ENVIRONMENTAL MONITORING USING PHYSIOLOGICAL TELEMETRY – A CASE STUDY EXAMINING COMMON CARP RESPONSES TO THERMAL POLLUTION IN A COAL-FIRED GENERATING STATION EFFLUENT

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Abstract. During the winters of 1998 and 1999, the response of common carp (*Cyprinus carpio*) to fluctuating thermal conditions was studied in the Nanticoke Thermal Generating Station discharge canal on Lake Erie. Locomotory activity of fish in the canal was monitored using electromyogram telemetry of the axial musculature. Carp activity was variable but, in general, they were more active during times of rising and falling temperatures, and were least active during stable periods. The magnitude of water temperature fluctuation was not correlated with activity. Locomotory activity of fish was not generally correlated with absolute water temperature over a wide range of temperatures (∼2 to 18 °C) when examined on an hourly basis, but was moderately correlated at a finer temporal resolution (5 min). During a station shutdown, one carp stayed in the canal and experienced a substantial decrease in temperature yet exhibited no significant change in activity. The results of this study suggest that minor temperature changes (∼0.1 °C per hour) are sufficient to alter activity, probably through fine scale behavioral thermoregulation. The heightened activity resulting from slight changes in temperature may be energetically costly in environments that change as rapidly as thermal effluents. Physiological telemetry permitted us to study the *in situ* response of fish to dynamic environmental conditions with more precision than is possible using locational telemetry. We suggest that physiological telemetry can provide insights into the behavioral and physiological responses of fish to a diversity of pollutants and represents a robust environmental monitoring technique.

Keywords: activity, behavioral thermoregulation, common carp, environmental monitoring, physiological telemetry, thermal effluent, water temperature, winter

1. Introduction

An important component of environmental monitoring is determining how different forms of pollution and other anthropogenic disturbances alter the behavior and physiology of organisms. A variety of approaches can be applied to study these potential impacts in a range of systems. Aquatic systems provide several unique challenges in that the organisms live in an environment that is hostile to humans. To circumvent these problems, aquatic researchers typically collect organisms from their natural environment and conduct laboratory studies or perform

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some form of assay in the field. Immense value can be gained if individual organisms can be monitored over extended temporal and spatial scales. Advances in technology that permit the remote collection of data on the *in situ* behaviour and physiology of fish are improving our ability to monitor environmental pollution and disturbances. However, to date, application of this technology to environmental monitoring has been limited. Here, we describe a field study in a thermal effluent canal on Lake Erie where we test the application of locomotory activity telemetry for environmental monitoring through a case study of common carp (*Cyprinus carpio*).

Studies of thermal discharges employing continuously monitored fixed telemetry systems (e.g., Ross and Siniff, 1982; Cooke and McKinley, 1999; Cooke *et al*., 2000a; McKinley *et al*., 2000) have identified that some fish species spend more time in thermally altered areas than had previously been observed by studies employing manual tracking (e.g., Kelso, 1976; Ross and Winter, 1981; MacLean *et al*., 1982) or mark/recapture techniques (e.g., Romberg *et al*., 1974; Tranquilli *et al*., 1981). Furthermore, some fish residing in thermal discharge canals have been observed to spend significant amounts of time in generally restricted areas (Cooke *et al*., 2000a; Cooke and Schreer, 2002). On the assumption that the fish are located somewhere between adjacent antenna reception cells, or are continually located manually within a restricted area, analysis of conventional telemetry data would suggest that the fish are relatively inactive. However, fish have been shown to expend significant portions of their daily activity and energy budgets undertaking numerous small movements that would not be detectable using conventional monitoring techniques (Demers *et al*., 1996; Cooke *et al*., 2001). Studies examining activity at a finer resolution may detect differences in locomotory activity in response to the dynamic conditions in thermal effluents as fish attempt to behaviorally thermoregulate (Neill, 1979).

There is little question that dynamic situations, such as rapidly changing temperatures, are difficult to investigate (Crawshaw, 1979), but the advent of physiological telemetry has provided researchers with the opportunity to remotely obtain information on the response of fish to different environmental stressors (Lucas *et al*., 1993). One of the most widely used forms of physiological telemetry is a commercially available EMG*i* transmitter (Lotek Engineering Inc., Newmarket, ON) capable of transmitting information from a pair of electrodes placed in the axial red musculature (See Kaseloo *et al*., 1992; Beddow and McKinley, 1999). This information is useful for monitoring overall fish activity at a fine resolution, and can also be calibrated in a respirometer to provide estimates of oxygen consumption (Weatherley *et al*., 1982). Estimating energetic expenditure permits the identification of potentially costly behaviors resulting from environmental disturbances. Locomotory dynamics have been identified as robust indicators of the general health of fish (Schreck, 1990) and can also serve as indicators of stress (Cooke *et al*., 2000b).

The purpose of this study was to examine the behavioral response of fish to dynamic environmental and operating conditions within the Nanticoke Thermal Generating Station discharge canal. Our previous research suggested that the majority of fish activity in the discharge canal was localized and not correlated to environmental conditions using other available methods. We used EMG*i* transmitters to monitor and further elucidate the detailed activity patterns of common carp (*Cyprinus carpio*) in the discharge canal at finer resolutions than are capable with fixed telemetry systems, mobile tracking, or mark/recapture studies. We also provide a critical analysis of the utility of locomotory activity transmitters for assessing the response of fish to pollutants and environmental variation and for environmental monitoring.

2. Study Sites and Methods

2.1. Study site and plant operation

Nanticoke Thermal Generating Station, located at 42°48′N 80°04′W, is an 8-unit, 4000 MWe (500 MWe each) coal-fired station situated on the north shore of Lake Erie (Figure 1). 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 $m^3\ s^{-1}$, of which 88 $m^3\ s^{-1}$ is for condenser cooling and 66 $m^3\ s^{-1}$ is for the tempering of heated discharge water. The station discharges the heated effluent via a canal 550 m in length, 15.25 m wide, and 9.15 m deep. The Nanticoke Thermal Generating Station operates as a peak load station, contributing power to the grid during periods of peak demand. This typically requires 6 to 8 unit operation during the early morning, mid-day, and late afternoon periods. This 'two-shifting' mode creates fluctuating effluent temperatures in the discharge.

The inlet temperature was measured in the station forebay, while the discharge temperature shown was measured by two station recorders near the head of the outfall canal, just downstream from the tempering pump discharges. Discharge temperature was taken to be the average reading of the two recorders; however, differences >0.1 °C were rare. Both inlet and discharge water temperatures were recorded every halfhour. In 1999, we also deployed temperature probes (Hobo Model, Onset Inc.) that measured water temperature at 5 min intervals. Temperature profiles based upon the station recorder data are plotted for the study periods in 1998 and 1999 (Figure 2).

2.2. Telemetry equipment

The transmitters used (EMG*i*, Lotek Engineering Inc., Newmarket, ON) consisted of an epoxy-coated transmitter package with a pair of electrodes and a single antenna. Kaseloo *et al*. (1992) and Beddow and McKinley (1998) describe the

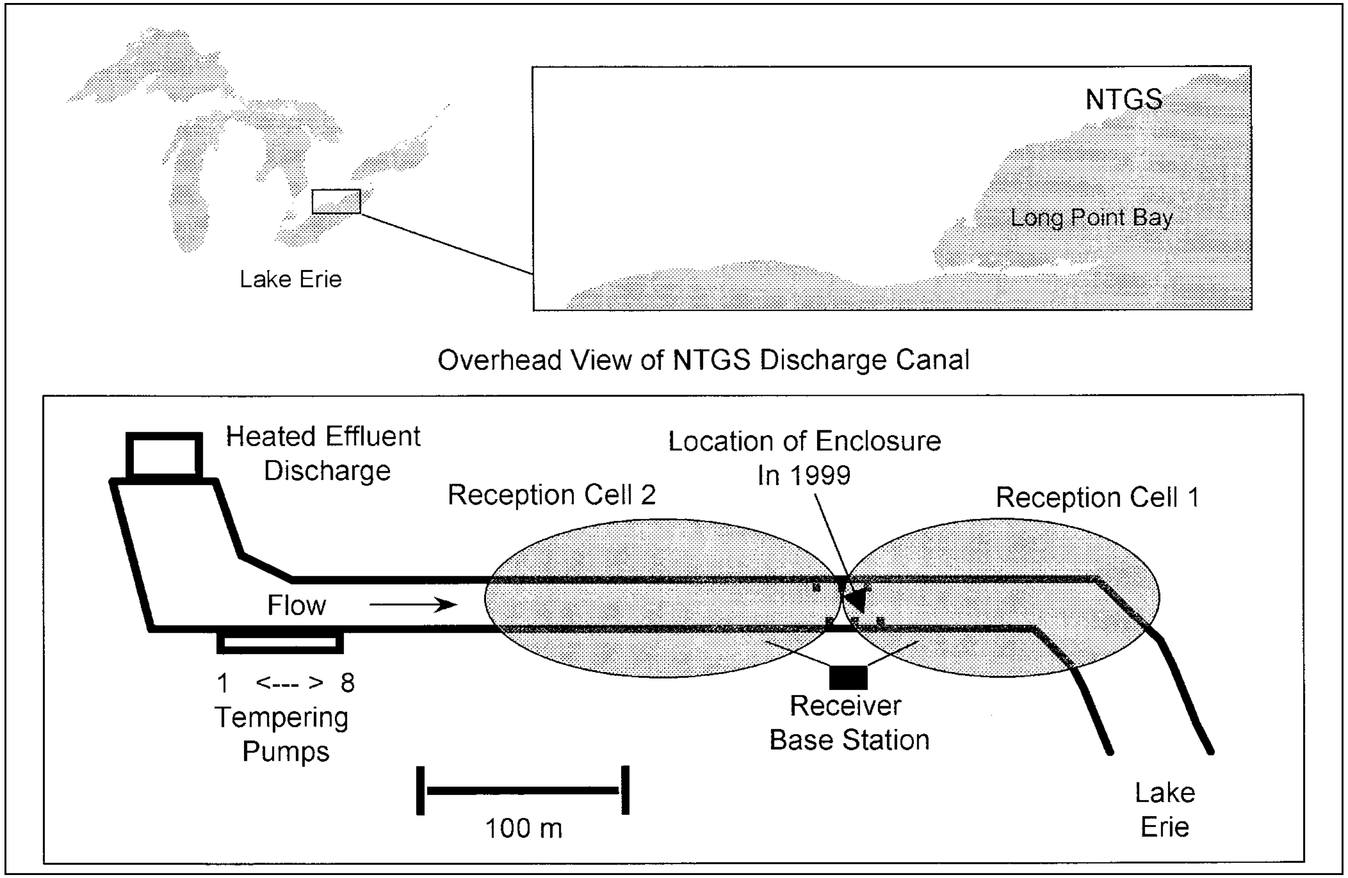

Figure 1. Map of Nanticoke Thermal Generating Station located east of Longpoint Bay, on Lake Erie. The lower inset diagram outlines the configuration of the 550 m discharge canal. Heated water exits the cooling loop and moves past 8 tempering pumps as it flows towards the Lake. A receiver base station located partway down the canal, collected EMG signals from 2 yagi antennas in 1998. One antenna pointed downstream (antenna 1) and one upstream (antenna 2). In 1999, one underwater antenna was used to monitor fish activity in a large enclosure.

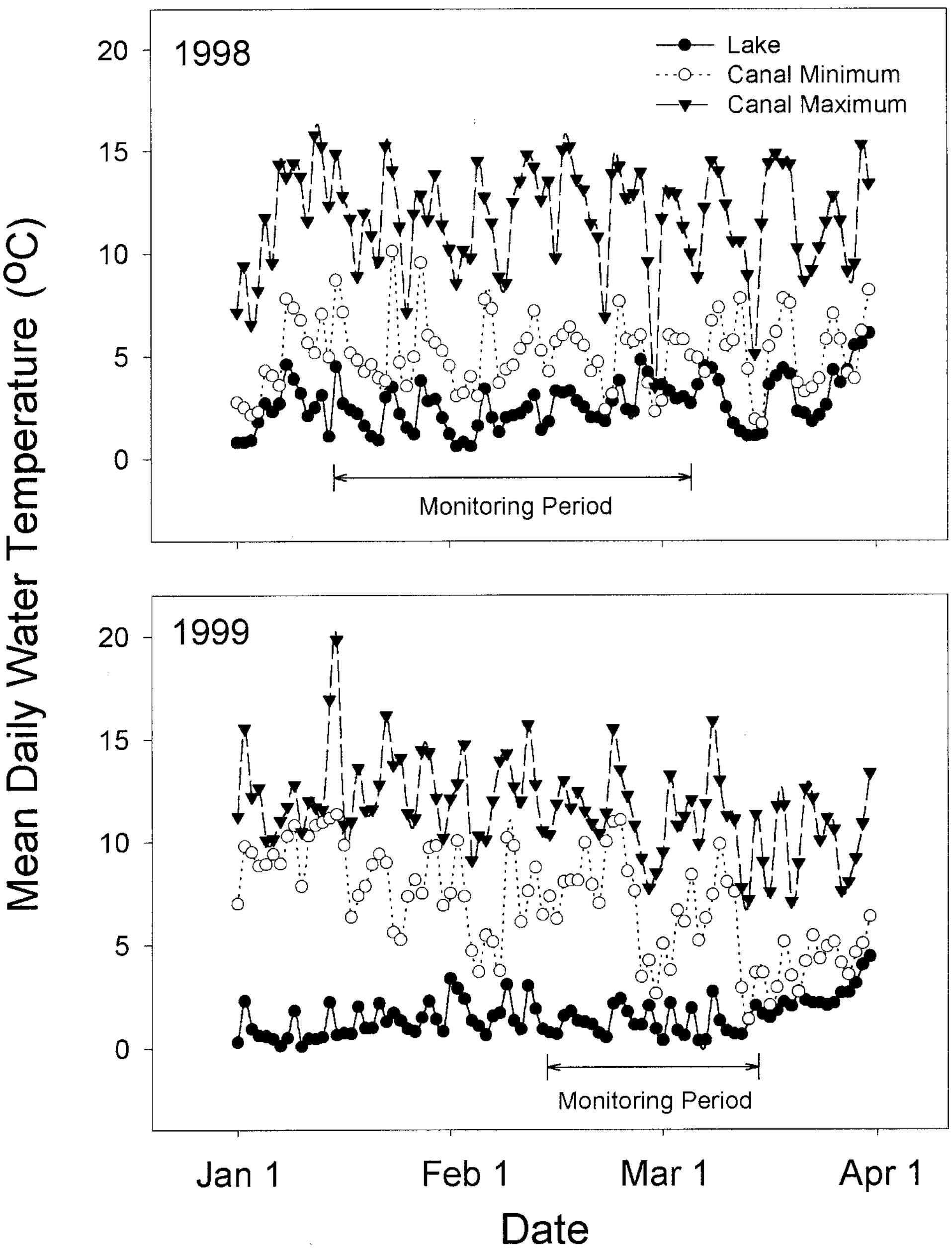

Figure 2. Thermal profile of water in the discharge canal and adjacent Lake Erie. Water temperatures are plotted for 1 January until 31 March in both 1998 and 1999. The lake temperature is based upon a daily mean calculated from half hour temperature records. The canal temperatures are based upon the daily maximum hourly temperature and the daily minimum hourly temperature. The periods during which fish were monitored in each year are indicated on the figures.

transmitters in detail. Briefly, 9 karat gold electrodes measuring 7 mm were affixed to the end of the electrode wires. The electrodes detect the electromyographic activity within the axial red muscle, which then charges a capacitor. When the capacitance has been reached, a pulse is emitted from the transmitter. This signal provides information on integrated electrical activity (EMG*i*), rather than data on individual muscle contractions. The signal recorded by the receiver is an EMG*i* pulse interval (ms), which is inversely related to muscular activity. As muscle activity increases, the muscle *EMGi's* increase, charging the capacitor more rapidly, thus decreasing the interval between pulses.

The tags used in this study measured 51 mm in length and 13 mm in diameter, and weighed 18.0 g in air. In all cases, the weight of the tag was less than 2% of the weight of the fish in air. Transmitters broadcast at distinct frequencies within an operating band of 148 to 150 MHz. Signals were detected and recorded automatically using an SRX_400 radio receiver with W/20 software (Lotek Engineering Inc., Newmarket, ON). The receiver was placed in an environmental chamber with an ASP-8 antenna switcher (Lotek Engineering Inc., Newmarket, ON).

In 1998, fish were permitted to swim freely in the discharge canal so an antenna array was erected. Four element yagi antennas were placed mid-way up the canal, with one oriented upstream and the other downstream (Figure 1). The receiver was set to scan continuously. It cycled through the first antenna, collecting 10 EMG*i* signals from every fish present, until switching to the second antenna. The receiver system was operational throughout the duration of the study, except when offline for downloading to a computer when the storage banks approached capacity. Downloading took less than 3 hr, every 3 to 4 days.

In our second field season (1999), we constructed an enclosure in the discharge canal to study the responses of fish in a more controlled manner. Visual observations indicated that carp were spending much of their time in the shallow shelf areas of the discharge canal. The carp enclosure was therefore erected in the same location. Substrate was primarily gravel and broken coble on top of an underlying bedrock shelf. Two sides of the enclosure were already present in the form of cement structural walls that were used for oil boom deployment. A blocking net comprised of knotless nylon netting (22 mm diameter mesh) was erected on the outer part of the retaining walls. The bottom was sealed with large cobble and the top was held up with numerous overhead support cables. The sides were sealed by securing the netting to ABS piping and placing them in a pair of aluminum guides which were affixed to opposite sides of the cement walls. The remaining side was the sloping shoreline and bank that provided a natural barrier. The mean water depth in the enclosure was 1 m and had a mean volume of 70 m^3. These values fluctuated slightly (depth $\sim$0.25 m with resultant changes in volume) with changes in operational output in the plant and lake levels.

The enclosure setup in 1999 required a different antenna configuration. Based upon background noise and interference levels, we opted for an underwater antenna system. The end of a piece of coaxial cable running from the receiver was stripped, sealed and affixed to a brick in the middle of the enclosure. The same receiver system and housing was used in both years. Data in 1999 were collected in the same manner as 1998, although we did not switch antennas as we did in 1998, because of the single antenna that we deployed.

2.3. Surgical procedure

Common carp were angled from the discharge channel using standard spinning gear. Fish were held in a tank continuously supplied with outfall canal discharge water for 24 hr prior to surgery. Fish were anesthetized using a 65 PPM induction bath of clove oil and ethanol (Anderson *et al.*, 1997). Fish lost equilibrium after several minutes and were then measured (Total length, TL) and weighed before being placed ventral side up in foam padding on a surgery table. A maintenance dose of anaesthetic (30 PPM) in oxygenated water continuously irrigated the gills.

Surgical procedure was similar to that of Kaseloo *et al*. (1992). A 3 cm incision was made on the ventral surface, just posterior to the pelvic girdle. Electrodes were positioned 10 mm apart, in the red axial musculature below the lateral line using $16\frac{1}{2}$ g rods. Electrode placement was standardized at the anterior portion of the dorsal fin (Beddow and McKinley, 1999). Once in place, a plunger was used to secure the electrodes in the muscle, allowing the rods to be removed. The transmitter was then inserted through the incision and pushed anteriorly into the body cavity. A $16\frac{1}{2}$ g hypodermic needle was then pushed through the body cavity wall and the antenna wire was passed through to the outside. The incision was closed using four independent braided silk sutures (2/0 Ethicon) and, prior to the last suture, tetracycline was injected interperitoneally (1 mg antibiotic kg^{-1} fish). The entire procedure lasted less than 5 min and fish recovered quickly when returned to fresh oxygenated water. Fish were held in the holding tank, where they were allowed to recover for several hours prior to release at the site of capture. During this time, we recorded *EMGi* signals from each fish, during periods of immobility, to determine resting EMG*i* values for each fish.

2.4. Data handling and analysis

To eliminate electronic differences among transmitters, fish activity is reported in percent increase in activity from resting. Resting values were obtained by monitoring fish in the holding pens prior to release and recording *EMGi* activity during times of immobility (Cooke *et al.*, 2001). This provides a proportional value of activity relative to resting levels that is useful for comparisons between fish and species. After data were sorted by fish and time, hourly averages were calculated from fish when there were at least 900 signals during the one hour period for data collected in 1998. We felt that a minimum number of signals were required prior to making inferences about hourly activity. The value of 900 signals would translate into a minimum of approximately 15 min, or one quarter of the sampling period, and was deemed the minimum value for analysis. In 1999, after data were sorted by fish and time, 5 min averages were calculated. We were able to do this for three fish. A minimum of 30 data records were used for the calculation of the 5 min averages.

T-tests were used to determine whether differences existed between times when water temperature was stable or when water temperatures fluctuated by more than 1 °C per hour in 1998, or more than 0.1 °C per 5 min period in 1999. To examine trends associated with rising, and falling temperatures, we used one-way analysis of variance with Tukey post-hoc tests. We tested for differences between, stable, rising and falling periods for each fish. Correlation analysis was used to test for relationships among activity and the magnitude of the temperature fluctuations. Wilcoxon signed-rank tests were used to compare the activity levels of fish below and above mean water temperatures. In several cases, *t*-tests were also used to compare the activity of fish during a station shut down to periods of normal operation. Regression analysis (using a third order polynomial model) was used to test for relationships between activity and water temperature for the data collected in 1999. All data presented are means ±1 SE. All statistical tests were considered significant at $\alpha = 0.05$.

3. Results

3.1. 1998

Several fish left the canal or spent periods of time in areas where signals were undetectable in 1998 (Table I). For complete data analysis purposes in 1998, we used two fish that provided consistent and reliable data and were free from radio interference (Fish 108 and 438). Limited analysis was also conducted on one additional individual (Fish 149).

3.1.1. *Common Carp 108*

Fish 108 was released in the canal on 27 January at 13:00 hr. The fish stayed in the canal until 6 February at 21:00 hr (Figure 3). Fish 108 was significantly more active during water temperature fluctuations greater than 1 °C per hour, with activity levels being higher during times of falling temperatures than during times of rising temperatures and stable periods (Figure 4). Fish activity and the magnitude of increasing or decreasing temperatures were not correlated and significant differences did not exist among different magnitudes (Figure 4). There were no significant differences in activity when water temperature was above or below the mean for the study period.

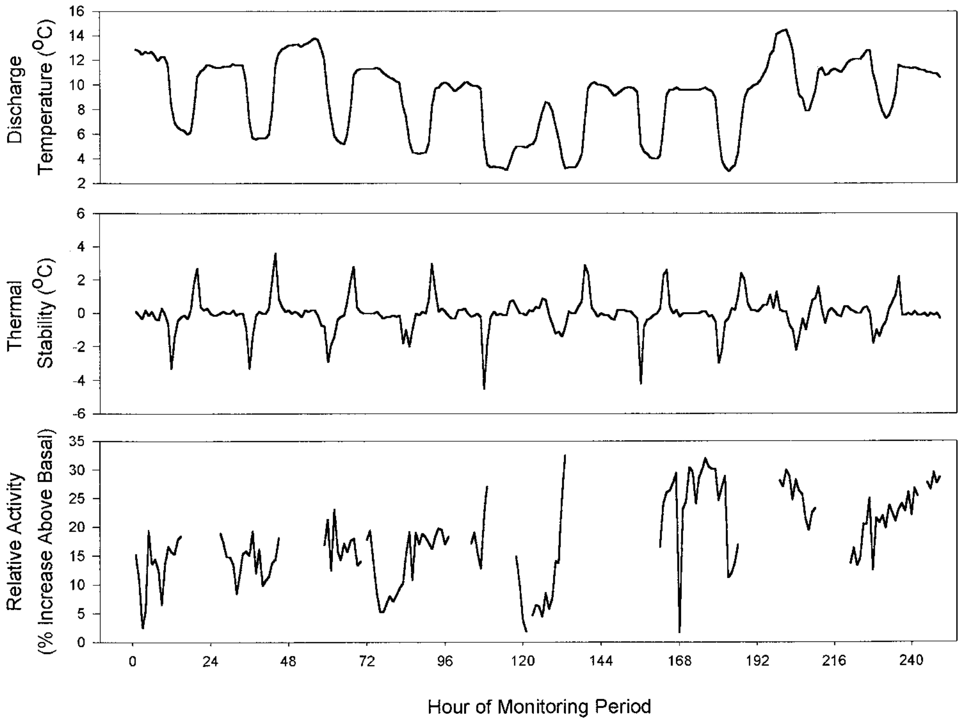

Figure 3. Common carp 108 was monitored from 27 January at 13:00 hr until 6 February at 21:00 hr. Hourly mean discharge temperature and hourly temperature change (thermal stability) are presented in the 2 upper panels. The relative increase in activity (%) is plotted on an hourly basis when there were at least 900 EMGi signals per hour in the lower panel.

3.1.2. *Common Carp 149*

Fish 149 was released in the canal on 27 January at 13:00 hr. The fish stayed in the canal until 31 January at 01:00 hr. Fish 149 was significantly more active during water temperature fluctuations greater than 1 °C per hour, although instances of this were sufficiently rare that it precluded further detailed analysis as with the other carp. There were no significant differences in activity when water temperature was above or below the mean for the study period.

3.1.3. *Common Carp 438*

Common carp 438 was released on 24 February at 13:00 hr. The fish was resident in the discharge canal until 5 March when it left suddenly at 01:00 hr and did not return during the remainder of the monitoring period (Figure 5). While resident in the canal, the fish spent the entire time in close proximity to the receiver stations. This fish was observed aggregating with untagged conspecifics on the shallow shelf area of the canal.

Activity of fish 438 was influenced by water temperature fluctuations. Fish 438 was significantly more active during water temperature fluctuations greater than

TABLE I
Meristics of common carp implanted with EMG transmitters

Fish #	Weight (g)	Total length (mm)	Date tagged	Last date recorded	Comments
169	3180	611	15 January 1998	4 March 1998	Sporadic signals
108	2650	590	27 January 1998	6 February 1998	Good signals
149	3100	581	27 January 1998	31 January 1998	Sporadic signals
046	2810	545	5 February 1998	No records	Major interference
724	2430	539	16 February 1998	No records	Left immediately
438	8900	731	24 February 1998	5 March 1998	Good signals
175	5180	685	18 February 1999	16 March 1999	Tag malfunction
331	1360	445	18 February 1999	16 March 1999	Good signals
555	1100	409	18 February 1999	15 March 1999	Good signals
575	2360	601	18 February 1999	10 March 1999	Tag malfunction
620	1200	430	18 February 1999	10 March 1999	Good signals

1 °C per hour, with activity being highest during times of rising temperatures (Figure 4). Fish were least active during stable periods. Water temperature increases greater than 2 °C an hour resulted in higher and significantly different activity levels than during stable periods, increases of less than 2 °C, or any decreases in water temperature (Figure 4). Despite these specific differences, overall, activity and the magnitude of the water temperature fluctuation were not correlated. Furthermore, there were no significant differences in activity when water temperature was above or below the mean for the study period.

During the time fish 438 was monitored, a station shutdown occurred and the canal normalized to low lake temperatures (∼2 °C). On 28 February, station net production capacity dropped from a four day previous average of 52.5 to 17% (Figure 5). Station capacity further dropped to near 0% on 1 March. Normal operations resumed on 2 March. During the shutdown, water temperatures remained low (∼2 °C) and did not exhibit the peaking nature characteristic of the study period. Water temperatures were significantly lower during the shutdown than the mean for the study period. Fish 438 remained in the canal in the same vicinity as prior to and after the shutdown. The activity of fish 438 was not significantly different during the station shutdown compared to the remainder of the study period.

3.2. 1999

In 1999, data were recorded by the receiver on a more continuous basis because fish were restricted to a large enclosure. This facilitated analysis of temperature

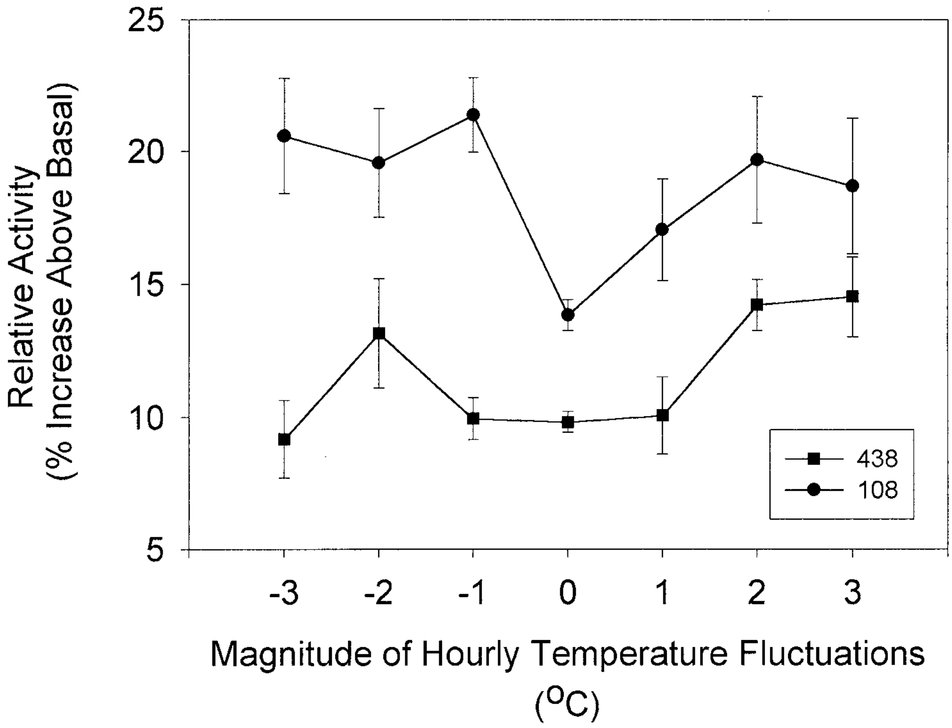

Figure 4. Relative activity during different magnitudes of directional temperature changes for common carp 108 and 438. Stable periods correspond to water temperature fluctuations of less than 1 °C. Temperature fluctuations are based upon 1 hr periods. All values are means ± SE.

and activity data at a finer resolution than in 1998 (5 min vs. 1 hr). The enclosure was typical of the habitats frequented by free-swimming carp and had appropriate habitat (i.e., cover, foraging areas, low velocities). Two of the fish we implanted with transmitters in 1999 did not provide useable data due to transmitter malfunction. The data that we present were collected between 18 February and 16 March 1999 for three fish (331, 555, and 620).

3.2.1. *Common Carp 331*

Fish 331 was released in the canal on 19 February at 12:00 hr and was monitored until 16 March. Fish 331 was significantly more active during water temperature fluctuations greater than 0.1 °C per hour than during stable periods (Figure 6). The fish was significantly more active during times of both falling and rising temperatures than during stable periods. However, the magnitude of the temperature fluctuation was not correlated with activity. Activity levels of fish were similar when water temperature was above and below the mean for the study period. There was however, a significant positive correlation between water temperature and

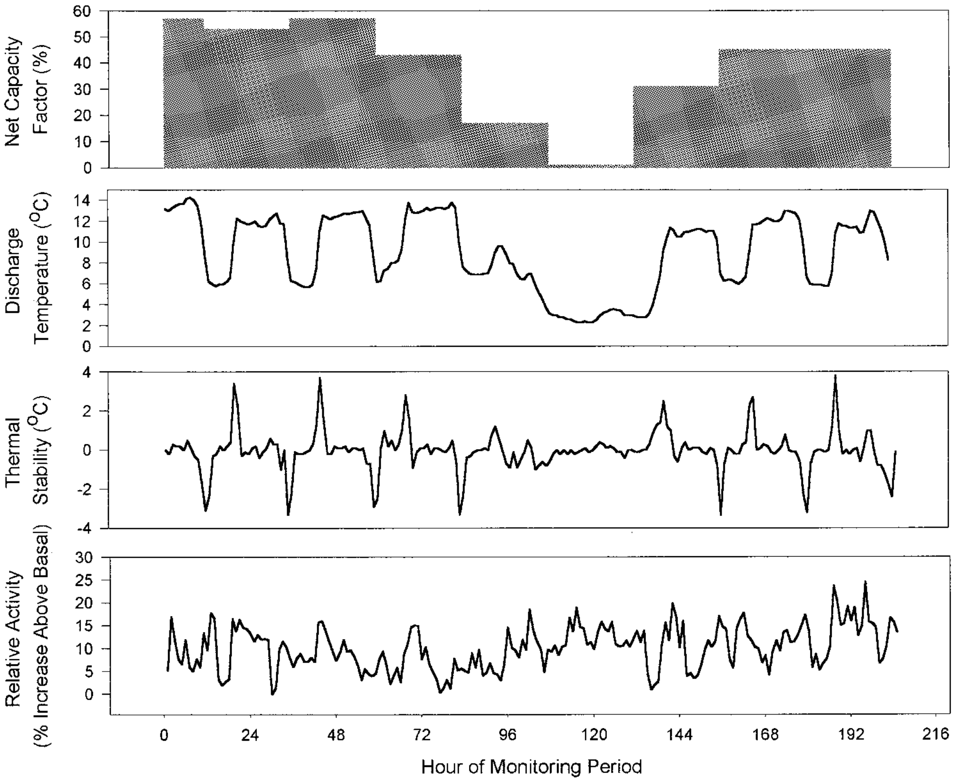

Figure 5. Common carp 438 was monitored from 24 February at 13:00 hr until 5 March when it left suddenly at 01:00 hr. The top two panels of the figure illustrate the net capacity factor (%) and hourly mean discharge temperature. A station shutdown occurred during this monitoring period that is evident in these panels. Hourly temperature change (thermal stability) was also graphed. The relative increase in activity (%) is plotted on an hourly basis when there were at least 900 EMGi signals per hour.

activity (Figure 7). It must be noted however that there was substantial variation in the data, the slope was minimal, and the r^2 value was low.

3.2.2. *Common Carp 555*

Fish 555 was released in the canal on 19 February at 12:00 hr and was monitored until 15 March. Fish 555 was significantly more active during water temperature fluctuations greater than 0.1 °C per hour than during stable periods (Figure 6). Fish were more active during times of both falling and rising temperatures than during stable periods although the magnitude of the change was not correlated with activity. There were no significant differences in activity when water temperature was above or below the mean for the study period. As with fish 331, there was also a significant positive correlation between water temperature and activity (Figure 7).

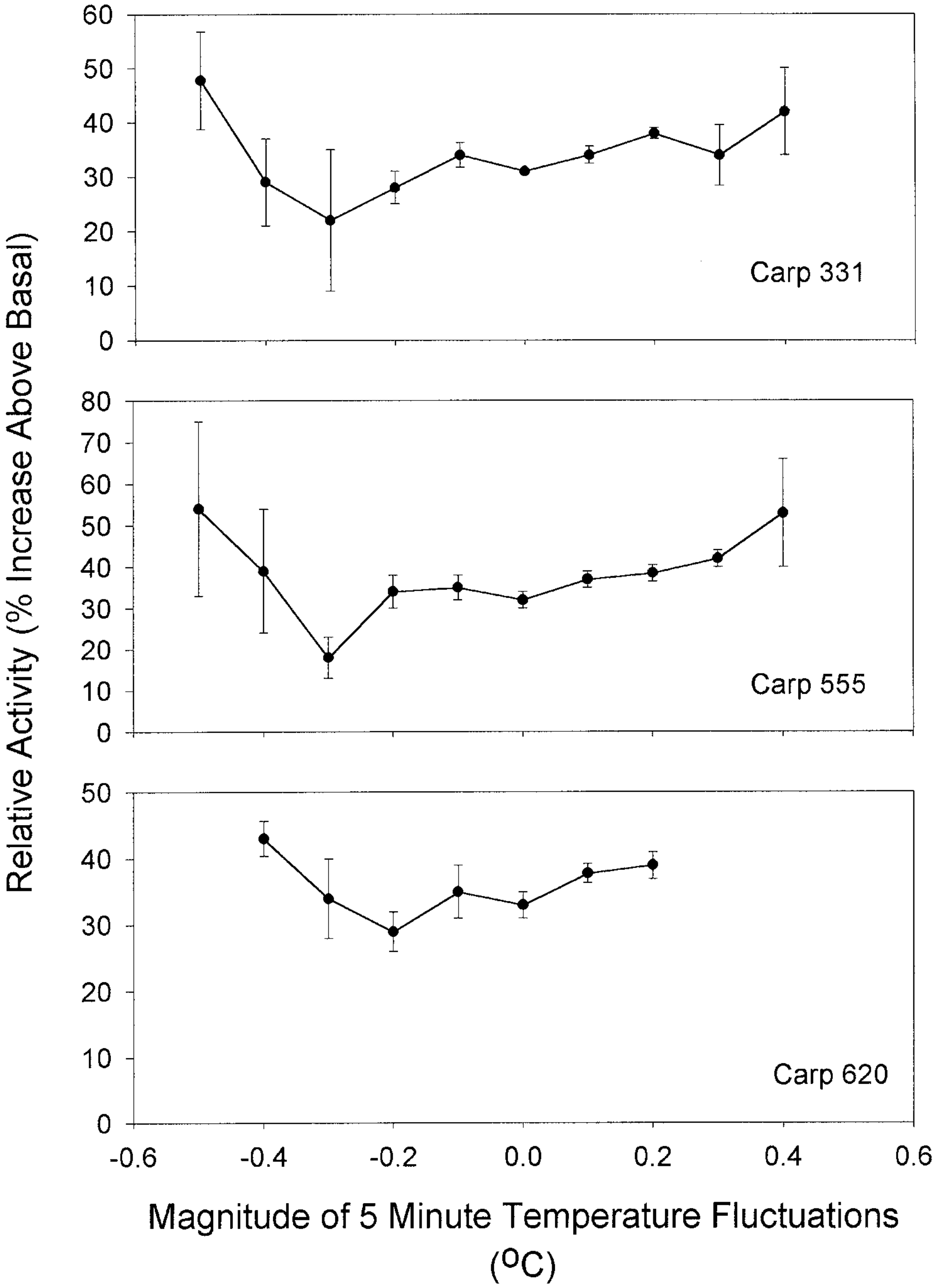

Figure 6. Relative activity during different magnitudes of directional temperature changes for common carp 331, 555, and 620. Stable periods correspond to water temperature fluctuations of 0 °C. Temperature fluctuations are based upon 5 min periods. All values are means ± SE.

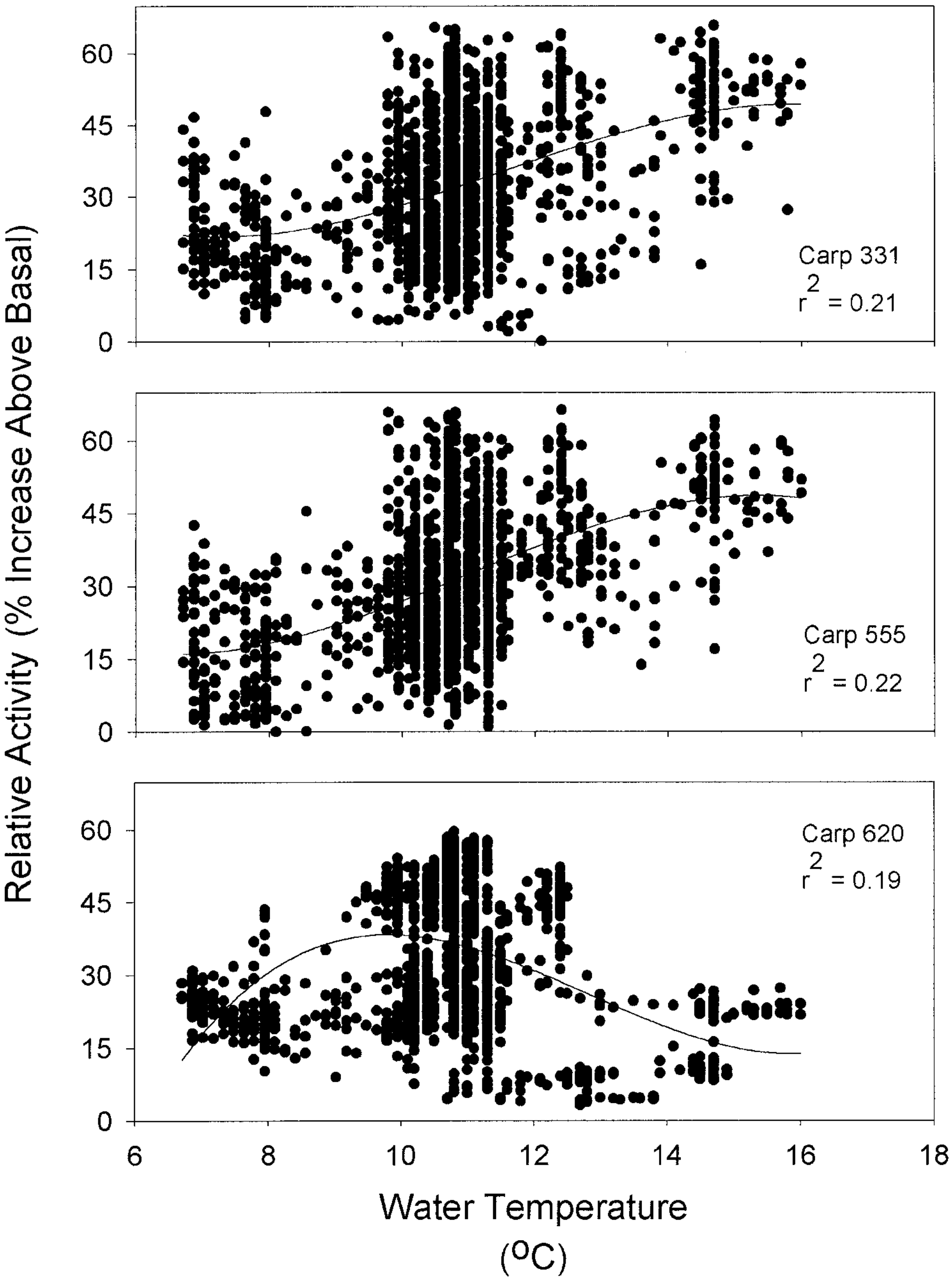

Figure 7. Relative activity trends associated with water temperature for common carp 331, 555, and 620. Significant third order polynomial relationships were plotted for all fish. Water temperature and activity are based upon 5 min average periods.

3.2.3. *Common Carp 620*

Fish 620 was released in the canal on 19 February at 12:00 hr and was monitored until 10 March. Fish 620 was significantly more active during water temperature fluctuations greater than 0.1 °C per hour than during stable periods with activity being highest during times of both falling and rising temperatures (Figure 6). The magnitude of the difference, however, did not result in significant differences in activity. Activity levels were similar when water temperature was above or below the mean for the study period. A significant third order polynomial model was parabolic in shape, with activity levels highest during intermediate water temperatures (Figure 7).

4. Discussion

Temperature is thought to exert control over fish more than any other abiotic factor and plays roles in distributional, physiological and behavioral ecology (Beitinger and Fitzpatrick, 1979). Thermal discharges associated with power generating stations create variable thermal conditions that may be harmful to fish (Coutant, 1970, 1977). This necessitates research on thermal pollution abatement, environmental impact assessment, and fisheries monitoring. In addition to the applied conservation and management concerns, thermal effluents actually provide unique opportunities to develop and test hypotheses regarding fisheries-environment interactions (e.g., Neill, 1979; Shuter *et al*., 1985; Schreer and Cooke, in press). Indeed, studies have repeatedly documented the attraction of fish and forage to heated discharges during cold months (Moore *et al*., 1973; Benda and Proffitt, 1974). Although other environmental parameters may change in concert with water temperature (e.g., dissolved oxygen, flow), at the NTGS thermal effluent water temperature has such a strong influence on temperature that it masks responses to other conditions. Thus, although our focus is on thermal effects, one must consider that our results reflect responses to a larger suite of changes that co-vary with water temperature.

Research in the NTGS thermal effluent has recently focussed on understanding how fish respond to the variable thermal conditions. A parallel study of common carp movement in the NTGS discharge canal using radio telemetry indicated that activity was not correlated to daily water temperature variables. Only common carp residency had significant positive correlations with mean and minimum daily discharge temperature. One possible explanation for the apparent lack of response to thermal change or conditions is attributable to the study method. Cooke and McKinley (1999) report that, while resident in the canal, fish were relatively immobile. Activity was measured on the basis of movements past reception cells that served as checkpoints. It is possible that fish are reacting to environmental change at levels that are undetectable using conventional monitoring techniques.

Using locomotory activity telemetry we were able to monitor the response of fish to thermal variation at finer resolutions. In 1998, using an hourly scale we documented little response to the variable thermal regime. Some fish exhibited heightened activity during periods of water temperature change that exceeded 2 °C per hour. In 1999, using 5 min resolution, our data suggest that fish were responding to temperature change that was as small as 0.1 °C per 5 min.

The effects of temperature on the activity of fishes are well documented (Fry, 1947) with it generally being accepted that as water temperature changes, the spontaneous activity level of fish increases (Peterson and Anderson, 1969; Olla and Studholme, 1971; Stevens and Fry, 1972) and therefore influences activity through metabolism (Crawshaw, 1979). When fish are given sufficient time to acclimate, decreasing temperature will decrease activity (Fry, 1971). Under this tenet, we may be able to better understand why we observed weak trends in terms of the relationship between temperature and activity in our study (especially in 1998). The time scale of water temperature change in this study (hours and minutes) may have been insufficient for fish to acclimate and realize marked decreases in activity when at the lower temperatures. Laboratory studies of numerous fish species and our field measurements of common carp would support this hypothesis. For example, Peterson and Anderson (1969) found that Atlantic salmon (*Salmo salar*) respond to temperature change with a corresponding increase in activity. However, the increase in activity was relatively short, with activity returning to lower levels as temperature stabilized. Fry (1971) also suggests that, although difficult to demonstrate, fish are randomly active during the initial period of temperature change. Our data further demonstrates such an increase in activity during periods of water temperature change.

The effect of sudden changes in temperature on metabolic rate necessitates major, acute cardiovascular and respiratory adjustments (Crawshaw, 1977), as has been noted for common carp (Meuwis and Heuts, 1957; Moffitt and Crawshaw, 1983). The initial increases in cardiovascular output observed by Meuwis and Heuts (1957) and the increase in metabolic rate, heart rate and ventilation frequency observed by Moffitt and Crawshaw (1983) following increasing water temperatures may be attributable to increases in overall activity and level of arousal (Fry, 1947; Fry and Hochachka, 1970) in addition to other physiological mechanisms (Johnston and Dunn, 1987). Our results would further substantiate this hypothesis of increasing activity levels during times of temperature change. Although overall activity quickly normalizes, the initial cardiac response to temperature increases and decreases may be prolonged (Reynolds, 1977).

Common carp in our study were significantly more active during times of increasing and decreasing water temperatures in contrast to a study of common carp by Siegmund and Vogel (1977). They indicated that a decrease of water temperature from 20 to 15 °C resulted in a 50% decrease in the locomotory activity of common carp whereas an increase from 15 to 20 °C resulted in a doubling of activity. These changes in activity were not accompanied by initial hyperactivity in contrast to our findings and those of other researchers. Also in contrast to our results, and some of the laboratory results above, are the results of a recent study employing EMG*i* telemetry. Briggs and Post (1997) reported that, following a sudden temperature drop from 12 to 10 °C, rainbow trout (*Oncorhynchus mykiss*) metabolic costs initially decreased then returned to previous levels within two days. The authors suggest the discrepancy between their results and the general conclusions of Fry (1971) and the experiments of Peterson and Anderson (1969) was attributable to the rate of temperature change. Temperature change in their field experiment was on the magnitude of days, compared to hours in our study (and in most laboratory studies).

Common carp are not an exception with previous research suggesting that both heart rate and locomotory activity of carp are mutually correlated with water temperature (r^2's for heart rate = 0.92; r^2,s for activity = 0.72) (Siegmund and Vogel, 1977). In our study, we found that using a 5-min temporal scale common carp activity was correlated to locomotory activity with variable r^2 values. Unlike Siegmund and Vogel (1977) our responses were not linear. Third order polynomials resulted in a superior fit. The activity of two of the fish in our study were positively correlated with water temperature (r^2 = 0.21 and 0.22), whereas one fish (620) yielded a parabolic relationship (r^2 = 0.19). The discrepancy in this response in unclear especially considering that these three individuals were generally the same mass (∼1200 g).

A possible explanation for this disparity is that fish 620 had resided in the canal for a longer period than fish 331 or 555. If fish 331 and 555 had spent substantial time in the cold lake prior to entering the canal and being implanted with a transmitter, they would be cold acclimated. The swimming velocity (i.e., fish swimming activity) that white muscle is recruited becomes higher as acclimation temperature is reduced (Rome *et al.*, 1984, 1985; Heap and Goldspink, 1986). Because our electrodes were placed in the red oxidative musculature, a fish that had resided in the discharge canal would be warm acclimated and would thus recruit white muscle at lower locomotory activity levels in low to intermediate water temperatures (i.e., 12 to 16 °C). Thus the transmitter in fish 620 would not detect heightened activity as readily because intermediate swimming activity was being powered by white glycolytic muscles. In our study it was impossible to determine how long fish had resided in the zone of thermal influence or if they had spent substantial time above the tempering pumps prior to capture and implantation. It is clear that carp frequently leave the canal for variable durations (Cooke and McKinley, 1999).

The free-swimming common carp observed in our study in 1998 behaved differently during water temperature fluctuations. For example, fish 438 was more active during rising water temperatures whereas fish 108 was more active during falling water temperatures. A possible explanation for this discrepancy could be attributed to body size. Spigarelli *et al.* (1977) studied the influence of body weight on heating and cooling of several fish species, including common carp. They reported that fish body weight was a powerful predictor of fish body temperature change, and a better predictor in heating regressions than in cooling regressions. Although individual regressions for common carp are not provided, the scatter plots of all fish species, including carp, were presented. Visual inspection of their data illustrates that the largest common carp (7958 g) took much more time to heat than the smaller conspecifics (approximately 3000 g) (from Spigarelli *et al.*, 1977). The relationship appears less distinct during times of cooling.

The largest common carp in our study (8900 g, fish 438) experienced heightened activity during times of both rising and falling water temperatures, although the highest activity was during rising temperatures. The large body size of this fish would retard the body temperature change, providing a longer period during which the fish could attempt to behaviorally thermoregulate. Another smaller common carp (2650 g, fish 108) experienced heightened activity during falling water temperatures, and was not significantly more active during rising temperatures. Fish 108 did not experience heightened activity during rising water temperatures as the body temperature equilibrated more rapidly with the water than did the larger common carp (fish 438).

The findings that fish including common carp heat more rapidly than cool (Crawshaw, 1976; Spigarelli *et al.*, 1977), combined with body size influences, may explain these differences. The activity increase noted for the smaller carp (108) during falling water temperatures may be indicative of the increased time required for cooling compared to heating. The fish achieved equilibrium when heated sufficiently rapidly that a significant activity increase was not noted. However, the cooling took longer, resulting in heightened activity while attempting to behaviorally thermoregulate. Although the larger fish (438) also experienced slight increases in activity with decreasing water temperatures, it was much lower than during increasing water temperatures. The body size relationship may not be as useful a predictor of cooling regressions (Spigarelli *et al.*, 1977). A number of hypotheses have been generated to explain the difference in heating and cooling rates, with the most relevant to our study being that spontaneous activity is stimulated by warm exposure and inhibited by cold exposure (Spigarelli *et al.*, 1977). Although this may indeed be the case during temperature fluctuations in either direction, increases in activity over stable conditions were noted in our study. Behavioral reactions to fluctuating temperatures are probably responsible for the initial increase in activity.

In another study Claireaux *et al.* (1995) illustrated how a slow but steady increase in water temperature (6.4 to 10.7 °C over 5 d) can affect the physiology and behavior of cod (*Gadhus morhua*) swimming freely in a tower tank. They differentiate between an initial phase during which activity rose quickly with increasing temperature denoting an avoidance reaction, and a second phase, when swimming activity dropped even though water temperature kept rising. They suggest that at this stage, the fish apparently reduced unnecessary energy expenditure (physiological response) as the behavioral avoidance was unsuccessful. The ranges of behavioral responses for fish in the Nanticoke Thermal Generating Station discharge canal were limited. Fish exert behavioral control of their body temperature in thermally heterogeneous environments through spatial displacement (Neill and Magnusson, 1974; Beitinger and Fitzpatrick, 1979; Neill, 1979), suggesting that fish in the Nanticoke Thermal Generating Station discharge canal may seek thermal refugia or leave the canal. Research has suggested that fish may be able to discriminate changes in temperatures as small as 0.03 °C (Bull, 1936). Evidence also suggests that fish are able to differentiate between increasing and decreasing water temperatures (Bardach and Bjorklund, 1957). If fish in the Nanticoke Thermal Generating Station discharge canal were to discriminate between temperature with that precision, they would be in a constant state of attempting to behaviorally thermoregulate. Perhaps the variable acclimation temperatures preclude sensitivity to smaller temperature changes with fish focusing on avoiding larger undesirable and potentially lethal temperature changes. The attempts to behaviorally thermoregulate are, on their own, major determinants of overall activity patterns of ectotherms (Whittow, 1970).

The response of cod to temperature change (Claireaux *et al.*, 1995) showed limited behavioral responses and that cod succumb to physiological regulation. Common carp in the Nanticoke Thermal Generating Station discharge canal behaved similarly. Thermal stresses can sometimes be abated by appropriate selection of microclimate (Crawshaw, 1979) although such opportunities are minimal in the Nanticoke Thermal Generating Station discharge canal. The large volume of water in the canal is well-mixed and thermal patches, which may occur during changing operating conditions, are dynamic. As such, fish would be constantly attempting to behaviorally thermoregulate until the canal becomes a rather isothermal environment within minutes of stabilizing operating conditions.

Previous studies at the Nanticoke Thermal Generating Station, that employed temperature sensitive transmitters in smallmouth bass (*Micropterus dolomieu*), found that temperatures occupied by the fish were rarely different from canal temperature by more than 2 °C (McKinley *et al.*, 2000). During the summer, the bedrock shelf would warm from solar radiation and, in some cases, cooler lake water would be drawn into the distal end of the canal via an eddy. Our reception limitations while recording EMG*i* signals omitted the possibility of fish occupying thermal refugia at the canal entrance and the winter conditions eliminated excessive warming of the shelves. As such, fish could either leave the canal and enter the lake and locate cooler and more stable temperatures or swim upstream of the tempering pumps where water temperature fluctuations were more extreme than downstream. Our antenna system in 1998 was tuned to pick up fish within a sector, which eliminated those two areas and, when not logging fish signals, we knew that the fish were not in the canal, but could be in the lake or upstream of the tempering pumps.

5. Conclusions

There are many advantages of studies employing physiological measures from the same individuals under field conditions. Perhaps of primary importance to studies of thermal effects was our ability to determine at least short-term thermal history. Undoubtably, there are differences in organisms acclimated to a specific constant temperature, rather than a seasonal temperature (see Wohlschlag *et al.*, 1968). The monitoring of the same individual allowed us to reconstruct the thermal history of the radiotagged individual, although we were unable to determine the total environmental complex faced by the fish (Fry, 1971) until the time we commenced monitoring.

Studies of free ranging radio-tagged fish are limited in that only when the fish are within a radio reception cell can data be collected. Fish could leave the discharge canal at any time and enter Lake Erie during which time it would not be possible to collect signals. Furthermore, radio telemetry is not always the preferred method for monitoring fish in deep water. Ultrasonic telemetry has signal propagation advantages under these conditions. However, the background noise (entrained air) in a discharge canal would preclude the collection of a continuous stream of data, free of interference.

Despite the technological limitations and study site constraints, we were able to collect sufficient data for analysis from most fish. EMG*i* telemetry devices permitted the collection of the *in situ* response of fish to the dynamic conditions experienced by fish in a thermal discharge canal. Furthermore, it would be nearly impossible to simulate discharge conditions in a laboratory setting. Although we were unable to collect useable data from all individuals, we were able to analyze large data sets from several individuals and generate hypotheses to explain different responses to temperature fluctuations.

Physiological telemetry can be used to monitor organismal parameters including heart rate, tail beats, and electromyogram activity (See Lucas *et al.*, 1993). Each of these tools has the potential for application to a wide range of environmental monitoring scenarios. However, it is tantamount that researchers choose an appropriate parameter to measure for the pollutant of interest. If the parameter being telemetered does not respond to the pollutant of interest, intuitively it will not permit effective environmental monitoring. To date, applications of physiological telemetry to environmental monitoring have been limited. This study represents one of the first attempts to use a commercially available physiological telemetry device (i.e., electromyogram activity transmitter) to document and describe the response of fish to pollution *in situ* and in real time. The only other *in situ* study employing this type of device to monitor pollution examined a heavy metal pollutants (zinc) effect on the activity of rainbow trout (Weatherley *et al.*, 1980). More recently, activity transmitters have been used in a controlled laboratory study that documented elevation in Atlantic salmon swimming activity following exposure to acidified water with aluminium (Brodeur *et al.*, 2001). We feel that although physiological telemetry is still limited in certain situations, it is currently the only method of monitoring behavioral and physiological responses in free-swimming fish. The use of physiological telemetry for environmental monitoring will become more common as other studies document the effectiveness of this technology for understanding how fish respond to different physical (i.e., silt, thermal) and chemical (i.e., bleached kraft mill effluent, gold mine tailings) pollutants.

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