The Effect of Thermal Effluent on Overwintering Channel Catfish (*Ictalurus punctatus*) in the Lower Red River, Manitoba

by

J. David Tyson

A thesis presented to the University of Manitoba in fulfilment of the thesis requirement for the degree of Master of Science in the Department of Zoology

Winnipeg, Manitoba

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BY

J. DAVID TYSON

A Thesis/Practicum submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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The object of this research project was to determine the effects of Manitoba Hydro's Selkirk Thermal Generating Station (STGS) discharge of cooling water into Cooks Creek on the overwintering behaviour of Red River channel catfish (*Ictalurus punctatus*). In December, 1987, and January, 1988, large numbers of channel catfish were killed by cold shock in Cooks Creek when the STGS shutdown. Catfish catch per unit effort (CPUE) in Cooks Creek was found to be 7579 catfish/100 m²/24 hr. Because channel catfish are a warmwater species, catfish were assumed to enter Cooks Creek whenever the STGS operated in the winter months. From October, 1991 to June, 1993, 29 channel catfish were radio-tagged and released at the confluence of Cooks Creek and the Red River. Cooks Creek and the Red River adjacent to the creek mouth were regularly sampled using standardized gill net gangs. When the STGS was not operating the annual catfish CPUE in Cooks creek peaked at 16.51 catfish/100 m²/24 hr. The CPUE averaged 4.27 catfish/100 m²/24 hr in the creek during the warmwater (above 5°C) non-STGS operating periods. When the STGS operated in the fall of 1991, catfish CPUE peaked at 3.51 catfish/100 m²/24 hr and averaged 1.42 catfish/100 m²/24 hr. When the STGS operated during the winter of 1992-1993, no catfish were caught in Cooks Creek. However, the CPUE in the Red River adjacent to Cooks Creek during STGS operation in 1992-1993 peaked at 5.73 catfish/100 m²/24 hr and averaged 2.10 catfish/100 m²/24 hr. Through radio telemetry it was found that above 5°C, channel catfish were active and using the
shallow river areas and tributaries; below 5°C, channel catfish leave tributaries such as Cooks Creek to overwinter in the Red River and Lake Winnipeg. A temperature based model for channel catfish behaviour was constructed. The model states: When the water temperature is above 5°C, catfish are active, having a high degree of spontaneous activity; when the water temperature falls below 5°C, the catfish enter a facultative dormancy characterized by reduced spontaneous activity; catfish will always select water temperatures which maximize surplus power. This model can be used to predict the effect of future STGS operation on channel catfish. If the STGS begins operating after the Red River drops below 5°C, there will not be any channel catfish in Cooks Creek and channel catfish in the Lower Red River will not be susceptible to recruitment by the STGS thermal plume. If the station begins operating before the Red River temperature falls below 5°C, then channel catfish will be recruited into the Cooks Creek thermal plume until the Red River temperature drops below 5°C. The number of fish recruited into the thermal plume is dependent upon the length of time the station operates while the river is above 5°C, and the proportion of Red River flow diverted to Cooks Creek by the STGS. Channel catfish entrained by the thermal plume will remain in Cooks Creek until the STGS shuts down and the creek returns to ambient Red River water temperatures. If minimum impact or intermediate impact operating schedules are used in combination with the modified shutdown procedure, installation of a fish fence in the mouth of Cooks Creek is not necessary to prevent channel catfish kills during winter STGS operation. This research has formed a basis for the STGS operating guidelines.
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It has been said that because I was dependent on so many people to assist me in my research, that the only way I could justly acknowledge my assistants would be by listing them as thesis co-authors. These people not only made field work possible, but their enthusiasm made going out to the field many times more enjoyable. I could not have conducted field research if not for the following people: Gavin Hanke helped work out field techniques in the first summer and his masochistic tendencies made the winter field work possible; Jeff Weibe's hard work and enthusiasm turned a mountain of frozen fish into a smaller mountain of greasy data sheets; Bruce McCulloch was always willing to take time out from thesis work, rock 'n' roll, and Joanne to substitute as a field technician; Ken Stewart was always too willing to instantly drop his important administrative responsibilities and offer his boat, fishing rod, and expert services to my research project; Marlene Gifford took pictures, substituted as a technician, and helped pass the time.

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DEDICATION

I dedicate this thesis, in part, to my friends who stuck with me, supported me, and were always there when I needed them through the trials and tribulations of my life as a graduate student: Especially, Ken, Dale, Tess, and Dwain. The greater part of this dedication I would like to reserve for my parents, Buzz and Judy, whose confidence and patience allowed me this indulgence.

"This was a classic example of how the human mind, lacking real solutions, managed its miseries."

Philip K. Dick, Radio Free Albemuth
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INTRODUCTION

In recent years, the channel catfish (*Ictalurus punctatus*) has become an increasingly important sport fish in the Red River, Manitoba. Until Macdonald's (1990) study of channel catfish in the lower Red River, little information on their biology in Manitoba was available. Macdonald's (1988) study was an investigation into the causes of channel catfish kills observed in 1987 and 1988 in Cooks Creek, a tributary of the Red River (figure 1). Macdonald found that a large number of channel catfish were inhabiting a thermal plume discharged into Cooks Creek by Manitoba Hydro's Selkirk Thermal Generating Station (STGS). After eliminating toxins, Macdonald (1988) concluded that these catfish were killed by cold shock during the STGS shutdowns.

Manitoba Hydro's STGS in East Selkirk, Manitoba, is a coal-burning thermal generating facility which draws cooling water from the Red River and discharges the heated water into Cooks Creek (fig. 2). The STGS uses Cooks Creek as a cooling channel through which the water is returned to the Red River at a temperature below the station outfall temperature. The STGS is a stand-by facility, to provide power on demand. However, it is also used to provide base load during periods of drought. In the last eighteen years, the STGS has operated continuously over the winter on two occasions: once in 1977-1978; and again in 1987-1988.

Water temperature plays an important role in the timing of seasonal activity in fishes (Munro 1990). Temperature acts as a proximate ecological factor in the behavioural thermoregulation of the brown bullhead (*Ameiurus nebulosus*) (Crawshaw
Figure 1: The Lower Red River, Netley/Libau Marsh, and Lake Winnipeg study area with major features labelled.
Figure 2: The Cooks Creek study area with the major features labelled.
et al. 1982a). Because temperature functions as a guide leading to an ultimate ecological factor, bullheads following a temperature cue can become trapped in a thermal plume. When bullheads encounter a thermal gradient such as a thermal plume being discharged from a generating station, they will enter the plume and congregate at preferred temperatures (Richards and Ibara 1977). Thermal discharges into lakes have been shown to interrupt normal migration patterns in brown bullheads (Kelso 1974). In rivers, bullheads will enter thermal discharge canals during the cool seasons and remain in the thermal plume for the duration of winter (Marcy 1976; Richards and Ibara 1977). The propensity for the bullheads to enter a thermal plume is greatest in the fall and winter when the difference between the thermal plume temperature and the ambient water temperature is greatest. When fish are trapped in a thermal plume at or near the preferred temperature for the duration of the winter, the higher metabolism, the increased energy requirements for maintaining position in the faster flowing discharge canals, and reduced food availability due to over crowding can lead to a reduction in condition (Massengill 1973; Richards and Ibara 1977; Stauffer et al. 1976). This has been demonstrated in both channel catfish and brown bullheads (Massengill 1973; Stauffer et al. 1976). The stressful environment created by this combination of factors could negatively affect growth in juvenile channel catfish (Peterson and Brown-Peterson 1992). At the same time, prolonged exposure to higher temperatures can lead to premature gonad development (Richards and Ibara 1977). Reduced spring condition and premature gonadal development may interfere with spawning success (Marcy 1976). Macdonald (1988) showed that
channel catfish are attracted to and will inhabit the thermal plume in Cook's Creek in the same manner as bullheads are attracted to and inhabit thermal plumes.

Hawkinson and Grunwald (1979) and Lubinski (1984) observed dormant Mississippi River channel catfish during the winter months and found that channel catfish undergo a low temperature dormancy similar to the low temperature dormancy observed in captive brown bullheads by Crawshaw et al. (1982b). Therefore, the behavioural and physiological processes associated with temperature response observed in channel catfish are probably similar to those in brown bullheads.

Macdonald (1988) concluded his report on the fish kills with recommendations for further research into reducing the impact of the STGS on channel catfish in Cooks Creek. These conclusions were based upon the hypothesis that whenever the STGS operated, catfish would enter Cooks Creek. According to this hypothesis catfish immigration would be greatest in the winter when the differences between the STGS discharge temperature and the ambient river temperature would be at a maximum. As detailed in the previous paragraphs, there is strong theoretical evidence to support this hypothesis.

In a subsequent study, Tyson et al. (1994) did not find channel catfish in Cooks Creek during winter STGS operation. The difference in timing of STGS operation between studies may have played a role in determining whether catfish were observed in Cooks Creek. Macdonald's (1988) observations were made during an atypically long and continuous STGS operating period, where as Tyson et al. (1994) made their observations during what is considered the normal intermittent STGS
operating schedule. The difference between Macdonald's (1988) and Tyson et al.'s (1994) observations is an indication that environmental factors in addition to STGS operation are responsible for the presence of channel catfish in Cooks Creek during the winter months. These factors include the level and length of STGS operation, and environmental conditions such as flow and temperature in the Red River and Cooks Creek.

The natural flow in Cooks Creek is intermittent. During most of the year, it carries almost no water, and when the STGS is operating during these flow conditions, it can discharge more than 99% of the creek flow. The temperature and flow of water in Cooks Creek are directly dependent upon the highly variable operating schedule of the STGS. Depending on system demands, the operating period can vary seasonally, weekly, and daily. The volume of warmed water discharged into Cooks Creek is highly variable. Therefore, changes in the STGS operating schedule affect the environment in Cooks Creek and the community of fish inhabiting the creek. Stress in catfish enduring the reduced condition and premature gonad development associated with prolonged exposure to the thermal plume may be compounded by the varying creek temperatures produced by changes in the STGS operating schedule.

Manitoba Hydro were concerned about the demonstrated effect of the Cooks Creek thermal plume to attract channel catfish during STGS operation. Prior to this research project, the presence of channel catfish in Cooks Creek was unpredictable. Catfish were attracted to the thermal plume during some STGS operating periods and
not during others. This research project was commissioned to determine the relationship between operation of the STGS in East Selkirk, Manitoba and the seasonal behaviour of Red River channel catfish.
METHODS

Study Sites

The Red River

The Red River is a turbid, prairie river that flows north out of the United States and discharges into the south basin of Lake Winnipeg in southern Manitoba (fig. 1). It drains 287,500 km² of farmland. The median annual discharge of the Red River at the St. Andrews Lock and Dam (50° 05' 05"N, 96° 56' 18"W) at Lockport, Manitoba is 137 m³/s (SENES 1992). The median monthly low is 39.6 m³/s. The median monthly high is 523.5 m³/s. The lowest monthly $Q_{7-10}$ for the river flow data is 17.8 m³/s. The $Q_{7-10}$ is the lowest rate of river flow over a seven day period in the past ten years.

Cooks Creek

Cooks Creek enters the Red River from the east side, 6 km north of the Selkirk bridge (50° 10' 52"N, 96° 50' 25"W) (fig. 1). Cooks Creek is one of only three major tributaries entering the Red River between the Assiniboine River in Winnipeg and the Red River mouth. The creek drains 698 km² of farmland east of the Red River. Because the creek drains ditched farmland, summer storms send sudden random pulses of flow down the creek. There are no recorded flows for Cooks Creek during the winter months, but underground springs provide a small winter flow (SENES 1992). The lower 6.1 km of the 7.2 km of Cooks Creek between the STGS outfall and the creek mouth can be described as a back bay of the Red River. The intermittent flows during spring run off and summer rain prevent this
region from silting in.

The Selkirk Thermal Generating Station (STGS)

Station Layout

The STGS is located in the Rural Municipality of St. Clements, in the town of East Selkirk, Manitoba, between the Lower Red River and Cooks Creek (50° 08' 06"N, 96° 51' 04"W) (fig. 2). It was commissioned in October, 1960 (SENES 1992). The STGS has two 66 megawatt high pressure steam generators, giving the station a maximum steam generated output capability of 132 megawatts. The generators are driven by natural circulation boilers with water-cooled furnaces. Steam generated in the boilers and used in the turbines is circulated at a lower temperature and pressure to the condenser. Cooling water drawn from the Red River is used to condense the steam. The condensate is recycled to the boilers and the cooling water is discharged into Cooks Creek. This is termed a once-through condenser cooling system. Specially treated well water is used for boiler make up water. Through most of the year, at least one of the generating units is used as a synchronous condenser for power generated elsewhere in the Manitoba Hydro power grid. Small amounts of cooling water are drawn to cool the alternator, bearing oil and hydrogen coolers required for this operation.

The STGS draws cooling water through two water pumps located on the east bank of the Red River, 400 m upstream of the Selkirk bridge (50° 07' 08"N, 96° 51' 17"W) (fig. 2). Each pump can at a maximum draw 4.54 m³/s of water at high speed, and 2.27 m³/s at half speed (SENES 1992). However, during normal
operation, the pumps are throttled and draw less than the maximum rates. Depending upon demand, the station can draw between 2.27 and 9.08 m$^3$/s of cooling water from the Red River. The cooling water is discharged into Cooks Creek adjacent to the STGS site, 7.2 km upstream of the confluence of the creek and the Red River ($50^\circ 08' 07''N, 96^\circ 50' 42''W$) (fig. 2).

The STGS is primarily a stand-by station to fulfil the following roles: to satisfy peak loads during periods of high demand; to provide power during periods of drought when hydraulic capabilities are reduced; to provide power during instances of failure of hydraulic units or at times of transmission interruptions; and, to create opportunities at hydraulic facilities to maintain or increase reservoir storage. Drought conditions are expected to occur once every eight years. Historically, generation has been highest in the winter between October and April (SENES 1992). December and January are the peak operating months. Between 1973 and 1990 the station operated at an average of 10.5% of its total capacity, and generated less than 1% the total power generated in Manitoba. Operating procedures require that the STGS operates at least once during the calender year to provide training for the staff. A training run is scheduled during for December and January in most years. During this time, the station operates week days only, shutting down for weekends and for the two weeks of Christmas holidays.

**Thermal Inputs**

Because the STGS is a stand-by facility and does not normally provide base load, the thermal inputs to Cooks Creek and the Red River are highly variable.
Baker (1994) observed the thermal inputs of the STGS to Cooks Creek and the Red River during 1993 and 1994. These observations will be used to illustrate the effect of the STGS discharge on thermal regimes in Cooks Creek and the Red River.

During summer operation, the STGS generated 41 MW and discharged 4.54 m³/s of cooling water into Cooks Creek. The temperature of the Red River was 23°C and the temperature of the STGS outfall was 30°C. Recent rainfalls had reduced Cooks Creek to 14°C. After mixing with the cooler creek water, the thermal plume temperature dropped 2°C to 28°C. The thermal plume entered the Red River at 25°C, 2°C above the ambient river temperature. Seventy-one per cent of the heat energy added to Cooks Creek by the STGS had been dissipated between the STGS outfall and the Red River. The travel time for the thermal plume from the STGS outfall to the Red River was 20-22 hrs. In the Red River, the thermal plume was almost completely mixed with the Red River after 500 m. However there was a barely discernable thermal plume trace along the east shore, extending to 1 km downstream.

During winter operation the STGS generated 114 MW and discharged 4.54 m³/s of thermal effluent into Cooks Creek. The Red River temperature was 0°C and the temperature of the STGS outfall was 15°C. The temperature of the thermal plume at the mouth of Cooks Creek was 4°C. Seventy-three per cent of the heat energy had been dissipated between the STGS outfall and the mouth of Cooks Creek. Because the 4°C water of the thermal plume was more dense than 0°C river water, the thermal plume entering the Red River slid along the river bottom to the deep central channel. However, the much greater river flow (72 m³/s) quickly cooled and mixed the thermal
plume reducing the temperature to 1.5°C. The thermal plume was barely detectable after 370 m and most likely did not persist after 1 km.

Field Techniques

Gill Net Collections

Cooks Creek was sampled using gill nets from June, 1991, to July, 1993. Collections were made twice per week during the open-water season and during periods of STGS operation. Collections were made in the Red River once per week during STGS operation. Gill nets were set for 24 hrs, parallel to the direction of current in the creek or river channel. Each gill net gang consisted of one 22.56 m x 1.83 m x 11.4 cm mesh panel, one 22.86 m x 2.15 m x 15.2 cm mesh panel, and one 30.48 m x 1.45 m x 22.9 cm mesh panel for a total length of 76.5 m and a total area of 105.83 m². Gill net gangs were often combined for a maximum length of 151.8 m and a maximum area of 211.66 m².

Channel catfish not released with radio transmitters were removed from the gillnets and taken to the laboratory. Sacrificed catfish were measured for fork length, whole weight, eviscerated weight, gonad weight, and liver weight. A pectoral spine was taken as an ageing structure.

Radio Telemetry Equipment

A total of 29 radio transmitters were attached to individual channel catfish in order to track their movements in the Red River and Cooks Creek. The radio telemetry equipment used in this project was manufactured by Advanced Telemetry Systems, Inc., of Isanti, MN. Nineteen 3v, 13 gm, 70 day transmitters, and ten 6v,
27 gm, 150 day transmitters were attached to channel catfish. A Model RS-2000 radio receiver with a tunable loop antenna was used to track the fish.

Transmitter Attachment

Catfish were removed from the gillnets and placed in tubs of river water. Fork length and weights were taken prior to radio transmitter attachment. Catfish were not anaesthetized prior to transmitter attachment. Radio transmitters were attached to the catfish below the dorsal fin. A sterile 7.5 cm, No. 11, hollow stainless steel veterinary needle was passed from the right side of the fish to the left side. The needle was pushed through the dorsal musculature, between the dorsal fin pterygiophores immediately posterior to the dorsal spine. The anterior mounting wire was passed through the needle from the left side and the needle removed from the fish. The procedure was repeated 2.5 cm posterior to the first mounting wire for the posterior mounting wire. The free ends of the mounting wires were passed through holes in an oval plastic mounting plate on the right side of the fish. The wires were crimped and knotted so as to snug the mounting plate against the skin of the fish. The left pectoral spine was taken as an ageing structure, and the catfish were then released into the water at the point of capture.

Radio Tracking

Channel catfish were released with radio transmitters during two radio telemetry field seasons. Ten channel catfish were released with 3v radio transmitters into Cooks Creek in October and November, 1991. Relocation runs were made from boat daily until the creek froze after STGS shutdown. Relocation runs by aircraft
were made once per month until April, 1992. Nineteen catfish, nine with 3v radio transmitters and ten with 6v transmitters, were released into the Red River between October, 1992 and June, 1993. Relocation runs were made from a boat in Cook's Creek twice weekly during STGS operation. Relocation flights were made once per week from 20 December, 1992 to 7 September, 1993. The area scanned during relocation flights (fig. 1) was the Lower Red River between the St. Andrews Dam and Lake Winnipeg, the major channels of the Red River Delta in the Netley-Libau Marsh, Cooks Creek to the STGS outfall, Devils Creek to the provincial highway 59 crossing, Netley and Wavey Creeks to their highway 9 crossings, the Brokenhead River to the power line crossing in the southwest corner of the Brokenhead Indian Reserve, and Lake Winnipeg from the mouth of Salamonia Channel to Stoney Point and out to a distance of four to five kilometres. For aerial relocation runs, a loop antenna was attached to the rear step of a Piper Cherokee Warrior. Signal relocation accuracy from the aircraft was tested in the Red River by suspending a radio transmitter at a depth of ten metres in the river a the mouth of Cooks Creek prior to a relocation flight. Signal relocation accuracy was tested in Cooks Creek by attaching a radio transmitter to a gill net anchor at a depth of two metres prior to a relocation run. The location of peak transmitter signals were marked on a map.

Calculations

**Catch Per Unit Effort (CPUE)**

CPUE was calculated by converting observed time and gill net area values into a standard time and gillnet area respectively. Values are expressed as fish caught per
unit time per unit area gill net fished. In this project the standard unit of time was 24 hr. The standard gill net area was 100 m². The CPUE expressed is the fish caught per 24 hr that a 100 m² gill net was fished. A sample calculation of CPUE is presented in Appendix 1.

**Mean Absolute Activity**

The radio telemetry was used to measure the mean absolute activity in channel catfish, and their movements in the Red River and Cooks Creek. Mean absolute activity is the distance a catfish travelled per day between relocations. The 1993 radio telemetry results were divided into three periods: 1) water temperature <5°C, 1 January to 31 March; 2) water temperature >5°C, 1 April to 21 July; 3) FLOOD, 22 July to 7 September. Initial relocations of individual channel catfish after radiotagging and relocations made at intervals more than two relocation flights apart were not included in calculations. The mean absolute activity, variance, and 95% confidence intervals were calculated for each observation period (Huntsberger and Billingsley 1987). The assumption of equal variance between observation periods was tested using the F-ratio (Huntsberger and Billingsley 1987). Degrees of freedom and t-values for each comparison were calculated using the Welch test (Huntsberger and Billingsley 1987). The t-values were then compared to table two-tailed critical t-values (Huntsberger and Billingsley 1987). A 95% confidence interval was calculated for each difference in mean absolute movements between observation periods (Huntsberger and Billingsley 1987).
RESULTS

Gillnet Samples

Channel catfish were extremely abundant in Cooks Creek during STGS operation in March, 1988. I converted Macdonald's (1988) sampling results from 15-17 March, 1988 to CPUE and plotted the results in figure 3. Macdonald's sample sites are shown in figure 4. Each site was sampled with a 22.86 x 0.91 m gillnet of 95 mm mesh size set for between 20 to 45 min. The CPUE was over 2000 catfish/100 m²/24 hrs between 2.10 and 6.65 km below the STGS outfall (fig. 3). The greatest CPUE was 7579 catfish/100 m²/24 hrs at 2.9 km. CPUE closer to the outfall, between 0.75 and 1.45 km, were much lower, less than 400 catfish/100 m²/24 hr. The lowest CPUE was 0 at the mouth of Cooks Creek. The average CPUE was 3426.4 catfish/100 m²/24 hrs.

Channel catfish were consistently caught in Cooks Creek during the fall 1991 STGS operating season, but were much less abundant than in March, 1988 (fig. 5). The maximum CPUE was 5.93 catfish/100 m²/24 hrs on 9 October, prior to STGS operation. Catfish were consistently caught during STGS operation, even after the ambient Red River temperature had fallen below 5°C. The CPUE averaged over 1.42 catfish/100 m²/24 hrs after the STGS began operations and peaked at 3.51 catfish/100 m²/24 hrs 17 November, 1991.

No channel catfish were caught in Cooks Creek during STGS operation in December, 1992 and January, 1993 (fig. 6). Channel catfish were only caught once in Cooks Creek during the sampling period. This was prior to both STGS operation
Figure 3: The CPUE of channel catfish at various sites along Cooks Creek during STGS operation in March, 1988 (After Macdonald 1988).
Figure 4: The areas of Cooks Creek where dead channel catfish were observed 29 December, 1987, and 16 January, 1988. Collection sites used by Macdonald (1988) are indicated by numbered circles.
Figure 5: The CPUE of channel catfish in Cooks Creek during the fall of 1991 and early winter 1992. The STGS operating period was 15 October to 16 November and is represented by the black bar below the x-axis. The Red River temperature is shown by the solid line. The Red River fell to 5°C 21 October and is represented by the dashed horizontal line.
Figure 6: The CPUE of channel catfish in Cooks Creek during the winter of 1992-1993. The STGS operating period was 1 December, 1992 to 20 January, 1993 and is represented by the black bar below the x-axis. The Red River temperature is shown by the solid line. The Red River fell to 5°C on 28 October and is represented by the dashed horizontal line.
Catfish/100 m²/24 hrs

Water temperature - celsius

Period of STGS Operation

Red River Water Temperature

CPUE

0 CPUE

October
November
December
January

Period of STGS Operation

Water temperature - celsius
and the ambient Red River temperature falling below 5°C. No channel catfish were caught in Cooks Creek after the Red River had fallen below 5°C.

Channel catfish were consistently caught in the Red River adjacent to the mouth of Cooks Creek (fig. 7). The highest CPUE was 5.73 catfish/100 m²/24 hrs on 2 November, 1992, the first day of sampling in the Red River. The ambient river temperature was 3.5°C. Channel catfish were caught prior to and during STGS operating period averaging 2.10 catfish/100 m²/24 hrs. showing that channel catfish were caught in the river after the water temperature had fallen below 5°C.

When the STGS was not in operation, the CPUE of channel catfish in Cooks Creek showed a pronounced seasonal pattern (fig. 8). Catfish were consistently caught in the creek while the ambient Red River temperature was above 5°C. Catfish were not caught in the creek when the ambient Red River temperature was below 5°C. The highest CPUE was 16.51 catfish/100 m²/24 hrs in mid-June. The CPUE averaged 4.27 catfish/100 m²/24 hrs during the warmwater season (above 5°C).

Radio Telemetry

The attachment of a loop receiving antenna to the rear step of a low-wing Piper Cherokee Warrior was an experimental configuration that proved to be more sensitive than the recommended configuration of attaching the antenna to the wing strut of a high-wing Cessna aircraft. By placing the antenna below and behind the aircraft wing, the distance between the antenna and engine was increased. This and the quenching effect of the metal wing, reduced the ignition noise on the receiver. By reducing the ignition noise, weaker signals not normally recognized while using the
Figure 7: The CPUE of channel catfish in the Red River during the winter of 1992-1993. The STGS operating period is represented by the black bar below the x-axis. The Red River temperature is shown by the solid line. The Red River fell to 5°C on 28 October, 1992 and is represented by the dashed horizontal line.
Red River Water Temperature

- 5°C

Catfish/100 m³/24 hrs

<table>
<thead>
<tr>
<th>Date</th>
<th>Catfish Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>October</td>
<td>5.22</td>
</tr>
<tr>
<td>November</td>
<td>2.90</td>
</tr>
<tr>
<td>December</td>
<td>1.74</td>
</tr>
<tr>
<td>January</td>
<td>0.58</td>
</tr>
</tbody>
</table>

CPUE

- 0 CPUE

Period of STGS Operation
Figure 8: The seasonal CPUE of channel catfish in Cooks Creek when the STGS did not operate. The Red River temperature is represented by solid line. The dashed horizontal line represent the date the Red River rose/fell to 5°C. This figure was constructed from data collected from October, 1991 to June, 1993.
Cessna configuration, became detectable.

There was no difference in detectability of signal between the two types of radio-tags. Signals from both models of transmitter were relocated in similar areas of the Red River and Lake Winnipeg, often side-by-side.

The accuracy of the radio transmitter relocations in the Red River and Lake Winnipeg by aircraft was ± 10 m, as determined by relocations of a transmitter suspended at a depth of ten metres in the Red River off the mouth of Cooks Creek. The accuracy of radio transmitter relocations in Cooks Creek by boat was ± 2 m, as determined by relocations of a transmitter suspended at a depth of two metres in Cooks Creek. The accuracy of radio transmitter relocations in Cooks Creek by aircraft was ± 100 m.

General Movements

1991-1992 Field Season

The STGS began operations prior to the Cooks Creek freeze-up. Because fish fence construction requires surface ice as a construction platform, the fish fence normally installed at the mouth of Cooks Creek was not installed. Ten channel catfish were radio-tagged and released into Cooks Creek during the operating period of 15 October - 16 November, 1991. All were relocated at least once in the creek after release (fig. 9). While the STGS was operating, six catfish were next relocated downstream and four were relocated either in the same location or upstream of the release site (fig. 9). Four catfish left the creek and did not return. One (catfish 251) left the creek but later returned while the STGS was still in
Figure 9: The relocations of channel catfish radio-tagged during the fall of 1991, during STGS operation.
operation (fig. 10). After the STGS ceased operation on 16 November, four of the tagged catfish were again relocated on 17 November in Cooks Creek (fig. 11). All the tagged catfish eventually moved out of Cooks Creek after the STGS shutdown. Eight of the ten tagged catfish were relocated in the Red River. Five catfish went upstream, one went downstream and two remained in the vicinity of the Cooks Creek mouth. Two catfish were not relocated after they left the creek. Catfish 251 remained in the vicinity of the creek all winter (fig. 10). Catfish 251 left Cooks Creek after tagging but immediately re-entered the creek and proceeded upstream until the STGS ceased operations. Catfish 251 then left the creek and remained in the vicinity of the creek mouth. When the STGS operated for 15 - 16 March, 1992, 251 was relocated in Cooks Creek, 75 m downstream of the fish fence (fig. 10).

After the STGS ceased operation 16 November, 1991, channel catfish 631 was relocated in the Red River 3.5 km upstream of the Cooks Creek mouth (fig. 12). When the STGS operated 15 - 16 March, 1992, 631 was relocated in Cooks Creek 5.7 km upstream of the mouth and 1.5 km downstream of the STGS outfall. 631 was next relocated 12 May, 1992, 100 m downstream of the 16 March location.

1992-1993 Field Season

Of the 19 channel catfish released with radio tags in the 1992-1993 field season, 18 were relocated. None of the catfish entered Cooks Creek during STGS operation (fig. 13). The average movement of channel catfish at each relocation flight date is shown in figure 14. During January, February, and March, 1993 the movements were directionless resulting in little absolute change (fig. 15). When the
Figure 10: The relocations of channel catfish 251 during the fall and winter of 1991-1992.
Figure 11: The relocations of channel catfish tagged during the fall of 1991, after the STGS had shutdown.
Figure 12: The relocations of channel catfish 631 during the winter and spring of 1992 - 1993.
Figure 13: The relocations of channel catfish tagged during 1992 - 1993.
Figure 14: The average channel catfish movements per relocation flight during 1993 plotted with the 20 year average and actual river flows.
Average Movement of Radio-tagged catfish between relocation flights (Jan.-Dec., 1993)

- 1993 Red River Flow
- Monthly 20 Year Average Flow
Figure 15: A scatterplot of the distances travelled by channel catfish between relocations in 1993. Relocations within each observation period are plotted with the same markers. Initial channel catfish relocations and catfish relocations made more than two relocation flights apart were removed from calculations. These relocations are indicated as "Data Removals" on the plot.
< 5°C  

> 5°C  

FLOOD  

Distance Moved (km)  

Distance Moved From Last Relocation  

Removals  

January  February  March  April  May  June  July  August  Sep  

1993
Red River reached 5°C, it was in flood. The channel catfish moved downstream with the increased discharge, and then upstream, after the spring runoff subsided (Appendix 2). A period of highly variable movement followed during June and July. During late July and August an unusual summer flood occurred. Channel catfish movements decreased as the discharge increased and were localized for the duration of the flood. In a scatterplot of the individual channel catfish movements during 1993 there was an initial period when fish moved up to 1800 m during January and February. In March, fish showed consistently low movements. The highest variability occurred during 1 April to 21 July. The variability in movement dropped to the lowest after 22 July. This variability is also shown in the mean absolute movements between periods of observation in table 1.

Individual relocation maps for each radio-tagged channel catfish are contained in Appendix 2.

Mean Absolute Activity

The radio relocations for the 1992-1993 field season were divided into three observation periods. The periods were defined as those observations made while the Red River was below 5°C (<5°C), above 5°C (>5°C), and during the late summer flood (FLOOD). The mean absolute movements of catfish were compared between each observation periods. The population means, variances, and 95% confidence intervals are contained in table 1. The greatest variability occurred during 1 April - 21 July. The least amount of variability occurred during the flood period of 22 July - 7 September. A comparison of the mean movements is shown in table 2. Using
Table 1: Results of the 1993 radio telemetry study showing groups of observations and the mean movements per group. The critical t-values are from Huntsberger and Billingsley (1987).

<table>
<thead>
<tr>
<th>Date</th>
<th>Observation Group</th>
<th>n</th>
<th>df</th>
<th>Critical t-value</th>
<th>$s^2$</th>
<th>mean (m/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan 5 - Mar 31</td>
<td>$\mu_1 = &lt;5^\circ$C</td>
<td>31</td>
<td>30</td>
<td>2.042</td>
<td>0.123</td>
<td>222 +/- 717</td>
</tr>
<tr>
<td>Apr 1 - Jul 21</td>
<td>$\mu_2 = &gt;5^\circ$C</td>
<td>127</td>
<td>126</td>
<td>1.980</td>
<td>1.106</td>
<td>560 +/- 2082</td>
</tr>
<tr>
<td>Jul 22 - Sep 7</td>
<td>$\mu_3 = $Flood</td>
<td>45</td>
<td>44</td>
<td>2.021</td>
<td>0.028</td>
<td>117 +/- 338</td>
</tr>
</tbody>
</table>
Table 2: The results of the F-ratio and Welch test comparison of means between observation groups showing a significant difference between $<5^\circ C$ ($\mu_1$) and $>5^\circ C$ ($\mu_2$), and $>5^\circ C$ ($\mu_3$) and FLOOD ($\mu_3$), but not $<5^\circ C$ ($\mu_1$) and FLOOD ($\mu_3$). The F-ratio 5% values and critical t-values are from Huntsberger and Billingsley (1987).

<table>
<thead>
<tr>
<th>Comparison</th>
<th>F-ratio</th>
<th>F-ratio 5% value</th>
<th>Degrees of Freedom</th>
<th>Welch t-value</th>
<th>Confidence Interval $\mu_i - \mu_j$</th>
<th>Critical t-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_1 - \mu_2$</td>
<td>8.98</td>
<td>1.8</td>
<td>141</td>
<td>3.005*</td>
<td>0.3384±1.658</td>
<td>1.960</td>
</tr>
<tr>
<td>$\mu_2 - \mu_3$</td>
<td>39.5</td>
<td>1.0</td>
<td>143</td>
<td>47.54*</td>
<td>0.4435±0.018</td>
<td>1.960</td>
</tr>
<tr>
<td>$\mu_1 - \mu_3$</td>
<td>4.4</td>
<td>1.8</td>
<td>39</td>
<td>1.550</td>
<td>0.1051±0.137</td>
<td>2.021</td>
</tr>
</tbody>
</table>

* Significant to the 95th percentile.
Figure 16: The relocations of the channel catfish implanted with an ultrasonic tag by Macdonald in 1987 (after Macdonald 1990).
Figure 17: The relocations of channel catfish tagged by Macdonald in 1988 (after Macdonald 1990).
with relocations of catfish during each study period. All except two of Macdonald's (1990) catfish relocations occurred in areas where catfish were relocated during this study.

**STGS Operation and Discharge**

In a comparison of the STGS discharge between the operating periods observed, the highest rate of discharge occurred during the 1987-1988 STGS operating period (fig. 19). The discharge into Cooks Creek was intermittent during August and September, but became continuous 28 September. The percentage of Red River flow diverted to Cooks Creek peaked at 26% 22 - 23 October, but fell to 14% by 1 November, when Red River temperature fell to 5°C. The STGS discharge averaged over 10% of the Red River flow for the remainder of the winter. The STGS operated intermittently during the 1991-1992 operating period. The longest continuous period the STGS operated was between 28 October and 8 November, 1991. On 25 October, the Red River temperature fell below 5°C. The STGS discharge during this time averaged four percent of the Red River flow. The STGS operated intermittently during the 1992-1993 operating period. The STGS did not operate for more than 5 continuous days. The average STGS discharge was six percent of the Red River flow. The STGS operated once, 27 to 30 October, 1992, prior to the Red River falling below 5°C.

**Red River Flow**

The Red River flow during the 1992-1993 radio telemetry project followed the 28 year average until late April, 1993 (fig. 20). In late April the discharge fell below
Figure 19: The discharge of cooling water by the STGS into Cooks Creek during the two periods of STGS operation in this study and the period observed by Macdonald (1988). STGS discharge is plotted as the percentage of Red River flow.
August  September  October  November  December  January  February  March

Average Red River Water Temperature

STGS Discharge:  
- 1987-1988
- 1991-1992
- 1992-1993
the average until mid-July. In late July an unusually rainy period caused the river to flood. The Red River flow peaked at 1340 m$^3$/s during 15 - 16 August, 12.3 times the monthly average of 109 m$^3$/s and 1.8 times the average spring flood of 739 m$^3$/s.
DISCUSSION

Equipment and Techniques

The severe winter in Manitoba limited the variety of equipment that could be used to sample the Red River and Cooks Creek. Thick winter ice cover prevented the use of trap nets, hoop nets, and electrofishing on the Red River. Because trap and hoop nets would block the shallow, narrow Cooks Creek, summer boat traffic precluded the use of such nets. In addition, the intermittent ice cover during the unpredictable STGS operation, would have damaged nets set in the lower reaches of the creek. Gillnets provided a consistent and effective method of collection that could be used both in the Red River and Cooks Creek year round with no major changes in efficiency between open water and winter ice conditions.

Radio telemetry was used to track channel catfish movements because the Red River and its tributaries below the St. Andrews Dam, the Netley-Libau Marsh, and the adjacent Lake Winnipeg could be scanned from an aircraft during one relocation flight. Ultrasonic telemetry was not practical for this study. Ultrasonics require a hydrophone to be placed into the water for signal relocation, and except for the open water season, relocation runs would not be possible. Radio telemetry is independent of water contact and allows larger areas to be searched in less time.

The channel catfish used in this study were caught during the cold water months (≤ 5°C) in the Red River and Cooks Creek. The cold water provided both advantages and disadvantages in radio-tagging catfish. Because of the cold water gillnets could be used to capture catfish for use in radio telemetry. Frequent net
checks and the low level of catfish activity prevented the catfish from sustaining mechanical damage from the gillnets. The near immobility of catfish at water temperatures below 5°C also allowed radio-tags to be attached without the use of anaesthetics to immobilize the fish. This provided an additional benefit in that the air temperature during tagging operations was below 0°C and shelter was not always available. The freezing temperatures also made it imperative that catfish were returned to the water as soon after tagging as possible in order to avoid damage from freezing of superficial tissues. The use of anaesthetics would have required a period of induction in addition to the time needed for measuring and tagging, and also a period of recovery before the catfish could be returned to the river. Externally attached radio-tags also helped in getting the channel catfish from net, through the tagging process, and back to the river in as short a time as possible.

The use of internal radio-tags would have required catfish to be anaesthetized prior to surgery. Furthermore, channel catfish are known to expel loose internal transmitters (Marty and Summerfelt 1986; Summerfelt and Mosier 1984). In order to ensure tag retention by the catfish, an internal radio tag must be sewn directly to the abdominal wall. The increased exposure of the catfish and researchers to below freezing temperatures during the time required to anaesthetize and operate on the catfish would have increased the probability of the catfish and researchers sustaining frost damage during the radio-tagging procedure.

Captive fish could not be used to assess the effects of external transmitter attachment because of the susceptibility of large catfish to skin infections when held in
captivity at low temperatures. This is a common problem in the channel catfish culture industry (Bly et al. 1993). However 28 out of a total of 29 catfish tagged were relocated at least twice and had moved between subsequent relocations.

The accuracy of the radio transmitter relocations was tested by flying over or driving over transmitters placed in known locations in the Red River and Cooks Creek. The difference in transmitter relocation accuracy by aircraft between the Red River and Cooks Creek is because signal propagation from a submerged transmitter is affected by water depth. Increasing water depth decreases transmitter signal strength exponentially and at the same time narrows the zone of signal relocation (Winter et al. 1978). Therefore, in the deeper areas of the Red River and Lake Winnipeg, the narrow zone of signal relocation provided accurate transmitter relocations, but at the same time decreased the probability of signal interception by aircraft. Conversely, the shallow Cooks Creek resulted in less accurate transmitter relocations, but a greater probability signal interception by aircraft.

The Behaviour of Red River Channel Catfish

Except under special or extreme conditions, catfish show little site fidelity in a river system (Dames et al. 1989). The direction of channel catfish movements are therefore difficult to predict. However, channel catfish have been shown to collect in areas of rivers with specific combinations of abiotic factors (Layher and Maughan 1985). Layher and Maughan (1985) found that run-off, fraction of runs (areas of swift, uniform flow), and water temperature accounted for half of the variability in channel catfish biomass. Though abiotic factors can be used to predict catfish
density, the catfish do not remain in one area of preferred conditions but circulate through those similar preferred areas throughout the river system. There are, however, seasonal and conditional periods under which the wide ranging and unpredictable movements of channel catfish are reduced and predictable. An example of a seasonal period in which catfish show high site fidelity during the warm water season is during spawning. Male catfish will guard a nest site and brood the young for a short time after hatching (Becker 1983). Temperature may play a role as a cue in the timing of seasonal catfish movements. In the Missouri River, channel catfish have been found to move downstream in the fall and upstream in the spring (Dames et al. 1989). The downstream movement of catfish in the fall may be directed towards finding deeper water in which to overwinter. In the Upper Mississippi River catfish have been observed during the winter to lay dormant on the river bottom (Hawkinson and Grunwald 1979; Lubinski 1984; Grace 1985; Newcomb 1989; Todd et al. 1989). This low temperature dormancy is similar to that described of brown bullheads by Crawshaw et al. (1982b). The similarity in temperature as a behavioural cue in catfish and bullhead extends further. The attraction and behaviour of brown bullheads to thermal plumes observed by Kelso (1974), Marcy (1976), and Richards and Ibara (1977), is similar to the attraction of channel catfish to the Cooks Creek thermal plume observed by Macdonald (1988; 1990). These patterns of behaviour, the seasonal upstream/downstream movements, low temperature dormancy, and attraction to thermal plumes, have also been observed in Red River channel catfish.

There was one previous telemetry study carried out on Red River channel
catfish. Macdonald (1990) attached ultrasonic tags to nine channel catfish. The small number of tags Macdonald used limited the conclusions that could be drawn and he was unable to provide more than a subjective analysis of the telemetry results. However, Macdonald's observations were found to be consistent with the general movement of catfish observed in this study and provided corroboration that the catfish observed during my study were following normal behaviour patterns. The catfish were observed to utilize the tributaries and channels of the Netley-Libau marsh and to travel great distances in short periods of time (up to 37 km in 2 days). Of the eight catfish tagged in 1988, one was presumed to have died. Two of the remaining seven catfish entered the Red River during the autumn. Macdonald presumed that the five remaining catfish scattered through the marsh during the autumn. However, with the reference to my results, Macdonald's catfish most likely overwintered in Lake Winnipeg and not the marsh. This is consistent with the radio telemetry results of my study, which showed that catfish move downstream, out of the tributaries to the Red River and Lake Winnipeg as water temperatures fell in the fall. This seasonal pattern has also been observed in the Missouri River by Dames et al. (1989). They found that distances travelled were greater in the spring than autumn and there was a trend to move downstream in the autumn and upstream in the spring.

The combination of results from the two seasons of radio telemetry during this study and the ultrasonic telemetry of Macdonald (1990) shows areas in the Lower Red River, Netley Libau Marsh, and adjacent Lake Winnipeg where channel catfish concentrate (fig. 18). The number of relocations from each study show the relative
extent and intensity of each study. These results also show the limitations of ultrasonic telemetry in the Lower Red River. Macdonald (1990) made the most frequent relocation runs yet he had relatively few relocations for the effort. This is probably because for practical purposes he restricted his telemetry runs to the mainstem of the Lower Red River during the open water season. Though there is no way to indicate in figure 18 the time of year the relocations were made or reflect the change in river flow and temperature, figure 18 does show the places of relocation within the study area common to each season of telemetry. Except for two relocations, all of Macdonald's (1990) catfish relocations were in areas where catfish were relocated during this current study. The consistent relocation of catfish in discrete areas of the Red River amongst telemetry studies is strong evidence that catfish most frequently use those areas indicated in figure 18. The relocations across the study periods in Cooks Creek and the lack of relocations in Netley Creek has shown (fig. 18) that Cooks Creek was the most important tributary to channel catfish in the Lower Red River. This repeated use of similar river and creek areas is consistent with the findings of Layher and Maughan (1985).

The radio telemetry results from 1993 were also used to determine a seasonal rate of spontaneous activity, or mean absolute activity in channel catfish. The coarseness is a result of the relocation flights varying between six and eighteen days apart. More precise rates of activity than seasonal comparisons could not have been made without more frequent relocation flights. Another factor that added to the coarseness of the calculations was that this rate calculation assumed that all catfish
movements between relocations were linear, away from the previous relocation. This method could not be used to measure mean absolute activity in a local area. A high level of mean absolute activity in a local area would appear as a low seasonal rate of mean absolute activity. However, for the requirements of this study the use of the radio telemetry relocations as a measure of the seasonal rate of mean absolute activity is accurate enough in that it provides a comparison of catfish activity between seasons.

In order to compare the mean absolute activity between successive observation periods, three assumptions had to be addressed (Huntsberger and Billingsley 1987). First, the assumption of randomness was not met. Macdonald (1990) showed that the size frequency distribution of channel catfish in the Red River was dumbbell shaped. That is that the catfish population consisted of small juveniles and large adults, with large juveniles and small adults absent. Gill net mesh sizes in this study were selected to sample the adult catfish. However, no catfish caught were rejected for radio-tag attachment for being undersize. The catfish that were used in radio-tagging probably represented a diverse sample of the adult catfish using the Red River. Dames et al. (1989) found that the majority of mainstem Missouri River catfish were transients. The Lower Red River between the St. Andrews Lock and Dam and the Red River Delta has one channel and two tributaries. Therefore, if the channel catfish in the Red River follow behavioural patterns observed by Dames et al. (1989), the majority of the fish in the Lower Red River should be transient. Sampling one site on the Lower Red River mainstem should then provide a sufficiently diverse
sample of the Lower Red River channel catfish population. Second, the assumption of normality is not a strong assumption and because of the central limit theorem, large departures from normality, with sufficiently large samples, will not greatly affect probabilities (Huntsberger and Billingsley 1987). The third assumption, common variance, was tested using the F-ratio. The variance was different for each observation period (table 2). This meant that the means could not be compared using pooled variances. However, the means could be compared using the Welch test. The Welch test allowed the test of the null hypothesis $H_0: \mu_i = \mu_j$ between each of the periods.

The significant difference in the rate of activity between the $<5^\circ C$ and $>5^\circ C$ observations (Tables 1 and 2) follows Crawshaw et al.'s (1982b) laboratory observations that there is a significant reduction in catfish activity below $5^\circ C$. The significant difference between the above $5^\circ C$ and FLOOD observations is in conflict with Crawshaw et al.'s (1982b) observations since the lowest rate of activity occurred at temperatures which should elicit a higher rate of mean absolute activity. The low rate of activity was most likely due to the high water velocities in the Red River created by the late summer flood. During this period, channel catfish did not travel great distances in the Red River and confined their movements to localized, lower energy areas of the Red River such as the river delta (figs. 13 and 14). This pattern of behaviour was also observed by local sportfishing guides and professional anglers. Catfish were reported to have moved out of the main channel into backeddies and backbays during the late summer flood (Stewart pers. comm.). The level of activity
during the flood was probably not representative of the rate of mean absolute activity at this time of year in the absence of flooding. It was for this obvious difference in mean absolute movement rates and variance that the relocations above 5°C were divided so that relocations made during the unusual late summer flood were considered separately.

Red River channel catfish were observed to be attracted to the Cooks Creek thermal plume during both this study and Macdonald (1988; 1990). The autumn relocation of one of Macdonald's (1990) ultrasonic tagged catfish in Cooks Creek during STGS operation in 1987 was the first indication of the Cooks Creek thermal plume attracting channel catfish. During my study two radio-tagged catfish released during the October and November, 1991 STGS operation were relocated in Cooks Creek during STGS operation in March, 1992 (figs. 10 and 12). Both catfish were relocated in the Red River prior to the March, 1992 STGS operation. Catfish 251 was relocated in Cooks Creek below the fish fence and catfish 631 was relocated above the fish fence. Tyson et al. (1994) concluded the fish fence was an effective barrier to fish immigration during STGS operation. Therefore, catfish 631 must have entered Cooks Creek prior to the February, 1992 fish fence construction.

Channel Catfish and the Cooks Creek Thermal Plume

The underlying hypothesis in Macdonald's (1988) report was that whenever the STGS operated, channel catfish would enter Cooks Creek. According to this hypothesis catfish immigration would be greatest in the winter when the differences between the discharge temperature and the ambient river temperature would be at a
maximum. Macdonald’s observation of an unnaturally high number of channel catfish in Cooks Creek in 1987 and 1988 is evidence that channel catfish are attracted to a thermal plume. This behaviour has also been observed in brown bullheads observed by Kelso (1974), Marcy (1976), and Richards and Ibara (1977). When bullheads encounter a thermal gradient such as a thermal plume being discharged from a generating station, they will enter the plume and congregate at preferred temperatures (Richards and Ibara 1977). Thermal discharges into lakes have been shown to interrupt normal migration patterns in brown bullheads (Kelso 1974). In rivers, bullheads will enter thermal discharge canals during the cool seasons and remain in the thermal plume for the duration of winter (Marcy 1976; Richards and Ibara 1977). The propensity for bullheads to enter a thermal plume is greatest in the autumn and winter when the difference between the thermal plume temperature and the ambient temperature is greatest. The observation of dormant Mississippi River channel catfish by Hawkinson and Grunwald (1979) and Lubinski (1984) is evidence that channel catfish undergo a low temperature dormancy similar to the low dormancy observed in captive brown bullheads by Crawshaw et al. (1982b). This demonstrated relationship between temperature and behaviour in channel catfish was also observed in Cooks Creek and the Lower Red River.

Macdonald (1988) investigated the fish kills of 1987-1988 to determine the cause of the fish kills and to describe the community of fish inhabiting Cooks Creek. In his report, Macdonald suggested several hypotheses to explain the cause of the fish kills and the conditions within Cooks Creek and the Red River which led to the fish
kicks. However, Macdonald's speculations were based upon one winter of observations during which the STGS operated for an unusually long period. As will be shown, there is evidence that the fish kills in 1987-1988 were a unique occurrence.

In order to determine the cause of the 1987-1988 fish kills, Macdonald (1988) tested the water quality parameters and determined that the fish kills were not the result of contaminants. He hypothesized that thermal shock was the most likely cause of the fish kills. He then performed an experiment in which he induced thermal shock in a sample of channel catfish acclimated to the thermal plume in Cooks Creek. Though microhematocrit values of blood samples taken from thermally shocked catfish were inconclusive, these catfish had distortions in blood cell shape consistent with literature descriptions of catfish undergoing thermal shock. Macdonald concluded that thermal shock resulting from the shutdown procedure of the STGS caused the fish kills. The STGS shutdown procedure in place at the time of the fish kills was to continue pumping cooling water from the Red River after the generating units had been taken off line. This resulted in a nearly instantaneous drop in discharge temperature from nearly 20°C to 0°C. Macdonald requested that Manitoba Hydro modify the STGS shutdown procedure to have the cooling water pumps turned off when the generators were brought off line. This allowed the thermal plume to cool more slowly, at a rate that would not induce thermal shock in the fish. Manitoba Hydro has adopted this modified shutdown procedure and no fish kills have since been reported.

Having explained the cause of the fish kills, Macdonald (1988) speculated as to
why there had never been a previous report of a fish kill in the Cooks Creek thermal plume even though the STGS had operated frequently for continuous periods in the winter months with the unmodified shutdown procedure. He suggested that it was only a recent recognition of channel catfish as a valuable addition to the local sport fishery that prompted a report of the fish kill. He further suggested that with the installation of the City of Winnipeg’s South End Waste Treatment Facility (SEWTF), the Red River has become a more attractive overwintering location. Macdonald speculated that before the construction of SEWTF, untreated sewage led to anoxic conditions in the Red River below Winnipeg.

There is little support for Macdonald’s speculations. The STGS had been operating since 1960 with the unmodified shutdown procedure and no fish kills were reported until the winter of 1987-88. When Tyson et al. (1994) investigated the effectiveness of a fish fence at preventing immigration of fishes into Cooks Creek during winter STGS operation, they did not find channel catfish schooling in the creek above or below the fence. Channel catfish were neither winter residents of Cooks Creek nor were they attracted to the Cooks Creek thermal plume during STGS operation in January, 1990 or March, 1993. In years previous to and after 1987, channel catfish had not entered Cooks Creek during winter STGS operation. Also, considering the environmental awareness of the residents along Cooks Creek, it is unlikely that fish kills could have occurred without being reported. Macdonald’s speculation that anoxic conditions from Winnipeg sewage disposal into the Red River may have made the river an unattractive place for channel catfish to overwinter is also
likely incorrect. The spilling of the Red River over the St. Andrews Dam would have been more than sufficient to oxygenate the river water. Also, there is an historic winter sport fishery for walleye in the lower Red River (Green and Derksen 1984). Given the avoidance of low oxygen concentrations by walleye (Craig 1987), the persistence of the walleye sport fishery indicates the Red River is not anoxic below Lockport.

The evidence that Macdonald’s (1988) investigation was carried out during unusual conditions is demonstrated in my results. There was a noticeable difference in the CPUE between the 1991-1992, the 1992-1993 sampling periods, and Macdonald’s (1988) results (figs 5, 6, and 3, respectively). The catfish CPUE during the period of my study was more than two and a half orders of magnitude lower than the CPUE recorded by Macdonald (1988) in the creek during the winter of 1987-1988 (fig. 3). The concentrations of catfish in Cooks Creek during the winter of 1991-1992 (fig. 5) were not different than summer CPUE (fig. 8). Macdonald caught channel catfish in Cooks Creek at rates which were more than two orders of magnitude greater than a spawning run (fig. 3 vs. 8). Although there was a difference in the mesh size and the method of employment of the gillnets between Macdonald’s study and this study, this would not have accounted for the large differences in CPUE. Macdonald used one 23 m² panel of 95 mm mesh set for not longer than 45 minutes compared to the two 150 m²+ gillnet gangs set for greater than 20 hr used in this study. One possibility which may have accounted for the high CPUE recorded by Macdonald was that he was able to identify fish concentrations by
species in the creek and set his net directly into the catfish school (Gillies, pers. comm.). However Macdonald did this only when he required catfish for the thermal shock experiments. The results in figure 3 are from a regular sample.

Further evidence that the 1987-1988 observations were unique is that the fish community structure observed by Macdonald (1988) was much different than that observed in this study. The fish community in Cooks Creek described by Macdonald consisted of warmwater species such as channel catfish, common carp (Cyprinus carpio), white suckers (Catostomus commersoni), and white bass (Morone crysops) (fig. 21). Cool water species such as walleye (Stizostedion vitreum), northern pike (Esox lucius), and sauger (Stizostedion canadense) composed a greater proportion of the fish community during STGS operation in my study (fig. 21). Though Macdonald’s gill nets did not sample smaller species, the difference in the species composing the fish community during Macdonald’s study and my study may be a result of the prolonged STGS operation in 1987-1988. When gillnet samples were drawn from above and below the Cooks Creek fish fence in 1993, carp, white bass, and brown bullheads were drawn to the creek in greater densities during STGS operation (fig. 22). The lack of walleye and sauger during Macdonald’s study may be an indication of an innate avoidance behaviour of these species to unseasonal water temperatures or dense fish concentrations. The high density of fish in Cooks Creek may have caused the territorial pike (Scott and Crossman 1985) to leave the creek.

Macdonald (1988) also observed that the fish in Cooks Creek were segregated by species and size. Generally the larger fish of a given species held the upstream
Figure 21: The gillnet catch in Cooks Creek during STGS operation by Macdonald in March, 1988 (after Macdonald 1988) (above), and the fish caught in Cooks Creek during STGS operation in March, 1993 (below). Key: BlB - black bullhead; Cp - common carp; NP - northern pike; WB - white bass; WS - white sucker; BrB - brown bullhead; Ge - goldeye; BB - bigmouth buffalo; Sr - sauger; Qu - quillback; FwD - freshwater drum; Bt - burbot; We - walleye; CC - channel catfish; ShR - shorthead redhorse; BC - black crappie, LF - leopard frog.
Figure 22: The gillnet catch in Cooks Creek during STGS operation in March, 1993 showing winter resident species above the fence and fish drawn to Cooks Creek by the thermal plume below the fence. Key: BlB - black bullhead; Cp - common carp; NP - northern pike; WB - white bass; WS - white sucker; BrB - brown bullhead; Ge - goldeye; BB - bigmouth buffalo; Sr - sauger; Qu - quillback; FwD - freshwater drum; Bt - burbot; We - walleye; CC - channel catfish; ShR - shorthead redhorse; BC - black crappie, LF - leopard frog.
locations followed by progressively smaller fish downstream. Channel catfish occurred furthest upstream, succeeded by common carp, white suckers, and white bass downstream (Gillies, pers. comm.). This distribution was not observed in my study. During my study the fish species were mixed through the creek, and the species assemblage was more diverse. In fact, fish did not travel as far upstream as was observed by Macdonald (1988). Low water levels during the 1991-1992 and 1992-1993 field seasons exposed barriers which prevented fish from accessing the upper reaches of the creek. The high concentrations of fish upstream may have begun to form prior to the falling water levels in the autumn of Macdonald's (1988) study. Because of the upstream concentrations, high densities, and sorting of fish by species and size, fish may have been attracted to, and inhabited the Cooks Creek thermal plume for an extended period of time prior to the autumn drop in water levels and temperature.

The most important result of the difference in the CPUE between observation periods was the time of the year at which channel catfish were observed in the creek. Channel catfish were not observed in Cooks Creek during STGS operation in the winter of 1992-1993 (fig. 6) even though catfish were regularly caught in the Red River adjacent to the mouth of Cooks Creek (fig. 7). The timing of STGS operation may play a role in the presence of catfish in Cooks Creek. The CPUE results as a whole are an indication that the timing, occurrence, and number of channel catfish in Cooks Creek are in part dependent upon the operation of the STGS. The STGS operating schedule differed during each of the periods of observation. It is this
difference which most likely led to the differences in observed CPUE.

It can be concluded from the CPUE results that channel catfish exhibit the following behaviour. Catfish use Cooks Creek during the seasons when the ambient water temperature is above 5°C (fig. 8). Five degrees celsius is the temperature below which Crawshaw et al. (1982b) observed brown bullheads to enter a facultative dormancy. Below 5°C the channel catfish leave Cooks Creek to overwinter in the Red River. Therefore, channel catfish are not winter residents of Cooks Creek and the presence of catfish in Cooks Creek after the water temperature has fallen below 5°C is the result of STGS operation. It is evident by a comparison of the data from the three observed STGS operating periods that the time of year and the level of production of the STGS determines the presence and number of channel catfish in Cooks Creek. Macdonald's (1988) assumption that channel catfish are attracted to the thermal plume is correct but not for all periods of STGS operation. When the STGS operates intermittently at low levels, the effect is reduced and varied. Channel catfish were caught in Cooks Creek after the Red River had fallen below 5°C only when the STGS had operated prior to the Red River falling below 5°C (figs. 4 and 5). Winter STGS operation alone did not account for the channel catfish in Cooks Creek. It is STGS operation prior to the Red River ambient temperature falling below 5°C which caused catfish to enter the creek.

STGS Operation

A factor that affects the attraction of channel catfish to the Cooks Creek thermal plume and their entrainment into the plume is the extent of the Cooks Creek
thermal plume in the Red River. The extent of the plume is dependent upon the level of STGS operation and the flow in the Red River. During STGS operation, one cooling water pump is operated for each generating unit operated. The pumps are operated at either full speed (4.54 m³/s) or half speed (2.27 m³/s). Generally, the pumps are operated at full speed during spring to autumn operation and at half speed during winter operation. All water drawn from the Red River by the STGS is returned to the river via discharge into Cooks Creek. Because all the water drawn from the Red River by the STGS is returned, and the STGS draws cooling water at a constant rate, changes in the Red River flow vary the ratio of river water to creek water when the thermal plume joins the river. During low Red River flows, a greater proportion of the Red River flow is diverted through the STGS. During extremely low flow years the STGS has the potential capacity to divert 53% of the Red River flow. With increasing proportions of river water diverted through the STGS there is a reduction in thermal plume dilution by the Red River when the plume joins the river. The result is that the extent of the Cooks Creek thermal plume in the Red River varies with river flow. Therefore, the extent of the Cooks Creek thermal plume in the Red River is dependent upon: 1) number of generating units in operation, 2) the rate at which the cooling water pumps operate, and 3) the rate of flow in the Red River.

The majority of heat in the thermal plume is lost as it flows down Cooks Creek (Baker 1994). Thermal plume heat loss in Cooks Creek during the winter was not observed to be significantly affected by air temperature or wind speed. Baker
described the extent of the Cooks Creek thermal plume in the Red River under conditions similar to the winter 1992-1993 STGS operating conditions. Baker found that the Cooks Creek thermal plume was quickly diluted by the much greater Red River flow (fig. 23). The warmer denser water of the Cooks Creek thermal plume slid underneath the cooler lighter Red River water into the central river channel. However, even though the Cooks Creek thermal plume was detectable 300 m downstream of the Cooks Creek mouth, by the time the plume had reached the central river channel the plume had been cooled by dilution to 1.5°C. Because channel catfish were present in the Red River channel under similar operating conditions in 1992-1993 it is concluded that catfish require more than 1.5°C in temperature change, or a temperature greater than 1.5°C to respond to a thermal gradient.

The most significant cooling during summer STGS operation occurs when the STGS discharge is diluted in Cooks Creek by run-off from summer rains (Baker 1994). Baker found that the thermal plume at this time of year was less likely to mix with the Red River water and was confined by the river flow to the shallow east bank of the river. The extent of the Cooks Creek thermal plume increases as the proportion of the Red River flow diverted through the STGS increases.

Classification of STGS Impact

Based upon the three observed STGS operating schedules, the effect of the STGS on overwintering channel catfish was classified as having a minimum, intermediate, or maximum impact. The classification was based upon the number of channel catfish observed in Cooks Creek during each of the operating periods
Figure 23: The temperature on the bottom of the Red River when the Cooks Creek enters the river during winter STGS operation (after Baker 1994).
observed.

The STGS had a minimum impact on channel catfish during the period of December, 1992, and January, 1993. No channel catfish were observed in Cooks Creek after the Red River had fallen to 5°C (fig. 6). No channel catfish were caught in Cooks Creek during STGS operation. However, channel catfish were consistently caught in the Red River adjacent to the mouth of Cooks Creek after the Red River temperature had fallen below 5°C (fig. 7). Several of these catfish were tagged with radio transmitters prior to and during STGS operation. These channel catfish dispersed along the Red River and out into Lake Winnipeg (fig. 14). No radio-tagged channel catfish entered Cooks Creek during STGS operation. Therefore, channel catfish were present in the Red River adjacent to the mouth of Cooks Creek but no channel catfish were caught or observed in the creek during STGS operation. The catfish either did not encounter the thermal plume exiting Cooks Creek or the temperature difference between the plume and the ambient Red River temperature was not great enough to cause the catfish to break dormancy and follow the plume.

The STGS had an intermediate impact when it operated from 15 October to 16 November, 1991. The STGS operated intermittently except for a period of 10 days around the time the Red River ambient temperature fell to 5°C (fig. 19). Unlike the minimum impact, channel catfish were regularly caught in Cooks Creek during STGS operation prior to and after the ambient Red River temperature had fallen below 5°C (fig. 5). The STGS began operations 15 October, 1991, when the Red River was 15°C. Channel catfish had not entered seasonal dormancy and were still active.
Channel catfish were still active and thus encountered the thermal plume. That the catfish encountered the thermal plume and entered Cooks Creek is consistent with Crawshaw's (1984) observations of brown bullhead temperature-dependent activity. Because the thermal plume was at the surface, channel catfish could only have encountered the thermal plume if they were active and using the east bank shallows or were still using Cooks Creek. Once the Red River temperature had fallen below 5°C, channel catfish in the Red River were no longer susceptible to the Cooks Creek thermal plume. Below 4°C, the conditions during STGS operating would continue as described for the minimum effect period.

The STGS had a maximum impact when it operated from 4 August, 1987 to April, 1988. These observations were made by MDNR (Fisheries Branch) personnel in an investigation of two reported fish kills. They found unnaturally high numbers of channel catfish in Cooks Creek. This is due to the near continuous STGS operation prior to the ambient Red River temperature falling below 5°C. Also, the proportion of Red River flow diverted through the STGS during this period increased. Therefore, as the temperature difference between the Cooks Creek thermal plume and the ambient Red River temperature increased, so did the proportion of Red River flow diverted to Cooks Creek. This resulted in a greater area of thermal plume influence in the Red River. During this time, channel catfish would be active, using the sloughs and tributaries. With the increase in the extent of the thermal plume there was an increase in the probability that channel catfish would encounter the plume. Therefore the extended period of time and the extended area of influence by the
Cooks Creek thermal plume resulted in the unnaturally high numbers of channel catfish observed in Cooks Creek in the winter of 1987-1988. Once the ambient Red River temperature had fallen below 5°C, the conditions would have occurred such as were observed during the minimum impact schedule.

The Behavioural Thermoregulation of Fishes

Temperature may serve both as a proximate, and as an ultimate ecological factor in fishes. As a proximate factor, temperature serves as a cue by which fishes alter their behaviour so as to stay within the preferred range of an ecological variable (Reynolds 1977). An example of a proximate factor in fishes is thermal cues as guides in the migration of fishes to spawning grounds (Reynolds 1977). An ultimate factor is an ecological variable which has an adaptive value in the genetic contribution to successive generations (Reynolds 1977). That is, a variable "...most important for the direct physiological or ecological well-being of the individual or for its genetic contribution to the continuation of the species..." (Reynolds 1977). Reynolds (1977) used the selection of preferred temperatures by fishes in a heterothermal environment (behavioural thermoregulation) to define temperature as an ultimate factor. At the time of Reynold's (1977) paper, the mechanisms by which the fishes selected preferred temperatures and the reasons specific temperatures were selected were not understood.

We now know that temperature is more unlikely to be an ultimate factor but a proximate factor acting as a cue to promote the ultimate factor of maximization of energy flow through the fish system (Bryan et al. 1990). There is now a better
 outline of the mechanisms of behavioural thermoregulation in fishes and the basis for
behavioural thermoregulation and as an ultimate ecological factor. Neill (1979)
described the mechanisms of behavioural thermoregulation as falling into two classes,
predictive and reactive. Predictive thermoregulation involves directed movements by
a fish to a particular habitat area in which the fish "expects" to find preferred
temperatures. The basis of these movements is individual or evolutionary experience.
An example of a predictive mechanism would be seasonal migration. Reactive
thermoregulation is a series of undirected movements resulting in the net movement
towards the preferred temperature. These movements are modified by recent thermal
experience. An example of a reactive mechanism would be the movement of bluegills
(Lepomis macrochirus) up a thermal gradient (Neill and Magnuson 1974).

Temperature can therefore be described as a proximate factor acting through
either predictive or reactive mechanisms to promote the ultimate factor of the
maximization of energy flow in the fish system (Bryan et al. 1990). The process that
best describes this is the maximum power principle. The maximum power principle
states that systems evolve such that the flow of useful energy is maximized (Odum
1983). Ware (1982) concluded that the maximum power principle has acted in the
natural selection of teleost fishes. The basis of the theory that the maximization of
power serves as an ultimate factor is rooted in the selection of preferred temperatures
by fishes. Kelsch and Neill (1990) provided a general physiological model in which
they showed why a fish would prefer one temperature over another. The premise of
their model was that fish prefer temperatures that afford the maximum potential for
the fish to do work in the environment. The preferred temperature is therefore that at which there is the greatest difference between the standard metabolic rate and the active metabolic rate. Fry (1947) referred to this as the temperature giving the maximum scope for activity. The preferred temperature can then be described as the temperature that affords the greatest potential for the fish to do work. At this temperature, obligatory metabolic processes are a small proportion of the metabolic scope, allowing for larger amounts of energy to be used in growth, reproduction, escape from predators, etc. Kelsch and Neill (1990) predicted that fishes that exhibit Precht's (1958) "partial" metabolic compensation prefer temperatures that are increasing functions of acclimation temperatures.

The maximum power principle applied to temperature predicts that fish will most frequently inhabit the temperatures which afford the greatest potential to do work. Temperature is therefore a proximate factor guiding the fish to conditions which maximize the potential energy in the fish system. Bryan et al. (1990) developed a model based on their experimental data on the behaviour of bluegills in a temperature gradient for the behavioural thermoregulation of fishes using the maximum power principle. Maximum scope for metabolic activity was defined in this model as the surplus power capacity. The probability of a fish occurring at a particular temperature is correlated with the surplus power capacity afforded by that temperature. As the preferred temperature is approached, the fish should reduce swimming velocity so as to maximize the surplus power capacity. Once the preferred temperature has been reached, fish will increase turning so that residence time in the
zone of maximum surplus power capacity is maximized. Surplus power capacity is
maximized by both producing the necessary conditions, through the reduction in
energy used in swimming, and maximizing the time spent under those conditions.
Bryan et al. (1990) used their bluegill data as experimental support for this model.
However, this model would also account for the quiescence in brown bullheads
observed by Crawshaw et al. (1982b) at the high end of a temperature gradient, and
the slower swimming and increased turning of unrestricted bullheads which
encountered a thermal plume in Lake Ontario (Kelso 1974).

Catfish Thermal Physiology

The bluegill sunfish used in the development of Bryan et al.'s (1990)
maximum surplus power theory is a warmwater fish with partial metabolic
compensation to changes in temperature (Neill 1977). The channel catfish is also a
warmwater fish but there is little direct information on channel catfish behavioural
thermoregulation. There is, however, significant temperature information, derived
from both laboratory and field research on the brown bullhead, a confamilial species.
The brown bullhead is a warmwater fish which shows partial metabolic compensation
to temperature change. It can be used as a basis for constructing hypotheses about
channel catfish overwintering behaviour.

Teleosts have a central nervous system thermoregulatory mechanism similar to
that of mammals (Crawshaw 1977). Once a fish has acclimated to a temperature,
small shifts in temperature can result in major shifts in metabolism, fluid-electrolyte
balance and acid-base relationships (Crawshaw 1977). Unlike mammals,
thermoregulatory centres in fishes can not maintain a constant internal temperature (Crawshaw 1977). However, Crawshaw et al. (1982a) concluded that neither the acid-base relationship nor metabolism were important in determining the behavioural response to temperature. Fishes may use the difference in temperatures between core temperature change in the anterior brainstem (medulla) and environmental temperature changes as detected by the peripheral sensory transducers (skin) to orient themselves in a heterothermal environment (Crawshaw and Hammel 1974; Neill 1979). Therefore, the precision of response to temperature change is greater in larger fishes than small fishes (Neill 1979).

The behaviour of the brown bullhead at low temperature has been well documented in the laboratory. The bullhead shows a high degree of compensation for spontaneous activity down to 5°C (Crawshaw et al. 1982b). That is, the degree of spontaneous activity observed at temperatures above 5°C is similar for each temperature at which bullheads were observed. Below 5°C, spontaneous activity is much reduced. At all temperatures the bullhead will partially bury itself for a period of time (Crawshaw et al. 1982b). The frequency of burials and time spent buried is inversely proportional to the ambient temperature. Once the bullhead has become dormant, the ability to rouse it is proportional to the ambient temperature (Crawshaw 1984). At these low temperatures the bullhead experiences respiratory arrhythmia, a common behaviour in hibernating animals (Crawshaw 1984). However, there is no evidence of discontinuous function (metabolic shutdown) that would be expected with hibernation (Crawshaw 1984).
Brown bullheads responded to a temperature gradient by moving towards warmer water. Given that lethal temperatures are avoided, the bullhead will always migrate to the warmest water in a thermal gradient (Crawshaw et al. 1982b). Falling water temperatures and photoperiod have no effect on the selection of water temperature in which to become dormant (Crawshaw et al. 1982b; Crawshaw 1984). That is, the falling water temperatures and shorter days that are characteristic of seasons changing from fall to winter, do not cause the bullhead to prepare for dormancy by selecting cooler water. The bullhead can complete acclimation to the preferred temperature range of 29 to 31°C in 24 hr (Crawshaw 1975).

A Temperature Dependent Model for Channel Catfish Behaviour

Using observations made during my study along with literature sources, a model of temperature dependent catfish behaviour was constructed from which predictions of the effect of STGS operating schedules on Red River channel catfish can be made.

A Statement of the Model

As previously described, the observations of wild brown bullheads in response to thermal plumes are consistent with the observations of channel catfish in response to the Cooks Creek thermal plume in this study. It therefore follows that the more quantitative observations of captive brown bullheads can also be used to describe more quantitatively the response of channel catfish to varying thermal regimes. The temperature dependent model for channel catfish behaviour states: 1) When the water temperature is above 5°C, catfish are active, having a high degree of spontaneous
activity, 2) When the water temperature falls below 5°C, the catfish enter a facultative dormancy characterized by reduced spontaneous activity, 3) Catfish will always select water temperatures which maximize surplus power.

Application Of The Model

The application of the temperature model predictions to the observations of channel catfish from this study more fully explains the differences in CPUE observed during the winter operation of the STGS. The model can be used to explain how channel catfish are entrained into the Cooks Creek thermal plume.

Normal Channel Catfish Behaviour

The temperature model for channel catfish behaviour can be used to describe the normal seasonal movements of channel catfish in the Red River system. As has been shown, the behaviour of channel catfish in the Red River outside of STGS operation is consistent with the temperature model for channel catfish behaviour. These observations can be interpreted to describe the normal seasonal behavioural patterns in channel catfish. In the autumn, when the Red River falls below 5°C, channel catfish enter a facultative dormancy, characterized by reduced spontaneous activity. In the spring, when the river temperature rises above 5°C, the channel catfish exit dormancy and increase activity (table 1; fig. 13). When the run-off floods the Red River, channel catfish move downstream, returning upstream after the flood subsides (fig. 13). Dames et al. (1989) found that 73% of channel catfish they tagged in the Missouri River moved upstream. The movements were generally from the main and border channel areas to the slower side channels, sloughs, and tributaries to
feed and spawn. The slower waters off the main and border channels provide spawning grounds. Male channel catfish establish nests in sheltered areas (Busch 1985). Channel catfish spawn between 21 and 29°C with 26°C considered optimum (Busch 1985). Red River channel catfish spawn in late June and early July (fig. 8). Because the specific timing of spawning in other river systems is dependent upon temperature (Busch 1985), it is reasonable to assume that the specific timing of catfish spawning in the Red River system is also dependent upon the water temperature. Though channel catfish activity is high, the spawning season is characterized by greater localized movements (Dames et al. 1989; Stang and Nickum 1985). After spawning, channel catfish activity remains high, and the distance travelled increases (Dames et al. 1989; Stang and Nickum 1985). In the autumn, when the river temperature is declining, channel catfish move downstream, leaving the tributaries and back-bays to overwinter in the main and border channels (Dames et al. 1989; Newcomb 1989; Todd et al. 1989). In contrast to the spring catfish movements, Dames et al. (1989) found that 73% of the channel catfish they tagged in the fall in the Missouri River were relocated downstream. Because of the depth of winter ice (up to 90 cm), the sloughs, back-bays, and tributaries along the Red River are not deep enough to support channel catfish during the winter. Therefore, all channel catfish found in the Red River back-bays and tributaries during the warmwater months are from the stock of channel catfish found in the Lower Red River and Lake Winnipeg during the winter months. This migration is accomplished by the time the river temperature falls to 5°C (fig. 6). During the winter, the channel catfish inhabit
the deep slow water of the main channel and enter a facultative dormancy (Hawkinson and Grunwald 1979; Lubinski 1981; Grace 1985; Newcomb 1989; Todd et al. 1989). This dormancy is characterized by reduced activity. Hawkinson and Grunwald (1979) and Lubinski (1981) have directly observed dormant, overwintering channel catfish. The channel catfish were covered with a fine layer of silt, presumably from long periods of inactivity. However, the dormant catfish avoided contact by the divers. The catfish also avoided the high energy habitats such as tail waters (Stang and Nickum 1985). The catfish oriented themselves into the current behind sand waves, rocks, logs, and other debris (Lubinski 1981). This use of current breaks and the selection of low energy areas of the river is consistent with the maximum surplus power principle in that the catfish were acting to conserve energy during the period of lowest metabolic scope. Below 5°C, the difference between standard metabolic rate (SMR) and active metabolic rate (AMR) is the least. In order to maximize surplus power (the difference between AMR and SMR), river areas that require the channel catfish to expend the least amount of energy (i.e. behind current breaks) are selected. Because the Red River has few current breaks and there are so many channel catfish in the Red River, channel catfish also move out to overwinter in Lake Winnipeg. The diffused flow in the Lake Winnipeg south basin allows channel catfish to maximize surplus power while using very little energy to maintain position.

Channel Catfish Entrainment

The STGS discharge of thermal effluent into Cooks Creek attracted Red River catfish. The thermal plume exiting Cooks Creek mixed with the Red River
flow and created an increasing gradient from the river channel into Cooks Creek. Catfish in the Red River encountered the thermal plume exiting Cooks Creek and followed the temperature gradient in to the creek. Following Neill's (1979) model, Red River catfish encountering the thermal plume would go through a series of undirected turns that would result in their moving up the thermal gradient, towards the preferred temperature, and thus into Cooks Creek. According to Bryan et al.'s (1990) maximum surplus power model, once catfish were in Cooks Creek they would continue up the creek towards the preferred temperatures. However, the highest ambient Red River temperature is at the lower end of the channel catfish preferred temperature range of 23 - 32.5\(^\circ\)C (Danzmann et al. 1991) and the maximum STGS outfall temperature of 30\(^\circ\)C (Baker 1994) is still below the high end of the preferred temperature range. The narrow breadth, uniform temperature profile, and 7.2 km length of creek channel between the STGS outfall and the Red River created an elongate, linear temperature gradient of 4 -15\(^\circ\)C. Catfish can either swim up or down the thermal gradient. Following the maximum surplus power model, a catfish would swim up the gradient, towards the preferred temperature. However physical obstructions such as riffles and beaver dams would prevent them from reaching the warmest water. Attempting to maximize surplus power, the catfish would hold below the obstructions until another factor such as crowding caused them to swim downstream, away from the holding areas. They would swim down the gradient until the crowding stimulus was reduced and the temperature cue had regained prominence. They would then reverse direction and swim up the gradient again. This process
would be repeated until the accessible reaches of Cooks Creek filled with catfish. As the creek filled with catfish, those swimming downstream away from crowding in the higher reaches would encounter a sharper decrease in temperature as the thermal plume entered the Red River. The more rapid change in temperature would cause them to slow and turn more quickly, heading back up the creek. When the Red River ambient temperature dropped as the season got colder, the temperature gradient where the Cooks Creek thermal plume mixed with the Red River water increased. This sharp temperature gradient at the Cooks Creek/Red River interface created a barrier to catfish trying to leave the creek. This created a temperature trap whereby catfish were held in the creek between their attempts to reach a preferred temperature and their avoidance of cold water. This temperature trap was first suggested by Richards and Ibara (1977) for a population of brown bullheads overwintering in a thermal effluent discharge channel on the Connecticut River. The channel catfish in Cooks Creek were never able to reach their preferred temperatures. Catfish in the thermal plume approached the preferred temperature during the summer when the STGS discharge temperature was 30°C. However, the winter discharge temperature of 15°C was below the preferred temperature range. According to the maximum surplus power model, swimming velocity towards the preferred temperature is proportional to the distance from the preferred temperature. Swimming velocity away from the preferred temperature is inversely proportional to the distance from the preferred temperature. Therefore, catfish would have on average swam at a greater velocity up the creek and at a slower velocity down the creek during the winter. The thermal
plume would then have been more attractive in the winter and the temperature trap stronger, at lower STGS discharge temperatures. The temperature trap would have held the channel catfish in Cooks Creek for the duration of winter STGS operation and subjected the catfishes to the variations in STGS operating schedule. STGS shutdowns caused the fish kills. During extended winter shutdowns the rapid heat dissipation (Baker, 1994) would have reduced the sharp temperature gradient at the mouth of Cooks Creek and would have allowed catfish in the lower reaches to escape to the Red River.

**Impacted Channel Catfish Behaviour**

With the normal annual channel catfish movement pattern in the Red River described, the effects of various STGS operating schedules can be seen by the changes in channel catfish movements during each period of STGS operation. During this study, observations from three different STGS operating schedules were used. During each of the observed STGs operating periods, the STGS operated under different conditions. The season of the year, amount of generation, amount of Red River flow, and the amount of Red River water diverted through the STGS to Cooks Creek varied among periods. After analysis, the three operating periods were ranked as to the impact of the STGS on the normal seasonal movement of channel catfish. The classification is as follows: the STGS had a minimum impact when it operated during December, 1992, and January, 1993; the STGS had an intermediate impact when it operated during October and November, 1991; the STGS had a maximum impact when it operated from August, 1987 to April, 1988.
The STGS had a minimum impact on normal seasonal movements of channel catfish in the Red River when it operated intermittently during the December, 1992, and January, 1993. When the STGS began operations the Red River was below 5°C. The channel catfish had withdrawn to overwinter in the Red River and Lake Winnipeg in a facultative dormancy. The relatively low flow of the Cooks Creek thermal plume was below 5°C by the time it reached the Red River and was rapidly diluted so that when it reached the overwintering area of the channel catfish in the Red River the catfish did not respond to it.

When the STGS began operating 15 October, 1991, the STGS had an intermediate impact on the normal seasonal movement patterns of Red River channel catfish. The Red River was at 15°C, and thus channel catfish were active and utilizing the sloughs and tributaries of the Red River. The channel catfish therefore encountered the Cooks Creek thermal plume and, following the third prediction of the temperature model for channel catfish behaviour, moved into Cooks Creek and continued up the creek towards the preferred temperature range. The channel catfish remained in the creek until the STGS ceased operations 16 November, 1991, and Cooks Creek returned to the normal ambient seasonal temperature.

The STGS had a maximum impact when it operated 4 August, 1987, to April, 1988. The high level of production prior to the Red River temperature falling to 5°C created an extended entrainment period lasting 86 days. During the entrainment period the percentage of Red River flow diverted through the STGS increased, resulting in an increase in the extent of the Cooks Creek thermal plume in the Red
River. This resulted in unnaturally high numbers of channel catfish in Cooks Creek. Recruitment into the Cooks Creek temperature trap may have continued through the winter.

The results of Macdonald’s (1988) investigation were incorporated into the STGS environmental impact assessment (SENES 1992). These results were also given significant consideration in the STGS operating license. However, Macdonald’s results and conclusions have since been shown to be derived from a unique STGS operating period with a unique combination of operating conditions. Macdonald’s (1988) observations were of an extreme STGS impact situation and should, considering the mitigation procedures now in place, be given less significance in the future licensing of the STGS.

The mitigation procedures recommended by Macdonald (1988) should continue and, in the case of the fish fence, be expanded. The fish fence installed at the mouth of Cooks Creek was seen as a panacea for the impact of the STGS on Red River fishes. The fence was originally intended to prevent the entrainment of channel catfish and the possible entrainment of walleye into the Cooks Creek thermal plume. Walleye have since been shown not to inhabit Cooks Creek during the winter months and channel catfish have been shown not to be normally drawn into the thermal plume during winter STGS operation. The continued installation of the fish fence is therefore not required to mitigate the effects of winter STGS operation on channel catfish. However, the fence does prevent the entrainment of less economically valuable species such as carp, white bass, black bullheads (*Ameiurus melas*), white...
suckers, and bigmouth buffalo (*Ictiobus cyprinellus*) and should be continued to be installed for winter STGS operations. For the fish fence to serve its original intent and be effective in preventing the entrainment of catfish under the conditions observed by Macdonald (1988), the use of the fence must be expanded to the openwater seasons. Since the majority of the catfish observed in Cooks Creek by Macdonald (1988) entered the creek prior to the Red River temperature falling to 5°C, the fence would have to be installed prior to STGS operation in the warmwater seasons for the fence to be effective. The most effective of Macdonald's (1988) recommendations, the modified shutdown procedure, should be continued, regardless of whether channel catfish are resident in the Cooks Creek thermal plume. The modified shutdown procedure ensures that any fish inhabiting the thermal plume do not undergo thermal shock when the STGS shuts down.
CONCLUSIONS

The temperature model for channel catfish behaviour is consistent with channel catfish movements in the Missouri and Mississippi Rivers. The model is also consistent with the normal seasonal movement patterns of channel catfish in the Red River. This broad spectrum of consistent observations validates the temperature dependent model for seasonal channel catfish behaviour. Because channel catfish were observed through a range of STGS operating schedules, the effect of future STGS operating schedules, within the described range of operating conditions, can be predicted.

(1) When the STGS began operating after the Red River temperature fell below 5°C, channel catfish were not recruited into Cooks Creek. According to the second prediction of the temperature model for channel catfish behaviour, overwintering channel catfish were dormant in the deep slow areas of the Red River and Lake Winnipeg. Because of the low channel catfish activity and the limited extent of the Cooks Creek thermal plume, the probability of channel catfish encountering and detecting and following the Cooks Creek thermal plume was lower. Therefore, the possibility of the STGS having an observable effect on channel catfish movement patterns is very low. There is an exception: if the STGS diverts more than 10% of the Red River flow for a continuous period of time, the probability that the Cooks Creek thermal plume will persist at temperatures high enough for channel catfish to detect increases.

(2) When the STGS operated while the Red River temperature was above 5°C,
channel catfish were recruited to the Cooks Creek thermal plume trap. As predicted by the temperature model for channel catfish behaviour, when the Red River temperature was above 5°C channel catfish were active and using the sloughs and tributaries such as Cooks Creek. This was observed in 1991 when the STGS operated 15 October to 16 November across the point which the Red River fell to 5°C. This was also observed in 1987 during the Macdonald (1988) investigation.

(3) The number of channel catfish recruited into Cooks Creek is dependent upon:

a) the length of time the STGS operates prior to the 5°C point in the Red River, and

b) the proportion of the Red River flow diverted through the STGS to Cooks Creek.

The longer pre-5°C STGS operating period in 1987 and the larger proportion of the Red River diverted down Cooks Creek resulted in many times more channel catfish being entrained in the Cooks Creek thermal plume in 1987-1988 than were observed in 1991-1992.

(4) Channel catfish will remain in Cooks Creek until the creek water temperature falls to 5°C. Because channel catfish will always move up a thermal gradient towards the preferred temperature range, once channel catfish enter Cooks Creek, they are trapped by their innate pursuit of preferred temperatures. Therefore, upon entering Cooks Creek, channel catfish are trapped until the STGS shutdown returns the creek to ambient Red River temperatures and channel catfish can exit the creek.

(5) The following possible STGS operating scenarios will lead to the following consequences:

i) if the STGS begins operating after the Red River temperature drops below
5°C, there will not be any channel catfish in Cooks Creek and channel catfish in the Lower Red River will not be susceptible to recruitment by the STGS thermal plume, ii) if the station begins operating before the Red River temperature falls below 5°C, then channel catfish will be recruited into the Cooks Creek thermal plume until the Red River temperature drops below 5°C, iii) the number of fish recruited is dependent upon a) the length of time the station operates while the river temperature is above 5°C b) the proportion of Red River flow diverted to Cooks Creek by the STGS.

iv) channel catfish entrained by the thermal plume will remain in Cooks Creek until the STGS shuts down and the creek returns to ambient water temperatures.

(6) If minimum impact or intermediate impact operating schedules are used in combination with the modified shutdown procedure, installation of a fish fence in the mouth of Cooks Creek is not necessary to prevent channel catfish kills during winter STGS operation.
LITERATURE CITED


Crawshaw, L. I., D. E. Lemons, M. Parmer, and J. F. Messing. 1982b. Behavioral and metabolic aspects of low temperature dormancy in the brown bullhead,


Green, D. J., and A. J. Derksen. 1984. The past present and projected demands on Manitoba's freshwater fish resources. Manitoba Department of Natural Resources Fisheries Branch MS report No. 84-4.


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APPENDIX 1

The following is a sample calculation for catch per unit effort (CPUE).

Where:

\[
\begin{align*}
\text{n} & = \text{The total number of channel catfish caught during the set,} & = 7 \\
\text{a} & = \text{The total area of gillnet in the set in m}^2, & = 125 \text{ m}^2 \\
\text{t} & = \text{The length of time for the set in hours,} & = 20 \text{ hr}
\end{align*}
\]

\[
\text{CPUE} = n\{(100/a)\times(24/t)\}
\]

\[
= 7\{(100/125)\times(24/20)\}
\]

\[
= 7\{(0.8)\times(1.2)\}
\]

\[
= 6.72
\]

The result of this calculation is a rate at which channel catfish were caught during the set. Seven channel catfish caught in a 125 m\(^2\) net set for 20 hr is therefore expressed as 6.72 channel catfish per 100 m\(^2\) of gillnet per 24 hrs.
APPENDIX II

The following pages are individual relocation maps for each channel catfish radio-tagged during this study. Pages 93 to 102 contain the relocation maps of channel catfish radio-tagged in the 1991-1992 field season. Pages 103 to 121 contain the relocation maps of channel catfish radio-tagged in the 1992-1993 field season.