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Role of Temperature, Dissolved Oxygen, and Backwaters in the Winter Survival of Freshwater Drum (*Aplodinotus grunniens*) in the Mississippi River

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Published in *Canadian Journal of Fisheries and Aquatic Sciences*, Vol. 49, No. 1 (January 1992) at DOI: 10.1139/f92-021

Recommended Citation

Bodensteiner, Leo R. and Lewis, William M. "Role of Temperature, Dissolved Oxygen, and Backwaters in the Winter Survival of Freshwater Drum (*Aplodinotus grunniens*) in the Mississippi River." (Jan 1992).

Role of Temperature, Dissolved Oxygen, and Backwaters in the Winter Survival of Freshwater Drum (*Aplodinotus grunniens*) in the Mississippi River

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Bodensteiner, L. R., and W. M. Lewis. 1992. Role of temperature, dissolved oxygen, and backwaters in the winter survival of freshwater drum (*Aplodinotus grunniens*) in the Mississippi River. Can. J. Fish. Aquat. Sci. 49: 173–184.

Annual winter impingement of large numbers of freshwater drum (*Aplodinotus grunniens*) on screens of a power station intake on the Mississippi River led to an investigation of the cause of impingement. Impingement occurred most abundantly in winter and early spring and primarily involved juvenile fish. Pronounced drift of moribund and dead fish was found in the main channel above and below the power station in late winter. Laboratory studies indicated that juvenile freshwater drum became disoriented, incapacitated, and suffered increased mortality as water temperature dropped to 1°C and below. In winter and early spring, temperatures were 0°C in the main and side channels of the river, but pockets of water above 1°C existed in some backwaters. Dissolved oxygen concentrations declined through the winter, becoming very low in some backwaters. An aggregation of fishes including freshwater drum was observed in the warmer backwaters. Variations in river flow and dissolved oxygen depletion in some backwaters were postulated to cause periodic disruption of the thermal refuges and an associated appearance of incapacitated and dead juvenile freshwater drum in the drift. If man-induced changes to the river eliminate backwater winter refuges, the ichthyofauna of the river could ultimately be altered.

Des quantités importantes de malachigans (*Aplodinotus grunniens*) viennent se heurter à chaque hiver aux grilles de protection de la prise d'eau d'une station hydroélectrique de la rivière Mississippi et une étude visant à en déterminer les causes a été réalisée. Le phénomène se produit surtout en hiver et au début du printemps et intéresse généralement des poissons juvéniles. Des quantités appréciables de poissons moribonds ou morts ont été décelés, à la fin de l'hiver, dérivant dans le chenal principal tant en amont qu'en aval de la station. Des études en laboratoire ont montré que les malachigans juvéniles devenaient désorientés, incapables de réagir et présentaient un taux de mortalité accru lorsque la température tombaient à 1°C ou moins. En hiver et au début du printemps, des températures de 0°C ont été notées dans le chenal principal et les chenaux latéraux du cours d'eau, mais des zones à température supérieure à 1°C ont été décelées dans des zones de contre-courant. Les teneurs en oxygène dissous diminuaient tout au long de l'hiver pour tomber à de très faibles valeurs dans certaines zones de contre-courant. Un groupe de poissons comprenant des malachigans a été décelé dans ces eaux plus chaudes. On formule l'hypothèse que les variations de l'écoulement et l'absence d'oxygène dissous dans certaines zones de contre-courant ont pour effet de perturber de façon périodique les refuges thermiques et que cela correspond à l'apparition de malachigans juvéniles incapables de réagir, ou morts, dans les eaux d'écoulement. La réalisation de travaux ayant pour effet de faire disparaître les refuges d'hiver situés dans les zones de contre-courant pourrait éventuellement perturber l'ichthyofaune du cours d'eau.

Received December 30, 1988
Accepted July 30, 1991
(J9996)

Reçu le 30 décembre 1988
Accepté le 30 juillet 1991

During winter, large numbers of fishes have been observed by station fishery biologists impinged on the cooling water intake screens of the Quad Cities Nuclear Station (QCS), located at River Mile 506.4 (RM, above the confluence with the Ohio River) on Pool 14 of the Mississippi River. Although several species were affected, the freshwater drum (*Aplodinotus grunniens*) was selected for detailed study because it is one of the most abundant species in the fish communities of large rivers of the central United States and has the greatest latitudinal range of North American freshwater fishes (Barnickol and Starret 1951; Scott and Crossman 1973). In the section of river adjacent to Illinois, freshwater drum greater than 250 mm total length are harvested commercially, and the mean annual harvest from Pool 14 of 11 812 kg from 1980 through 1985 ranks third among commercial species taken from that pool (UMRCC 1982–85). Estimated standing stock of freshwater drum in Pool 14 greater than 220 mm ranged between 99 and 309 fish$\cdot$ha^{-1} for the same period (LMS 1986).

Observations of freshwater drum near the surface at the power station intake indicated that these fish were physically incapacitated, incapacitation being characterized by disoriented and uncoordinated swimming behavior with alternating periods of quiescence (L. Bodensteiner, pers. obs.). We hypothesized that small freshwater drum were intolerant of some environmental factor present in the main channel of the Mississippi River during winter.

Our first objective was to determine the spatial occurrence of incapacitated freshwater drum: were they limited to the vicinity of the power plant, confined to Pool 14, or did they occur on a widespread basis with incapacitated fish drifting

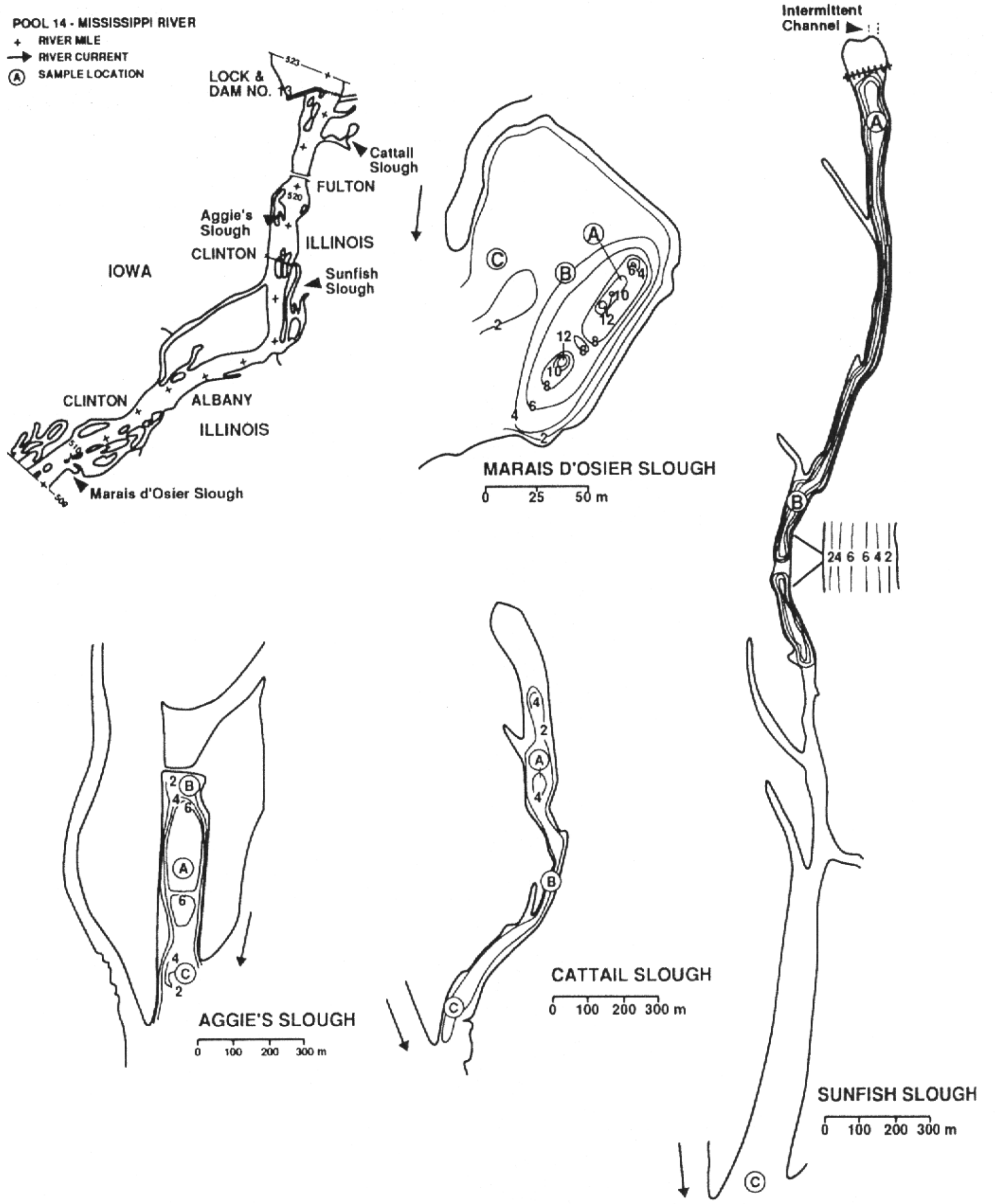

FIG. 1. Location and morphometry of backwater study sites in Pool 14, with 2-m contours indicated on individual site maps.

between pools? The second objective was to determine the factor affecting the health of the fish resulting in incapacitation. Field studies were conducted during the winters of 1983–84 and 1984–85, the interpretation of which was aided by some earlier laboratory studies reported here for the first time.

Study Sites

Our study sites were located on Pool 14 located at 42°N latitude forming the border between Iowa and Illinois. Mississippi River navigation pools, including Pool 14, are broadly characterized as having the upper ends relatively unmodified from the original river with deep sloughs and wooded islands, the midsections with large open areas of marsh habitat, and the lower ends with deeper, open water markedly affected by siltation (Sternberg 1971; Rasmussen 1979). Pool 14, with a surface area of 4165 ha, comprises the section of the river from Lock and Dam 13 at RM 522.5 to Lock and Dam 14 at RM 493.3 (Fig. 1).

Most sampling took place in tailwaters and backwaters. Tailwaters are defined for fisheries purposes as the region of the main channel, the main channel borders, and water directly below a navigation dam to 0.8 km down river characterized by turbulence (Sternberg 1971). Backwaters, composed of sloughs and river lakes and ponds in this study, are characterized primarily by lack of current (Sternberg 1971). Two slough sites, Marais d'Osier Slough and Sunfish Slough, were examined in 1984 and 1985. Cattail Slough and Aggie's Slough were added in 1985. We selected the deepest available slough sites in Pool 14, assuming that differences in environmental conditions, especially temperature, between the two types of habitat were most likely to be detected there. Substrate in the sloughs ranged from hard clay to loose silt and gravel. Human activities (e.g. dredging and gravel quarrying) have resulted in greater depths relative to many other sloughs in Pool 14 which have been severely aggraded by sedimentation in recent years (McHenry et al. 1984).

Materials and Methods

Drift of Freshwater Drum in Tailwaters

We sampled tailwater areas of Lock and Dam 13 and Lock and Dam 14 in 1984 and 1985 to examine the main channel for drifting freshwater drum during late winter. Tailwaters were selected because the area of this habitat adjacent to the lock facilities is outside the line of navigation, so sampling is not disrupted by boat traffic. Also, the river is constricted at this point, and the increased current enabled a greater proportion of the river volume to be sampled in a given period. Flow with its associated drift from upstream lotic habitats converges at this location.

On 21–23 February 1984, six nets consisting of a 1-m-diameter hoop with a 6-m conical bag of 0.6-cm bar mesh were anchored on a transect perpendicular to river flow approximately 150–200 m downstream from each dam (Fig. 2, for example). Ice floes were present in the channel. Nets were set for 24 and 48 h in the Pool 13 tailwater and for 24 h in the Pool 14 tailwater. Freshwater drum in the catch were counted and total length (TL) was measured. Current was measured near each net in place at 0, 24, and 48 h by a direct-read velocity meter lowered to 0.5 m above the bottom at the estimated position of the net. Flow through each net was calculated by multiplying net cross-sectional area by velocity. Because estimated sample volumes ranged from 221 000 to 962 000 m^3, catch was adjusted to number per 100 000 m^3 of water.

In late winter of 1985, this sampling scheme was repeated over the 1984 transect in the Pool 13 tailwater, where conditions were less hazardous at high water levels. To reduce clogging by debris and increase sampling effectiveness, we changed net design to a 1.13-m-diameter hoop with a 4-m cylindrical bag of 1.0-cm bar mesh. Between 16 and 20 nets were used depending on river conditions at 22 net locations (Fig. 2). Samples were collected 6–12 and 21–27 March 1985 at 24-h intervals. Ice breakup on Pool 13 began during the first sample period. Statistical decisions were made using an alpha of 0.05.

Fish Collections and Observations in Sloughs

In 1984, fish were sampled 20–21 March by deploying 1.8 × 0.9 m rectangular frame trap nets with 13-mm bar mesh and a single 15-m lead on the bottom under the ice. Four nets were set in Marais d'Osier Slough and one in Sunfish Slough for 1 d. Trapnet sampling was repeated in all four sloughs 21–26 March 1985 with two or three nets at each site set for 4 or 5 d. Captured fish were identified and measured.

Further observations of fish in the backwater sites were made in 1985 with SCUBA. On 5 and 6 February the deepest locations at Marais d'Osier Slough and Sunfish Slough were examined by a diver. Dives were performed at these sites again on 21 February, and the deepest area of Cattail Slough was examined on 22 February. Lack of visibility prevented examination of Aggie's Slough. The diver spent 60–75-min examining the bottom within a 45-m radius of the entry hole. A 200 000-candlepower hand-held light was used for illumination. Species composition, size composition, and numbers of fish were estimated and behavior was observed.

State of Health

Physical characteristics of incapacitated freshwater drum were compared with healthy individuals to determine if differences were present that could account for the apparent difference in the state of health. Incapacitated fish, characterized by their inability to escape impingement by the slight current at the barrier net, were collected near the intake of QCS in March 1981. Fish that appeared active and healthy were collected by seining in the Marais d'Osier Slough site during this period.

All fish were frozen and transported to the laboratory. After thawing, individual lengths and weights were recorded and fish were necropsied. Seven characters were examined: (1) fluid in the body cavity, (2) gall bladder distension, (3) bile color, (4) muscle texture, (5) liver color, (6) liver weight, and (7) presence of material in the gut. Body condition factor (K) was calculated by dividing weight (grams) by the cube of length (TL, in millimetres) and multiplying by 100 000. The liver somatic index (LSI) was calculated by dividing the wet weight of the liver (grams) by the body weight (grams) and multiplying by 100. Gonad weight was not excluded from body weight, since all fish were immature. Statistical comparisons between groups were made using an alpha of 0.05.

As an index of nutritional status, total lipids were measured in a sample from each collection. Carcasses were dried to a constant weight at 60°C in a vacuum of −80 kPa and weighed to determine moisture content. Dried carcasses were individually ground through a number 40 screen in a Wiley shearing mill. A sample between 2 and 4 g was weighed to the nearest 0.0001 g. The sample was refluxed for 4 h in diethyl ether in a Goldfisch fat extractor. The solvent was then evaporated from the tared container, and the quantity of lipids present was determined by subtraction.

Physical and Chemical Measurements

In 1984 we measured temperature and dissolved oxygen on 18–19 January, 8–9 February, 6 March, and 21–22 March in Marais d'Osier Slough and in an adjacent side channel where there was a pronounced current. Sunfish Slough was examined 9 February and 6 March. Vertical changes in water temperature were recorded at 2-m intervals from surface to bottom to the nearest 0.05°C during the first three sampling periods. Dissolved oxygen was measured 0.5 m above the bottom with a polarographic probe attached to a 1.9-cm-diameter perforated plastic pipe used to contain the thermistor.

In 1985, sampling procedures were modified so that measurements were repeated at three locations in each slough. Temperature and dissolved oxygen were measured at surface, middepth, and near the bottom at the point of maximum depth near the slough confluence with the channel, midslough, and distal to the confluence and also in the main channel border down river of Marais d'Osier Slough at RM 508. Two other backwaters, Cattail Slough and Aggie's Slough, were added to the study, and the four backwaters and the main channel border were examined on 12 and 28 December, 16 January, 5–7 and 20–22 February, and 9–11 and 25–27 March.

To characterize the source of heat in the backwater sites, substrate temperatures were also examined in 1985 on each sampling date at the deepest sample location in each site. A 1.9-cm-diameter plastic pipe fitted with a metal point was pushed into the substrate. Four thermistors flush with the pipe surface and exposed to the outside at the bottom and 30, 60,

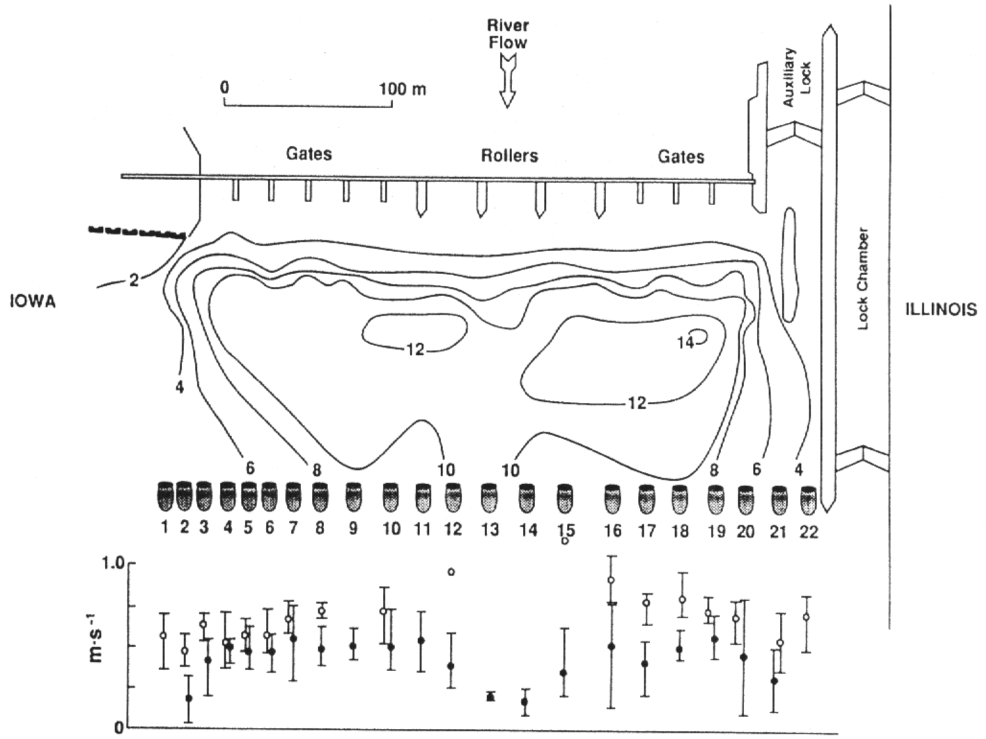

FIG. 2. River morphometry and drift net locations in the Pool 13 tailwater in 1985. Contours are 2-m intervals at normal pool. Mean water velocity and range are indicated for each net location (solid circles: 6–12 March; open circles: 21–27 March).

and 90 cm deeper were used simultaneously to measure substrate temperatures 5 min after insertion.

To examine other possible causes of debilitation in freshwater drum, we used a nonmetallic Kemmerer bottle to collect two water samples 0.5 m above the bottom at the deepest sample location in the sloughs and middepth at the main channel border. One sample was preserved for analysis of total concentrations of copper, iron, and zinc, as indicators of changes in metal species concentrations in the water column as winter progressed. Dissolved carbon dioxide, hydrogen sulfide, total ammonia, methyl orange alkalinity, and pH were measured in the other sample. Samples were taken on 12 and 28 December, 16 January, 5–7 and 20–22 February, and 9–11 and 25–27 March. Metal analyses were not conducted on the 12 December sample.

Laboratory Study

To examine the relationship between temperature and state of health of freshwater drum, laboratory studies were conducted in 1982–83. Fish for the study were collected by shoreline seining in Rend Lake, Illinois (38°N, 89°W), during the fall of 1982, when water temperatures were 21–25°C. After transport to the laboratory, water temperature was initially lowered to 15°C for 14 d and then raised to 20°C to allow effective treatment of fungus and facilitate prophylactic measures for other pathogens over a 30-d period. Feed was offered on alternate days until initiation of the experiment. When disease was no longer evident, fish were distributed in the experimental facility, which consisted of six 700-L covered circular tanks each equipped with a 1-hp water chiller, a supply of dechlorinated tap water, and an incandescent 40-W light source. Two tanks were assigned to each of the nominal final temperatures of 1, 5, and 10°C, and fish were randomly stocked with four tanks receiving 39 fish each and two tanks 40 fish each. Water temperature was lowered at a maximum rate of 1°C·d^{-1} and photoperiod was adjusted from 12L:12D to 9L:15D during this period. Final temperatures were set and maintained by a thermostatically controlled relay. Tanks set to 10°C were ±1°C 92.6 and 95.1% of the period and ±2°C 98.6 and 96.7% of the period with extremes of 6 and 14°C; tanks set to 5°C were ±1°C 82.7 and 93% of the period and ±2°C 91.3 and 98.3% of the period with extremes of 1 and 9°C; and tanks set to 1°C were ±1°C 85.2 and 92.2% of the period and ±2°C 90.1 and 100% of the period with extremes of 0 and 4°C based on daily temperature readings. Mortality also was recorded daily. After 12 d at the final temperature, a group of fish was removed from each tank to determine osmolality. Three further removals occurred at 45-d intervals. Since a portion of the fish was removed initially and then again at 45-d intervals, overall mortality was assessed for each of the three intervals based on fish remaining at the beginning of the interval.

At the conclusion of each sample period, individual fish were administered a sharp blow to the head and measured. The caudal peduncle was severed, and blood was collected in heparinized hematocrit capillary tubes. Samples were refrigerated at 4°C up to 3 h and then spun for 5 min in a clinical centrifuge. The plasma fraction was separated from the packed cells, and an 8-μL plasma sample was inserted into a Wescor 5100C Vapor Pressure Osmometer (sensitivity ±2 mosm (=2 mmol·kg^{-1})) with at least one replicate per fish.

To compare plasma osmolality of fish held at the three temperatures in the laboratory with both healthy and incapacitated fish from the river, blood samples were taken from seven fish collected by 24-h trapnet sets in the Marais d'Osier Slough backwater site on 21 March 1984 and from eight fish collected

TABLE 1. Daily discharges and catch of freshwater drum by drift nets in late winter 1984 and 1985.

Tailwater	Date	Catch	Sample volume $(\mathrm{m}^3 \times 10^5)^a$	Freshwater drum·$\mathrm{m}^{-3} \times 10^5$	River discharge $(\mathrm{m}^3 \times 10^5)^b$
			February 1984		
Lock and Dam 13	21–23	5	2.26	2.20	998
	22–23	2	2.48	0.80	1675
Lock and Dam 14	21–22	5	3.50	1.42	2037
			March 1985		
Lock and Dam 13	6–7	2	3.98	0.50	1598
	7–8	4	7.38	0.54	1675
	8–9	24	6.37	3.76	1861
	9–10	23	6.26	3.68	1979
	10–11	45	6.86	6.55	2000
	11–12	5	6.52	0.77	1998
Lock and Dam 13	21–22	3	6.04	0.50	2091
	22–23	20	5.94	3.37	2086
	23–24	12	6.79	1.77	2159
	24–25	19	7.63	2.49	2197
	25–26	14	9.36	1.50	2224
	26–27	11	9.62	1.14	2297

[a] Estimated from flow measurements at each net at the beginning and end of each sample period.
[b] Data provided by the U.S. Army Corps of Engineers, Rock Island District.

from a 2-h set of the power station intake barrier net on 24 February 1984. All fish were transported to the power station environmental laboratory, held for 4 h while warming to 7°C, individually netted, administered a sharp blow to the head, and measured. The caudal peduncle was severed and two heparinized capillary tubes of blood were collected from the caudal artery. Blood samples were treated the same as those from the laboratory-held fish with at least one replicate per fish. Statistical decisions comparing plasma osmolality between groups were made using an alpha of 0.05.

Results

Drift of Freshwater Drum in Tailwaters

Sampling in the Pool 13 tailwater for 2 d in 1984 yielded seven freshwater drum (Table 1); the Pool 14 tailwater yielded five freshwater drum in the 1-d sample. The daily catches adjusted for flow were 2.20 and 0.80 freshwater drum·100 000 m^{-3} in the Pool 13 tailwater and 1.42 freshwater drum·100 000 m^{-3} in the Pool 14 tailwater. Catch in the Pool 13 tailwater may have been reduced in the second day of sampling by the entanglement of the two nets in the center of the river. This problem was not encountered in subsequent samples.

Two of the captured freshwater drum were dead and decaying. Cause of death could not be determined. The fresh fish were 89–147 mm TL with a mean of 126 mm. The two decaying fish had no caudal fins, and total lengths were estimated to be 104 and 230 mm.

Samples from the drift in the Pool 13 tailwater after 12 d in late winter of 1985 totaled 182 freshwater drum. Effort from 6 to 12 March was 97 net-days yielding 103 freshwater drum, and effort from 21 to 27 March was 100 net-days with a catch of 79 freshwater drum. Effort at a particular net location within a sampling period varied from 2 to 6 d. Daily catch per 100 000 m^3 ranged from 0.50 to 6.55 for 6–12 March and 0.50 to 3.37 for 21–27 March (Table 1). Distribution across the channel was nonuniform during the 6–12 March period (Fig. 3); the daily catch of 1.13 freshwater drum per net-day at the 11 lateral net positions (six on Iowa side and five on Illinois side) was significantly greater than the 0.13 fish·net-day^{-1} at the 11 central net positions (Mann–Whitney test, $P = 0.007$). No significant difference in distribution was detected during the 21–27 March period when the daily catch per net-day was 0.78 in the lateral nets and 0.64 in the central nets (Mann–Whitney test, $P = 0.68$). Daily catch per net-day was not correlated with river discharge (Spearman's rho, 6–12 March: $P = 0.59$, 21–27 March: $P = 0.70$).

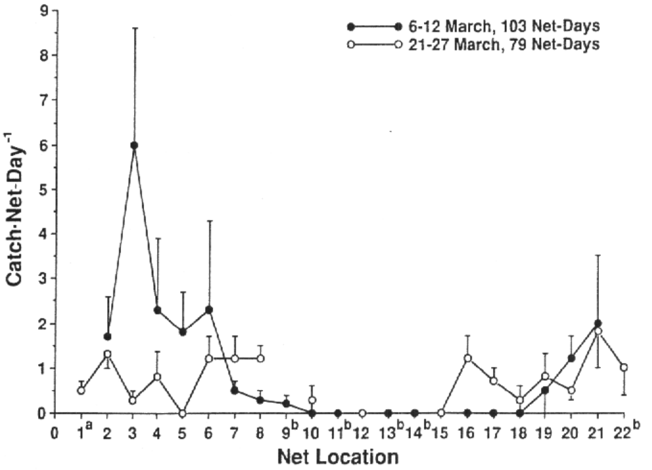

FIG. 3. Catch of freshwater drum by net location in the Pool 13 tailwater during each sample period in 1985. Vertical bars represent either plus or minus 1 SE as space allowed.

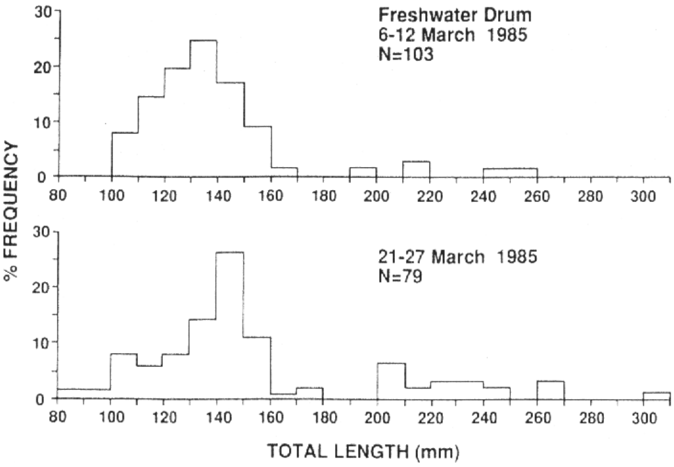

FIG. 4. Length frequency distributions of freshwater drum collected in the Pool 13 tailwater in 1985.

Nearly all (98%) of the freshwater drum in 1985 were live or had only recently died versus being in an advanced state of decay. Small fungal growths were noted on the pectoral or pelvic fins in 33% of the fresh fish. For 6–12 March the modal length group was 130–139 mm, with 90% of the fish less than 160 mm (Fig. 4, top panel). For 21–27 March the mode had increased slightly to 140–149 mm, and 75% of the fish were less than 160 mm (Fig. 4, bottom panel). A second smaller group (19%) was 200–270 mm long. The length distributions of fish from both periods indicated that small fish, of the sizes characteristic of the first or second year of life, were most susceptible to factors causing incapacitation. Their presence in both tailwaters also indicated that drifting fish were not confined to Pool 14 and that the causative agent was not specific to this pool.

Fish Collection and Observations in Sloughs

In 1984, the four nets set for 1 d in Marais d'Osier Slough caught 162 freshwater drum ranging from 95 to 202 mm TL with the mode at 120–129 mm (Fig. 5, top panel). Temperatures in the vicinity of the nets ranged from 0.55 to 1.40°C and dissolved oxygen from 8.2 to 12.8 $mg \cdot L^{-1}$. The single net in Sunfish Slough contained no freshwater drum after 1 d (3.85°C; 1.9 mg dissolved $oxygen \cdot L^{-1}$). In 1985, trapnet effort ranged from 8 to 15 net-days at each site, and adjusted catches increased from 2.3 freshwater $drum \cdot net\text{-}day^{-1}$ in Sunfish Slough to 5.0 in Aggie's Slough, 43.8 in Cattail Slough, and 102.8 in Marais d'Osier Slough.

Length frequency distributions were unimodal, with most fish 80–170 mm TL, except in Cattail Slough, where the distribution was distinctly bimodal. There the group of large fish ranged from 180 to 260 mm with a second mode at 210–219 mm. Primary modal length groups were 140–149 mm (Marais d'Osier Slough) 120–129 mm (Sunfish Slough), 130–139 mm (Aggie's Slough), and 140–149 (Cattail Slough) (Fig. 5, bottom four panels). Length frequency distributions from trapnet capture in the backwaters were very similar to the stationary net capture in the main channel tailwaters (see Fig. 4).

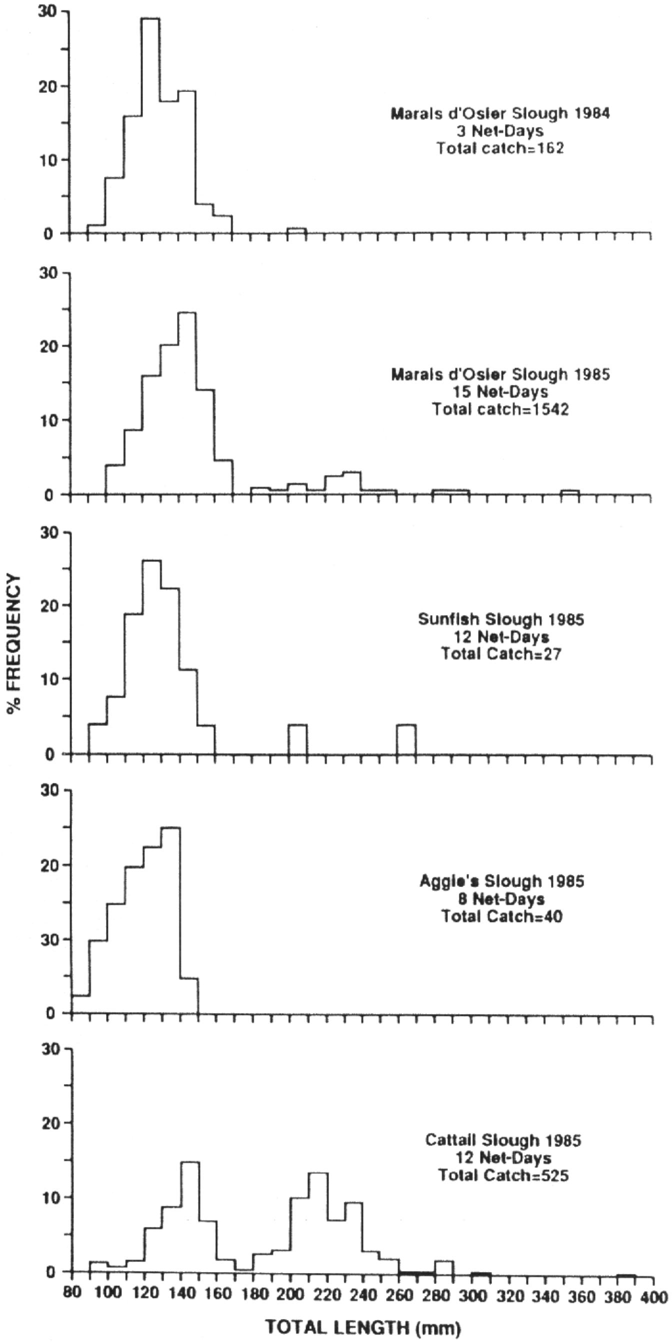

FIG. 5. Length frequency distributions of freshwater drum captured by trap nets in the backwater sites in March of 1984 and 1985.

On 5 February at the Marais d'Osier Slough site an estimated 75 freshwater drum from 50 to 100 mm TL were observed resting on the bottom in shallow, circular depressions with a diameter slightly greater than the length of the fish. Visibility was less than 1 m. These fish allowed the approach of the diver and light within 25 cm. Larger freshwater drum estimated to be 150–200 mm TL were seen swimming 15–30 cm above the bottom and appeared to avoid the diver. In Sunfish Slough, two freshwater drum in the 50–100 m TL range were found on the bottom where visibility was 2 m. On 20 February in Marais d'Osier Slough, 35 larger freshwater drum (TL > 150 mm) were seen swimming, and 10 in the 50–100 mm length group were found on the bottom. Fish activity was greater than on the previous dive. In Sunfish Slough, visibility had increased to 6 m, but no live fish were seen. Dead fish, including 20–30 freshwater drum ranging from 70 to 250 mm, were found on the bottom. In Cattail Slough, three freshwater drum, all less than 150 mm TL, were seen swimming near the bottom, and

TABLE 2. Mean and range of size, condition factor (K_{TL}), and liver somatic index (LSI) of freshwater drum impinged on the intake barrier net at QCS and seined from a Marais d'Osier Slough backwater in March 1981. No significant differences were detected between collections (Student's *t*-test, $P < 0.05$).

	Barrier net		Seine haul	
	N	Mean (range)	*N*	Mean (range)
Total length (mm)	113	129 (94–264)	63	136 (90–345)
Body weight (g)	113	27 (7–243)	63	50 (6–698)
K_{TL}	113	1.02 (0.62–1.45)	63	1.00 (0.75–1.70)
Liver weight (g)	90	0.28 (0.04–1.65)	54	0.22 (0.05–0.84)
LSI	90	1.05 (0.34–1.85)	54	1.16 (0.48–2.22)

TABLE 3. Mean percent body fat by 10-mm length group of freshwater drum collected from the barrier net at QCS and from the gravel quarry in Marais d'Osier Slough in March 1981.

Length group (mm)	Barrier net		Gravel quarry	
	N	% body fat	*N*	% body fat
70–79	2	5.10	7	4.73
80–89	27	5.41	14	4.91
90–99	26	5.75	9	5.02
100–109	32	5.66	18	7.81
110–119	21	6.12	10	5.61
120–129	6	4.93	2	5.83

three dead ones were found on the bottom. Turbidity in Aggie's Slough prevented visual observations.

The presence of large numbers of apparently healthy small freshwater drum in the backwaters, while similar-sized incapacitated fish were drifting in the main channel, indicates that the factor causing incapacitation was not present in backwater habitat. Further, the sedentary behavior of small fish in the backwaters in midwinter suggests that shelter from lotic habitat is required during winter.

State of Health

Based on subjective assessment of appearance, gross indications of starvation including gall bladder distention, clear bile, and watery muscles were not present in fish from the backwater or from the barrier net. Liver color and texture were similar in both groups. Ingested material was not present in any stomachs, but highly digested matter was found in the posterior segment of the intestine in 20% of the barrier net sample and 25% of the backwater sample. Fluid in the body cavity, based on observable flow from a midline incision when the fish was held upright, occurred in 36% of the barrier net fish and 57% of the backwater fish. Mean condition factor was slightly higher in the barrier net sample, but the difference was not significant (Table 2). LSI was higher in the backwater sample, but this difference also was not significant. Lipid content was similar between the two samples for all size groups (Table 3).

One nematode parasite was commonly noted, and it was present in fish from the backwaters and from the barrier net. The nematode, which was only found in the oculo-orbital sockets of the fish and ranged in size up to 150 mm, was identified as a member of the genus *Philometra*. The presence of nematodes was outwardly indicated by a dark red to black ring around the margin of the eye, and the eye was exopthalmic. In the March 1981 samples the parasite was present in 58.6% of the fish from the backwater and 60.0% of those from the barrier net. No other parasites or diseases were evident. The lack of distinction between collections indicates that the cause of incapacitation cannot be attributed to a prior poor state of health.

Physical and Chemical Measurements

Temperature increased with depth in the sloughs. In the deepest area of Marais d'Osier Slough in January 1984, temperature near the bottom was 3°C, in contrast with the 0°C temperature throughout the side channel. Similar results were obtained during the February and March samples, following a general trend of increase in temperature with an increase in depth at any given sample point. Maximum temperature on 8 February was 5.20°C and on 6 March was 2.70°C, again at times when the side channel we measured was at 0.00°C. Minimum dissolved oxygen concentrations were 8.2, 4.1, and 2.1 $mg \cdot L^{-1}$ for each of these three sample periods, and these concentrations occurred at points that corresponded to maximum temperatures. Elevated temperatures were also found in Sunfish Slough in 1984, increasing with depth and distance from the confluence with the river to a maximum of 4.20°C at 5.0 m on 9 February; instrument limitations prevented bottom temperature measurement (8 m depth). Dissolved oxygen was very low throughout the water column, ranging from 1.4 down to 0.5 $mg \cdot L^{-1}$ at the point of maximum depth. On 6 March, maximum water temperature had fallen to 1.00°C, while dissolved oxygen had increased to 12.8 $mg \cdot L^{-1}$ at the same point. In the period between samples the pool stage measured at the Lock and Dam 13 tailwater had risen from 1.95 m to a peak of 3.71 m on 2 March, falling to 3.23 m on 6 March. This rise caused water to flow from the channel into the slough through an intermittent connection at the upper end.

Water temperature profiles at the four backwater sites examined during the winter of 1984–85 were similar to profiles of the previous winter. At all four sites, water temperature was highest near the bottom (Fig. 6). Maximum temperatures under complete ice cover were 2.65°C at the Marais d'Osier Slough site, 4.60°C at the Sunfish Slough site, 1.40°C at the Aggie's Slough site, and 3.15°C at the Cattail Slough site during periods when the main channel was at or near 0°C.

In 1984–85, dissolved oxygen decreased at all sites to minimum concentrations on 5 and 20–21 February, in contrast with the continually high levels at the main channel site (Fig. 6). The lowest concentrations of 1.2 $mg \cdot L^{-1}$ occurred in Sunfish Slough, the site of the extreme low concentration of 0.5 $mg \cdot L^{-1}$ the previous winter. Vertical profiles showed declining dissolved oxygen concentrations from surface to bottom, while ice cover was intact, except in sunfish Slough where concentrations were uniform throughout the water column. Warm rainy weather on 21 February 1985 caused holes and cracks in the ice cover and could have altered the physical/chemical profile so that it differed from sites examined the previous day.

Hydrosoil temperatures increased with depth into the substrate at all four backwater sites (Fig. 7). Maximum temperatures occurred 90 cm into the substrate at all sites and ranged from 3.75°C in Cattail Slough on 11 March to 6.25°C in Aggie's Slough on 28 December. Minimum substrate temperatures at each site were recorded on the bottom and ranged from 0.65°C in Aggie's Slough on 16 January to 2.10°C in Sunfish Slough on 11 March. The greatest difference in temperature over the 90-cm distance was 2.55°C in Marais d'Osier Slough and

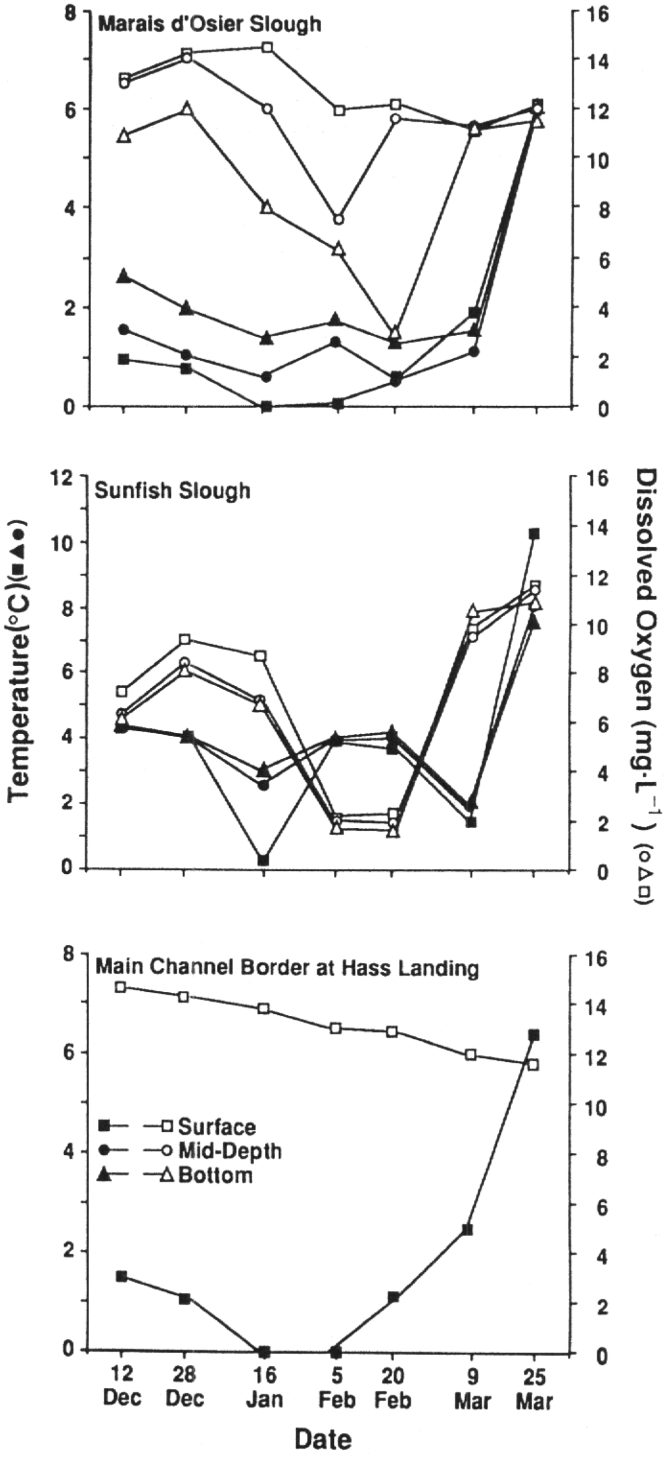

FIG. 6. Temperature and dissolved oxygen profiles at selected backwater and main channel border sites during 1984–85.

2.85°C in Cattail Slough on 20 February, 2.90°C in Sunfish Slough on 11 March, and 4.75°C in Aggie's Slough on 28 December. Neither absolute temperature nor temperature differences between strata were related to water depth. Substrate temperatures were also independent of substrate composition and compaction.

The highest unionized ammonia (NH_3-N) concentration was calculated to be 0.004 mg·L^{-1}. Dissolved carbon dioxide ranged from 10 to 48 mg·L^{-1}, and methyl orange alkalinity had extremes of 88 and 208 mg·L^{-1}. The pH varied from 6.80 to 7.95. Hydrogen sulfide was not detected in any of the samples. The highest total concentrations of copper, iron, and zinc in the backwaters were 0.068, 3.53, and 0.161 mg·L^{-1}, respectively, with similar concentrations in the main channel.

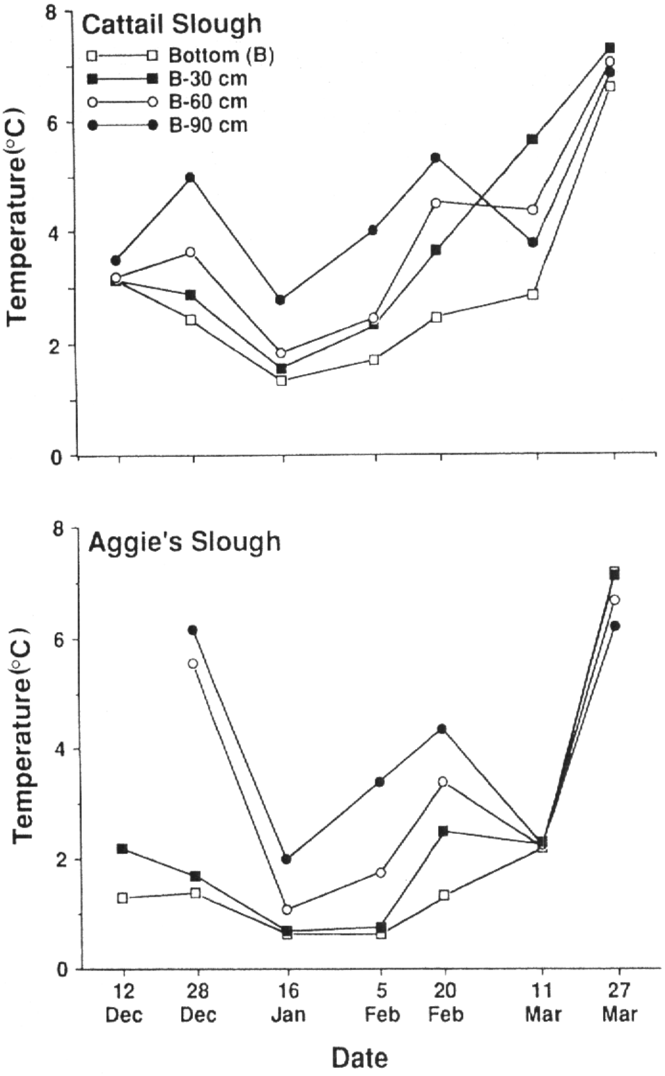

FIG. 7. Substrate temperature profiles of selected backwater sites during 1984–85.

The most obvious differences between the lotic channel habitat and the lentic backwater habitat were in temperature and dissolved oxygen. Warmer temperatures were available to fish in the backwaters, but unlike channel habitat, some backwaters were susceptible to dissolved oxygen depletion in midwinter, compromising their suitability as winter refuges.

Laboratory Studies

Mortality at 1°C was 56, 29, and 83% during the 0- to 45-d, 46- to 90-d, and 91- to 135-d periods; mortality at 5°C was 41, 33, and 29% during the three successive periods; and mortality at 10°C was 33, 29, and 43% for the three periods. Mortality was similar at all three temperatures during the 46- to 90-d period, but it was highest at the 1°C during the 0- to 45-d and 91- to 135-d periods. In addition, two malfunctioning thermostat relays yielded important information regarding behavior at low temperature. One of the 1°C tanks continued cooling within a 24-h period to 0°C. Fish in this tank demon-

TABLE 4. Mean plasma osmolality and size of freshwater drum held at low temperatures in the laboratory and collected from Pool 14 during winter. Significant differences ($P < 0.05$) indicated by different letters.

	Laboratory tanks												
	1°C			5°C			10°C				Pool 14		
	N	mosm (1 SE)	TL	*N*	mosm (1 SE)	TL	*N*	mosm (1 SE)	TL		*N*	mosm (1 SE)	TL
0 d	11	270 (3.1)	165	13	255 (3.8)	164	16	267 (5.3)	173	Backwater	7	276 (4.3)^a	133
45 d	7	275 (3.3)	178	9	273 (4.0)	173	7	269 (6.3)	181	Barrier net	8	251 (1.7)^b	138
90 d	4	265 (2.8)	185	7	272 (6.1)	180	8	267 (4.3)	182				
135 d	1	249 (–)	200	5	259 (4.3)	195	4	257 (2.7)	203				

strated loss of equilibrium and orientation; they swam very slowly, sometimes inverted, and collided with the tank surfaces, or they lay on the bottom. These behavioral abnormalities were also observed in a nominally 5°C tank when the temperature dropped to at least 2°C, although the minimum temperature is not known. Fish in both tanks recovered when the intended temperatures were restored. The focus of the laboratory studies was to determine the effects of long-term exposure to low temperature on fish health, and it was apparent that the 1°C temperature alone was a major stressor as indicated by the higher overall mortality. Also, immediate adverse effects on health were observed when these fish were cooled to near 0°C.

Plasma osmolalities were not significantly different between acclimation temperatures (ANOVA, $P = 0.99$), nor was the interaction of sampling period and acclimation temperature significant (ANOVA, $P = 0.26$). The main effect sampling period was significant (ANOVA, $P = 0.03$) with post hoc analyses indicating that the mean plasma osmolality of 272 mosm at 45 d was significantly greater than the mean of 255 mosm at 135 d (Tukey, $P < 0.05$). Significant trends were present in osmolality through time at 1°C ($P = 0.036$) and 5°C ($P = 0.003$) but not at 10°C ($P = 0.52$) using a second-degree polynomial regression model. Inspection of the data indicates that osmolalities initially rose at all three temperatures and then progressively declined in the last two sampling periods (Table 4). Also, fish at 1°C had the lowest osmolality in those two sample periods. Mean plasma osmolality of freshwater drum collected from the barrier net was significantly lower than that of fish from the backwater (ANOVA, $P = 0.0001$) and most closely corresponded to that of the single remaining fish sampled at 135 d from the 1°C treatment in the laboratory. As a measure of fish health, plasma osmolality further supported the results derived from examination of mortality and behavior of freshwater drum at temperatures from 0 to 1°C in implicating temperature as the factor causing incapacitation in the river.

Discussion

Our study supports the hypothesis that small freshwater drum require refuge from the main channel to survive through the winter. We found that small freshwater drum were incapacitated and drifted downriver in the main channel, while healthy and active fish were present in the backwaters. Thermal regimes differed between backwater and main channel habitat, with water warmer than the channel temperature of 0°C being available to fish in the backwaters. In the laboratory, incapacitation similar to that observed in the main channel occurred at 0°C, and mortality at 1°C was higher than at 5 and 10°C. Based on these results we concluded that small freshwater drum were intolerant of temperatures near 0°C.

Alternative explanations for the cause of incapacitation that were examined were a poor state of health prior to incapacitation and poor water quality. The absence of differences in condition factors and energy reserves between healthy fish from the backwater and incapacitated fish from the barrier net and the lack of other signs of starvation (Love 1970) indicate that gross nutritional depletion was not causing incapacitation. Although parasitism was evident, pathogenicity of this *Philometra* sp. is unknown and it occurred at a similar rate in healthy and incapacitated fish. Water quality factors other than dissolved oxygen were similar between habitats, and concentrations were at levels considered nontoxic to fish. Winterkill in lakes has been primarily attributed to dissolved oxygen depletion, and ammonia, carbon dioxide, and hydrogen sulfide generally have not been found at toxic levels (Scidmore 1957), and our results support this contention. Concentrations of the three representative metals also were less than those reported to exert toxic effects on fish (see Thurston et al. 1979).

Drift of small freshwater drum in the main channel was documented using passive stationary nets that sifted the flow in the tailwaters of both Pool 13 and Pool 14. We assume that these fish were incapable of sustained and directed swimming efforts and were drifting down river. The harsh environmental conditions in tailwaters including high velocity, high turbulence, and scoured bottom strongly suggest that few species, especially small size classes, would normally inhabit this area of the river. The net design that allowed healthy fish to readily escape and the tendency toward higher catches in the lateral areas of the channel both support the assumption that these fish occurred as drift, since drifting objects tend to be displaced toward shore (Leopold et al. 1964). Their presence both entering and leaving Pool 14 indicates that incapacitation and drift is a winter phenomenon which is not restricted to Pool 14.

We did not assess the magnitude of drift in terms of numbers through the winter, but some indication can be derived from impingement collections at QCS. Since 1984, the mean annual freshwater drum impingement has been 135 000 fish. Age analysis indicates that 87% are age 0 and age 1, with sizes ranging from 80 to 150 mm TL. Impingement occurs during every month of the year, but the largest numbers are encountered from February through April and are often an order of magnitude higher than the summer and fall numbers even though cooling water intake volume during November through mid-April is only half of that during the rest of the year. Examination of winter impingement indicates that up to 90% of these fish are either dead or moribund, with the proportion of dead fish to moribund fish increasing through the winter (L. LaJeone, Quad Cities Nuclear Power Station, Cordova, IL 61242, pers.

comm.). Our collections from the tailwaters and those from the intake screens at QCS were largely composed of small fish in the first year of life, suggesting that this is the most vulnerable group to factors causing incapacitation and that large numbers are exposed to these factors. Evidence of size-dependent low-temperature mortality during winter exists for young-of-the-year of several other species including smallmouth bass (*Micropterus dolomieui*) (Oliver and Holeton 1979; Shuter et al. 1980), largemouth bass (*Micropterus salmoides*) (Toneys and Coble 1979; Isely 1981; Miranda et al. 1984), bluegill (*Lepomis macrochirus*) (Toneys and Coble 1979), sander (*Stizostedion lucioperca*) (Svardson and Molin 1973), common carp (*Cyprinus carpio*) (Svardson and Molin 1973), and cisco (*Coregonus artedii*) (Edsall and Colby 1970).

Aggregations of healthy freshwater drum, corresponding to the same size classes as those occurring as drift, were observed and collected in backwaters. In midwinter the small fish were inactive, resing in shallow depressions on the bottom, but by late winter, activity had increased enough to allow effective use of trap nets. Movement by other fish species to specific wintering sites, often characterized by lack of flow or warmer temperatures, has been documented. McLean et al. (1985) found living threadfin shad (*Dorosoma petenense*) in coves where groundwater seepage resulted in temperatures 3–4°C warmer than the ambient lethal temperature characteristic of the rest of the reservoir. During winter, smallmouth bass congregate in deep, still waters (Henshall 1904; Beeman 1924; Langlois 1935; Hubbs and Bailey 1938; Webster 1954; Munther 1970). Minnows have been found to overwinter 0.5 m into gravel substrates, in logs, and under mats of twigs (Emery 1978). Most fish species collected in the Missouri River main channel during winter are found in ''wintering holes'' in the vicinity of wing dikes (Hesse and Newcomb 1982). Rock cover and ''interspacial'' areas of sand provide winter habitat for catfishes (Ictaluridae) in the Mississippi River (Hawkinson 1980). The blacknose dace (*Rhinichthys atratulus*) winters in crevices beneath stream rubble in southern Ontario (Cunjak and Power 1986). A number of typical midwestern reservoir species were found to aggregate in areas of influx of warmer groundwater during winter (Hancock 1954). Even juveniles of coldwater species such as coho salmon (*Oncorhynchus kisutch*) appear to have specific winter habitat requirements in the form of deep pools, log jams, undercut banks with tree roots, and riverine ponds (Bustard and Narver 1975; Peterson 1982a, 1982b; Tschaplinski and Hartman 1983).

Main channel border and side channel habitat fell to temperatures at or near 0°C for much of the winter and were uniformly cold from top to bottom, which is common for lotic environments during subfreezing weather (Parsons 1942; Devik 1944; Pivovarov 1973). Since backwaters exhibit lentic conditions within the riverine system, we expected that the thermal profiles of these areas would be similar to those of ice-covered lacustrine environments (see Welch 1935). This was confirmed in all four backwaters where the water column was thermally stratified under ice cover, and elevated temperatures relative to the main channel persisted through the winter. Bottom temperatures between backwaters did not appear related to morphometric variables, but bottom temperatures within a site increased with depth, similar to lakes where water at maximum density at 4°C flows downslope to pool in local depressions (Mortimer and Mackereth 1958). Although the small, shallow depressions associated with the small freshwater drum in the backwaters may be only incidental to their sedentary behavior during winter, these could also provide a trap for warmer water. Retention of warmer water within a backwater may be dependent on the relation of its morphometry to that of the adjoining channel, i.e. its ability to trap warmer water. The thermal gradient in the substrate of the backwaters also was similar to lakes where heat stored in the substrate during the summer is conducted and reconvected to the water during winter (Birge et al. 1927; Mortimer and Mackereth 1958). The higher temperatures and lack of a distinct vertical profile in Sunfish Slough indicated that another thermal source was present. Ice thickness at this site was 20 cm when it was 45 cm at the other backwaters, and conversations with local residents led us to conclude that groundwater inflow was occurring. Springs have been identified as maintaining higher temperatures in localized areas of rivers and streams during winter (Benson 1953; Sheridan 1961; Schreier et al. 1980), and groundwater inflow would be expected to function similarly in Mississippi River backwaters, as an additional mechanism to provide warmer water for fish seeking thermal refuges.

Exposure of fish in backwaters to the prevailing low temperature of the channel habitat can occur when the river stage increases from ice and snow melt during late winter and inundates some of these areas as observed in Sunfish Slough. When the channel temperature is low enough to cause incapacitation, the resulting current could transport the fish from the backwater to the channel.

Dissolved oxygen concentrations decreased from surface to bottom, another characteristic of lakes under ice (Greenbank 1945). Dissolved oxygen depletion in the backwaters could stimulate fish to move toward the higher concentration in the adjacent flowing channels where they would be exposed to lower temperatures. During winter, several fish species have been observed to orient to and migrate to habitats with higher dissolved oxygen concentrations but lower temperatures as depletion occurred (Magnuson et al. 1985). Largemouth bass and bluegill have demonstrated a threshold avoidance response to low oxygen concentrations in the laboratory (Whitmore et al. 1960). Sunfish Slough has extremely low concentrations in midwinter, possibly attributable to inflow of hypoxic groundwater, and dissolved oxygen depletion is suspected as the cause of the extensive fish kill at that site. Subsequent inundation by channel flow would move these fish into the drift of the main channel.

Mortality in the laboratory study occurred through the 135-d period, indicating that low temperature tolerance of freshwater drum is a function of time as well as temperature. Based on metabolic rate and depletion of energy stores, the highest mortality would be expected at 10°C and the lowest at 1°C in the laboratory treatments. However, the 1°C group had the highest overall mortality, followed by the 10°C group and then the 5°C group, leading us to conclude that the lowest temperature had other adverse effects on fish health. This is further supported by the lower osmolality in fish at 1°C than in those at 5 and 10°C with corresponding differences in fish collected from the main channel near 0°C versus those from a backwater near 3°C.

Osmotic disturbances in other species caused by low temperature exposure include decreased ability to regulate sodium, chloride, and glucose (Bergstrom 1971; Umminger and Bair 1973; Wendt and Saunders 1973; Virtanen and Oikari 1984). Atlantic salmon (*Salmo salar*), rainbow trout (*Oncorhynchus mykiss*), and brook trout (*Salvelinus fontinalis*) all demonstrated large variations in osmolality near 0°C explained by reduced osmoregulatory capacity (Saunders et al. 1975; Saunders 1986). To determine actual tolerance to winter thermal conditions, exposure time may have to correspond to the actual duration of environmental temperatures. In addition, small changes in temperature may greatly affect the health of the fish. Fish held at 1°C that were temporarily lowered to 0° became incapacitated but recovered when temperature was restored to 1°C. Doudoroff (1942) described immediate effects, termed primary chill-coma, to lethal low temperatures: ''mild distress and disturbance of equilibrium to a violent, convulsive paroxysm.'' If fish were returned to nonlethal temperatures within a short period, they rapidly recovered with no apparent permanent effects. Secondary chill-coma described the gradual loss of response to stimulus and cessation of opercular movements over periods of hours to days. The persistent mortality of freshwater drum at 1°C through the 135 d in the laboratory appears to correspond to Doudoroff's secondary chill-coma, and the behavior of these fish near 0°C is described by the mild indications of primary chill-coma. The assumption that freshwater fish in regions of persistent winter ice cover are physiologically adapted to withstand water temperatures down to 0°C, i.e. until freezing occurs, may not be valid for all species and size classes. In tolerance tests of seawater-adapted young chum salmon (*Oncorhynchus keta*) and young sockeye salmon (*O. gorbuscha*) to temperatures near 0°C, neither species survived more than 3 d at −0.5°C, at least 0.2°C above their freezing point (Brett and Alderdice 1958). While it cannot be concluded that low temperature is a significant cause of mortality in salmonids, it is evident that the lower lethal limit is not always determined by the freezing point of the body fluids of the fish.

The apparent incongruency between the presence of a thriving commercial fishery for freshwater drum in Pool 14 and the occurrence of large-scale drift and probable mortality of young freshwater drum caused by low temperatures characteristic of Pool 14 can be explained by the ability of young freshwater drum to exploit the thermal differences between riverine habitats. Intolerant of the 0°C temperature in the main channel, these fish can survive in winter thermal refuges. Some of the most prominent habitats that provide warmer conditions are the river backwaters composed of sloughs, lakes, and ponds. However, existing backwaters are disappearing due to sedimentation, while the formation of new ones is mostly precluded by man's constraints on meandering and other fluvial processes that create new backwaters. Implications for freshwater drum and other fish populations which may require winter thermal refuges provided by backwaters are increased susceptibility to winter mortality and increased fluctuations in population size as winter severity becomes a greater factor in determining year-class strength.

Acknowledgments

Financial support was provided by Commonwealth Edison Company of Chicago. W. Davin performed the underwater observations. We acknowledge R. Heidinger, R. Sheehan, B. Tetzlaff, and B. Doerr for their assistance with this project. Support facilities were provided by the SIUC Fisheries Research Laboratory.

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