fish that left the canal in response to the chlorination pulse. However, none of the fish that were tracked returned during the monitoring period. This opportunistic set of observations highlights the potential of fixed telemetry arrays for assessing the response of fish to different biofouling treatments in order to identify concentrations and conditions that minimize negative effects.

Fixed Telemetry Arrays and Environmental Auditing

Fixed telemetry arrays provide several benefits over the sequential location of individuals using mobile tracking, or focused tracking of individual fish for periods ranging from several hours to ~24 hours. Continuous telemetry arrays permit the monitoring of fish movement rates in real time rather than determining movement from the sequential locations identified by manual tracking. Fish movements are rarely linear; thus, conventional tracking generally underestimates movement rates and the costs of these behaviors. Fixed telemetry arrays such as the one deployed in this study are most effective if deployed as a series of checkpoints in narrow, defined regions. If interested in movements in more lentic environments, such as where the effluent plume extends into an adjacent lake, the fixed telemetry data can be supplemented with manual tracking. It is also possible to deploy a fixed ultrasonic telemetry array that can position fish in three dimensions. However, these systems are most effective when there is a line of sight among moored hydrophones. The expenses associated with the fixed ultrasonic systems are generally greater, and there can be problems associated with entrained air or high water velocities in effluents (Winter 1996). However, in more open plume environments, researchers should give serious consideration to the use of an ultrasonic system (e.g., Voegeli 1988, O'Dor and others 1998). Radio telemetry also is not without limitation. Deep water or highly conductive physiochemical properties attenuate radio signals (Winter 1996). In addition, ambient electronic noise common to large industrial sites can also collide with valid radio signals, resulting in interference with logging legitimate signals. To circumvent problems with noise, it is possible to use underwater antennas or reduce gain on aerial antennas. We have used underwater antennas for several applications (e.g., Cooke and McKinley 1999, Cooke and others 2001) and believe that they are much less likely to receive interference from noise; however, the zone of reception is significantly smaller when using underwater antennas.

In our study, telemetry provided direct information on patterns of residency, indicating when fish were in the effluent and when they were in the lake. Although we did not observe any mortality in our study, transmitters stationary for long periods may indicate mortality and can be used for the development of mortality projections and estimates for different perturbations. When correlated with detailed environmental conditions, habitat variables, and operating conditions, it is possible to assess the effects of effluents during "normal" operating conditions. Also, it is possible to conduct interventions to simulate different operating conditions including abatement strategies, proposed regulatory changes, or other experimental management strategies and to monitor how fish respond to those changes. The *in situ* approach provides managers with site-specific information that is directly relevant to the operation and management of utilities that generate thermal effluents. Continuous telemetry arrays also can serve as a nonbiased source of record that can be shared among regulators and utilities with little opportunity for manipulation of data. Conventional tracking may be somewhat subjective and based largely on field notes, as opposed to a continuous stream of time-stamped data.

Although we have focused our discussions on how fish respond to thermal effluents, it is also possible to use telemetry to examine how fish respond to other effluents associated with treatment of sewage, pulp mill effluents, or altered flow regimens downstream of hydrogenerating stations (e.g., Thorstad and others 2003). Fixed telemetry systems provide unprecedented opportunity to monitor fish responses to different industrial discharges that have to potential to alter fish behavior and survival. Instead of relying on laboratory based LC 50, or laboratory-derived dose–response curves, it is possible to examine survival *in situ,* as well as documenting a suite of ecologically relevant sub-lethal effects (e.g., behavior, movement, distribution, activity). Assessments of movement and behavior could also be supplemented with physiological telemetry devices (e.g., Lucas and others 1993). Cooke and Schreer (2003) presented results for a study of common carp in a thermal effluent and summarized the capabilities and utility of physiological telemetry for environmental monitoring. Devices such as heart rate transmitters, opercular transmitters, and locomotory activity transmitters all can provide more detailed information on activity and metabolic rate, enabling a bioenergetic analysis of environmental pollutants (Beyers and others 1999, Cooke and Schreer 2003). Many physiological telemetry devices can now be directly integrated with fixed telemetry arrays. A subset of animals tagged with physiological telemetry devices could provide even more detailed information at finer temporal and spatial scales than is possible from fixed telemetry alone (Cooke and others 2001, Cooke and Schreer 2003). Data from telemetry arrays could also be coupled with real-time visual assessments using underwater videography (Cooke and Schreer 2002) or hydroacoustics (Minns and others 1978). It would also be valuable to ensure that detailed information on habitats and environmental conditions are available that complement the high-resolution data on fish locations. Temperature and depth-sensing transmitters may be an appropriate approach if it is not possible to monitor the environmental conditions throughout the desired study site continuously.

Although we have advocated an approach that focuses on using telemetry as a tool for experimental analysis or assessment, it is also possible to deploy this type of technology as part of a long-term biomonitoring and operations infrastructure. Adaptive management decisions associated with facility operations could be made in real time to respond to observed differences in fish behavior. Although this type of deployment would require development of appropriate monitoring software, it could prove a useful biomonitoring technique for ensuring that a specific operating strategy is not resulting in disturbance to a larger suite of untagged organisms. Baseline studies would be required to assess responses of different organisms to different levels and combinations of stressors. Monitoring of a suite of species with differing sensitivities may prove particularly useful for identifying the magnitude of a perturbation and its potential for larger effects on populations, communities, and ultimately ecosystems.

Conclusions

In this paper, we presented a case study on the use of a fixed telemetry array to assess the response of individual fish to conditions in a thermal effluent canal on Lake Erie. Collectively, our results suggest that during the winter of 1999, water temperatures in the region upstream from the tempering pumps, or associated thermal variation did not result in mortality or stimulate any instantaneous mass departures. Instead, smallmouth bass residency in the canal declined steadily, particularly in April. Fish that are acclimated to high and variable temperatures may be particularly susceptible to stress associated with other perturbations and may require large amounts of food to offset the costs of living in such a dynamic environment. Thermal effluents should be considered as fish habitat and managed accordingly to minimize mortality and sublethal effects on resident and transient fish, not just those in the adjacent receiving waters. At present, the prevailing paradigm is that fish habitat begins where the effluent reaches a receiving body, not in a canal or channel through which the effluent flows. This study, combined with the other research from our group, suggests that many fish species reside in the Nanticoke thermal discharge canal (Cooke and Schreer 2002) and some even reproduce within the canal (Cooke and others 2003). Thus, the efforts to manage and conserve fisheries including environmental regulations should also consider the entire area of generating station complexes that are accessible to fish from the receiving waters (e.g., upstream of tempering pumps). This approach is consistent with the need to recognize and manage industrial ecosystems (Coleman 1996).

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