THE EFFECTS OF THE LUDINGTON PUMPED STORAGE POWER PROJECT ON FISH PASSAGE THROUGH PUMP-TURBINES AND ON FISH BEHAVIORAL PATTERNS

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ABSTRACT

THE EFFECTS OF THE LUDINGTON PUMPED STORAGE POWER PROJECT ON FISH PASSAGE THROUGH PUMP-TURBINES AND ON FISH BEHAVIORAL PATTERNS

By

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PART I. AN EVALUATION OF MORTALITY INCURRED BY FISH PASSING THROUGH PUMP-TURBINES AT THE LUDINGTON PUMPED STORAGE POWER PLANT - Passage success of fish through pump-turbines at the Ludington Pumped Storage Power Plant was studied in 1974 and 1975. Methods were developed for introducing fish to the turbines using weighted paper sacks and for recapturing individuals using jaw-fastened styrofoam floats. The passage of various sized wooden boards was also studied to provide additional information on object size and mechanical damage.

Twenty fish tests were conducted in 1974 and 1975 using rainbow trout, chinook and coho salmon, and yellow perch. A total of 2742 fish were used; 1017 in 1974 and 1725 in 1975. Control groups of fish were used in 1975 to assess handling and recovery losses.

Pumping mode mortality estimates were derived from five tests in 1974 and six tests in 1975. Mortalities in 1974 varied from 33 - 63% and averaged 56.5% ± 13.3%. During 1975, adjusted mortalities ranged from 54 - 75% and averaged 67.7% ± 7.2%.

Damage rates for fish killed during pumping passage were 37.2% in 1974 and 61.5% in 1975. Most injured fish displayed lacerations or decapitation implying that mechanical contact and shearing forces were causative agents.

Size-selective mortality could not be unquestionably established in pumping experiments. The narrow size range of fish used may have obscured detection of this relationship.

Estimates of generating mortality were obtained from one experiment in 1974 and four experiments in 1975. Mortality was 67.2% in 1974 and averaged 40.7% ± 27.1% in 1975. Adjusted experimental estimates varied from 35 - 75% in 1975.

About half (47.8%) of the fish killed during generation were damaged. Nearly all of the injuries were lacerations or decapitations. Releases of known dead fish showed similar damage rates and injury forms.

Evidence for size-selective mortality in generating trials was absent. This was expected due to the relatively wide wicket gate settings during generating tests. Presumably, the large difference in wicket gate setting between pumping and generating modes also effected the observed differences in recovery and mortality rates between the two modes.

Seven pumping and two generating wooden board tests were performed in 1974 using 1402 boards. Board size ranged from 6 - 26 inches. In the pumping tests, recovery and damage rates increased with board size. Damage was low for the smaller boards (6-inch - 3.9%) but was nearly complete for the largest boards (26-inch - 97.1%). In the generating tests, damage rates also increased with board size although these were much less than pumping estimates for boards greater than 12 inches. The differential wicket gate setting between the operating modes probably effected these damage rate differences.

Board damage rates were less than the mortality rates of fish. Several explanations are advanced for these discrepancies. The most

plausible is that factors other than mechanical contact contribute significantly to fish death during passage.

Unresolved problems in applying the mortality estimates derived from these studies are identified.

PART II. MOVEMENT PATTERNS AND ORIENTATION OF FISHES IN THE LUDINGTON PUMPED STORAGE RESERVOIR AS REVEALED BY TRACKING STUDIES - Movement patterns, activity levels, and residence periods of carp and trout were studied in the Ludington Pumped Storage Reservoir during 1974 and 1975 using ultrasonic telemetry and float-tracking procedures. Sixty-five fish were monitored for daily tracking periods of 1 - 24 hr, for a total of 159 tracks covering 1159 hr.

Most fish movements were restricted to areas adjacent to the reservoir embankment. The shoreline appeared to serve as a reference marker for locomotory activity. Significant differences in movement pattern were not detected between species, between sonic and float-tagged individuals, or between day and night.

Mean swimming speed for carp was 0.17 body lengths/sec (range 0.01 - 0.64 body lengths/sec) and 0.63 body lengths/sec (range 0.01 - 1.30 body lengths/sec) for trout. Movement rates were similar between sonic and float-tagged fish and between years for carp. Rates of movement differed between pumping and generating power plant modes but this trend was inconsistent between years. Mean swimming speeds were lower than those reported from laboratory studies.

Both carp and trout exhibited a crepuscular rhythm in swimming speed. Both groups of fish remained active at night and this behavior may account for their passage into the reservoir.

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Factors affecting swimming speed were analyzed for their relative importance by a stepwise linear multiple regression analysis. The independent variables explained 83 percent of the variation in speed for trout, and 0 to 65 percent of the variation in speed for carp. Behavioral, environmental, and power plant features influenced trout activity, while water currents and water-level drawdown were most important in affecting carp swimming rates.

Minimum residence period of fish in the Ludington reservoir was assessed for 62 individuals during 1975. Carp appeared to remain in the reservoir longer than any of the other species examined, although the data from each species were variable.

The need for future studies related to the impact of hydroelectric development on fish behavior and population dynamics is indicated.

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PART II. MOVEMENT PATTERNS AND ORIENTATION OF FISHES IN THE LUDINGTON PUMPED STORAGE RESERVOIR AS REVEALED BY TRACKING STUDIES

By

Fredric Michael Serchuk

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GENERAL INTRODUCTION

The development of pumped storage facilities for the generation of hydroelectric energy has rapidly increased during the last decade in the United States (Schoumacher, 1976). These installations have been incorporated into electric power networks since they improve production reliability by providing peaking power and supply an immediately available reserve capacity in the event of system failures. Also, pumped storage plants are functionally attractive because they can absorb or generate large energy loads almost instantaneously.

Pumped storage units operate similar to storage batteries. Low-valued, off-peak electric energy is used to pump water from a lower to an upper storage reservoir from which it is released to flow through reversible pump-turbines and generate electric power. Pumping is normally performed at night and during weekends while power generation usually occurs during the mornings and evenings of weekdays.

Although the physical and economic aspects of pumped storage development have been widely studied (Woodruff, 1971; Velz *et al.*, 1968; Ley and Loane, 1962; Salzman, 1962) much remains to be learned about the biological impact of these projects on aquatic resources, particularly fishes. Detailed studies are needed on the mortality rates sustained by fish passing through pump-turbines and the associated causative agents (Hauck and Edson, 1976). Also, a critical need exists to examine the behavior of anadromous and resident fish species in areas affected by plant-induced flows. Through these studies, it should be possible to gain an understanding of the relationships between plant design and operation and fish survival and activity. Such information is helpful in developing effective methods to protect fishery resources within habitats affected by pumped storage systems.

The objectives of the present research studies were: (1) to evaluate passage success of fish through pump-turbines at the Ludington Pumped Storage Power Project near Ludington, Michigan, and (2) to assess the movement patterns and behavioral activity of fish species residing in the Ludington Reservoir. The experimental findings of both studies were examined in relation to power plant characteristics and biological and environmental parameters.

DESCRIPTION OF THE STUDY AREA

The Ludington Pumped Storage Power Plant, located four miles south of Ludington, Michigan on the eastern shore of Lake Michigan, is the largest pumped storage project in existence with a maximum generating capacity of 1,872 Mw (Comninellis, 1973). The upper, man-made reservoir is 2.5 mi long (4.02 km), approximately 0.75 mi wide (1.21 km), and has a total surface area of 842 acres when full ($3.41\ km^2$). Total capacity at full pond is 27 billion gallons ($1.02 \times 10^8\ m^3$) with 63% of this volume available for power generation. Maximum water depths range from 97 ft (30 m) in the south to 112 ft (34 m) in the north end. During plant operations, water levels can fluctuate a vertical distance of 67 ft (20 m).

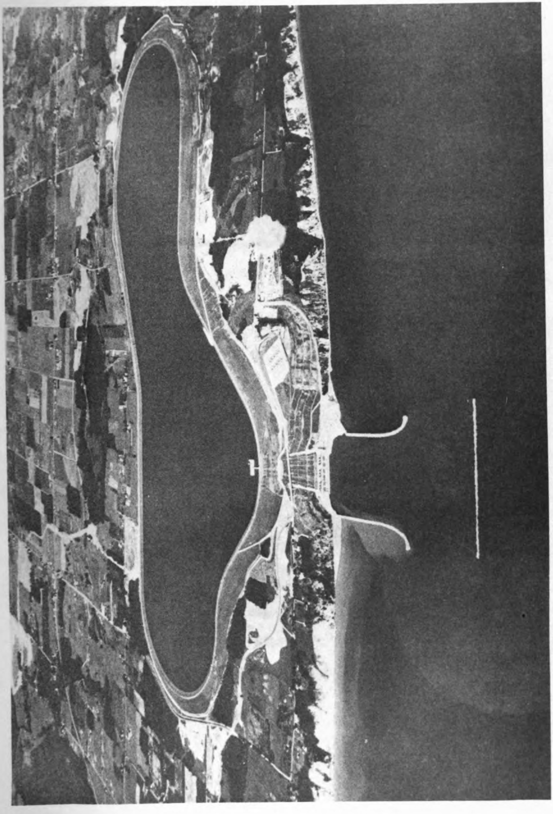
Transfer of water between the upper reservoir and Lake Michigan, which serves as the lower basin 370 ft below (113 m), is accomplished through six large penstocks, each 1300 ft long (396 m). The lower end of each penstock leads to a Francis-type reversible turbine capable of pumping 11,100 cfs ($314\ m^3/s$) at minimum head and 7,000 cfs ($196\ m^3/s$) at maximum head. When all turbines are operable, water can be transferred at a maximum flow of 75,960 cfs during generation ($2151\ m^3/s$) and 66,600 cfs during pumping ($1886\ m^3/s$).

Lakefront facilities to reduce wave action on the power house include two 1600 ft long (490 m) jetties and an 1850 ft long (565 m) breakwall constructed of large rock boulders. The jetties rise 10 ft

(3 m) above the water surface and are separated from each other by a 1100 ft (335 m) channel, dredged to a minimum depth of 28.5 ft (8.7 m). The outer breakwall, also 10 ft (3 m) above the water surface, is positioned parallel to the shore about 2700 ft (825 m) from the power house. Water currents between the jetties are estimated to average 2.2 ft/s (0.67 m/s) while those between the jetties and the breakwall are estimated at 1.5 ft/s (0.46 m/s).

An aerial view of the pumped storage reservoir and adjacent Lake Michigan waters is shown in Figure 1.

Figure 1. Aerial view of the Ludington Pumped Storage Project including the offshore jetties and breakwall.



AN EVALUATION OF MORTALITY INCURRED BY FISH PASSING THROUGH PUMP-TURBINES AT THE LUDINGTON PUMPED STORAGE POWER PLANT

By

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Part I

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INTRODUCTION

Since 1971, the Department of Fisheries and Wildlife, Michigan State University, under contract with Consumers Power Company, has been conducting field studies to assess the effects of the Ludington Pumped Storage Power Plant on the aquatic resources adjacent to the plant and in the Ludington Reservoir. Research efforts have been focused on documenting the temporal and spatial patterns of the biological communities in these waters and in characterizing the limnological features of the lake and reservoir environments through time (Liston and Tack, 1975, 1974).

During 1973, environmental studies indicated that nearly all of the fish species in the inshore Lake Michigan waters had entered the Ludington Reservoir. Also, visual observations and dead fish surveys taken during this period (and afterwards) showed that fish passage through the pump-turbines resulted in some physical damage and mortality. Consequently, a two-year study of fish passage was undertaken in 1974 to assess the magnitude of this mortality and delineate, if possible, the causative physical and biological agents.

REVIEW OF FISH PASSAGE STUDIES

Field evaluation of fish passage success through turbines at pumped storage sites, other than Ludington, has not yet been accomplished. Data are available, however, on fish passage at conventional hydroelectric installations. Though much of this information was derived from the passage of small, migrant salmonids at mainstem dams in the Pacific Northwest, many of the findings appear relevant to pumped storage situations.

Early studies on fish and hydraulic turbines (Cramer and Oligher, 1964, 1960; Monten, 1963; Lucas, 1962; Schoeneman *et al.*, 1961, 1954; Von Guten, 1961; U. S. Army Corps of Engineers, 1960; Muir, 1959) established that a variety of factors produced mortality during passage. Of these, four general categories are recognized: (1) mechanical damage due to contact with fixed or moving equipment; (2) pressure-induced damage due to exposure to low pressure conditions within the turbine; (3) shearing action damage due to passage through areas of extreme turbulence or boundary conditions; and (4) cavitation damage due to exposure to regimes of partial vacuum. Although specific injuries are often characteristic of each factor, similar forms of damage can result from the different sources (Bell, 1973; Bell *et al.*, 1967).

Experiments with model turbines to assess the physical features inducing mortality has enabled comparative studies to be performed under a variety of turbine operating conditions (Bell, 1974;

Cramer, 1965, 1960; Cramer and Oligher, 1964, 1961; Von Guten, 1961; Muir, 1959; Von Raben, 1957). These efforts have shown that passage success is related to turbine efficiency which itself is influenced by wicket gate opening, water head, and runner speed. Also, turbine position relative to the tail-water and clearance distance between the runner blades and wicket gates were shown to be important for fish survival. Corroboration of these results has been accomplished in field tests at conventional hydroelectric plants in the United States and Europe (Bell *et al.*, 1967). Similar verification at pumped storage facilities is lacking.

Research on the biological factors contributing to passage mortality has not been extensive. Little is known about the relation between fish size and passage success in field situations. Some studies have found that the spatial distribution of fish in the forebay of the turbine is a critical factor in turbine kills (Long, 1968; Schoeneman *et al.*, 1961) but confirmatory data for pumped storage systems is absent.

METHODS AND MATERIALS

Methodology Development

Determination of procedures to successfully introduce and recover fish at the Ludington site was the principal objective of the initial mortality tests conducted in 1974 (Serchuk *et al.*, 1975; Tack and Liston, 1973). Emphasis was placed on developing an experimental design that would yield good statistical precision in the mortality estimates with a limited number of fish and a good recapture rate. Standard fish recovery methods were considered impractical because of the large investment of equipment, time, manpower, money, and fish required for statistical confidence. Many of the techniques and sampling gear used in mortality studies at conventional plants were similarly discounted due to the physical features of the Ludington plant and the tremendous velocity and discharge of water at the site. Accordingly, the use of buoyant tag devices was considered the most productive approach since these tags bring fish to the water surface rapidly after turbine passage. Previously, buoyant styrofoam floats had been successfully used in tests at the Bonneville Hydraulics Laboratory (Bell, 1973) and provided good recovery data in field trials at conventional power plants on the Connecticut River (Johnson, 1970).

A variety of methods of float attachment and introducing fish into the draft tubes were evaluated. Jaw attachment of the float proved most efficient as was the use of 2-inch bell-shaped styrofoam tags. The most successful fish introduction technique was with a weighted paper sack placed in front of the draft tube opening. In this procedure, tagged fish are placed in a sack containing a small sandbag and about a gallon of water. The sack is then lowered by line into the water where subsequently it becomes saturated and disintegrates, thereby releasing the enclosed fish into the draft tube.

Modifications of the initial procedures and adoption of new techniques were implemented based on early test results. The finalized procedure consisted of: (1) the use of commercially procured rainbow trout as test specimens; (2) anesthetization of fish prior to tagging with both floy tags and floats; (3) length measurements of all fish; (4) retention of recaptured fish in a holding facility for 72 hours after a test to assess delayed mortality; and (5) use of a control group of fish for the evaluation of handling losses (only in 1975 tests). Also, fish were placed individually in mesh bags after tagging to enhance the recapture rate of damaged individuals and reduce recovery loss of fish caused by float removal during turbine passage.

In 1974, passage studies of various-sized wooden boards (1 x 3 inches) were conducted in a supplementary effort to determine the relation between object size and mechanical damage. Each board was numbered and weighted with a small bag of sand secured to the wood by several rubber bands. These sandbags were sufficient to displace the naturally buoyant boards from the water surface to the turbine intake.

Complete descriptions of the procedures used in the fish and board turbine tests are presented in Tables 1 and 2, respectively.

Table 1. Mortality test procedures for 1974 and 1975 fish passage studies at the Ludington Pumped Storage Power Plant.

Preparatory Activities:

1. Procurement of fish from commercial game fish dealer.
2. Transport of experimental fish in hatchery tank to Ludington fisheries laboratory.
3. Retention of fish overnight in transport tank at laboratory site. Constant aeration and water flow through tank maintained during this holding interval.
4. Preparation (labeling) of float tags and mesh bags for test trial.
5. Establishment of holding tank to maintain recovered specimens from turbine test for 72 hours for determing delayed losses.

Pre-trial Processing of Fish:

6. Anesthetization of fish with MS-222 for marking and handling. Usually done several hours prior to the field trial.
7. Measurement of body length and weight for each individual fish.
8. Attachment of float tag to fish jaw and floy tags to dorsal musculature.
9. Data recording of body measurements and float and floy numbers for each test specimen.
10. Placement of fish individually into mesh bags tied with string.
11. Return of fish into hatchery tank after processing for recovery from anesthetic.

Introduction of Fish into Draft Tube:

12. Transport of marked, experimental fish in aerated hatchery site from laboratory to pumped storage site.
13. Placement of several fish into a paper sack containing a sandbag and about a gallon of water. Immediately prior to sack placement, the condition of each fish is observed and recorded.
14. Attachment of paper sack to line and lowering of apparatus into water in front of intake structure.
15. Saturation of sack and release of fish into turbine intake.
16. Repetition of steps 13-15 until entire lot of fish has been processed.

Table 1 (cont'd):

Retrieval of Fish:

17. After turbine passage, recovery of fish and floats is accomplished by one or two boat crews near the discharge areas.
18. Recaptured individuals are placed in a holding trough aboard boat. Live specimens are removed from the mesh bag and the float tag is detached.
19. A record is maintained by each boat crew of the condition of each fish at recapture and the float number of the float-only recoveries.
20. Reconnaissance of the discharge area is conducted for approximately 2 hours after introduction of fish into the turbine to locate all test individuals.

Post-test Activity:

21. After power plant activity has ceased, observations are made at the intake structure for specimens that did not undergo turbine passage. These individuals are recovered and recorded appropriately.
22. All recaptured fish and floats from the discharge area are transported to the fisheries laboratory for data processing.
23. Live recaptured fish are placed in an aerated holding tank for three days to assess any delayed mortality resulting from turbine passage.
24. Dead recaptures are examined for internal and external physical damage.
25. Data analysis of the results in performed.

Table 2. Damage test procedure for 1974 board passage study at Ludington Pumped Storage Power Plant.

Preparatory Activities:

1. Procurement of lumber (pine or spruce) from commercial dealer.
2. Sectioning of lumber into 1 x 3 inch boards of various lengths (6, 8, 12, 18, 24 or 26 inches).
3. Numbering of boards in the middle and on both ends to permit identification of pieces in the event of cracked or split boards resulting from turbine passage.
4. Immersion of boards in polyurethane (twice) to reduce waterlogging upon release in the draft tube.
5. Preparation of paper bags filled with sand to serve as weights to permit the boards to sink from the water surface during the turbine experiment.
6. Attachment of the sandbags to the boards (one per board) via rubber bands.

Introduction of Boards into the Draft Tube:

7. Transport of marked, weighted boards to the pumped-storage site.
8. Placement of groups of boards into a wooden box which is lowered to the water surface by guide ropes.
9. Overturn of the box and release of the boards into the draft tube opening.
10. Repetition of steps 8 and 9 until entire batch of boards has been released to the turbine unit.

Retrieval of Boards:

11. After turbine passage, recovery of boards and pieces of boards is accomplished by boat crews near the discharge area.
12. Reconnaissance of the discharge area is conducted for several hours after the board introduction to locate all pieces.
13. Survey of discharge area is performed for several days following test to further retrieve boards.

Post-test Activity:

14. Upon shut-down of turbine unit, observations are made at the intake structure for boards which did not undergo turbine passage. These are retrieved and noted accordingly.
15. Recaptured boards are transported to the fisheries laboratory and examined for mechanical damage.
16. Data analysis of the results is performed.

RESULTS

Nineteen turbine tests were performed between 28 April and 14 November 1974 (Table 3). Ten trials were accomplished with 1017 fish, comprising three species: rainbow trout, chinook salmon, and yellow perch. Nine experiments were conducted with 1402 wooden boards of the following sizes: 324 6-inch boards, 145 8-inch boards, 338 12-inch boards, 291 18-inch boards, 256 24-inch boards, and 48 26-inch boards.

During 1975, ten fish passage tests were run between 15 June and 9 November (Table 4). A total of 1725 fish were used; all but 51 fish were rainbow trout. Control groups of fish were used in each experiment except for the 19 October test in which large coho and chinook salmon were utilized.

Details of all turbine trials in 1974 and 1975 are summarized in Tables 5 and 6, respectively.

Fish Passage - Pumping Mode

Pumping mortality estimates were derived from data from five experiments in 1974 and six experiments in 1975. The field trials of 28 April, 3 May and 19 May 1974 differed substantially in technique from the standard procedure and have therefore been excluded from the present analysis. Results of these tests are elaborated in Serchuk *et al.* (1974) and are briefly listed in Table 5.

Table 3. Turbine passage tests conducted in 1974.

Date	Type and Size of Sample	Size Range	Operational Mode
	FISH PASSAGE STUDIES		
28 Apr 74	144 chinook salmon	130-260 mm	Pumping
3 May 74	10 chinook salmon	136-175 mm	Pumping
19 May 74	116 rainbow trout	140-316 mm	Pumping
	11 chinook salmon	140-172 mm	Pumping
21 June 74	95 rainbow trout	162-320 mm	Pumping
12 July 74	101 rainbow trout	215-395 mm	Pumping
14 Aug 74	166 chinook salmon	84-180 mm	Generating
28 Aug 74	90 yellow perch	96-270 mm	Generating
6 Oct 74	85 rainbow trout	282-390 mm	Pumping
20 Oct 74	105 rainbow trout	227-470 mm	Pumping
3 Nov 74	94 rainbow trout	228-363 mm	Pumping
	BOARD PASSAGE STUDIES		
10 May 74	99 pine boards	6 and 12 inches	Pumping
21 June 74	87 pine boards	18 and 24 inches	Pumping
12 July 74	98 spruce boards	6 and 12 inches	Pumping
14 Aug 74	178 spruce boards	6,12,18,24 inches	Generating
28 Aug 74	190 spruce boards	6,12,18,24 inches	Generating
3 Oct 74	48 pine boards	6,12,18 inches	Pumping
6 Oct 74	179 pine boards	6,8,12,18,24 inches	Pumping
20 Oct 74	233 pine boards	6,8,12,18,24 inches	Pumping
14 Nov 74	300 pine boards	6,8,12,18,24,26 inches	Pumping

Table 4. Fish passage turbine tests conducted in 1975.

Date	Species and Number of Fish	Size Range (mm)	Operational Mode
15 Jun 75	196 rainbow trout	233-462	Pumping
20 Jul 75	214 rainbow trout	215-466	Pumping
8 Aug 75	205 rainbow trout	130-470	Generating
25 Aug 75	183 rainbow trout	173-477	Generating
21 Sep 75	173 rainbow trout	233-490	Pumping
4 Oct 75	171 rainbow trout	227-532	Generating
17 Oct 75	157 rainbow trout	231-510	Generating
19 Oct 75	46 coho salmon	535-780	Pumping
	5 chinook salmon	582-800	Pumping
2 Nov 75	186 rainbow trout	180-152	Pumping
9 Nov 75	189 rainbow trout	174-510	Pumping

Table 5. Summary of 1974 fish passage experiments.

Test Date	Operating Mode	No. of Fish Released	Recovered Fish		No. of Floats-Only Recovered	Fish Recovery %	Total % Recovery Fish & Floats	Mortality Rate**		
			# Alive	# Dead				M_1	M_2	M_3
28 Apr	Pump	120 (A)*	4	--	--	2.5	2.5			
		24 (D)	--	--	--	--	--			
3 May	Pump	10 (A)	3	1	--	40.0	40.0	25.0	25.0	70.0
19 May	Pump	127 (D)	--	45	17	35.4	48.8	--	--	--
21 Jun	Pump	95 (A)	11	22	35	34.7	71.6	66.7	83.8	88.4
12 Jul	Pump	76 (A)	24	14	19	50.0	75.0	36.8	57.9	68.4
		25 (D)	--	13	2	52.0	60.0			
14 Aug	Gen	166 (A)	38	73	--	66.9	Mortality rate cannot be determined as in other tests since more than 1 fish per bag (5/bag)			
28 Aug	Gen	75 (A)	20	41	2	81.3	84.0	67.2	68.2	73.3
		15 (D)	--	8	3	53.3	73.3	--	--	--
6 Oct	Pump	75 (A)	15	22	19	49.3	74.7	59.5	73.2	80.0
		10 (D)	--	3	6	30.0	90.0	--	--	--
20 Oct	Pump	105 (A)	20	28	35	45.7	79.0	58.3	75.9	80.9
3 Nov	Pump	94 (A)	17	27	42	46.8	91.5	61.4	80.2	81.9

* (A) = Alive upon turbine release.
(D) = Dead upon turbine release.

** M_1 = # of dead recapture/total recaptured fish X 100
M_2 = # of dead recaptures and recaptured floats/recaptured fish and floats X 100
M_3 = # of dead recaptures, recaptured floats and unrecovered fish/total fish released into turbine X 100

Table 6. Summary of 1975 fish passage experiments.

Test Date	Operating Mode	No. of Fish Released	Recovered Fish # Alive	Recovered Fish # Dead	No. of Floats-Only Recovered	Fish Recovery %	Total % Recovery Fish & Floats	Mortality Rate** M1	Mortality Rate** M2	Mortality Rate** M3
15 Jun	Pump	51 (C)*	32	6	1	94.1[a]	96.1	15.8		
		40 (A)	3	8	10	62.5[b]	87.5	72.7	85.7	67.6
		105 (D)	-	39	36	37.1	71.4			
20 Jul	Pump	50 (C)	46	4	-	100.0	100.0	8.0		
		148 (A)	10	16	91	22.3[c]	83.8	61.5	91.5	58.2
		16 (D)	-	4	10	25.0	87.5			
8 Aug	Gen	50 (C)[d]	11	38	-	98.0	98.0	77.6		
		(C)[e]	46	3	-	98.0	98.0	6.1		
		133 (A)	19	61	21	61.7[f]	77.4	76.3	81.2	74.8
		22 (D)	-	16	2	72.7	81.8			(1.06)[g]
25 Aug	Gen	30 (C)	18	11	-	100.0[h]	100.0	37.9		
		79 (A)	11	40	24	64.6	94.9	78.4	85.3	65.2
		74 (D)	-	33	24	44.6	77.0			
21 Sep	Pump	45 (C)	31	14	-	100.0	100.0	31.1		
		127 (A)	14	30	39	45.7[i]	76.4	68.2	83.1	53.8
		1 (D)	-	-	-	0.0	0.0			
4 Oct	Gen	40 (C)	35	5	-	100.0	100.0	12.5		
		129 (A)	48	37	37	65.9	94.6	43.5	60.7	35.4
		2 (D)	-	2	-	100.0	100.0			
17 Oct	Gen	40 (C)	35	5	-	100.0	100.0	12.5		
		114 (A)	29	43	20	63.2	80.7	59.7	68.5	53.9
		3 (D)	-	2	1	66.7	100.0			

Table 6 (continued)

Test Date	Operating Mode	No. of Fish Released	Recovered Fish # Alive	Recovered Fish # Dead	No. of Floats-Only Recovered	Fish Recovery %	Total % Recovery Fish & Floats	Mortality Rate** M_1	Mortality Rate** M_2	Mortality Rate** M_3
19 Oct	Pump	No controls used								
		49 (A)	2	19	25	42.9	93.9	90.5	95.7	-
		2 (D)	-	2	-	100.0	100.0			
2 Nov	Pump	46 (C)	42	4	-	100.0	100.0	8.7		
		137 (A)	9	31	52	29.9[j]	67.8	77.5	90.2	75.4
		3 (D)	-	1	1	33.3	66.7			
9 Nov	Pump	46 (C)	43	3	-	100.0	100.0	6.5		
		138 (A)	14	31	41	33.3[k]	63.0	68.9	83.7	66.7
		5 (D)	-	2	1	40.0	60.0			

* (C) = Control fish
(A) = Alive upon turbine release
(D) = Dead upon turbine release

** M_1 = # of dead recaptures/total recaptures X 100

$$M_2 = \frac{\text{\# of dead recaptures and recaptured floats}}{\text{total recaptures and recaptured floats}}$$

M_3 = adjusted M_1 (using control loss rate)

a = includes 10 fish, recovered late, but not used in the analysis.
b = includes 14 fish, recovered late, but not used in the analysis.
c = includes 7 fish, recovered late, but not used in the analysis.
d = excludes 4 fish, dead at release and subsequently recovered.
e = data based on fish, alive at field recapture, regardless of subsequent mortality.
f = includes 2 fish, recovered late, but not used in the analysis.
g = estimate derived by using control loss rate of 77.6.
h = includes 1 fish, recovered late, but not used in the analysis.
i = includes 14 fish, recovered late, but not used in the analysis.
j = includes 1 fish, recovered late, but not used in the analysis.
k = includes 1 fish, recovered late, but not used in the analysis.

In the five 1974 pumping trials, of a total of 445 live fish released to the turbines, 200 or 45% were recovered. Known dead trout releases of 162 individuals resulted in a 38% recapture rate (61 fish). No significant difference ($x^2 = 2.29$, $P > 0.10$) existed between the recovery rates implying that the recovery percentage of dead fish (those killed in passage) was equal to that for all test fish. This is a necessary condition for use of float-recapture procedures.

Recovery rates in 1975 were similar to those in 1974. In 1975, 224 salmonids were recaptured from 639 pumping releases (35.1%). The recovery rate of known dead releases was 36.4% (48 fish). Again, differences between the recovery rates were not evident ($x^2 = 0.04$, $P > 0.80$). Similarly, yearly differences in known dead fish recovery rates were absent ($x^2 = 0.01$, $P > 0.90$). A highly significant difference, however, was detected in the live release recapture rates between years ($x^2 = 10.69$, $P < 0.005$). Reasons for this inequality are not known.

Variations in mortality rate were apparent among trials in both 1974 and 1975. Pumping mortalities in 1974 ranged from 33 - 63% while unadjusted values (used for comparison) varied from 62 - 78% in 1975. Inter-trial mortality differences, within each year, were not significant (1974, $x^2 = 7.99$, $P > 0.05$; 1975, $x^2 = 2.07$, $P > 0.70$) when mortality was assessed from recaptured fish. The large salmon mortality estimate (91% - 19 October 1975) was not included in the 1975 inter-trial comparison since fish used in this test were much longer than in the other experiments (mean salmon length = 677 mm; mean trout length = 353 mm). The homogeneity of the inter-yearly mortality estimates and the relative constancy of turbine characteristics between experiments (Tables 7 and 8) permitted pooling of the mortality data within each year.

Table 7. Summary of physical data on live fish passage experiments conducted on the pumping mode in 1974. Only tests using standard procedures are included.

Test Date	Operating Mode	Turbine Unit	Wicket Gate Opening	Effective Head (Range in ft.)	Water Temperature(°C)	No. of Recovery Boat Crews
21 Jun	Pump	1	64%	336 - 345	11	2
12 Jul	Pump	1	64%	348 - 351	19	2
6 Oct	Pump	1	65%	348 - 351	11	1
20 Oct	Pump	1	65%	337 - 340	11	1
3 Nov	Pump	1	65%	343 - 346	10	2

Table 8. Summary of physical data on fish passage experiments conducted in 1975.

Test Date	Operating Mode	Turbine Unit	Wicket Gate Opening	Effective Head (Range in ft.)	Water Temperature(^{o}C)	No. of Recovery Boat Crews
15 Jun	Pump	1	66%	330 - 340	13	2
20 Jul	Pump	1	64%	335 - 344	19	2
8 Aug	Gen	2&3 ?	88%	340 - 325	13	2
25 Aug	Gen	1-4 ?	85%	356 - 338	19	2
21 Sep	Pump	2	64%	331 - 336	14	2
4 Oct	Gen	2	82%	328 - 326	13	2
17 Oct	Gen	2,4,6 ?	72%	333 - 326	13	2
19 Oct	Pump	2	64%	339 - 343	9	1
2 Nov	Pump	2	63%	337 - 340	11	1
9 Nov	Pump	2	64%	334 - 340	12	1

For 1974, pumping mortality averaged 56.5% with a 95% confidence interval of ± 13.3% based on recaptured fish (mortality rates computed by assuming detached floats and unaccounted fish represented dead fish are 75.1 and 81.4%, respectively). In 1975, the mean, unadjusted pumping mortality was 69.9% (72.2% with salmon) with a confidence belt of ± 7.2% (Table 9). A corrected mortality rate of 65.1% (67.7% with salmon) was obtained when the data were adjusted for handling losses determined from control fish (mean handling loss = 13.8%). Adjusted values derived by considering detached floats and unaccounted fish as dead specimens were 85.5% (86.4% with salmon) and 90.6% (91.9% with salmon), respectively.

Damage rates for live releases differed between years ($x^2 = 13.59$, $P < 0.005$). In 1974, only about a third (37.2%) of the fish that died in passage exhibited physical damage (Table 10), while 61.5% of the killed fish were injured in 1975 (Tables 11 and 12). Damaged individuals generally displayed lacerations or suffered decapitation (73.5% of 1975 injuries) suggesting that mechanical contact and shearing forces may have been the causative factors. Analysis of immediate and delayed mortalities in 1975 (Tables 13 and 14) indicated that the majority of deaths (61.5%) occurred during turbine passage.

In both years, known dead releases experienced less damage than live releases (19.7% in 1974; 47.9% in 1975). The biological significance of this discrepancy is unclear although it may indicate that live fish are hampered by the floats. The types of injury exhibited by the dead releases, however, were similar to those shown by fish killed in passage (69.6% of the 1975 damaged dead releases were cut or decapitated).

Table 9. Comparison of recapture and mortality data derived from fish passage experiments performed on the pumping and generating modes in 1975.

Operating Mode	No. of Fish Released	Recovered Fish		No. of Floats-Only Recovered	Fish Recovery %	Total % Recovery Fish & Floats	Mortality Rate**		
		# Alive	# Dead				M_1	M_2	M_3
Pumping	238 (C)*	194	31	1	98.7[a]	99.2	13.8		
	639 (A)	52	135	258	35.1[b]	75.4	72.2	88.3	67.7
	132 (D)	---	48	48	36.4	72.7			
Generating	160 (C)	99	59	---	99.3[c]	99.3	37.3		
	455 (A)	107	181	102	63.7[d]	86.2	62.8	72.6	40.7
	101 (D)	---	53	27	52.5	79.2			

* (C) = Control fish
(A) = Alive upon turbine release
(D) = Dead upon turbine release

a = includes 10 fish, recovered late, but not used in the analysis
b = includes 37 fish, recovered late, but not used in the analysis.
c = includes 1 fish, recovered late, but not used in the analysis.
d = includes 2 fish, recovered late, but not used in the analysis.

** M_1 = # of dead recaptures/total recaptures X 100

$$M_2 = \frac{\text{\# of dead recaptures and recaptured floats}}{\text{total recaptures and recaptured floats}} \times 100$$

M_3 = adjusted M_1 (using control loss rate)

Table 10. Damage data from 1974 rainbow trout passage experiments.

Test Date	No. of Dead Fish Recaptured	No. of Recaptured Dead Undamaged	No. of Recaptured Dead Damaged	% of Damaged Dead Recaptured Fish
19 May	45*	37	8	17.8
21 Jun	22	21	1	4.5
12 Jul	14	10	4	28.6
	13*	10	3	23.1
6 Oct	22	16	6	27.3
	3*	2	1	33.3
20 Oct	28	12	16	57.1
3 Nov	27	12	15	55.6

* Recaptured fish that were dead upon release into turbine.

Table 11. Summary of damage data from 1975 fish passage experiments.

Test Date	Operating Mode	No. of Dead Fish	No. of Dead Fish Undamaged	No. of Dead Fish Damaged	% Damaged of Dead Fish	Damage Categories*				
						S	D	IB	BIS	BB
15 Jun	Pump	6 (IM)**	1	5	83.3	1	4			
		2 (DM)	2	--	0.0					
		39 (RD)	20	19	48.7	7	5		7	
20 Jul	Pump	9 (IM)	6	3	33.3	1	2			
		7 (DM)	7	--	0.0					
		4 (RD)	2	2	50.0	2				
8 Aug	Gen	10 (IM)	6	4	40.0	3	1			
		51 (DM)	50	1	2.0				1	
		16 (RD)	16	--	0.0					
25 Aug	Gen	15 (IM)	10	5	33.3	2	2			1
		25 (DM)	22	3	12.0			3		
		33 (RD)	21	12	36.4	6	6			
21 Sep	Pump	18 (IM)	4	14	77.8	9	4			1
		12 (DM)	12	--	0.0					
4 Oct	Gen	8 (IM)	4	4	50.0	2	2			
		29 (DM)	27	2	6.9	1			1	
		2 (RD)	2	--	0.0					
17 Oct	Gen	13 (IM)	4	9	69.2	7	2			
		30 (DM)	26	4	13.3	2			2	
		2 (RD)	2	--	0.0					

Table 11 (Cont'd)

Test Date	Operating Mode	No. of Dead Fish	No. of Dead Fish Undamaged	No. of Dead Fish Damaged	% Damaged of Dead Fish	Damage Categories*				
						S	D	IB	BIS	BB
19 Oct	Pump	15 (IM)	3	12	80.0	6	6			
		4 (DM)	3	1	25.0	1				
		2 (RD)	1	1	50.0	1				
2 Nov	Pump	14 (IM)	--	14	100.0	7	4			3
		17 (DM)	10	7	41.2	2	1	1		3
		1 (RD)	1	--	0.0					
9 Nov	Pump	21 (IM)	1	20	95.2	8	4	4		4
		10 (DM)	3	7	70.0	1		3		3
		2 (RD)	1	1	50.0	1				

*

S = Slashed or cut
D = Decapitated
IB = Internal bleeding
BIS = Broken isthmus
BB = Broken backbone

**

IM = Immediate mortality
DM = Delayed mortality
RD = Released dead upon introduction in turbine

Table 12. Comparison of damage data from fish passage experiments performed on the pumping and generating modes in 1975.

Operating Mode	No. of Dead Fish	No. of Dead Fish Undamaged	No. of Dead Fish Damaged	% Damaged of Dead Fish	Damage Categories*				
					S	D	IB	BIS	BB
Pumping	83 (IM)**	15	68	81.9	32	24	4		8
	52 (DM)	37	15	28.8	4	1	4		6
	48 (RD)	25	23	47.9	11	5		7	
Generating	46 (IM)	24	22	47.8	14	7			1
	135 (DM)	125	10	7.4	3		3	4	
	53 (RD)	41	12	22.6	6	6			

*
S = Slashed or cut
D = Decapitated
IB = Internal bleeding
BIS = Broken isthmus
BB = Broken backbone

**
IM = Immediate mortality
DM = Delayed mortality
RD = Released dead upon introduction to turbine

Table 13. Incidence of immediate and delayed mortality of recaptured fish from 1975 fish passage experiments.

Test Date	No. of Dead Fish	No. of Immediately Killed Fish	No. of Delayed Mortality Fish	% Immediate Mortality of Dead Fish
15 Jun	8	6	2	75.0
20 Jul	16	9	7	56.3
8 Aug	61	10	51	16.4
25 Aug	40	15	25	37.5
21 Sep	30	18	12	60.0
4 Oct	37	8	29	21.6
17 Oct	43	13	30	30.2
19 Oct	19	15	4	78.9
2 Nov	31	14	17	45.2
9 Nov	31	21	10	67.7

Table 14. Comparison of immediate and delayed mortality data of recaptured fish from fish passage experiments performed on the pumping and generating modes in 1975.

Plant Mode	No. of Dead Fish	No. of Immediately Killed Fish	No. of Delayed Mortality Fish	% Immediate Mortality of Dead Fish
Pump	135	83	52	61.5
Gen	181	46	135	25.4

Size-selective mortality was assessed by an analysis of variance of fish length in four possible recapture categories (recaptured live; recaptured dead or died after capture; float-only recaptured; not recaptured at all) for each experiment. If size-selective mortality existed, the mean length of the live recaptures should differ statistically from that of the fish killed by passage. Similarly, if size influenced float retention or recapture itself, this should be evident in the mean length of fish comprising these groups.

Results of these analyses for 1974 and 1975 are given in Tables 15 and 16, respectively. Normally, a probability level less than 0.05 would be indicative of significant variation. Hence, no size selective mortality is indicated. A pair-wise comparison of mean fish length between all possible categories using Scheffe's interval (Gill, 1973) further substantiated the lack of significant variation between category means ($P > 0.05$ for all contrasts).

Since the fate of fish not recaptured or from which only a float was recaptured could not be accurately established, inclusion of these individuals in the size-selectively analyses may be misleading. Accordingly, the 1974 and 1975 experiments were reanalyzed by comparing the mean size of the live recaptures to that of the killed fish. In all but one experiment, no difference existed between the two categories ($P > 0.110$ for all trials). In the test of 20 October 1974, the mean length of the live recaptures was significantly greater than that of the dead fish (311 *vs* 288 mm, $P = 0.022$).

The average length of fish used in the pumping trials varied between 267 - 331 mm in 1974 and 316 - 677 mm in 1975. Mean length differed significantly between experiments within both years ($P < 0.001$

Table 15. Analysis of variance of body lengths of fish for four possible recapture groups (recaptured live; recaptured dead or died later; float-only recaptured; not recaptured at all) in pumping mortality tests performed in 1974.

Date	Source	df	MS	F	P
21 Jun 74	Between groups	3	575.26	0.75	0.53
	Within groups	91	767.28		
12 Jul 74	Between groups	3	754.99	0.77	0.52
	Within groups	72	985.23		
6 Oct 74	Between groups	3	943.64	2.20	0.10
	Within groups	71	429.86		
20 Oct 74	Between groups	3	3711.39	2.02	0.12
	Within groups	101	1841.84		
3 Nov 74	Between groups	3	168.05	0.29	0.83
	Within groups	90	574.89		

Table 16. Analysis of variance of body lengths of fish for four possible recapture groups (recaptured live; recaptured dead or died later; float-only recaptured; not recaptured at all) in pumping mortality tests performed in 1975.

Date	Source	df	MS	F	P
15 Jun 75	Between groups	3	481.75	0.18	0.91
	Within groups	22	2703.99		
20 Jul 75	Between groups	3	3111.97	1.40	0.25
	Within groups	137	2231.29		
21 Sep 75	Between groups	3	1170.97	0.50	0.68
	Within groups	109	2347.50		
19 Oct 75	Between groups	3	2095.50	0.59	0.63
	Within groups	45	3581.23		
2 Nov 75	Between groups	3	4349.09	1.19	0.32
	Within groups	132	3660.15		
9 Nov 75	Between groups	3	10107.32	2.61	0.05
	Within groups		3871.21		

for each year). Hence, if size-selective mortality existed within the size range of fish used, differences in size between live and dead recaptures should have been most pronounced in those tests in which relatively large fish were used. No evidence for this premise was detected, however. These results suggest that pumping mortalities may be dependent upon factors such as spatial distribution of fish in the intake or discharge, rather than on fish length.

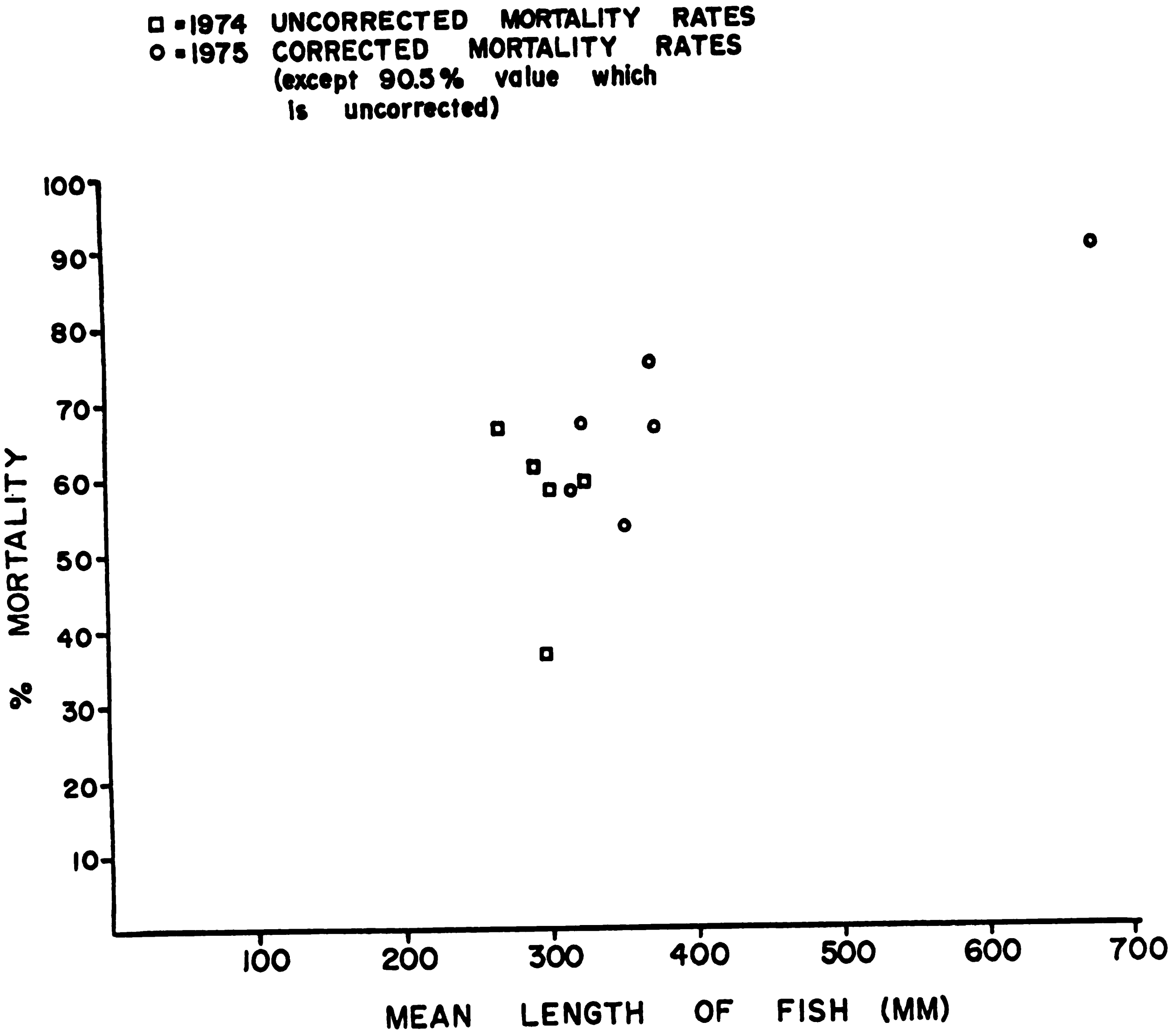
The salmon experiment of 19 October was the only pumping trial in which relatively large fish were used. Passage mortality was the highest of any of the tests (90.5%) and indicated that, despite previous analyses, fish size may be decisive in passage success. Examination of the relation between mortality and fish size (Fig. 2) tends to illustrate this although it is obvious that most of the estimates are derived from a narrow size range of fish.

Fish Passage - Generating Mode

Six mortality experiments were performed during power generation; two trials in 1974 and four tests in 1975. Yellow perch and chinook salmon was used in 1974 and rainbow trout were employed in 1975. The test of 14 August 1974 was procedurally different from the other tests and was deleted from the present analyses. Generating trial results for both years are listed in Tables 5 and 6.

Seventy-five live yellow perch were used on 28 August 1974. Recovery of fish was the highest of any of the generating tests (81.3%) as was the initial proportion of live recaptures (46/76, 60.5%). However, 26 of these fish died during the holding period resulting in

Figure 2. Relationship between fish size and mortality rate for pumping tests, 1974 and 1975.


□ =1974 UNCORRECTED MORTALITY RATES
○ =1975 CORRECTED MORTALITY RATES
(except 90.5% value which
is uncorrected)
% MORTALITY
100
90
80
70
60
50
40
30
20
10
100
200
300
400
500
600
700
MEAN LENGTH OF FISH (MM)

a total mortality rate of 67.2%. Only three of the 41 dead recoveries exhibited physical damage (7.3%).

Fifteen dead perch were also released on 28 August. Of these, eight were recaptured (53.3%) with two fish sustaining damage (both slashed in half). Recapture rates differed between the live and dead releases ($x^2 = 4.02$, $P < 0.05$) when based on recovered fish but were not significantly different ($x^2 = 0.38$, $P > 0.50$) when recaptured floats were also considered. This disparity is not unexpected with the low sample sizes involved.

In 1975, 455 live and 101 dead rainbow trout were used in generating trials. As in 1974, recapture rates based on recovered fish (63.7% live releases, 52.5% dead releases) differed between the two groups ($x^2 = 3.97$, $P < 0.05$) but were non-significant ($x^2 = 2.59$, $P > 0.10$) when recovered floats were included. Recovery rates between years differed significantly for the live releases ($x^2 = 8.14$, $P < 0.0005$) but did not differ for the dead releases ($x^2 = 0.046$, $P > 0.40$). Since inter-trial recovery rates of live releases varied only slightly in 1975 (61.7 - 65.9%), the discrepancy between the one 1974 run and the four 1975 tests is considered biologically meaningless.

Adjusted generating mortality rates varied from 35.4 - 74.8% in 1975 (Table 6, M_1 estimates). Although mean fish size (Table 4) and turbine operating conditions (Table 8) differed little between tests, significant inter-trial differences in mortality existed ($x^2 = 25.32$, $P < 0.0005$). The two summer experiments (8 and 25 August) had much higher mortality values than the two fall runs (4 and 17 October). This probably resulted from the high summer water temperatures and prolonged handling inducing stress and mortality. Control group losses were 3 - 6 times greater in August than in October. A striking consequence of the high control losses in the 8 August test was that the adjusted survival rate assumed an impossible value (> 100% survival). Accordingly, the summer mortality estimates may not be representative of generating passage success.

The pooled 1975 generating data resulted in a mean unadjusted mortality rate of 62.8% with a 95% confidence interval of ± 27.14% (Table 9). Rates derived by considering detached floats and unrecovered individuals as dead fish were 72.6 and 76.4%, respectively. Adjusted mortality estimates (using a mean handling loss of 37.3%) were 40.7% for recaptured fish, 56.3% for recaptured fish and floats, and 60.8% assuming all fish not recaptured alive were killed.

Nearly half (47.8%) of the fish killed during passage were physically damaged (Table 12). Lacerations and decapitations accounted for almost all (95.5%) of the injuries. Similarly, these damage types were the only forms displayed by injured dead releases. Damage rates differed significantly ($x^2 = 35.79$, $P < 0.0005$) between the immediate and delayed mortality groups of fish but no difference was observed ($x^2 = 0.38$, $P > 0.50$) in damage incidence between the live and dead releases (17.7% *vs* 22.6%).

Evidence for size selective differences between live and dead recaptures in each generating trial was lacking ($P > 0.065$ for all runs). Also, no trend was discerned among experiments between mean fish length and mortality rate (Table 17), although mean fish size differed little in the four tests. The absence of size selective mortality during generating passage may be a consequence of the relatively wide wicket gate setting used on this mode during the tests

Table 17. Summary of adjusted mortality rates for generating fish passage experiments performed in 1975.

Date	No. of Live Fish Released	Mean Length	Adjusted Mortality
8 Aug 75	131	347 mm	74.8% [a]
25 Aug 75	79	358 mm	65.2%
4 Oct 75	129	358 mm	35.4%
17 Oct 75	114	380 mm	53.9%

[a] Based on a handling loss of 6.1% (Table 6)

(approximately 82% open during generation *vs* 65% open during pumping). This larger opening may allow a wide size range of fish to pass by the turbine blades unimpaired. Presumably, the difference in wicket gate settings between operational modes also accounts for the differences in recovery and mortality rates between the pumping and generating experiments (Table 9).

Board Passage - Pumping and Generating Modes

Pumping Mode

In 1974, seven board passage turbine tests were performed during pumping (Table 18). In these trials, 224 6-inch boards, 145 8-inch boards, 242 12-inch boards, 190 18-inch boards, 185 24-inch boards and 48 26-inch boards were used. Of the 1034 boards, 636 were subsequently recovered (61.5% recapture rate). Recovery and damage rate generally increased with board size in each experiment. The pooled data indicate that board mutilation was minimal for the smaller sizes but was nearly 100% for the larger boards (Fig. 3). In most cases, damaged boards were split in two or more pieces. Hence, the recovery rates of the larger boards (more susceptible to damage) were expected to be higher than the smaller ones since more than one piece per board (after mechanical contact) was usually available for recapture.

Generating Mode

Generating mode board passage trials were performed on 14 and 28 August 1974. A total of 368 boards were used comprising four categories: 100 6-inch boards, 96 12-inch boards, 101 18-inch boards, and 71 24-inch boards (Table 18). Recovery rates were not significantly different

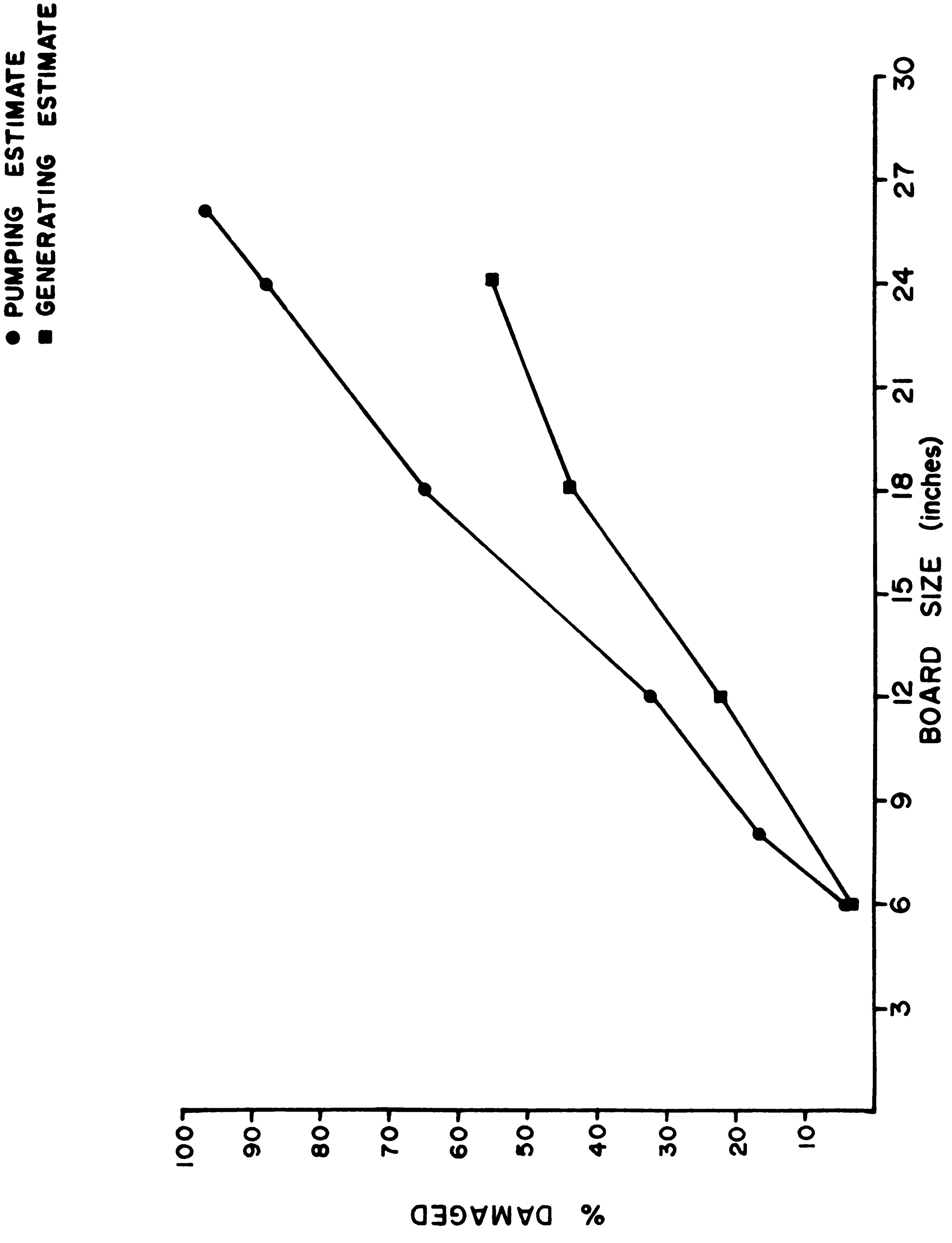
Table 18. Summary of 1974 board passage experiments.

Test # and Date and Operational Mode	Board Size (inches)	No. of Boards Introduced	No. of Boards Recovered	Recovery %	Recovered Boards: # Intact No Damage	Recovered Boards: # Hit or Cracked	% Damaged of the Recovered Boards
#3 - 10 May 74	6	50	15	30.0	13	2	18.3
Pumping Mode	12	49	19	38.8	8	11	57.9
#5 - 21 June 74	18	44	27	61.4	7	20	74.1
Pumping Mode	24	43	31	72.1	5	26	83.9
#8 - 12 July 74	6	49	27	55.1	26	1	3.7
Pumping Mode	12	49	29	59.2	23	6	20.7
#10 - 14 Aug 74	6	51	45	88.2	44	1	2.2
Generating Mode	12	50	46	92.0	34	12	26.1
	18	53	45	84.9	24	21	46.7
	24	24	22	91.6	10	12	54.5
#12 - 28 Aug 74	6	49	41	83.7	39	2	4.9
Generating Mode	12	46	38	82.6	31	7	18.4
	18	48	42	87.5	25	17	40.5
	24	47	41	87.2	18	23	56.1
#13 - 3 Oct 74	6	9	5	55.6	5	0	0.0
Pumping Mode	12	34	24	70.6	16	8	33.3
	18	5	1	20.0	0	1	100.0
#14 - 6 Oct 74	6	31	16	51.6	16	0	0.0
Pumping Mode	8	47	26	55.3	22	4	15.4
	12	12	6	50.0	5	1	16.7
	18	43	36	83.7	16	20	55.6
	24	46	41	89.1	5	36	87.8

Table 18. (Cont'd):

Test # and Date and Operational Mode	Board Size (inches)	No. of Boards Introduced	No. of Boards Recovered	Recovery %	Recovered Boards		% Damaged of the Recovered Boards
					# Intact No Damage	# Hit or Cracked	
#17 - 20 Oct 74 Pumping Mode	6	36	19	52.8	18	1	5.3
	8	49	27	55.1	24	3	11.1
	12	49	24	50.0	15	9	37.5
	18	49	44	90.0	17	27	61.4
	24	47	44	93.6	6	38	86.4
#19 - 14 Nov 74 Pumping Mode	6	49	21	42.9	21	0	0.0
	8	49	20	40.8	15	5	25.0
	12	49	24	50.0	18	6	25.0
	18	49	32	65.3	9	23	71.9
	24	49	43	87.8	3	40	93.0
	26	48	35	72.9	1	34	97.1
TOTALS:							
Pumping	6	224	103	46.0	99	4	3.9
	8	145	73	50.3	61	12	16.4
	12	242	126	52.1	85	41	32.5
	18	190	140	73.7	49	91	65.0
	24	185	159	85.9	19	140	88.1
	26	48	35	72.9	1	34	97.1
		1034	636	61.5	314	322	
Generating	6	100	86	86.0	83	3	3.5
	12	96	84	87.5	65	19	22.6
	18	101	87	86.1	49	38	43.7
	24	71	63	88.7	28	35	55.6
		368	320	87.0	225	95	

Figure 3. Relationship between board size and damage rate for pumping and generating tests, 1974.


● PUMPING ESTIMATE
■ GENERATING ESTIMATE
% DAMAGED
100
90
80
70
60
50
40
30
20
10
3
6
9
12
15
18
21
24
27
30
BOARD SIZE (inches)

between board sizes ($x^2 = 0.356$, $P > 0.90$) and averaged 87.0% overall. Damage rates, however, increased with board size (Fig. 3).

Comparison of the pumping and generating damage rates revealed no significant difference for the 6-inch ($x^2 = 0.059$, $P > 0.80$) and 12-inch boards ($x^2 = 0.59$, $P > 0.40$), but a marked difference for the larger boards (18-inch, $x^2 = 9.09$, $P < 0.005$; 24-inch, $x^2 = 26.63$, $P < 0.0005$). As in the fish passage trials, these operational mode differences are probably due to the wider wicket gate opening on the generating mode permitting more larger sized boards to pass unmarred than was possible during pumping.

DISCUSSION

The turbine passage experiments conducted at Ludington during 1974 and 1975 represent the first intensive field assessment of fish mortality at a pumped storage facility. As such, the procedures and methodologies developed may prove suitable for similar studies at other pumped storage sites. The use of float tags and net bags to conduct these tests is believed to offer great potential for evaluating passage success given a modest amount of equipment, personnel, and money.

Although the float and bag gear have great utility, little information exists on the effects of float attachment or bag enclosure on the orientation and survival of fish in fish passage situations. Because of the confining nature of the bag to fish movement, fish survival during passage may be adversely affected. If this is true, derived mortality rates using this equipment may be too liberal; that is, mortality may be over-estimated (or conversely, survival under-estimated). Although this question warrants further research, the effect of the float and bag technique may never be adequately resolved. Hence, interpretation of results will vary depending on how the methodology is perceived as affecting fish behavior.

Derivation of mortality quotients from each of the Ludington experiments was accomplished in three ways: (1) by considering only recaptured fish; (2) by considering the float-only recaptures as dead fish and combining these with the recaptured fish results; and (3) by considering all fish not recaptured alive as mortalities. Method 1 and 2 provide the most realistic estimates of turbine mortality. Method 3 assumes that fish release to the turbines is 100% successful (*i.e.*, no fish are caught in the trash slots or missed penstock entry) and that all fish surviving passage are recaptured. Fulfillment of these criteria was not always accomplished at Ludington as demonstrated by the recapture of test fish many miles from the plant (missed turbine entry) and the recovery of fish surviving passage for several days after the initial recapture efforts. Observations at the intake of turbine units after shut-down further substantiated that turbine releases were seldom complete.

The recapture rates of fish, and fish and floats, for the pooled Ludington data, were 35.7 and 73.3% during pumping and 61.3 and 84.2% during generation (combined data, both years, live releases). Hence, an average of 26.7 and 15.8% of the introduced fish were unrecovered. Similar mean recapture rates (78.6% fish and float recovery, 21.4% not retrieved) were obtained in Connecticut River passage tests (Johnson, 1970) and illustrate that incomplete fish recovery is not unique to the Ludington studies. Power plant features, release methodology and intensity of recapture effort may all influence the recovery rate.

The average adjusted pumping mortality in 1975 (67.7%) was greater than the unadjusted rate in 1974 (56.5%). Although the mean size of fish was generally slightly larger in 1975, both mortality values are believed to estimate the same overall parameter. The clustering of the point estimates shown in Figure 2 appears to support this premise. For generating experiments, the mean 1975 adjusted mortality value

(40.7%) was much lower than the one 1974 estimate (67.2%). Interpretation of this difference is difficult, however, because of the large differences in sample size between years and the use of different species. This latter aspect is especially important since yellow perch are physoclistous and may be more prone to pressure-related injury than the physostomous trout (Beck *et al.*, 1975; Tsvetkov *et al.*, 1972; Foye and Scott, 1965).

The disparity between pumping and generating fish mortality estimates is presumably a function of turbine characteristics, particularly wicket gate opening. Wooden board damage rates (between modes) paralleled the operating mode differences found in fish and further substantiated the importance of engineering factors in passage success. These data agree well with laboratory results of mortality in relation to the dynamic characteristics of turbines (Bell *et al.*, 1967).

Although an obvious relation between board size and damage existed, a similar pattern was not clearly apparent in either the pumping or generating fish trials. Several explanations can be advanced for the inconsistency between the two sets of results. Most plausible, perhaps, is that mechanical damage is not the sole factor in causing fish passage mortality. Rather, shearing forces and cavitation may also be operable. Existence of these factors in the tests is suggested by recapture of decapitated fish and fish with missing pieces of flesh (shearing action), and metal pitting of the turbine blades (cavitation). Damage data from the 1975 live releases (using both immediate and delayed mortalities) indicated that only 43.4% of the pumping injuries (36/83) and 53.1% of the generating injuries (17/32) were of a mechanical nature (slashes, cuts or abrasions - Table 12). Weekly observations of dead fish in the reservoir also showed that many fish lacked heads or displayed other shearing action type damage (*i.e.*, broken gill arches). Hence, the finding by Long (1968) that factors other than fish size (*i.e.*, spatial distribution near the turbine) affect fish mortality may apply at Ludington as well.

A second interpretation of the discrepancy between the fish and board data is that the size range of fish used in the tests was too narrow for size-selective mortality effects to be detected. Excluding the salmon test in which good agreement with the board data was evident (mean fish size = 27 inches, mortality = 90.5%; board size = 26 inches, damage = 97.1%), the mean length of trout in any experiment never exceeded 15 inches (381 mm) with all fish included within a range of 96 - 532 mm (3.8 - 20.9 inches). Thus, the damage rates observed for the larger sized boards (greater than 18 inches) could not possibly be statistically paralleled in the fish due to a lack of the appropriate-sized individuals. Comparison of the fish mortality data with board results of a similar size (12 inches) showed that both pumping and generating fish mortalities were much higher than the respective board damage rates (Table 17, Figs. 2 and 3). Again, the importance of factors other than mechanical contact is implied.

Conceivably, handling mortalities were of sufficient magnitude as to "mask" in the fish tests the size selective effects seen with the boards. This probably occurred in the generating trial of 8 August 1975 and may have also taken place in the tests of 25 August and 21 September 1975. However, for all other runs, handling mortality never exceeded 16.0% and was thus well-controlled. Accordingly, the "masking" of size-selective mortality in fish via handling losses is considered remote.

CONCLUSIONS

Mortality studies at Ludington indicated that passage success of fish through the pump-turbines was relatively low, particularly during pumping. Much effort was expended in the development of techniques to provide accurate and precise estimates of turbine mortality. Although a limited number of species was studied and a narrow size-range of fish used, the mortality assessments are the first of their kind for a pumped storage facility. Hence, these studies should prove valuable as a foundation on which future investigations can be based.

Several problems remain unsolved in using the derived mortality estimates. Foremost of these is the determination of the number of fishes passing through the turbines. Population estimates are needed for lake species affected by the power plant as well as for species found within the reservoir. Only with this knowledge can yearly estimates of fish loss be obtained.

Secondly, the significance of turbine losses to the welfare of fish stocks is unclear. In some cases, the *ecological* consequences of plant mortality are probably slight (*i.e.*, kills of spawning-run Pacific salmonids that would naturally die shortly after spawning). However, data are lacking on the proportion of the lake populations that undergo turbine passage. Consequently, an assessment of biological impact is difficult.

Even if the number and proportion of each of the lake species affected by the power plant is known, the resiliency of these species to losses is obscure. Fishes exhibit many compensation mechanisms in response to population removals and thus turbine mortalities may not necessarily significantly affect either carrying capacity or sustained yield. Further information of the dynamics of the lake populations in relation to mortality would be helpful.

The state-of-the-art for evaluating fish passage and its impact on fish population dynamics is admittedly in its infancy. As more data and refinements in technique become available, a clearer understanding of these interactions will assuredly ensue.

SUMMARY

Passage mortality of fish through pump-turbines at the Ludington Pumped Storage Power Plant was studied in 1974 and 1975. Procedures were developed for introducing fish to the turbines using weighted paper sacks, and for recapturing individuals using jaw-fastened styrofoam floats. Commercially procured fish were used in almost all the field trials. Passage studies of various sized wooden boards were also performed to provide supplementary data on size and mechanical injury.

Ten fish tests were accomplished in both 1974 and 1975. In 1974, 1017 fish were used comprising three species: rainbow trout, chinook salmon and yellow perch. During 1975, 1725 fish were used with all but 51 fish being rainbow trout. Control groups of fish were used in each trial during 1975 except one run in which coho and chinook salmon were tested.

Pumping mode mortality estimates were derived from five tests in 1974 and six tests in 1975. Data from three 1974 pumping experiments were excluded because of procedural differences. A total of 445 live fish were released in the five valid 1974 tests of which 200 or 45% were recovered. Known dead fish releases resulted in a 38% recapture rate which was not significantly different ($P > 0.10$) from the live release rate. Satisfaction of this equality was requisite for using the float-recapture technique. In 1975, 639 live fish were used during pumping; 35% were recaptured. The recovery rate of 132 dead releases (36.4%) was again similar to the live fish ($P > 0.70$). Yearly differences in live recapture rates could not be explained.

Unadjusted pumping mortalities ranged from 33 - 63% in 1974 tests and averaged 56.5% with a 95% confidence interval of ± 13.3%. In 1975, adjusted mortality varied from 53.8 - 75.4% with a pooled corrected mean estimate of 67.7% ± 7.2%. Average handling mortality in 1975 was 13.8%. Mean adjusted mortality values derived by considering detached floats and unrecovered fish as dead fish were 75.1 and 81.4% in 1974, and 86.4 and 91.9% in 1975, respectively. Although differences in pumping mortality existed between years, both of the mean mortality rates are thought to be estimates of the same parameter.

Damage to the live releases was lower in 1974 (37.2%) than in 1975 (61.5%) ($P < 0.005$). In 1975, 73.5% of the injuries were lacerations or decapitations implying that mechanical contact and shearing forces were causative agents. The majority of 1975 deaths (61.5%) were immediate in nature.

The results of size-selective mortality analyses proved ambiguous for pumping experiments. Most analyses showed no difference in size between dead and live fish. However, mortality was highest (90.5%) in one trial in which large salmon were used. The narrow size range of fish used in most of the pumping trials may have obscured the detection of size-related mortality.

Six generating mortality experiments were performed; two in 1974 and four in 1975. One of the 1974 trials was inappropriate for comparative analysis. Seventy-five yellow perch were used in the one valid 1974 test; 81.3% of these fish were recaptured. Eight of 15 dead releases were recovered as well (53.3%). These recapture rates were significantly different ($P < 0.05$) but proved non-significant when recaptured floats were also included ($P > 0.40$). Mortality in this test averaged 67.2%. Only three of the live releases and two of the dead releases exhibited damage.

In 1975, 455 live and 101 dead rainbow trout were used in generating tests. Recapture rates between the groups were different (63.7 *vs* 52.5%, $P < 0.05$) but were similar when recovered floats were included ($P > 0.10$). Yearly differences in the live release recovery rates are probably biologically meaningless.

Adjusted 1975 generating mortalities varied from 35.4 - 74.8% and averaged 40.7% ± 27.1%. Average handling mortality was 37.3%. Mean adjusted mortality values derived by considering detached floats and unrecovered fish as dead fish were 56.3 and 60.8%, respectively. Due to high handling losses, mortality estimates from summer generating tests may not be representative.

Almost half (47.8%) of the fish killed during generating passage were damaged; nearly all of the injuries were lacerations or decapitations (95.5%). Damage rates differed between fish sustaining immediate and delayed mortality ($P < 0.0005$) but were similar between the live and dead releases (17.7 *vs* 22.6%, $P > 0.50$).

Evidence for size-selective mortality in generating trials was absent. The relatively wide wicket gate setting (82% open) probably allowed a large size range of fish to pass by the turbine blades unimpaired. Presumably, the difference in wicket gate setting between operational modes (82% generating, 65% pumping) accounts for much of the difference in recovery and mortality rates between the pumping and generating trials.

Nine wooden board passage tests were conducted in 1974; seven pumping and two generating tests were performed. A total of 1034 boards were used (comprising six size groups) during pumping of which 61.5% were recovered. In pumping tests, recovery and damage rates increased with board size. Mutilation was low for the smaller sized boards (6-inch - 3.9%) but virtually complete for the largest boards (26-inch - 97.1%). In the generating tests, 368 boards were used (four size categories) resulting in an overall recapture rate of 87.0%. Recapture rates did not differ between size groups ($P > 0.90$) although damage rates increased with board length.

Pumping and generating board damage rates were similar for size groups 12 inches or less ($P > 0.40$) but differed among the larger sized boards ($P < 0.005$). These differences were attributed to the difference in wicket gate setting between the operating modes.

Several explanations are advanced for the discrepancy in mortality and damage between the fish and board studies. The most plausible is that factors other than mechanical contact contribute significantly to fish death. Also, the limited size range of fish used relative to the board lengths may account for the differing results. Fish losses due to handling mortality are thought not to have "masked" size-selective mortality in the fish tests.

Unresolved problems in applying the mortality quotients derived from these studies are delineated.

LITERATURE CITED

LITERATURE CITED

Beck, A. P., G. V. Poje, and W. T. Waller. 1975. A laboratory study on the effects of the exposure of some entrainable Hudson River biota to hydrostatic pressure regimes calculated for the proposed Cornwall Pumped Storage Plant, pp. 167-204. *in* S. B. Saila (ed.) Fisheries and Energy Production: A Symposium. D. C. Health and Company, Toronto.

Bell, M. C. 1974. Fish passage through turbines, conduits, and spillway gates, pp. 251-261. *in* L. D. Jensen (ed.) Proceedings of the Second Workshop on Entrainment and Intake Screening. Rept. 15, Electric Power Research Institute, Palo Alto, California.

Bell, M. C., A. C. DeLacy, and G. J. Paulik. 1967. A compendium on the success of passage of small fish through turbines. Rept. to the U. S. Army Corps of Engineers, Contract No. DA-35-026-CIVENG-66-16. 268 p.

Comninellis, E. 1973. Ludington pumped storage project. Journal of the Power Division, ASCE, 99(PO1): 69-88.

Cramer, F. K. 1960. Fish passage through turbines, model turbine experiments. U. S. Army Corps of Eng., Walla Walla District, Prog. Rept. 1: 17 p.

Cramer, F. K. 1965. Fish passage through hydraulic turbines. U. S. Army Corps of Eng., Walla Walla District, Memorandum Rept. 1: 16 p.

Cramer, F. K., and R. C. Oligher. 1960. Fish passage through turbines - tests at Cushman No. 2 hydroelectric plant. U. S. Army Corps of Eng., Walla Walla District, Prog. Rept. 2: 26 p.

Cramer, F. K., and R. C. Oligher. 1961. Fish passage through turbines, further model turbine experiments - Francis runners. U. S. Army Corps of Eng., Walla Walla District, Prog. Rept. 3: 33 p.

Cramer, F. K., and R. C. Oligher. 1964. Passing fish through hydraulic turbines. Trans. Amer. Fish. Soc. 93: 243-259.

Foye, R. E., and M. Scott. 1965. Effects of pressure on survival of six species of fish. Trans. Amer. Fish. Soc. 94: 88-91.

Gill, J. L. 1973. Current status of multiple comparisons of means in designed experiments. J. Dairy Sci. 56: 973-977.

Hauck, F. R., and Q. A. Edson. 1976. Pumped storage: its significance as an energy source and some biological ramifications. Trans. Amer. Fish. Soc. 105: 158-164.

Johnson, F. A. 1970. A device for fish recovery during turbine-passage mortality studies. Prog. Fish-Cult. 32: 236-239.

Ley, R., and E. Loane. 1962. Symposium on pumped storage: general planning of pumped storage. Journal of the Power Division, ASCE, 88(PO2): 211-232.

Liston, C. R., and P. I. Tack. 1974. A study of the effects of installing and operating a large pumped storage project on the shores of Lake Michigan near Ludington, Michigan. 1973 Ann. Rept. to Consumers Power Co., Vol. 1, Dept. Fish and Wildl., Michigan State Univ., 174 p.

Liston, C. R., and P. I. Tack. 1975. A study of the effects of installing and operating a large pumped storage project on the shores of Lake Michigan near Ludington, Michigan. 1974 Ann. Rept. to Consumers Power Co., Vol. 1, Fisheries Research, Dept. Fish and Wildl., Michigan State Univ., 166 p.

Long, C. 1968. Diel movement and vertical distribution of juvenile anadromous fish in turbine intakes. U. S. Fish Wildl. Serv., Fish. Bull. 66: 599-609.

Lucas, K. C. 1962. The mortality to fish passing through hydraulic turbines as related to cavitation and performance characteristics, pressure changes, negative pressures, and other factors, pp. 1-24. *in* Symposium on Cavitation and Hydraulic Machinery. International Association for Hydraulic Research.

Monten, E. 1963. The possibility of salmon smolt passing unharmed through power plant turbines when descending to the sea. Translated from Swedish by the U. S. Joing Publication Service, for the Fish Passage Research Program, U. S. Bureau of Commercial Fisheries, Seattle, Washington. June, 1963.

Muir, J. F. 1959. Passage of young fish through turbines. Journal of the Power Division, ASCE, 85(PO1): 23-46.

Salzman, M. 1962. Symposium on pumped storage: site investigation of pumped storage facilities. Journal of the Power Division, ASCE, 88(PO2): 233-251.

Schoeneman, D. E., and C. O. Junge, Jr. 1954. Investigations of mortalities of downstream migrants at two dams on the Elwha River. Wash. St. Dept. Fish. Res. Bull. 3: 43 p.

Schoeneman, D. E., R. T. Pressey, and C. O. Junge, Jr. 1961. Mortalities of downstream migrant salmon at McNary Dam. Trans. Amer. Fish. Soc. 90: 58-72.

Schoumacher, R. 1976. Biological considerations of pumped storage development: introductory remarks. Trans. Amer. Fish. Soc. 105: 155-157.

Serchuk, F. M., C. R. Liston, and P. I. Tack. 1974. A study of the effects of installing and operating a large pumped storage project on the shores of Lake Michigan near Ludington, Michigan. I. Mortality tests through turbines. II. Movement patterns and orientation of fish in the Ludington reservoir as determined by ultrasonic telemetry. Ninth Quarterly Report to Consumers Power Co., Dept. Fish and Wildl., Michigan State Univ., 33 p.

Serchuk, F. M., C. R. Liston, and P. I. Tack. 1975. An evaluation of fish passage through hydraulic turbines at the Ludington Pumped Storage Facility. Tenth Quarterly Report to Consumers Power Co., Dept. Fish and Wildl., Michigan State Univ., 21 p.

Tack, P. I., and C. R. Liston. 1973. A study of the effects of installing and operating a large pumped storage project on the shores of Lake Michigan near Ludington, Michigan. Eighth Quarterly Report to Consumers Power Co., Dept. Fish and Wildl., Michigan State Univ., 17 p.

Tsvetkov, V. I., D. S. Pavlov, and V. K. Nezdoliy. 1972. Change of hydrostatic pressure lethal to the young of some freshwater fish. J. of Ichthyology 12: 307-318.

U. S. Army Corps of Engineers, North Pacific Division. 1960. Effect of structures at main Columbia River and certain other dams on downstream migration of fingerling salmon. Research Rept., Fisheries Engineering Research Program, U. S. Army Corps of Engineers District, Portland. 83 p.

Velz, C. J., J. D. Calvert, Jr., R. A. Deininger, W. L. Heilman, and J. Z. Reynolds. 1968. Pumped storage for water resources development. Journal of the Sanitary Engineering Division, ASCE, 94(SA1): 159-170.

Von Guten, G. H. 1961. Fish passage through turbines. Journal of the Hydraulics Division, ASCE, 87(HY3): 59-72.

Von Raben, K. 1957. Regarding the problem of mutiliation of fishes by hydraulic turbines. (Translation from the German, "Zur Frage der Beschädigung von Fischen durch Turbinen." Die Wasserwirtschaft 4: 97-100). Translated by the Fish. Res. Board Can. Transl. Ser. 448.

Woodruff, R. 1971. Pumped storage: state-of-the-art. Journal of the Power Division, ASCE, 97(PO3): 675-695.

MOVEMENT PATTERNS AND ORIENTATION OF FISHES IN THE LUDINGTON PUMPED STORAGE RESERVOIR AS REVEALED BY TRACKING STUDIES

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INTRODUCTION

Behavioral investigations of fishes in habitats affected by pumped storage operation are few and have been generally restricted to netting, seining, and mark and recapture procedures (Robbins and Mathur, 1976; Estes, 1971). Little information exists on the response of fish to water velocity changes, alteration of habitat, and related aspects associated with the biological impact of pumped storage projects (Schoumacher, 1976). Data are also lacking on the environmental and ecological components related to the passage of fish into pumped storage systems, and the behavior of species retained within these facilities.

Environmental studies at the Ludington Pumped Storage Power Project showed that nearly all fish species in the adjacent Lake Michigan waters have entered the Ludington reservoir (Liston and Tack, 1974, 1975). The purpose of the present research was to determine movement patterns, activity cycles, and residence periods of free-ranging fish in the Ludington reservoir and to relate these attributes to environmental cues and operational characteristics of the power plant. Field observations were accomplished during 1974 and 1975 with carp (*Cyprinus carpio*), brown trout (*Salmo trutta*), and rainbow trout (*Salmo gairdneri*). These species were studied because of their availability, seasonal abundance in the reservoir, and capability of retaining sonic and float tags.

METHODS AND MATERIALS

Ultrasonic telemetry and float tracking techniques were used to determine the behavioral patterns and orientation of fish. These procedures have been previously employed in fish homing and movement studies (Stasko *et al.*, 1976; Kelso, 1976, 1974; Groot *et al.*, 1975; Warden and Lorio, 1975; Dodson and Leggett, 1974, 1973; Jahn, 1969, 1966; McCleave, 1967; see Stasko, 1975 for others), and are attractive since they leave fish relatively unhindered and allow prolonged contact under a variety of environmental conditions. Float tagging is especially productive because a large sample size can be obtained at low cost without sacrificing accuracy (Stasko, 1971).

Equipment

Ultrasonic transmitters and receiving equipment were procured from commercial sources. Two models of ultrasonic transmitters were used: Smith-Root SR 69-B units and Bayshore Systems Corporation Acoustic T-2 tags. Both were cylindrical, polystyrene-housed, location-type transmitters possessing constinuous pulsed output. The SR 69-B tags were 64 mm long by 14 mm in diameter, weighed 12 g in water, and had an operating frequency of 74 kHZ. The T-2 transmitters were 51 mm long by 14 mm in diameter, weighed 9 g in water, and possessed transmitting frequencies from 52-73 kHZ. Both models yielded detection ranges of 500-1000 m. Tags with useful lives of

7, 14, and 35 days were used, as were various pulse rates (1-4 pulses/sec) to permit individual fish identification.

The receiving units consisted of a Smith-Root TA-60 Sonic Receiver and a Bayshore Systems LF-25 Receiver. Both were portable, battery-operated, and tunable in a frequency range of 60-180 kHZ. During operation, the receiver was coupled to a hand-held, unidirectional hydrophone (Smith-Root SR-70-H) having a conical beam pattern of 8° with a peak sensitivity of 74 kHZ. Earphones were used during sonic operations to exclude extraneous background noises.

Float-tracking devices consisted of styrofoam spheres, 10.2 cm in diameter, color-coded with flourescent paint, and numerically labelled to afford specific identification of individuals. Each tag was connected by 5.5 m of monofilament nylon line to a looped metallic fish pin used in attaching the device to the fish.

Capture and Tagging of Fish

Adult fish were captured in the Ludington reservoir by gill nets. Fish used for tracking were selected from individuals that lacked extensive gill net lesions or other visible injury, and were normally marked, at the time of capture, with two floy tags for identification. The average total body length for tracked fish was 61 cm for carp and 62 cm for trout. In 1974, fish were placed in a holding cage in the reservoir or a continuous flow maintenance tank at the fisheries laboratory prior to transmitter or float attachment. In 1975, fish were processed aboard boat soon after capture.

Two methods of ultrasonic tagging were used. For trout, transmitters were administered orally and inserted into the stomach by a syringe constructed of PVC piping. Care was taken not to rupture the stomach linings or otherwise inflict injury during this process. With carp, the sonic tags were fastened externally just below the anterior section of the dorsal fin. Transmitters were affixed with their axis parallel to that of the fish by pins inserted through the uppermost back of the fish. The pins were secured to the transmitter with a small vinyl covering wrapped tightly about the tag with electrical tape. Once inserted through the fish, the pins were fitted with a Peterson disc to retain the transmitter snugly to the body. No anesthetics were used prior to either mode of tagging. The entire procedure was generally accomplished in less than two minutes, after which the fish was returned to water.

Float tags were attached by drawing the steel fish pin, knotted to the nylon line securing the float, through the dorsal musculature immediately anterior to the dorsal fin. The pin was then crimped against a Peterson disc to hold the tag firmly in place. This procedure was modified slightly with some carp where attachment was made by tying the float line to the base of the anterior spine in the dorsal fin.

During 1974, tagged fish were held in a live box in the reservoir for at least 12 hr after tagging to assure recovery from handling and to permit buoyancy adjustments due to tag weight. In 1975, fish were observed in a tank aboard the tracking boat for 5-15 min after tagging and subsequently released in the reservoir if activity appeared normal. In this latter year, fish were usually not tracked on the day of release to avoid recording possible abnormalities in behavior induced by tagging trauma.

Tagged fish were either released in the reservoir by overturning the live box or by transporting netted fish to various randomly-selected shoreline release sites. Time between capture and release varied from 0.1 (immediate release) to 259.4 hr (released after 11 days in the laboratory holding tank).

Tracking Procedures

Movements of tagged fish were monitored by maneuvering the tracking vessel close to and in line with the position of the fish. Fish location was assessed by the intensity and directionality of the incoming signal, or visually with float-tagged individuals. Although boat noise appears to have little effect on fish (Peterson, 1975; Stasko *et al.*, 1973; McCleave and Horrall, 1960; Hasler *et al.*, 1969; Johnson, 1960), the direction of approach was varied to avoid biasing the orientation of tracked specimens. A position fix was recorded once every 10-30 min (generally 20 min for carp; 15 min for trout) and was determined by triangulation with a marine sextant using embankment features (20 reservoir dike-load centers) as landmarks. On several occasions (particularly with float-tagged fish), two or more fish were tracked simultaneously by alternating between fish locations on a fixed time schedule. These tracks proved useful in assessing the variability in movement pattern and speed among individuals exposed to similar environmental conditions.

Throughout each track, data on wind strength and direction, sun visibility, light penetration, water and air temperature, and atmospheric pressure were recorded coincident with fish position. Environmental information records maintained by Consumers Power Company at the plant were also used when field measurements were inconsistent or lacking. Information on the operational status of the pumped storage facility during tracking periods (operational mode, number of turbines on, and water elevation changes) was also accessed from Company records.

Data Analysis

Position fixes for each track were plotted on a large-scale map of the Ludington reservoir by use of a three-arm protractor. The plotted course of each fish consisted of a series of points connected by lines best thought to represent the path of movement between successive positions. Digitization of the mapped position plots facilitated computer analysis of the field observations and permitted the determination of swimming speed, angular change of movement, and movement pattern for each interval, for selected intervals, and for the entire track.

Swimming speed was calculated from the distance travelled along the estimated course and is considered a "calculated speed" since corrections for current velocity, swimming depth, and non-linear movement could not be accurately assessed. Movement rate was usually expressed in body lengths/second (L/s) since this is the simplest and most useful method of comparing swimming speed performance of fish of different sizes (Webb, 1975). Angular change was evaluated by determining the direction change (in degrees) between the straight line course established for an interval, and the line constructed for the subsequent interval. Angular means, rather than arithmetic means, were computed for all track-level analyses (Batschelet, 1965, 1972). Movement patterns were appraised from graphs of tracks derived from CalComp maps.

Periodicity in swimming speed was determined by grouping movement rate data according to time of day (hourly intervals). Speed estimates were averaged from all members of the same species to provide a mean value for each time interval. Data obtained from the same fish on different tracking days were considered independent and were included together in the determination of each of the hourly means.

The influence of environmental, behavioral, and power plant operating characteristics on fish movement was evaluated by stepwise linear multiple regression procedures (Draper and Smith, 1966). An $\alpha = .25$ significance level was chosen for both the entry and deletion criteria of a variable. A direct examination of residuals for each analysis was performed to check for lack of linearity and to determine whether the assumptions concerning the error components were met. All residual examinations (graphs not included) indicated that a linear relationship was appropriate and that the data were relatively free of abnormalities.

The minimum retention time for individuals in the Ludington reservoir was assessed by noting the date on which tagged fish were last observed or detected in the reservoir. Supplementary information on residence time was obtained from mark and recapture efforts using gill nets.

RESULTS

In 1974, 29 carp were tracked for periods ranging from 1-24 hr (median 8 hr) for a total of 630 hr covering 80 tracking efforts (Table 1). Thirty tracks were accomplished using 8 sonic-equipped fish and 50 tracks were performed with 21 float-tagged individuals. During 1975, 36 fish were tracked; 23 carp were observed from 2.6-24.0 hr per effort (7 hr median) for a total of 351 hr, and 13 trout (brown and rainbow) were followed for periods of 2.4-24.0 hr (median 7 hr) for a total of 178 hr (Table 2). Sonic tags were used with 28 of the 51 carp tracks (55%) and 23 of the 26 trout tracks (88%).

Distance of individual carp tracks in 1974 ranged from 0.07-16.49 km (median 2.40 km) for a total of 219.40 km (Table 3). In 1975, individual carp paths varied from 0.39-9.23 km (median 1.90 km) for a total of 129.70 km. Trout tracks covered distances of 0.15-27.44 km (median 7.90 km) for a total of 242.40 km (Table 4).

Most tracks commenced in the morning and terminated in late afternoon. Three carp and one brown trout were tracked through the night. Seven tracks were conducted at dawn (6 carp and 1 brown trout) and five tracks at dusk (all carp). In some cases, tracks were abbreviated because of loss of signal or equipment failure, lack of fish movement for an extended time (several hours), or adverse weather conditions.

Table 1. Summary of 1974 tracking activities.

Track Type	Species	No. of Tracks	Duration of Tracks
Sonic	8 carp	30	287.6 hours
Float	21 carp	50	342.7 hours
Total	29 carp	80	630.3 hours

Table 2. Summary of 1975 tracking activities.

Track Type	Species	No. of Tracks	Duration of Tracks
Sonic	8 carp	28	188.5 hours
	8 brown trout	16	124.0 hours
	3 rainbow trout	7	36.6 hours
Float	15 carp	25	162.6 hours
	2 brown trout	3	17.2 hours
TOTALS:			
Sonic	19 fish	51	349.1 hours
Float	17 fish	28	179.8 hours
Total	36 fish	79	528.9 hours

Table [illegible]. Quantitative description of individual tracks accomplished in the Ludington Reservoir, 1974.

Table 3. Quantitative description of individual tracks accomplished in the Ludington Reservoir, 1974.

Date	Species	Track No.	Fish No.	Track Type	Total Length (mm)	Track Duration (hrs)	Distance (km)	Average Track Speed (cm/s)	Average Track[a] Speed (cm/s)	Body Lengths[b] s-1	Average Angle of Turn	Average Water Temperature (C)
6/26	Carp	74-01	74-01	Sonic	640	9.10	4.75	14.5	14.0	.22/.22	55	11
6/27	Carp	74-02	74-01	Sonic	640	9.55	6.49	18.9	18.2	.29/.28	35	11
6/28	Carp	74-03	74-01	Sonic	640	9.42	3.62	10.7	11.1	.16/.17	50	9
6/30	Carp	74-04	74-01	Sonic	640	8.93	2.99	9.3	9.4	.14/.15	42	12
7/1	Carp	74-05	74-01	Sonic	640	7.70	0.95	3.4	3.6	.05/.06	109	12
7/9	Carp	74-06	74-01	Sonic	640	8.97	4.63	14.3	17.3	.22/.27	56	19
7/11	Carp	74-07	74-02	Sonic	388	6.63	0.60	2.5	2.9	.06/.07	131	19
7/16	Carp	74-08	74-03	Sonic	570	10.07	3.49	9.6	9.1	.16/.16	82	20
7/17	Carp	74-09	74-03	Sonic	570	4.98	1.00	5.6	5.4	.09/.09	94	18
7/18	Carp	74-10	74-03	Sonic	570	10.20	2.72	7.4	7.6	.12/.13	88	19
7/19	Carp	74-11	74-03	Sonic	570	6.98	0.63	2.5	2.7	.04/.05	113	20
7/23	Carp	74-12	74-03	Sonic	570	8.52	4.36	14.2	13.6	.24/.24	55	18
7/24	Carp	74-13	74-03	Sonic	570	9.45	3.20	9.4	9.3	.16/.16	56	18
7/26	Carp	74-14	74-03	Sonic	570	8.97	2.16	6.7	7.0	.11/.12	57	18
7/26	Carp	74-15	74-04	Sonic	630	9.68	0.74	2.1	2.5	.03/.04	127	18
7/27	Carp	74-16	74-04	Sonic	630	8.72	0.69	2.2	2.3	.03/.04	103	19
7/27	Carp	74-17	74-03	Sonic	570	9.53	8.75	25.5	26.9	.44/.47	58	19
7/29	Carp	74-18	74-04	Sonic	630	24.00	6.07	7.0	7.9	.11/.12	51	19
7/29	Carp	74-19	74-03	Sonic	570	12.07	2.62	6.0	7.8	.10/.14	80	19
8/1	Carp	74-20	74-03	Sonic	570	21.37	4.42	5.8	5.7	.10/.10	119	19
8/1	Carp	74-21	74-04	Sonic	630	11.72	0.33	0.8	0.9	.01/.01	122	19
8/5	Carp	74-22	74-05	Sonic	650	2.08	0.84	11.2	16.7	.17/.26	56	19
8/8	Carp	74-23	74-05	Sonic	650	17.77	16.49	25.8	26.4	.40/.41	69	20
9/3	Carp	74-24	74-06	Float	550	8.00	3.72	12.9	13.2	.23/.24	105	16
9/3	Carp	74-25	74-07	Float	485	8.00	1.78	6.2	6.2	.13/.13	19	16
9/3	Carp	74-26	74-08	Float	565	8.00	3.68	12.8	16.2	.23/.29	50	16
9/3	Carp	74-27	74-09	Float	595	8.00	2.39	8.3	9.3	.14/.16	113	16
9/4	Carp	74-28	74-06	Float	550	9.55	2.88	8.4	8.1	.15/.15	43	15
9/4	Carp	74-29	74-07	Float	485	9.55	0.97	2.9	3.1	.06/.06	57	15
9/4	Carp	74-30	74-08	Float	565	9.00	3.10	9.6	9.6	.17/.17	11	15

Table 3 (cont'd)

Date	Species	Track No.	Fish No.	Track Type	Total Length (mm)	Track Duration (hrs)	Distance (km)	Average Track Speed (cm/s)	Average Track[a] Speed (cm/s)	Body Lengths[b] s^{-1}	Average Angle of Turn	Average Water Temperature (C)
9/4	Carp	74-31	74-09	Float	595	9.00	3.76	11.6	11.6	.19/.19	20	15
9/5	Carp	74-32	74-07	Float	485	8.00	0.43	1.5	2.0	.03/.04	104	15
9/5	Carp	74-33	74-09	Float	595	8.00	1.98	6.9	6.9	.12/.12	115	15
9/5	Carp	74-34	74-10	Float	505	9.00	6.39	19.7	23.4	.39/.46	58	15
9/5	Carp	74-35	74-11	Float	545	9.00	1.35	4.2	5.0	.08/.09	68	15
9/6	Carp	74-36	74-06	Float	550	8.48	1.08	3.5	3.6	.06/.06	74	14
9/6	Carp	74-37	74-08	Float	565	8.50	1.38	4.5	4.8	.08/.08	49	14
9/6	Carp	74-38	74-10	Float	505	8.57	1.31	4.2	4.2	.08/.08	74	14
9/6	Carp	74-39	74-11	Float	545	8.58	1.58	5.1	5.1	.09/.09	20	14
9/9	Carp	74-40	74-12	Float	615	9.00	3.34	10.3	9.3	.16/.15	43	17
9/9	Carp	74-41	74-13	Float	634	8.50	5.78	18.9	21.0	.30/.33	127	17
9/9	Carp	74-42	74-14	Float	480	8.33	1.59	5.3	5.3	.11/.11	75	17
9/9	Carp	74-43	74-15	Float	675	8.50	1.81	5.9	5.1	.09/.07	35	17
9/10	Carp	74-44	74-13	Float	634	4.50	3.52	21.7	25.8	.34/.41	23	17
9/10	Carp	74-45	74-14	Float	480	5.00	2.90	16.1	18.0	.34/.37	63	17
9/10	Carp	74-46	74-06	Float	550	2.50	0.07	0.8	1.0	.01/.02	99	17
9/12	Carp	74-47	74-06	Float	550	7.00	0.55	2.2	2.5	.04/.05	43	19
9/12	Carp	74-48	74-12	Float	615	7.50	2.09	7.7	8.6	.13/.14	135	19
9/12	Carp	74-49	74-14	Float	480	7.00	0.22	0.9	1.0	.02/.02	36	19
10/2	Carp	74-50	74-16	Float	543	1.67	1.08	18.0	18.0	.33/.33	37	12
10/3	Carp	74-51	74-17	Sonic	630	5.58	1.51	7.5	7.4	.12/.12	144	11
10/3	Carp	74-52	74-18	Float	620	3.67	2.29	17.3	16.5	.28/.27	125	11
10/4	Carp	74-53	74-17	Sonic	630	8.00	1.68	5.8	6.1	.09/.10	46	10
10/9	Carp	74-54	74-17	Sonic	630	8.42	2.49	8.2	7.9	.13/.12	63	11
10/9	Carp	74-55	74-16	Float	543	4.33	3.79	24.3	24.3	.45/.45	20	11
10/9	Carp	74-56	74-18	Float	620	3.33	0.27	2.3	2.5	.04/.04	32	11
10/10	Carp	74-57	74-17	Sonic	630	8.00	0.66	2.3	2.8	.04/.04	113	11
10/10	Carp	74-58	74-19	Float	675	5.78	1.77	8.5	13.2	.13/.20	54	11
10/11	Carp	74-59	74-20	Float	645	3.00	1.60	14.8	15.1	.23/.23	45	12
10/11	Carp	74-60	74-21	Float	682	1.33	0.80	16.6	16.8	.24/.25	54	12

Table 3 (cont'd)

Date	Species	Track No.	Fish No.	Track Type	Total Length (mm)	Track Duration (hrs)	Distance (km)	Average Track Speed (cm/s)	Average Track[a] Speed (cm/s)	Body Lengths[b] s^{-1}	Average Angle of Turn	Average Water Temperature (C)
10/11	Carp	74-61	74-16	Float	543	3.00	0.43	3.9	5.1	.07/.09	102	12
10/15	Carp	74-62	74-16	Float	543	6.08	2.37	10.8	10.6	.20/.20	30	12
10/15	Carp	74-63	74-19	Float	675	8.00	3.23	11.2	10.8	.17/.16	43	12
10/15	Carp	74-64	74-20	Float	645	8.67	2.75	8.8	10.4	.14/.16	58	12
10/16	Carp	74-65	74-22	Sonic	610	8.13	4.11	14.0	14.0	.23/.23	42	12
10/23	Carp	74-66	74-23	Float	600	6.38	5.66	24.6	25.6	.41/.43	29	10
10/23	Carp	74-67	74-24	Float	620	6.37	1.83	8.0	7.9	.13/.13	71	10
10/23	Carp	74-68	74-25	Float	642	6.88	4.13	16.7	17.4	.26/.27	58	10
10/24	Carp	74-69	74-24	Float	620	7.00	1.11	4.4	4.9	.07/.08	115	10
10/24	Carp	74-70	74-25	Float	642	7.00	3.56	14.1	14.1	.22/.22	44	10
11/1	Carp	74-71	74-26	Sonic	720	8.03	4.43	15.3	15.4	.21/.21	60	12
11/1	Carp	74-72	74-27	Float	678	7.95	0.90	3.1	3.9	.05/.06	26	12
11/1	Carp	74-73	74-28	Float	680	6.62	4.68	19.7	19.6	.29/.29	62	12
11/4	Carp	74-74	74-26	Sonic	720	5.00	3.53	19.6	19.6	.27/.27	39	10
11/4	Carp	74-75	74-25	Float	642	4.50	1.85	11.4	11.7	.18/.18	56	10
11/6	Carp	74-76	74-27	Float	678	7.00	1.89	7.5	8.8	.11/.13	108	12
11/6	Carp	74-77	74-29	Float	650	7.00	4.35	17.3	17.2	.27/.26	58	12
11/7	Carp	74-78	74-25	Float	642	7.33	3.68	14.0	14.0	.22/.22	60	12
11/7	Carp	74-79	74-27	Float	678	7.37	1.62	6.1	6.7	.09/.10	61	12
11/7	Carp	74-80	74-29	Float	650	7.33	3.11	11.8	11.8	.18/.18	50	12

[a] Only those time periods with movement were included.

[b] Body lengths s^{-1} for both whole track and for time periods in which movement was observed.

Table 4. Quantitative description of individual tracks accomplished in the Ludington Reservoir, 1975.

Date	Species	Track No.	Fish No.	Track Type	Total Length (mm)	Track Duration (hrs)	Distance (km)	Average Track Speed (cm/s)	Average Track[a] Speed (cm/s)	Body Lengths[b] s-1	Average Angle of Turn	Average Water Temperature (C)
6/19	Carp	75-01	75-01	Sonic	490	6.00	1.53	7.1	7.4	.14/.15	71	15
6/20	Carp	75-02	75-01	Sonic	490	8.00	0.95	3.3	3.5	.07/.07	126	14
6/25	Carp	75-03	75-01	Sonic	490	8.33	0.99	3.3	3.8	.07/.08	71	17
6/25	Carp	75-04	75-02	Float	550	8.33	0.65	2.2	2.6	.04/.05	93	17
6/26	Carp	75-05	75-01	Sonic	490	8.00	0.88	3.0	3.9	.06/.08	102	18
6/26	Carp	75-06	75-03	Float	590	8.00	1.94	6.7	7.7	.11/.13	69	18
6/30	Carp	75-07	75-04	Sonic	650	7.33	0.78	2.9	3.1	.04/.05	84	18
6/30	Carp	75-08	75-02	Float	550	6.67	6.93	28.9	28.9	.53/.53	54	18
7/1	Carp	75-09	75-03	Float	590	6.78	0.42	1.7	2.2	.03/.04	78	19
7/1	Carp	75-10	75-05	Float	710	8.00	4.86	16.9	17.5	.24/.25	41	19
7/2	Carp	75-11	75-04	Sonic	650	24.00	9.23	10.7	11.6	.16/.18	62	18
7/2	Carp	75-12	75-03	Float	590	12.00	3.34	7.8	7.8	.13/.13	95	18
7/7	Carp	75-13	75-06	Sonic	710	8.00	0.99	3.5	3.5	.05/.05	55	18
7/7	Carp	75-14	75-07	Float	590	8.00	1.77	6.1	7.0	.10/.12	47	18
7/9	Carp	75-15	75-08	Sonic	580	8.67	2.51	8.0	8.0	.14/.14	36	17
7/9	Carp	75-16	75-07	Float	590	8.67	1.85	5.9	5.9	.10/.10	59	17
7/11	Carp	75-17	75-08	Sonic	580	7.00	4.98	19.8	19.6	.34/.34	50	12
7/11	Carp	75-18	75-09	Float	580	7.00	3.12	12.4	12.4	.21/.21	67	12
7/14	Carp	75-19	75-08	Sonic	580	3.00	1.23	11.4	10.9	.20/.19	93	12
7/14	Carp	75-20	75-09	Float	580	2.67	1.42	14.7	15.7	.25/.27	62	12
7/16	Brown Trout	75-21	75-10	Sonic	640	8.00	1.11	3.9	4.2	.06/.07	66	14
7/16	Carp	75-22	75-09	Float	580	8.00	4.97	17.3	19.6	.30/.34	66	14
7/17	Brown Trout	75-23	75-10	Sonic	640	24.00	27.44	31.8	39.0	.50/.61	51	16
7/17**	Carp	75-24	75-08	Sonic	580	5.08	2.98	16.3	16.2	.28/.28	165	16
7/21	Carp	75-25	75-11	Sonic	562	7.25	1.34	5.1	5.3	.09/.09	122	19
7/21	Carp	75-26	75-12	Float	650	7.17	3.66	14.2	15.3	.22/.23	163	19
7/22	Carp	75-27	75-11	Sonic	562	9.00	2.24	6.9	7.4	.12/.13	67	19
7/22	Carp	75-28	75-13	Float	530	8.00	2.56	8.9	9.0	.17/.17	37	19
7/23*	Carp	75-29	75-11	Sonic	562	4.00	2.91	20.2	25.5	.36/.45	60	20
7/23*	Carp	75-30	75-09	Float	580	4.05	1.17	8.1	10.7	.14/.18	148	20

Table 4 (cont'd)

Date	Species	Track No.	Fish No.	Track Type	Total Length (mm)	Track Duration (hrs)	Distance (km)	Average Track Speed (cm/s)	Average Track[a] Speed (cm/s)	Body Lengths[b] s^{-1}	Average Angle of Turn	Average Water Temperature (C)
7/24	Carp	75-31	75-11	Sonic	562	5.67	0.42	2.0	2.5	.04/.04	116	20
7/24	Carp	75-32	75-14	Float	595	5.00	6.86	38.1	40.0	.64/.67	30	20
7/28*	Carp	75-33	75-15	Sonic	625	4.33	1.98	12.7	12.7	.20/.20	119	21
7/28*	Carp	75-34	75-14	Float	595	4.00	2.08	14.4	18.2	.24/.31	107	21
7/28**	Carp	75-35	75-15	Sonic	625	3.00	1.89	17.5	19.3	.28/.31	34	21
7/28**	Carp	75-36	75-16	Float	640	3.00	1.33	12.3	12.3	.19/.19	32	21
7/29	Carp	75-37	75-15	Sonic	625	3.00	1.18	10.9	12.2	.17/.20	26	21
7/29	Carp	75-38	75-14	Float	595	2.67	2.48	25.9	25.8	.44/.43	79	21
7/30*	Carp	75-39	75-15	Sonic	625	4.33	0.68	4.3	4.7	.07/.08	94	22
7/30**	Carp	75-40	75-15	Sonic	625	4.67	3.67	21.9	21.9	.35/.35	8	23
7/31	Carp	75-41	75-15	Sonic	625	5.00	0.40	2.2	3.7	.04/.06	85	23
8/1	Carp	75-42	75-15	Sonic	625	8.00	1.93	6.7	8.5	.11/.14	112	23
8/1	Carp	75-43	75-17	Float	695	7.33	4.15	15.7	17.1	.23/.25	73	23
8/4	Carp	75-44	75-18	Sonic	658	7.00	0.39	1.5	1.8	.02/.03	109	23
8/4	Carp	75-45	75-19	Float	646	6.95	3.41	13.6	17.3	.21/.27	28	23
8/6*	Carp	75-46	75-18	Sonic	658	4.02	3.12	21.6	26.0	.33/.39	48	22
8/6**	Carp	75-47	75-18	Sonic	658	4.67	2.98	17.8	17.4	.27/.26	44	21
8/7	Carp	75-48	75-18	Sonic	658	6.67	3.53	14.7	14.8	.22/.22	87	17
8/11	Carp	75-49	75-18	Sonic	658	7.-0	0.98	3.9	3.9	.06/.06	106	18
8/12	Carp	75-50	75-20	Float	635	7.00	0.59	2.4	3.2	.04/.05	75	18
8/12	Carp	75-51	75-21	Float	590	3.33	2.11	17.6	17.0	.30/.29	45	18
8/13	Carp	75-52	75-20	Float	635	7.00	1.33	5.3	7.4	.08/.12	106	19
8/14	Carp	75-53	75-22	Float	700	8.00	6.32	22.0	22.0	.31/.31	36	20
8/14	Carp	75-54	75-23	Float	590	4.97	2.39	13.4	15.3	.23/.26	103	20
8/18	Brown Trout	75-55	75-24	Sonic	650	6.03	11.86	54.6	57.8	.84/.89	30	21
8/19	Brown Trout	75-56	75-24	Sonic	650	8.03	20.99	72.6	76.1	1.1/1.2	31	20
8/20*	Brown Trout	75-57	75-24	Sonic	650	4.03	7.19	49.5	60.1	.76/.92	38	19
8/26	Brown Trout	75-58	75-25	Sonic	590	6.62	16.45	69.1	79.3	1.2/1.3	39	19
8/27	Brown Trout	75-59	75-26	Sonic	635	8.18	0.23	0.8	1.6	.01/.03	109	20
8/27	Brown Trout	75-60	75-27	Float	645	6.00	6.05	28.0	31.1	.43/.48	40	20

Table 4 (cont'd)

Date	Species	Track No.	Fish No.	Track Type	Total Length (mm)	Track Duration (hrs)	Distance (km)	Average Track Speed (cm/s)	Average Track[a] Speed (cm/s)	Body Lengths[b] s^{-1}	Average Angle of Turn	Average Water Temperature (C)
8/27	Brown Trout	75-61	75-28	Float	510	5.00	6.39	35.5	37.9	.70/.74	42	20
8/28	Brown Trout	75-62	75-27	Float	645	6.22	9.16	40.9	53.9	.63/.84	49	20
9/4	Carp	75-63	75-29	Sonic	630	7.50	1.25	4.6	5.3	.07/.08	108	15
9/16	Brown Trout	75-64	75-30	Sonic	615	7.50	2.88	10.7	12.9	.17/.21	92	14
9/17	Brown Trout	75-65	75-30	Sonic	615	8.08	14.07	48.4	50.1	.79/.81	32	14
9/18	Brown Trout	75-66	75-30	Sonic	615	8.00	15.99	55.5	61.0	.90/.99	30	15
9/19	Brown Trout	75-67	75-30	Sonic	615	7.05	11.90	46.9	50.9	.76/.83	42	15
9/23	Brown Trout	75-68	75-31	Sonic	605	6.00	0.88	4.1	4.3	.07/.07	110	15
9/25	Rainbow Trout	75-69	75-32	Sonic	680	7.00	4.98	19.8	24.6	.29/.36	24	14
10/2	Brown Trout	75-70	75-33	Sonic	620	7.05	20.27	79.9	83.6	1.3/1.4	28	14
10/6	Brown Trout	75-71	75-33	Sonic	620	3.00	8.62	79.8	81.6	1.3/1.3	24	13
10/9	Rainbow Trout	75-72	75-34	Sonic	690	7.50	1.70	6.3	6.4	.09/.09	24	13
10/14	Rainbow Trout	75-73	75-34	Sonic	690	3.00	0.91	8.4	10.0	.12/.14	38	13
10/15	Rainbow Trout	75-74	75-35	Sonic	600	2.75	0.15	1.5	2.3	.03/.04	57	14
10/20	Rainbow Trout	75-75	75-35	Sonic	600	2.35	5.44	64.3	70.7	1.1/1.2	39	11
10/21	Rainbow Trout	75-76	75-35	Sonic	600	7.00	18.67	74.1	79.6	1.2/1.3	32	11
10/22	Rainbow Trout	75-77	75-35	Sonic	600	7.00	13.27	52.7	55.7	.88/.93	32	11
10/29	Brown Trout	75-78	75-36	Sonic	590	6.95	13.91	55.6	57.6	.94/.98	27	11
10/30	Brown Trout	75-79	75-36	Sonic	590	5.50	1.88	9.5	13.6	.16/.23	108	11

[a] Only those time periods with movement were included.
[b] Body lengths s^{-1} for both whole track and for time periods in which movement was observed.
[c] Sunrise track.
[d] Sunset track.

Movement Patterns

Movements of the 65 fish tracked in the Ludington reservoir (159 tracks) were distinctly patterned. Each track was assigned to one of three general categories depending on the orientation of locomotory activity (Tables 5 and 6). Additionally, specific behavioral patterns such as milling, passage behind and in front of the upper intake structure, and movement across open-water were noted for each track.

Both carp and trout tended to restrict their movements to areas adjacent to the reservoir wall (Figures 1-4). Seventy-five percent of the carp tracks and 92% of the trout tracks exhibited this pattern. Differences between float and sonic-equipped individuals, both within and between years, were not significant (x^2 analyses, $P > 0.05$) for the distribution of behavioral patterns. Similarly, the frequency of on-the-wall tracks was not significantly different between carp and trout ($x^2 = 2.78$, $P > 0.05$).

The movements of individuals tracked during the same day appeared to be independent as evidenced by activity in different sectors of the reservoir (Fig. 2A). Fish traversed the reservoir in both clockwise and counterclockwise directions (Track 70, Fig. 2B; Track 55, Fig. 4A) and showed little consistency in directionality of movement from day to day. All parts of the reservoir were frequented although many tracks were localized in one reservoir section or another. Individuals tracked on consecutive days were often found in different areas (Fig. 1A) indicating that site-preference behavior was minimal. Diel and operational-mode differences in movement pattern were not apparent (as determined from track maps), although statistical

Table 5. Qualitative description of movement patterns of fish tracked in the Ludington Reservoir, 1974.

Track No.	Description[a]
1	ONW-S wall
2	ONW-SE,E walls
3	ONW-SE,E walls
4	ONW-S,SE walls
5	ONW-SE wall
6	ONW-NE,N,NW walls
7[b]	OFW-SW middle
8[b]	MIXED-SW wall; Central middle.
9	ONW-E wall
10	ONW-S,SW walls
11	ONW-SW wall; milling.
12	ONW-SE,S,SW walls
13	ONW-SE wall
14	ONW-NE wall
15[b]	OFW-Central middle; milling.
16[b]	OFW-Central middle; milling.
17	ONW-all around; BI.
18	ONW-W,SW,S,SE walls
19[b]	MIXED-W wall; Central middle.
20	MIXED-E wall; Central middle.
21	ONW-W wall; milling.
22[b]	OFW-Central middle.
23	OFW-S,N & Central middle; Spiral pattern.
24	ONW-E,SE walls
25	ONW-SE,E walls
26	ONW-SW,S walls; SE-SW.
27	ONW-SW wall
28	ONW-SW,W walls
29	ONW-S wall
30	ONW-SE wall
31	ONW-SE,E,NE walls
32	ONW-SE wall
33	ONW-E wall
34	MIXED-NW wall; BI; N middle; SE-NW.
35	ONW-SE wall
36	ONW-SE wall
37	ONW-N,NW walls
38	ONW-W wall; BI.
39	ONW-S,SW walls
40	ONW-NE,E,SE walls
41	ONW-N,NE,E walls
42	ONW-SE wall
43	ONW-SE wall
44	ONW-W,NW walls; BI.
45	ONW-S,SW walls
46	ONW-W wall; milling.
47	ONW-SE wall
48	ONW-E wall
49	ONW-SE wall
50	ONW-N,NW walls
51	ONW-E wall
52	ONW-SE wall
53	ONW-E wall
54	MIXED-W wall; S middle.
55	ONW-W,SW,S,SE,E walls
56	ONW-S wall
57	ONW-SE wall
58	MIXED-E wall; W-E; Central middle.
59	OFW-parallel to W wall
60	ONW-NE wall
61	ONW-W wall
62	MIXED-E wall; N middle.
63	MIXED-SE wall; S middle.
64	ONW-SW,S,SE walls
65	ONW-SW,S,SE walls
66	ONW-W,SW,S,SE,E,NE walls
67	ONW-S wall
68	ONW-SW,S,SE walls
69	ONW-E wall
70	ONW-SE,S,SW walls
71	ONW-S,SE,E,NE walls
72	ONW-SE wall

Table 5. (continued)

Track No.	Description[a]	Track No.	Description[a]
73	MIXED-SW wall; SW-SE; S middle.	78	MIXED-S,SE wall; S middle.
74	ONW-SW wall; E-W.	79	MIXED-E wall; S middle.
75	OFW-Central middle		
76	ONW-SE wall	80	OFW- S middle
77	OFW-S middle		

[a] ONW = Movements were confined to shoreline contours (on the wall) for greater than 80% of the track duration.

OFW = Movements were confined to open-water locations (off the wall) for greater than 80% of the track duration.

MIXED = Movements were distributed in both along-shore and open-water locations.

BI = Movement behind upper intake structure occurred at least once during track duration.

W-E,SE-SW,NE-SE, etc = Movement from one shore location, across open water, to another shore location occurred at least once during track duration.

Milling = Localized zig-zag movements.

[b] Fish was released at buoy in center of reservoir.

Table 6. Qualitative description of movement patterns of fish tracked in the Ludington Reservoir, 1975.

Track No.	Description[a]
1	ONW-E wall
2	ONW-E wall
3	ONW-SE wall
4	ONW-SW wall
5	ONW-S wall
6	ONW-E wall
7	ONW-SE wall
8	ONW-E wall
9	ONW-E wall
10	ONW-E wall
11	ONW-3/4 around; W-E; BI.
12	MIXED-SE wall; S middle.
13	ONW-SE wall
14	ONW-SE wall
15	ONW-SE wall
16	MIXED-SE wall; SE middle.
17	OFW-S middle
18	MIXED-E wall; SW-SE.
19	ONW-E wall
20	ONW-SE wall
21	ONW-SE wall
22	MIXED-E wall; E-W; S middle.
23	ONW-all around; BI.
24	ONW-E wall
25	ONW-E wall
26	ONW-NE wall
27	ONW-E wall
28	MIXED-N wall; N middle.
29	ONW-SE,S, SW walls
30	ONW-W wall
31	ONW-SE wall; milling.
32	ONW-3/4 around; SW-NE
33	MIXED-SW wall; SW middle.
34	ONW-W wall
35	ONW-SW wall; SE-SW.
36	ONW-E wall
37	ONW-S wall
38	OFW-S middle
39	ONW-E wall
40	ONW-E wall
41	ONW-E wall
42	ONW-S wall
43	MIXED-SW wall; S middle.
44	ONW-SE wall; milling.
45	ONW-SE,E walls
46	ONW-S,SE walls; SW-SE.
47	ONW-E,S walls; SE-S.
48	MIXED-S,SE walls; S middle.
49	ONW-S wall; milling.
50	ONW-SE wall
51	OFW- parallel to W wall
52	ONW-W wall
53	OFW-N middle; W-N; Spiral pattern.
54	ONW-W wall by intake; BI; entered intake.
55	ONW-3/4 around; BI; E-W.
56	ONW-all around; BI; W-E.
57	ONW-½ around; BI; W-NE wall.
58	ONW-3/4 around; BI; IFI.
59	ONW-SE wall; milling.
60	ONW-SE,E,NE,N walls
61	MIXED-N,NW walls; S middle.
62	ONW-S,SE,E,NE walls; SE-SW.
63	OFW-S middle
64	ONW-SE,S walls
65	ONW-all around; BI.
66	ONW-all around; BI; NE-NW.

Table 6. (continued)

Track No.	Description[a]	Track No.	Description[a]
67	ONW-3/4 around	74	ONW-S wall
68	ONW-SW wall	75	ONW-S,SW,NE,N walls; SW-NE.
69	ONW-NE,N,NW walls; BI.	76	ONW-all around; BI; SE-SW.
70	ONW-all around; BI; E-SW; NE-SE.	77	ONW-3/4 around; BI; SE-SW.
71	ONW-3/4 around; BI; SW-NE.	78	ONW-W,SW,S,SE walls; BI.
72	ONW-SW wall		
73	ONW-N wall	79	MIXED-SE wall; S middle.

[a] ONW = Movements were confined to shoreline contours (on the wall) for greater than 80% of the track duration.

OFW = Movements were confined to open-water locations (off the wall) for greater than 80% of the track duration.

MIXED = Movements were distributed in both along-shore and open-water locations.

BI = Movement behind upper intake structure occurred at least once during track duration.

IFI = Movement in front of upper intake structure occurred at least once during track duration.

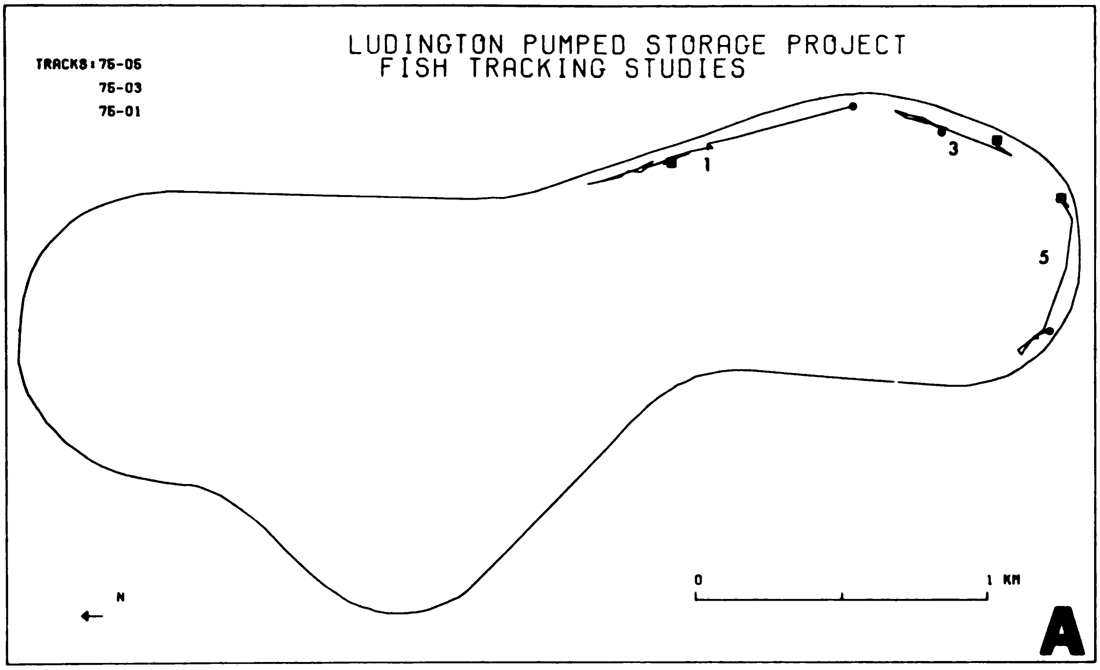
W-E, SE-SW, NE-SE, etc = Movement from one shore location, across open water, to another shore location occurred at least once during track duration.

Milling = Localized zig-zag movements.

Figure 1. (A) Behavioral patterns of a sonic-tagged carp (Fish 75-01) on three different dates in June 1975.

(B) Behavioral patterns of a sonic-tagged carp (Track 75-15) and a float-tagged carp (Track 75-30) on two separate dates in 1975.

Solid circle (●) represents the start of a track. Solid rectangle (■) represents the end of a track.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FISH TRACKING STUDIES
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75-03
75-01
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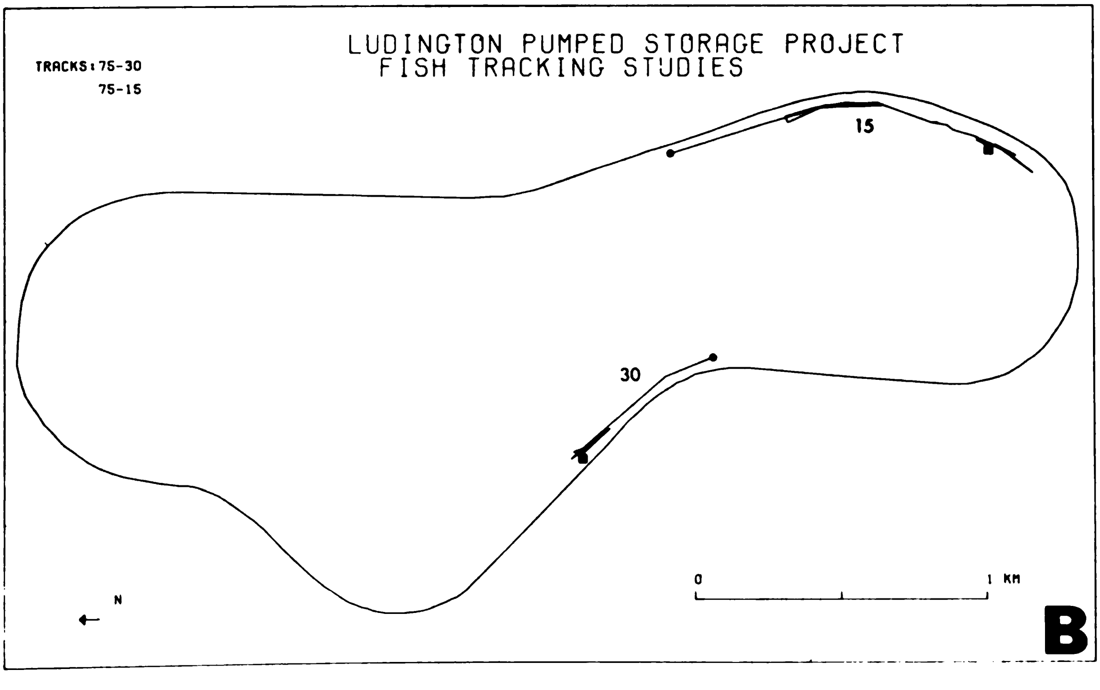
3
5
0
1 KM
N

A


LUDINGTON PUMPED STORAGE PROJECT
FISH TRACKING STUDIES
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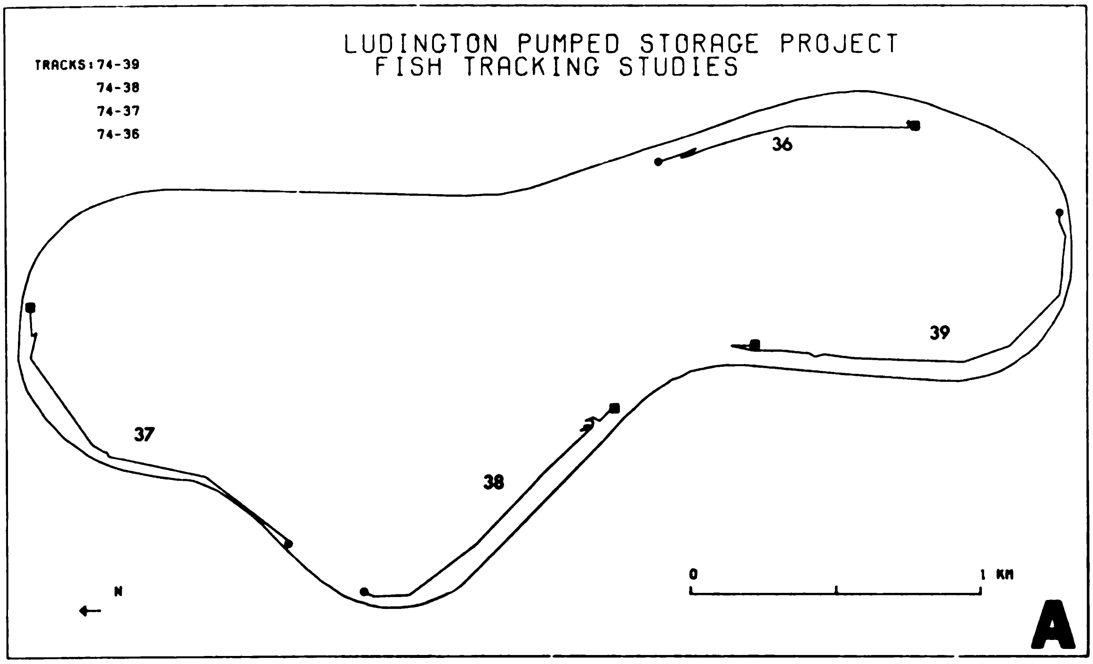
75-15
15
30
0
1 KM
N

B

Figure 2. (A) Behavioral patterns of four float-tagged carp tracked simultaneously on September 9, 1974.

(B) Behavioral pattern of a sonic-tagged brown trout (Fish 75-33) tracked on October 2, 1975.

Symbols as in Figure 1.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FISH TRACKING STUDIES
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74-37
74-36
36
39
37
38
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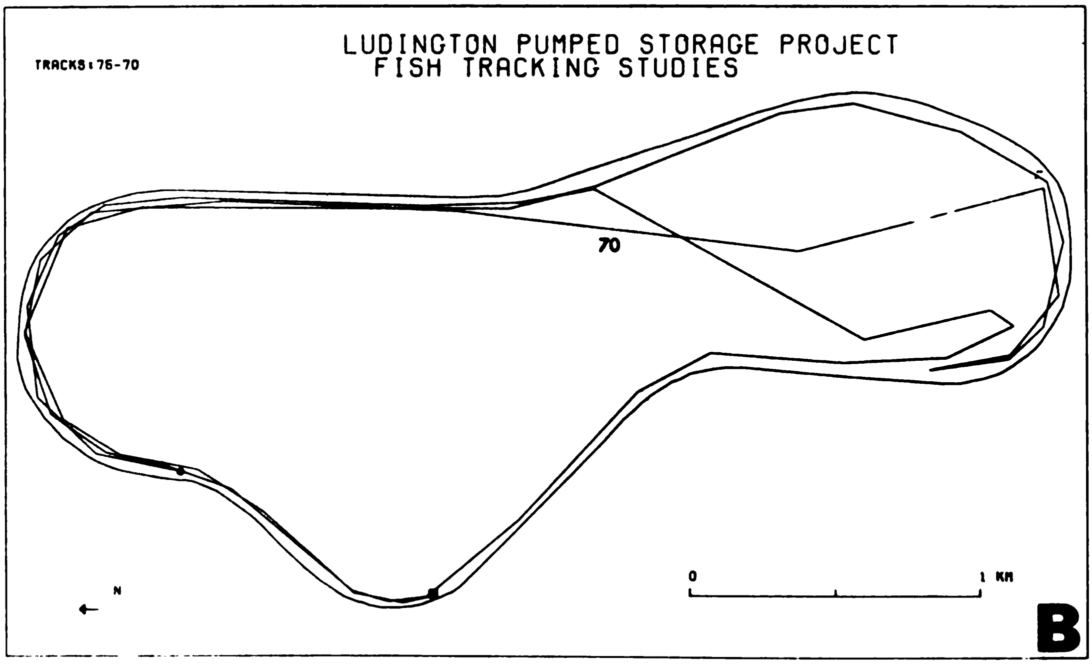
0
1 KM
A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FISH TRACKING STUDIES
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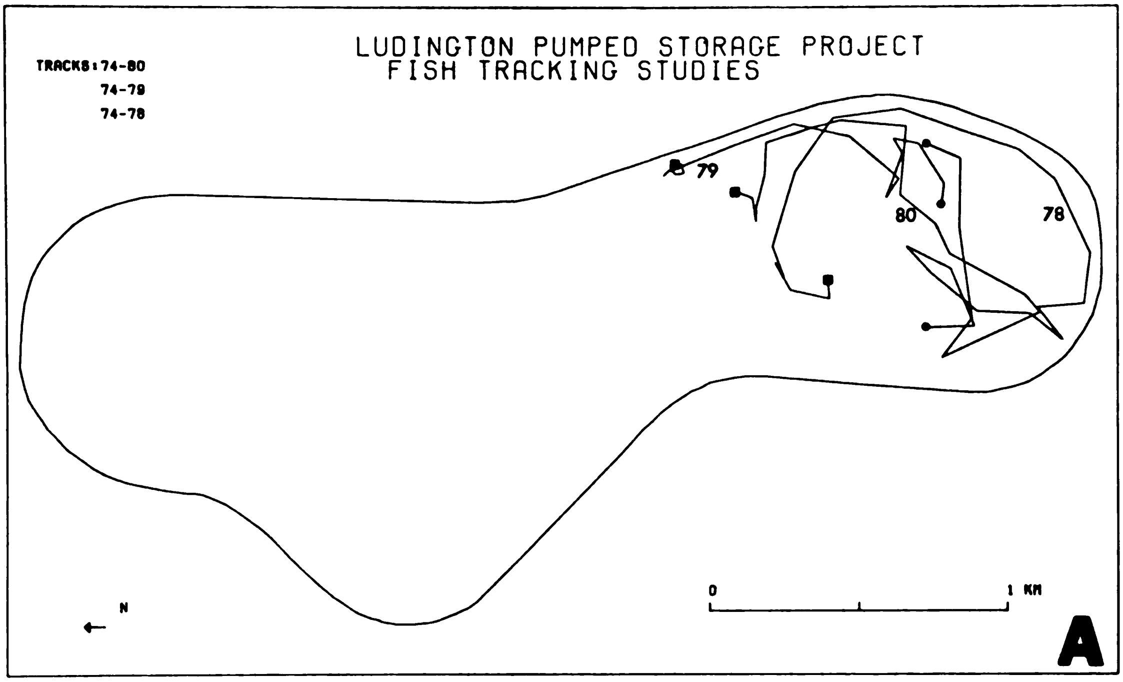
1 KM
B

Figure 3. (A) Behavioral patterns of three float-tagged carp tracked simultaneously on November 7, 1974.

(B) Behavioral patterns of a sonic-tagged carp (Track 75-25) and a float-tagged carp (Track 75-26) simultaneously tracked on July 21, 1975.

Symbols as in Figure 1.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80
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N
A

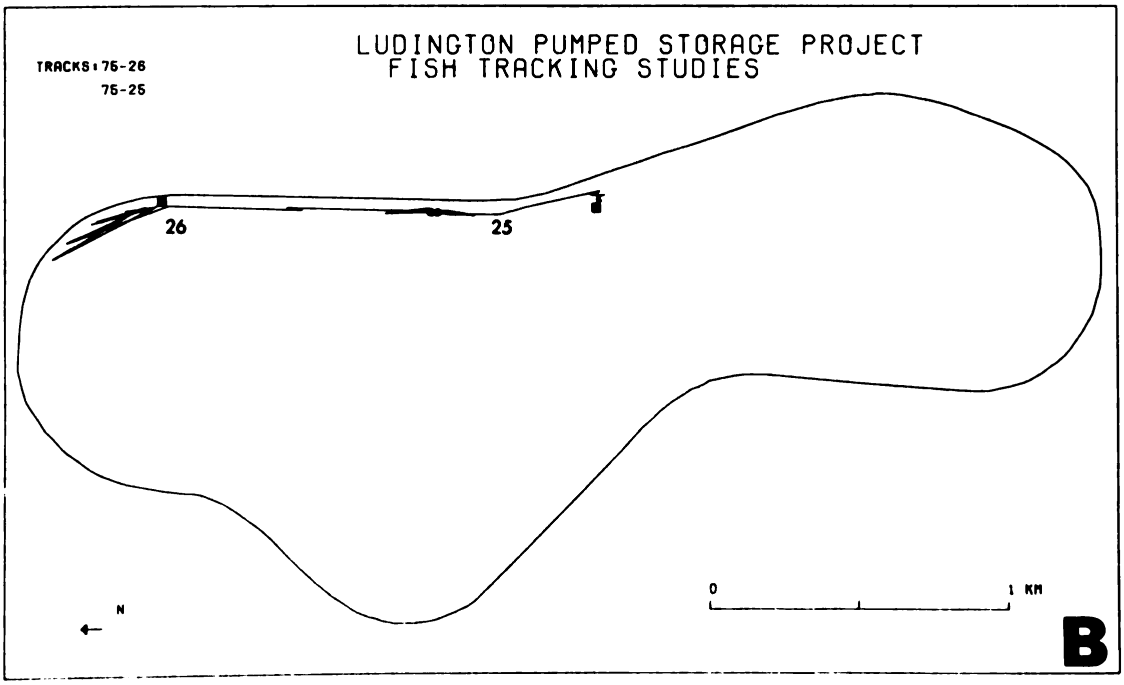
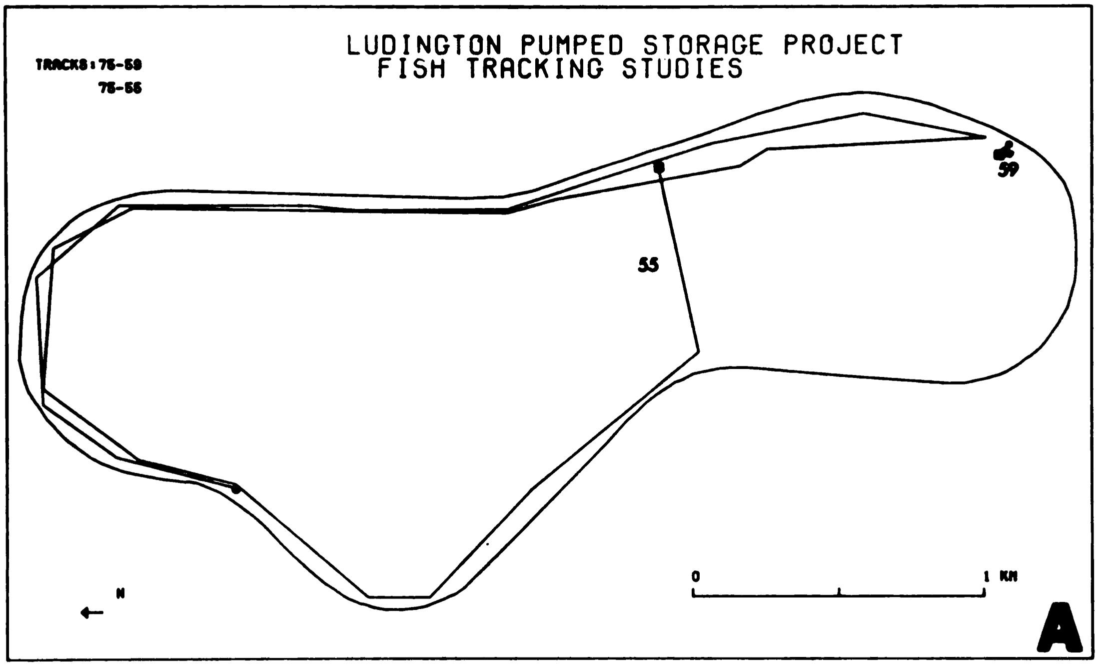

LUDINGTON PUMPED STORAGE PROJECT
FISH TRACKING STUDIES
TRACKS: 75-26
75-25
26
25
0
1 KM
N
B

Figure 4. (A) Behavioral patterns of two sonic-tagged brown trout tracked on two separate dates in August 1975.

(B) Behavioral patterns of three float-tagged carp tracked on two separate dates (Track 75-45, August 4, 1975; Tracks 75-53 and 75-54, August 14, 1975).

Symbols as in Figure 1.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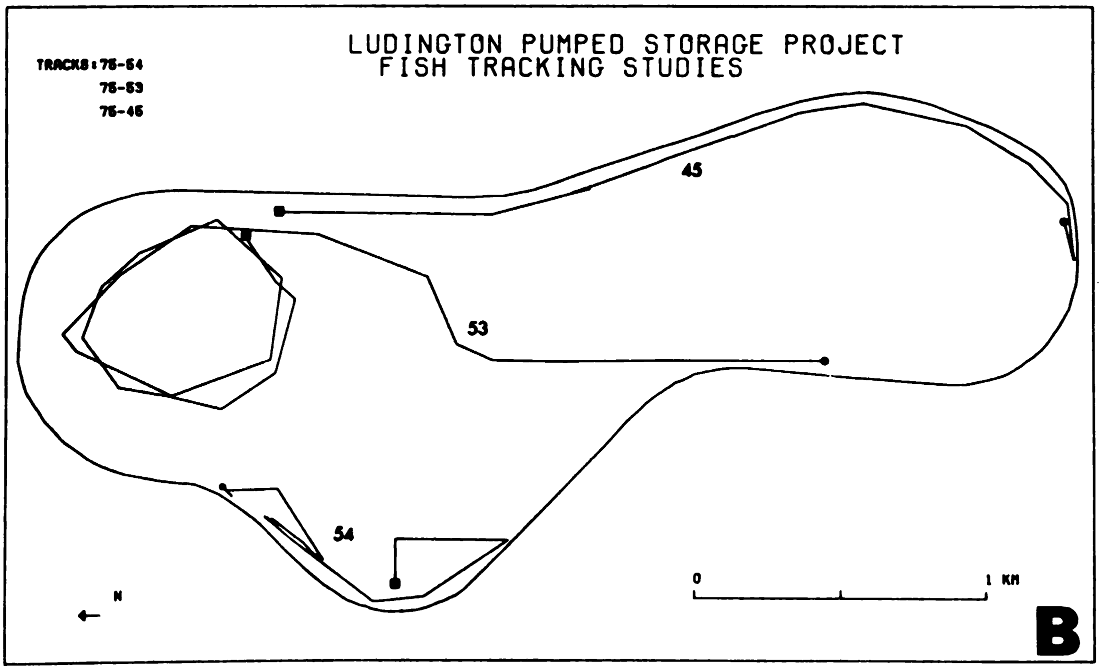
1 KM
A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FISH TRACKING STUDIES
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75-45
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53
54
N
0
1 KM
B

comparisons could not be made due to the small number of observations taken at night and during pumping operations.

During late fall, carp tended to move in the open-water areas of the reservoir (Fig. 3A). Gill net collections accomplished during this time supported these data as catches were higher in the bottom gill nets (set off-shore) than in the surface gear set near the reservoir embankment (Gulvas, 1976).

On several occasions, interactions between monitored fish occurred (Fig. 3B). This behavior was seen when tracked fish were part of the same school (carp) or frequented the same reservoir locality. In this latter instance, the juxtaposition of individuals most often occurred at suspected feeding sites (rock-rubble area adjacent to the reservoir ramp - see Track 30, Fig. 1A; and ground-water pump outfall area on the mid-east bank of the reservoir - see middle of Track 45, Fig. 4B).

Several other types of movement activity were observed apart from the general on-the-wall, open-water, and patrolling patterns (Tracks 1 and 3, Fig. 1A; Track 15, Fig. 1B). The most common of these was movement *behind* the upper intake structure (Track 70, Fig. 2B; Trace 55, Fig. 4A). This occurred in five carp tracks and in 13 of the 26 trout tracks (Tables 5 and 6). Fish approached the intake structure from both northerly and southerly directions and normally remained quite close to the reservoir wall. Individuals seemed little affected by water currents in the intake vicinity as this behavior occurred during both generating and pumping operations.

Milling (localized zig-zag movement) was noted in seven carp tracks but only once in trout (Track 59, Fig. 4A). Apparently, this behavior indicates stress since it was observed (in 6 of the 8 tracks) on either the first day after a fish was released or on the last day tracked. Also, two carp accounted for five of the milling tracks. These observations suggest that milling may result from either individualized behavior or physiological disturbances caused by handling and tagging.

A prominent spiral pattern of movement was observed in carp tracks 74-23 and 75-53 (Fig. 4B). During both efforts, this occurred in the north-central section of the reservoir during power generation. Although the stimuli evoking this behavior are unknown, it is possible that the fish were responding to current gyres in this locale.

Fish 75-23 (Track 54, Fig. 4B) was the only monitored individual directly observed to leave the reservoir during tracking. Initially, this fish passed behind the upper intake structure and then proceeded in front of the intake where it was soon lost from sight. The float tag was not recovered in either the reservoir or the lake.

Angular Change

Mean track turning angles ranged from 11-144° for carp in 1974 and 8-165° for carp during 1975. Trout monitored in 1975 exhibited average turning angles from 24-110° (Tables 3 and 4). Frequency of turning (using data pooled into 45° intervals) was not significantly different between carp in 1974 and 1975 ($x^2 = 2.92$, $P > 0.40$). Likewise, no difference was detected in the frequency of large turning angles (> 45°) for carp between years ($x^2 = 0.34$, $P > 0.50$). Comparison of the frequency of angular changes greater than 45° between carp and trout indicated a significant difference ($x^2 = 25.93$, $P < 0.005$). Only 19.2% of the trout tracks had large mean turning angles while the corresponding frequency in carp was 73.7%. Since both species tended to lead along the reservoir wall during most of their movements, these results indicate that trout were more directional (in terms of straightness) than carp, and seldom meandered.

Swimming Speed

Calculated average swimming speeds of individual fish varied from 0.01 - 0.64 L/sec (0.8 - 38.1 cm/sec) for carp and 0.01 - 1.30 L/sec (0.8 - 79.9 cm/sec) for trout (Tables 3 and 4). The overall mean rate of movement was 0.16 L/sec (9.9 cm/sec) for carp tracked in 1974, 0.19 L/sec (11.3 cm/sec) for 1975 carp, and 0.63 L/sec (38.6 cm/sec) for trout. No significant differences were detected in track swim speed between individuals tracked on multiple days for carp (Table 7) or trout ($F = 1.84$, $P = .201$). Similarly, differences in swimming rates between brown trout and rainbow trout were not evident ($F = 0.46$, $P > 0.75$). These analyses indicate that, for generating-mode observations, pooling of individual track swim data by fish group (carp; trout) is statistically appropriate. The low number of tracks accomplished during pumping operations precluded their analysis by parametric procedures.

Comparison of swimming speed between sonic and float-tagged carp (Table 8) showed no difference in 1974 but a highly significant difference in 1975 ($P = 0.008$). Surprisingly, in both years, the mean speed for float-tracked organisms was greater than that of sonic-equipped fish (1974 - 0.18 *vs* 0.17 L/sec; 1975 - 0.22 *vs* 0.10 L/sec). Results of a two-way analysis of variance of carp mean track speed (Table 8) revealed that, overall, neither tag type nor year differences

Table 7 . Results of analyses of variance of specific swimming speed for fish tracked on multiple occasions in the Ludington Reservoir (only generating-mode tracks).

Source	df	MS	F	P
1974 Sonic Fish, Carp				
Between fish	4	.0159	1.050	0.408
Within fish	19	.0151		
1974 Float Fish, Carp				
Between fish	16	.0152	1.394	0.212
Within fish	29	.0109		
1975 Sonic Fish, Carp				
Between fish	5	.0089	1.643	0.229
Within fish	11	.0054		
1975 Float Fish, Carp				
Between fish	4	.0313	1.628	0.269
Within fish	7	.0193		
1974 Sonic & Float Fish, Carp				
Between fish	21	.0148	1.179	0.311
Within fish	48	.0126		
1975 Sonic & Float Fish, Carp				
Between fish	10	.0189	1.756	0.143
Within fish	18	.0108		
1974 & 1975 Sonic & Float Fish, Carp				
Between fish	32	.0166	1.373	0.138
Within fish	66	.0121		

Table 8 . Results of analyses of variance of tag type (sonic or float) on specific swimming speed of fish tracked in the Ludington Reservoir (only generating-mode tracks).

Source	df	MS	F	P
1974 Carp				
Between tag types	1	.0023	0.153	0.693
Within tag types	75	.0149		
1975 Carp				
Between tag types	1	.1317	7.920	0.008
Within tag types	38	.0166		
1974 & 1975 Carp				
Between tag types	1	.0694	4.379	0.039
Within tag types	115	.0158		
2-Way ANOVA, 1974 & 1975 Carp, Sonic & Float Tags				
Main Effects	2	.0430	2.773	0.065
Year	1	.0500	3.199	0.073
Tag Type	1	.0020	0.148	0.999
Interactions	1	.0680	4.389	0.036
Year X Tag Type	1	.0680	4.389	0.036
Residual	113	.0160		

were significant ($P > 0.05$). However, a significant interaction between year and tag type was apparent. This was effected by the relatively low rate of movement of 1975 sonic carp compared to the 1974 sonic fish (41% slower) and the 1975 float-equipped carp (55% slower). Reasons for this low rate of swimming speed are not known. For trout, swimming speed was similar between float and sonic-tagged individuals ($F = 0.008$, $P = 0.93$).

No consistent relation was found between swimming speed of carp and operational mode. In 1974, 8 of 9 fish tracked through pumping and generating periods showed a higher movement rate during generation than during pumping activity. Generating speeds were significantly higher than pumping speeds (Wilcoxon Signed Ranks Test (Conover, 1973), $P < 0.05$). In contrast, 10 of 12 1975 multi-mode tracked fish exhibited higher swimming speeds during pumping than generating. Again, the difference was significant (Wilcoxon Signed Ranks Test, $P < 0.05$). Interpretation of the discrepancy between these data is hampered by the absence of current measurements, and the confounding of pumping and generating activities with light levels (*i.e.*, pumping occurring at night, generation during the day).

A distinct diel cycle of swimming speed was demonstrated in both carp and trout (Fig. 5 and 6). In the two species, movement occurred regularly during both daylight and nighttime periods but speeds were highest during dawn and dusk. Crepuscular activity patterns were similar for float and sonic-tagged individuals and was evident in both years. Accordingly, swim speed data were pooled from all individuals of each group (Table 9). Maximum mean carp speeds occurred between 0530 - 0730 hr and, to a lesser degree, at 2100 hr.

Figure 5. Diel pattern of specific swimming speed for carp carrying ultrasonic transmitters and float tags in 1974 and 1975. Hourly means from 0000 to 0600 hr are used again for the 2400- to 3000-hr period to show more clearly the trend at 2400.

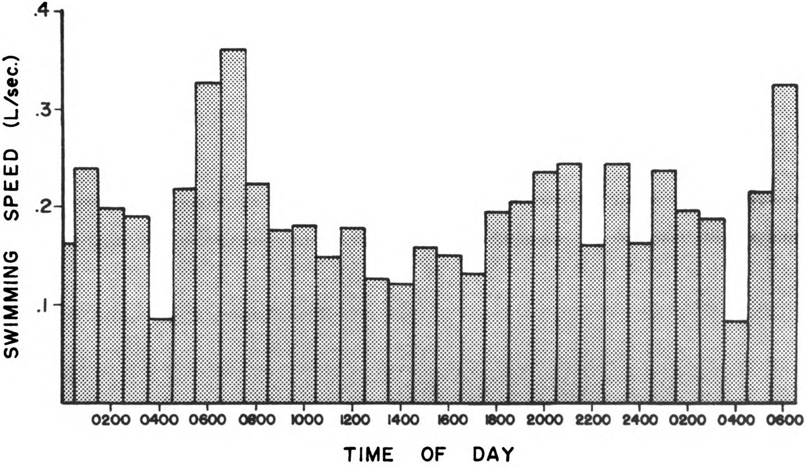
SWIMMING SPEED (L/sec.)
.4
.3
.2
.1
0200
0400
0600
0800
1000
1200
1400
1600
1800
2000
2200
2400
0200
0400
0600
TIME OF DAY

Figure 6. Diel pattern of specific swimming speed for trout carrying ultrasonic transmitters and float tags in 1975. Hourly means from 0000 to 0600 hr are used again for the 2400- to 3000-hr period to show more clearly the trend at 2400.

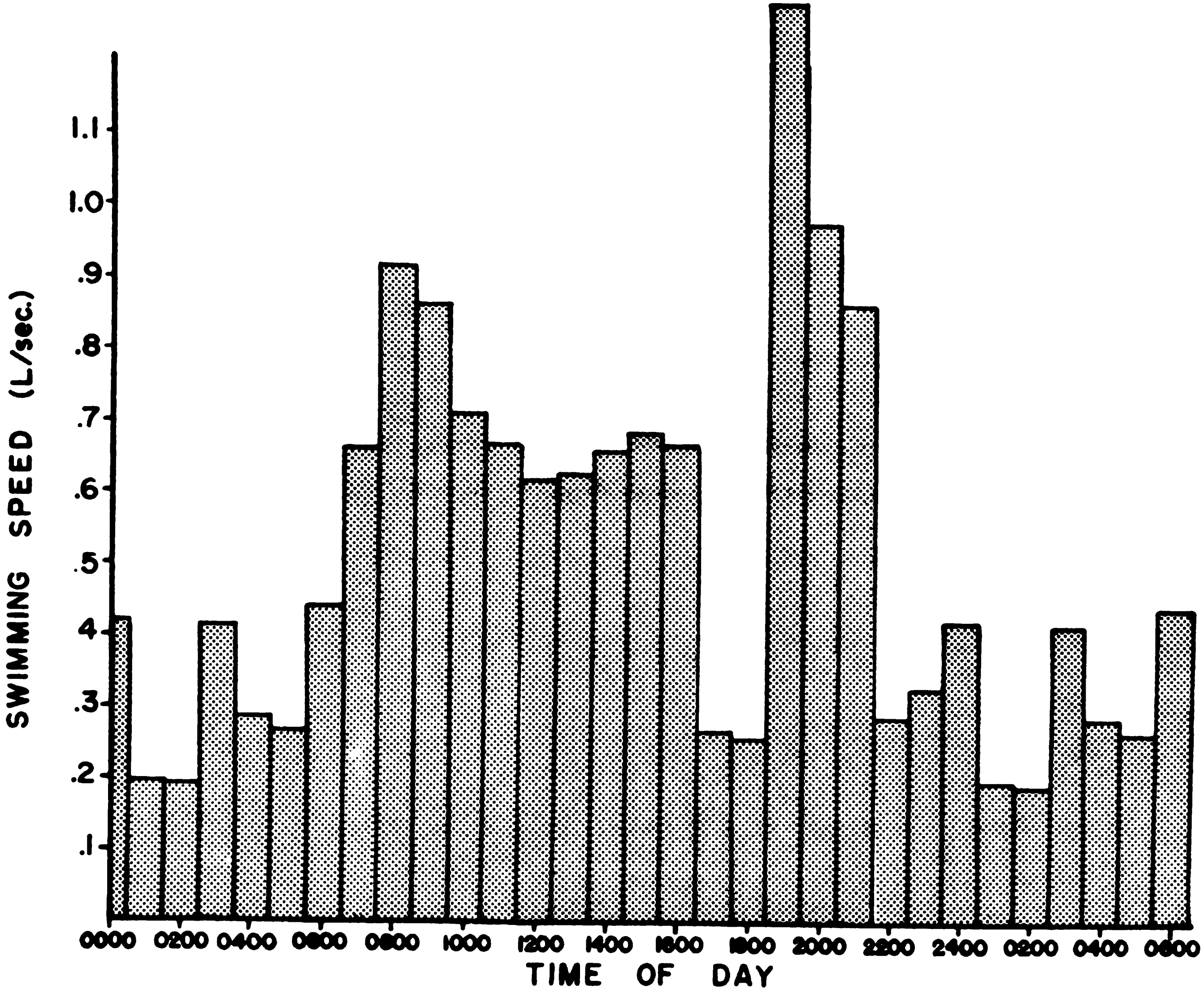
SWIMMING SPEED (L/sec.)
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0000
0200
0400
0600
0800
1000
1200
1400
1600
1800
2000
2200
2400
0200
0400
0600
TIME OF DAY

Table 9 . Frequency distribution of hourly specific swimming speed estimates used in diel periodicity analysis.

Hour of Day	No. of Observations (Carp)	No. of Observations (Trout)
0100	4	1
0200	4	1
0300	3	1
0400	3	1
0500	3	2
0600	9	2
0700	8	3
0800	13	5
0900	57	15
1000	94	23
1100	108	23
1200	113	23
1300	111	22
1400	107	20
1500	104	20
1600	98	16
1700	79	5
1800	48	1
1900	10	1
2000	12	1
2100	9	1
2200	9	1
2300	5	1
2400	4	1
Total	1015	190

Minimum values (except for three observations at 0400) occurred about mid-day. For trout, maximum mean speed values occurred from 1830 - 2130 hr, with a secondary peak of activity at 0830 hr. Rate of movement was generally higher during the night than in the day for carp but the reverse of this pattern was observed in trout. Sun visibility did not appear to have any effect on the daytime swimming speeds of either group of fish (Carp: F = 0.939, P = 0.394; Trout: F = 0.317, P = 0.732).

Multiple regression analyses of mean track swimming speed (generating-mode tracks only) for carp and trout were accomplished using 12 independent variables (Table 10). Track-level analyses were used for analysis because they encompass "lag responses" to external stimuli and meet the statistical assumption of independence of observations.

Seven regression analyses were performed on the carp swim speed data to account for possible differences in the importance of variables between study years and among sonic and float-tagged fish (Table 11). In most cases, the proportion of variance explained by the significant variables was small; only in the 1975 sonic track analysis was more than 36% of the variability in swim speed accounted for ($R^2 = 0.65$). Of the significant parameters, water-level and current variables (Resfluct, Fluxrate, and Noturbon) appeared in five of the seven analyses. The addition of several quadratic variables (interaction terms) as independent factors did not significantly alter the multiple correlation coefficients (data not included).

The analysis of trout movement rate resulted in the inclusion of seven variables into the multiple regression equation and a

Table 10. Independent variables used in stepwise linear multiple regression analyses of swimming speed of fish in the Ludington Reservoir.

Variable	Variable Name	Units
Air Temperature	Tempair	°C
Water Temperature	Tempsurf	°C
Atmospheric Pressure	Barpress	Inches Hg
Wind Direction	Winddir	Degrees
Wind Velocity	Wind1	Knots
Light Penetration	Lightpen	Meters
Holding Time of Fish From Capture to Release	Holdtime	Hours
Days Fish Was at Liberty in Reservoir After Release	Daysfree	Days
	Daysfree2 (Quadratic Term)	Days^2
Turbines in Operation	Noturbon	Units (0-6)
Fluctuation in Reservoir Water Level from Start to End of Track	Resfluct	Feet
Average Rate of Water Level Fluctuation During Track	Fluxrate	Meters/Second

Table 11. Results of stepwise linear multiple regression of independent variables on speed of movement (body lengths/sec) of carp tracked in the Ludington Reservoir.

Variable Name	Variable Significance	Multiple R	R^2	Simple R	Regression Significance	Beta	Standard Error Beta
			1974 & 1975, Sonic & Float Tracks				
Resfluct	.015	.223	.050	-.223	.015	-.216	.090
Holdtime	.128	.263	.069	.150	.017	.139	.090
			1974, Sonic & Float Tracks				
Noturbon	.008	.300	.090	-.300	.008	-.318	.107
Holdtime	.033	.380	.145	.200	.003	.232	.107
Winddir	.217	.403	.162	-.154	.005	-.134	.107
			1974 Sonic Tracks				
Lightpen	.038	.401	.160	.401	.038	.401	.180

Table 11. (continued)

Variable Name	Variable Significance	Multiple R	R^2	Simple R	Regression Significance	Beta	Standard Error Beta
			1974 Float Tracks				
Fluxrate	.003	.415	.173	-.415	.003	-.253	.175
Holdtime	.094	.470	.221	.225	.003	.225	.123
Daysfree	.173	.502	.252	-.029	.004	-1.004	.341
$Dayfree^2$	.036	.568	.323	.067	.001	.826	.333
Resfluct	.113	.600	.361	-.401	.001	-.300	.183
			1975, Sonic & Float Tracks				
			NO SIGNIFICANT VARIABLES				
			1975 Sonic Tracks				
Tempsurf	.003	.652	.425	-.652	.003	-.864	.157
Noturbon	.005	.807	.651	.168	.001	.521	.157

Table 11. (continued)

Variable Name	Variable Significance	Multiple R	R^2	Simple R	Regression Significance	Beta	Standard Error Beta
1975 Float Tracks							
Noturbon	.150	.325	.106	.325	.150	.512	.240
Resfluct	.162	.448	.200	-.094	.134	-.360	.240

multiple $R^2 = 0.83$ (Table 12). Time at liberty in the reservoir (Daysfree) exhibited the highest correlation with swimming speed ($R = 0.605$). Surface water temperature, however, possessed the largest standardized regression coefficient (Beta = 0.846) and hence can be considered the most relatively important factor influencing fish speed. A broad range of water temperature-fish speed observations (11 - 21°C) was incorporated in the regression analysis and thus the statistical results should be biologically valid. Reservoir water-level drawdown (Resfluct) was also an important parameter as indicated by its moderately large standardized coefficient and the substantial increase in R^2 (17%) gained when this variable entered the regression equation. Although air temperature (Airtemp) had a relatively high standardized coefficient (Beta = -0.824), the biological significance of this variable in affecting swimming rates is obscure.

Retention Time

In 1975, 62 fish comprising four species (32 carp, 25 brown trout, 4 rainbow trout, and 1 lake trout) were observed for their residence time in the Ludington reservoir (Table 13). Thirty individuals were equipped with sonic transmitters; 32 fish carried float tags. Although determination of precise residence times was constrained by tag characteristics (battery-life, shedding of tag, and tag failure) and meteorological conditions (resulting in failure to check reservoir specimens due to adverse weather), "minimal retention periods" were ascertained, nevertheless.

Individual variability in minimum residence time was large. Values ranged from 125 days to less than one day. Carp appeared to

Table 12 . Results of stepwise linear multiple regression of independent variables on speed of movement (body lengths/sec) of trout tracked in the Ludington Reservoir, 1975.

Variable Name	Variable Significance	Multiple R	R^2	Simple R	Regression Significance	Beta	Standard Error Beta
Daysfree	.002	.605	.365	.605	.002	.781	.121
Winddir	.076	.678	.460	.212	.002	.415	.107
Tempsurf	.084	.735	.540	.073	.002	.846	.176
Tempair	.095	.780	.608	-.047	.001	-.824	.181
Resfluct	.002	.880	.774	.140	.001	.644	.145
Wind	.086	.902	.813	.253	.001	.264	.122
Holdtime	.249	.911	.829	.074	.001	.166	.134

Table 13. Summary of fish released in the Ludington Reservoir carrying ultrasonic transmitters or float tags (retention time analysis) in 1975.

Species	Was fish Tracked	Tag Type	Date of Release	Date last Observed	Minimum Retention Period	Remarks
Carp	Yes	Sonic(1wk)	6/18	6/27	9 days	Tag life exceeded
L. Trout	No	Sonic(1wk)	6/22	6/25	3 days	
Carp	Yes	Float	6/24	7/2	9 days	Tag recovered on 7/24
Carp	Yes	Float	6/24	7/2	9 days	
Carp	No	Float	6/24	?	?	Tag recovered on 6/27
Carp	No	Float	6/24	6/24	?	Tag recovered on 6/25
Carp	Yes	Sonic(5wk)	6/25	8/4	39 days	Tag life exceeded
Carp	Yes	Float	6/26	7/2	6 days	Tag recovered on 7/9
Carp	Yes	Sonic(1wk)	7/3	7/24	21 days	Fish recovered on 7/24
Carp	Yes	Float	7/3	9/4	63 days	Fish recovered on 9/4
Carp	Yes	Sonic(5wk)	7/3.	11/5	125 days	Fish recovered on 11/5
Carp	No	Float	7/3	?	?	
Carp	No	Float	7/3	?	?	Tag recovered on 7/14
Carp	Yes	Float	7/11	7/23	12 days	Tag string cut on 7/23
B. Trout	Yes	Sonic(1wk)	7/15	7/24	9 days	Tag life exceeded
Carp	Yes	Sonic(1wk)	7/17	7/24	7 days	Tag life exceeded
Carp	Yes	Float	7/17	7/24	7 days	Tag recovered on 7/25
Carp	Yes	Float	7/17	7/22	5 days	Tag recovered on 7/24
Carp	Yes	Float	7/17	7/29	12 days	Tag recovered on 7/31
Carp	Yes	Sonic(1wk)	7/24	8/1	8 days	Tag life exceeded

Table 13. (continued)

Species	Was fish Tracked	Tag Type	Date of Release	Date last Observed	Minimum Retention Period	Remarks
Carp	Yes	Float	7/24	7/28	4 days	Tag recovered on 8/1
Carp	Yes	Float	7/24	8/4	11 days	Tag recovered on 8/6
Carp	No	Float	7/24	7/30	6 days	Tag recovered on 8/26
Carp	No	Float	7/24	7/30	6 days	Tag recovered on 8/4
B. Trout	No	Sonic(1wk)	7/29	8/6	8 days	Tag life exceeded
Carp	Yes	Sonic(1wk)	8/1	8/11	10 days	Tag life exceeded
Carp	Yes	Float	8/1	8/5	4 days	Tag recovered on 8/7
Carp	No	Float	8/1	8/11	10 days	Tag recovered on 8/12
Carp	Yes	Float	8/7	8/19	12 days	Tag recovered on 8/21
Carp	Yes	Float	8/7	8/12	5 days	
Carp	Yes	Float	8/7	8/14	7 days	Fish entered intake
Carp	Yes	Float	8/7	8/14	7 days	
Carp	No	Sonic(1wk)	8/7	8/11	4 days	
B. Trout	No	Sonic(5wk)	8/14	8/14	0 days	Not detected on 8/15
B. Trout	Yes	Sonic(1wk)	8/15	8/20	5 days	
B. Trout	Yes	Sonic(5wk)	8/21	8/26	5 days	
Carp	No	Float	8/21	8/28	7 days	
B. Trout	Yes	Sonic(1wk)	8/26	8/27	1 day	
B. Trout	Yes	Float	8/26	8/28	2 days	
B. Trout	Yes	Float	8/26	8/27	1 day	Tag recovered on 9/4

Table 13. (continued)

Species	Was fish Tracked	Tag Type	Date of Release	Date last Observed	Minimum Retention Period	Remarks
Carp	Yes	Sonic(5wk)	8/15	9/9	25 days	
B. Trout	No	Float	8/26	8/28	2 days	
B. Trout	No	Float	8/26	8/27	1 day	
B. Trout	No	Float	9/4	9/4	0 days	Not observed on 9/5
B. Trout	No	Float	9/4	9/4	0 days	Not observed on 9/5
B. Trout	No	Float	9/4	9/4	0 days	Not observed on 9/5
B. Trout	No	Sonic(1wk)	9/4	9/4	0 days	Not detected on 9/5
B. Trout	No	Float	9/4	9/16	12 days	Fish recovered on 9/16
B. Trout	Yes	Sonic(1wk)	9/16	9/19	3 days	
B. Trout	No	Sonic(5wk)	9/16	9/18	2 days	
B. Trout	No	Float	9/16	9/25	9 days	
B. Trout	Yes	Sonic(2wk)	9/23	10/2	9 days	
R. Trout	Yes	Sonic(1wk)	9/23	9/25	2 days	
B. Trout	Yes	Sonic(2wk)	9/30	10/7	8 days	Fish recovered on 10/7
B. Trout	No	Sonic(5wk)	9/30	10/2	2 days	
B. Trout	No	Sonic(2wk)	10/7	10/7	0 days	Not detected on 10/8
R. Trout	Yes	Sonic(5wk)	10/9	10/15	6 days	
R. Trout	Yes	Sonic(1wk)	10/14	10/22	8 days	Tag life exceeded
B. Trout	No	Sonic(1wk)	10/15	?	?	Not detected on 10/20
B. Trout	No	Sonic(1wk)	10/21	10/28	7 days	Fish recovered on 10/28

Table 13. (continued)

Species	Was fish Tracked	Tag Type	Date of Release	Date last Observed	Minimum Retention Period	Remarks
B. Trout	Yes	Sonic(2wk)	10/28	10/30	2 days	
R. Trout	No	Sonic(5wk)	10/28	10/29	1 day	

remain in the reservoir longer than any of the other species examined (carp median retention = 8.5 days *vs* 2 days for brown trout, 4 days for rainbow trout, and 3 days for lake trout). Mark and recapture data (Gulvas, 1976) tended to corroborate these findings.

Little information exists on the residence time of fishes in the Ludington reservoir during winter due to a lack of sampling. However, eight fish (7 carp and 1 white sucker) were recaptured in reservoir gill nets during 1975, after having been released in the reservoir in 1974. Presumably, these individuals over-wintered in the reservoir, although it is conceivable (but highly improbable due to the mortality probabilities associated with turbine passage) that these fish left the reservoir and later returned.

DISCUSSION

Tracking investigations of carp and trout in the Ludington Reservoir afforded the unique opportunity to examine fish behavior, through intensive surveillance, in relation to both environmental stimuli and pumped storage activity. The results represent the initial effort to assess fish movement and orientation in a "pure" pumped-storage situation. Equally, the Ludington findings represent the first major field evaluation of fish in the absence of vegetative cover and daily water temperature gradients. While seemingly unnatural, these latter conditions may become more prevalent with the continued development of hydroelectric installations.

Movement Patterns

The most conspicuous behavioral pattern exhibited by tracked fish was the tendency to remain near the reservoir embankment during most of their movements. Excursions into open waters were generally brief, and usually resulted in movement away from one shore location to another. Apparently, the embankment-water interface served as a reference marker for fish orientation and movement. Such shoreline behavior is relatively common in fishes and has been documented for a variety of species (yellow perch, white sucker - Kelso, 1976; largemouth bass, smallmouth bass, spotted bass - Peterson, 1975; brown bullhead - Kelso, 1974; steelhead trout - Falter and Ringe, 1974;

coho salmon - Scholz *et al.*, 1973; cutthroat trout - McCleave and Horrall, 1970).

Diel differences in movement patterns for both carp and trout were not evident. Individual patterns were similar in all reservoir sectors during both plant operational modes, and during day and night. Fish movement patterns seemed little affected by magnitude or direction of water currents.

Patterns of movement were similar for sonic and float-tagged fish implying that float-tracking can be a profitable technique in behavioral studies. Corroboration of float-tracking results by telemetry has previously been accomplished (Hasler *et al.*, 1969; McCleave and Horrall, 1970) and suggests that the inclusion of both techniques in field studies may provide a financially-attractive and reliable approach for documenting fish movements.

Although seasonal differences in trout patterns were not apparent (perhaps because of the limited temporal nature of the trout studies), carp exhibited more open-water movements during the late fall than in the warmer months. This was especially obvious in November 1974 when seven of the ten tracks exhibited off-shore components. This pattern was consistent with reservoir gill net catches and with the seasonal distribution records noted by other investigators (McCrimmon, 1968; Mackay, 1963; Sigler, 1958; Adams and Hankinson, 1928; Tracy, 1910).

The sensory mechanisms involved in the intimate orientation of carp and trout with the reservoir embankments are not known. The display of similar patterns of movement during both daylight and darkness suggests that optical stimuli are not necessary, although visual clues may be used when available. Water currents (rheotaxis) may be important but, here too, differential directional movements under identical conditions as well as similar movements under different current regimes (operating modes) indicate the existence of other sensory cues. Of these, thigmotactic stimuli mediated through the acoustico-lateralis system seem most probable. A "distant touch orientation" (Lowenstein, 1957) between fish and the reservoir wall may exist in which the embankment is perceived from vibrations of the water waves against the wall created by swimming motions. This response has previously been observed in brown trout (DeVore, 1975; Baldes and Vincent, 1969) and may account, at least partially, for the "leading activity" noted when fish encounter fishing nets or other diversionary structures (Leggett and Jones, 1971; Hunter and Wisby, 1964). Most probably, fish in the Ludington reservoir (and elsewhere) utilize combinations of sensory modalities simultaneously and, in the absence of one environmental cue, readily switch to others.

Angular Change

Although angular change has been used as an important behavioral parameter in tracking studies by others (Kelso, 1974; Dodson and Leggett, 1974, 1973; Madison *et al.*, 1972), this statistic was accorded limited use in the Ludington study. This was due to the propensity of fish to orient in proximity to the Ludington embankment, thereby restricting movement and directional changes to those imposed by the physical features of the reservoir. As a result, the probability distribution of directional changes seldom approximated a circular distribution upon which the analysis is based (Batschelet, 1965).

Hence, the use of angular analysis for the Ludington data may not have been entirely appropriate.

The relation between angular change in direction and fish physiological processes remains obscure. Until more is known about this relationship, the use of angular change as a significant behavioral parameter should be constrained.

Swimming Speed

The average swimming speeds for tracked individuals (0.17 L/sec - carp; 0.63 L/sec - trout) are much less than values from laboratory studies. For *Carassius*, Fry and Hart (1948) reported a mean swim speed of 6.4 L/sec; Radcliffe (1950) cited a value of 3.4 L/sec; and Bainbridge (1960) observed speeds of greater than 5.0 L/sec. Laboratory findings on rainbow and brown trout speeds provide mean values of 3.3 L/sec (Paulik and DeLacy, 1957), 10.0 L/sec (Blaxter and Dickson, 1959), 5.0 L/sec (Reimers, 1956), and 1.9 L/sec (Bainbridge, 1962). Even the fastest observed swimming speeds for Ludington fish (1.1 L/sec, carp 74-5 during a six-minute interval in Track 74-17; 2.7 L/sec, brown trout 75-25 during a four-minute interval in Track 75-58) are low relative to the laboratory results. Similar low field fish swim speeds (Young *et al.*, 1972; Holliday *et al.*, 1974) suggest that fish seldom exhibit *sustained* activity levels (Webb, 1975) comparable to those obtained in experimental situations. This discrepancy may result from the short temporal nature of most performance tests, as well as the inability to incorporate into laboratory designed studies important behavioral aspects such as foraging, schooling, or territoriality known to influence swimming activity.

Activity levels of carp exhibited a diel periodicity. Dawn and dusk movement rates were higher than those observed during daylight (0900 - 1700 hr) and nighttime speeds were greater than those in the day. Similar fluctuations in carp activity were surmised from angling records by Marlborough (1970) and noted by Gibbinson (1968) and Cole (1905). Although winter movement observations of carp at Ludington are lacking, Johnsen and Heitz (1975) reported that carp in Lake Mendota only moved at night during this time of the year. They also reported that instrumented fish tended to move in the company of other monitored individuals. Similar behavior was observed on several occasions with Ludington carp. This behavior is not atypical of species which aggregate (school) for feeding and spawning.

Swimming speeds of trout also demonstrated a crepuscular rhythm. This pattern has been previously seen in sonic-tracked brown trout (Holliday *et al.*, 1974; Young *et al.*, 1972) but was absent in steelhead trout tracked in the Snake River, Idaho-Washington (Falter and Ringe, 1974). Unfortunately, almost all of the nighttime swim speed data for Ludington trout were obtained from one brown trout during a 24 hr track (Track 75-23). While conclusions based on these data are tentative, they do affirm earlier accounts that lake brown trout are both day and night active and exhibit peak activity at dusk (Brynildson *et al.*, 1973; Young *et al.*, 1972).

The tendency for both carp and trout to remain active at night may be responsible for the passage of these species into the Ludington reservoir. Pumping activities normally occur at night and presumably affect those species that are night-active. Hence, the reservoir fish composition may be different from that in the lake because of differential behavioral rhythms (and consequently passage susceptibility) of the lake fish species. This may explain the relatively low numbers of yellow perch in the reservoir (Gulvas, 1976) since, although this species is abundant in Lake Michigan, it is inactive at night (Eddy and Underhill, 1974; Scott and Crossman, 1973), and thus will have a low probability of being drawn into the reservoir during pumping.

Multiple regression analyses of movement speed of trout and carp revealed that swimming speeds were affected by both environmental factors and plant operation. Trout swimming speeds were significantly influenced by climatic variables (wind direction and velocity; air and water temperature), power plant conditions (water-level drawdown), and behavioral features (days at liberty). The most important parameter was Daysfree indicating that rate of movement increased with trout residence time. While this correlation may be spurious (due to low sample size of N = 23), the relation could reflect physiological adjustments to tag attachment and handling, or acclimation to the reservoir environment. Such disturbances in activity and orientation have been recorded in other behavioral studies (McCleave and Stred, 1975; Holliday *et al.*, 1974; Hart and Summerfelt, 1973; Shepard, 1973; Gallepp and Magnuson, 1972; Black, 1958, Spoor, 1941), although similar evaluations of post-handling effects are generally lacking in field-oriented, fish-tracking investigations. The swimming performance analysis of the Ludington trout suggests that these delayed locomotor responses may be substantial and should be assessed in future behavioral research. Without these data, the results of activity level studies should be evaluated with caution.

The response of carp movements (in terms of specific swimming speed) to external variables differed from that of trout in two respects: (1) the environmental and power plant factors used in the regressions accounted for only a small percentage of the variation in movement rate, and (2) the significant variables influencing movement rate were different between years, and between sonic and float-tracked individuals. In all cases, the extreme variation in swimming speed between tracks (within and among fish) resulted in low correlation coefficients. It is apparent, however, that carp speed varied inversely with changes in the reservoir water-level elevation (Resfluct and Fluxrate) during power generation. The significant negative correlation of movement rate with the number of turbines in operation (Noturbon) in the 1974 pooled analysis further implies that the inverse relation between movement and the magnitude of water drawdown was a real phenomenon rather than a mathematical artifact. Although water level manipulation has been a widely used management technique in carp control (McCrimmon, 1968; Jester, 1971; Sigler, 1958), previous documentation of this relationship is lacking.

A major constraint in the interpretation of the multiple regression analyses for both groups was the absence of biological factors in the predictive models. The inability to parameterize biological features such as competition, spawning, hunger, predation, and homing necessitated their exclusion from a mathematical treatment. The presence of these interactions may possibly be inferred from the data (*i.e.*, diel patterns suggesting feeding activity), but their importance in affecting fish movements remains unclear. A more sophisticated field-experimental approach to resolve the influence of these factors on swimming speed is plainly warranted.

Retention Time

Retention studies of selected fish during 1975 revealed that minimum residence periods in the reservoir were variable, ranging from 4 - 125 days for carp and 0 - 12 days for trout. Homing behavior may account for the apparent rapid departure of trout from the reservoir, although other factors (attraction to currents; increased movement activity with water level drawdown - note positive Resfluct results in the regression analysis) offer equally plausible explanations for this phenomenon.

The passage of fish out of the Ludington reservoir is known from the recapture of reservoir-tagged individuals in Lake Michigan. However, the tracking studies indicated only one instance (out of 159 tracks) in which an individual was actually observed to leave the reservoir. Though the tracking data seem inconsistent with the recapture findings (and gill-net studies which indicate that fish population abundance has not changed significantly in three years (Gulvas, 1976), this disparity may be resolved by considering the probability of a fish leaving the reservoir. If all members of a species in the reservoir are susceptible to removal, and hence loss rate a function of population size, then the probability of loss of any one fish will be small relative to the daily removal percentage of the population. Since normally only one or two fish were tracked each day, the likelihood of these fish being removed (especially during the restricted part of the day in which they were observed) was rather low. Furthermore, the departure rate of fish assuredly varies with the intensity and duration of generating activity, and thus the probability of recording the exit of a tracked individual on any one day must have fluctuated widely. From this perspective (and considering that most of the fish tracked were carp which appear to have a long residence time), it is not startling that only one of the 65 tracked fish was witnessed in its exit from the reservoir.

The turnover rate (loss rate) of the reservoir fish populations coupled with reservoir abundance estimates are necessary in assessing passage mortality during power generation. Thus, more intensive efforts to precisely delineate population size and residence time may be required in the future.

CONCLUSIONS

The behavioral studies conducted at Ludington during 1974 - 1975 indicate the importance of considering fish behavior in the siting, design, and operation of hydroelectric projects, particularly pumped-storage installations. An understanding of fish movements including swimming depths, activity cycles, and the influence of water flows will aid in constructing and operating power plants to minimize fish attraction, entrainment, and passage mortality.

Further information at Ludington would augment this study and help in the final impact analysis. The behavior of species near the plant and in the reservoir could be better defined by further analysis of existing field data or expansion of ultrasonic telemetry. Recent developments with automatic monitoring and multichannel transmitters (which relay data on depth, temperature, and location) offer great potential for interpretation of fish movements. Water currents near the plant and in the reservoir should also be better defined and compared with data from pre-operational modelling efforts for verification.

Knowledge thus gained should be imparted to design engineers so that placement and operation of power plants will minimally affect the normal activities and dynamics of fish populations. Detailed fish behavior data may lead to the development of efficient guidance barriers (including lights, water and air jets, sound, louvers, and conduits) which elicit attractive or avoidance responses from fish, thus reducing impact. Distinct near-shore movements noted in this study indicate the possibility for designing bypass channels in the upper reservoirs of pumped storage systems. This would permit an alternate fish pathway to the lower basins and thus possibly reduce overall fish passage mortality.

Modelling efforts of power plant impact and ecosystem dynamics should be developed which incorporate behavioral phenomena into the simulation framework. The inclusion, initially, of such behavioral aspects as spawning periods and seasonal migration patterns would be useful in developing a basic perspective from which to assess environmental events. More refined behavioral parameters (light-temperature-water current-locomotory relationships) should be integrated into these models as the data become available.

SUMMARY

Movement patterns, activity levels, and residence periods of carp and trout were investigated in the Ludington Pumped Storage Reservoir in 1974 and 1975 using ultrasonic telemetry and float-tracking procedures. These species were studied because of their availability and abundance, tag retention capabilities, and biological and recreational importance.

Sixty-five fish (52 carp, 10 brown trout, 3 rainbow trout) were monitored for a total of 1159 hr, spanning 159 tracks. Tracking periods ranged from 1-24 hr and were generally accomplished during the daytime. Four fish were tracked through the night and 12 individuals were monitored during dawn and dusk. Tracking sessions were terminated for a variety of reasons including equipment failure, expiration of the transmitter battery, cessation of fish movement, and adverse weather conditions.

The most common fish movement pattern was a straight path orientation parallel and adjacent to the reservoir embankment. The shoreline appeared to serve as a reference for locomotory activity. Open-water excursions occurred but were normally brief. Obvious seasonal differences in movement pattern were not evident in trout, although carp displayed more offshore movements in late fall than in the warmer months. Patterns of movement were similar between sonic- and float-tagged fish, and during both daylight and darkness.

Length of individual tracks ranged from 0.07 - 16.49 km for carp and 0.15 - 27.44 km for trout. Average swimming speed for carp varied from 0.01 - 0.64 L/sec (0.8 - 38.1 cm/sec), and from 0.01 - 1.30 L/sec (0.8 - 79.9 cm/sec) for trout. No significant differences ($P > 0.05$) were detected in movement rates between sonic and float tagged individuals, between brown and rainbow trout swim speeds, and between carp swimming rates for 1974 and 1975. A significant two-way interaction ($P < 0.05$) was evident, however, between year and track type for carp speeds. Rates of movement determined for carp during pumping and generating operations differed significantly ($P < 0.05$) for each year but this trend was inconsistent between years. Overall, the mean swimming speed for carp was 0.17 L/sec (10.5 cm/sec) and 0.63 L/sec (38.6 cm/sec) for trout. These values are lower than most activity levels reported from laboratory studies.

Pronounced diurnal activity levels were displayed by the tracked species. Trout exhibited activity peaks during dawn and dusk and remained active throughout the day and night. Carp displayed a similar crepuscular rhythm in swimming speed, but were much more active at night than during the day. The tendency for both groups of fish to remain night-active may account for their passage into the reservoir.

Factors affecting swimming speed were analyzed for their relative importance by stepwise linear multiple regression analysis. For trout, the independent variables explained 83% of the variation in movement rate. Behavioral features (days at liberty), environmental factors (water temperature), and power plant operations (reservoir drawdown) were influential in trout movement. For carp, the multiple correlation coefficients were low and had a range of 0 - 65%. Although different variables were significant in each of the carp analyses, water current parameters and power plant factors appeared in a majority of the regression equations. Biological factors were not evaluated in the regressions for either species and, hence, their importance on fish movement rate was not determined.

Residence period of fish in the Ludington reservoir was assessed from observations on 62 individuals accomplished during 1975. Minimum residence intervals ranged from several hours to 125 days. Carp seemed to remain in the reservoir longer than any of the trout species examined. Median retention period for carp was 8.5 days and 2 days for the combined trout species. Greater accuracy of residence time estimates can only be obtained by expanding this aspect of the Ludington research.

The need for future studies related to the impact of hydroelectric development of fish populations is indicated.

LITERATURE CITED

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Adams, C. C., and T. L. Hankinson. 1928. The ecology and economics of Oneida lake fish. Roosevelt Wildlife Ann. 1(3 & 4): 319-333.

Bainbridge, R. 1960. Speed and stamina in three fish. J. Exp. Biol. 37: 129-153.

Bainbridge, R. 1962. Training, speed and stamina in trout. J. Exp. Biol. 39: 537-555.

Baldes, R. J., and R. E. Vincent. 1969. Physical parameters of microhabitats occupied by brown trout in an experimental flume. Trams. Amer. Fish. Soc. 98: 37-41.

Batschelet, E. 1965. Statistical methods for the analysis of problems in animal orientation and certain biological rhythms. Amer. Inst. Biol. Sci. Monogr. 1: 57 p.

Batschelet, E. 1972. Recent statistical methods for orientation data, pp. 61-91. *in* S. R. Galler, K. Schmidt-Koenig, G. J. Jacobs, and R. E. Belleville (eds.) Animal Orientation and Navigation. National Aeronautics and Space Administration, Washington, D. C.

Black, E. C. 1958. Hyperactivity as a lethal factor in fish. J. Fish. Res. Board Can. 15: 573-586.

Blaxter, J. H. S., and W. Dickson. 1959. Observations on the swimming speeds of fish. J. Cons. int Explor. Mer. 24: 472-479.

Brynildson, O. M., V. A. Hacker, and T. A. Klick. 1973. Brown trout: life history, ecology and management. Wisc. Dept. Nat. Resour. Publ., 234: 16 p.

Cole, L. J. 1905. The German carp in the United States. Rept. U. S. Bur. Fish 1904: 525-641.

Conover, W. J. 1971. Practical nonparametric statistics. John Wiley and Sonc, New York. 462 p.

DeVore, P. W. 1975. Daytime behavioral responses of adult brown trout (*Salmo trutta*) to cover stimuli in stream channels. M.S. Thesis, Michigan State Univ., East Lansing. 38 p.

Dodson, J. J., and W. C. Leggett. 1973. The behavior of American shad (*Alosa sapidissima*) homing to the Connecticut River from Long Island Sound. J. Fish. Res. Board Can. 30: 1847-1860.

Dodson, J. J., and W. C. Leggett. 1974. Role of olfaction and vision in the behavior of American shad (*Alosa sapidissima*) homing to the Connecticut River from Long Island Sound. J. Fish. Res. Board Can. 31: 1607-1619.

Draper, N., and H. Smith. 1966. Applied regression analysis. John Wiley and Sons, New York. 407 p.

Eddy, S., and J. C. Underhill. 1974. Northern fishes (3rd edition). University of Minnesota Press, Minneapolis. 414 p.

Estes, R. D. 1971. The effects of the Smith Mountain Pumped Storage Project on the fishery of the lower reservoir, Leesville, Virginia. Ph.D. Thesis, Virginia Polytechnic Institute and State Univ., Blacksburg. 151 p.

Falter, C. M., and R. A. Ringe. 1974. Pollution effects on adult steelhead migration in the Snake River. Ecol. Res. Ser., EPA-660/3-73-017. 101 p.

Fry, F. E. J., and J. S. Hart. 1948. Cruising speed of goldfish in relation to water temperature. J. Fish. Res. Board Can. 7: 169-175.

Gallepp, G. W., and J. J. Magnuson. 1972. Effects of negative buoyancy on the behavior of the bluegill, *Lepomis macrochirus* Rafinesque. Trans. Amer. Fish. Soc. 101: 507-512.

Gibbinson, J. A. 1968. Carp. MacDonald, London.

Groot, C., K. Simpson, I. Todd, P. D. Murray, and G. A. Buxton. 1975. Movements of sockeye salmon (*Oncorhynchus nerka*) in the Skeena River estuary as revealed by ultrasonic tracking. J. Fish. Res. Board Can. 32: 233-242.

Gulvas, J. A. 1976. An evaluation of the composition and relative abundance of fishes pumped into the Ludington Pumped Storage Reservoir from Lake Michigan, 1972-1975. M.S. Thesis, Michigan State Univ., East Lansing.

Hart, L. G., and R. C. Summerfelt. 1973. Homing behavior of flathead catfish, *Pylodictis olivaris* (Rafinesque) tagged with ultrasonic transmitters. Proc. 27th Ann. Conf. S.E. Assoc. Game and Fish Comm: 520-531.

Hasler, A. D., E. S. Gardella, R. M. Horrall, and H. F. Henderson. 1969. Open-water orientation of white bass, *Roccus chrysops*, as determined by ultrasonic tracking methods. J. Fish. Res. Board Can. 26: 2173-2192.

Hauck, F. R., and Q. A. Edson. 1976. Pumped storage: its significance as an energy source and some biological ramifications. Trans. Amer. Fish. Soc. 105: 158-164.

Holliday, F. G. T., P. Tytler, and A. H. Young. 1974. Activity levels of trout (*Salmo trutta*) in Airthrey Loch, Stirling, and Loch Leven, Kinross. Proc. R.S.E. (B) 74: 315-331.

Hunter, J. R., and W. J. Wisby. 1964. Net avoidance behavior of carp and other species of fish. J. Fish. Res. Board Can. 21: 613-633.

Jahn, L. A. 1966. Open-water movements of the cutthroat trout (*Salmo clarki*) in Yellowstone Lake after displacement from spawning streams. J. Fish. Res. Board Can. 23: 1475-1485.

Jahn, L. A. 1969. Movements and homing of cutthroat trout (*Salmo clarki*) from open-water areas of Yellowstone Lake. J. Fish. Res. Board Can. 26: 1243-1261.

Jester, D. B. 1971. Effects of commercial fishing, species introductions, and drawdown control on fish populations in Elephant Butte Reservoir, New Mexico, p. 265-285. *in* G. E. Hall (ed.) Reservoir Fisheries and Limnology. Amer. Fish. Soc. Spec. Publ. No. 8.

Johnsen, P. B., and J. G. Heitz. 1975. Beep! Beep! Beep! Where are the carp? Wisc. Cons. Bull. (Nov-Dec 1975): 12-13.

Johnson, J. H. 1960. Sonic tracking of adult salmon at Bonneville Dam, 1957. U. S. Fish Wildl. Serv. Fish. Bull. 176: 471-485.

Kelso, J. R. M. 1974. Influence of a thermal effluent on movement of brown bullhead (*Ictalurus nebulosus*) as determined by ultrasonic tracking. J. Fish. Res. Board Can. 31: 1507-1513.

Kelso, J. R. M. 1976. Movement of yellow perch (*Perca flavescens*) and white sucker (*Catostomus commersoni*) in a nearshore Great Lakes habitat subject to a thermal discharge. J. Fish. Res. Board Can. 33: 42-53.

Leggett, W. C., and R. A. Jones. 1971. Net avoidance in American shad (*Alosa sapidissima*) as observed by ultrasonic tracking techniques. J. Fish. Res. Board Can. 28: 1167-1171.

Liston, C. R., and P. I. Tack. 1974. A study of the effects of installing and operating a large pumped storage project on the shores of Lake Michigan near Ludington, Michigan. 1973 Ann. Rept. to Consumers Power Co., Vol. 1, Dept. Fish and Wildlife., Michigan State Univ., 174 p.

Liston, C. R., and P. I. Tack. 1975. A study cf the effects of installing and operating a large pumped storage project on the shores of Lake Michigan near Ludington, Michigan. 1974 Ann. Rept. to Consumers Power Co., Vol. 1, Fisheries Research, Dept. Fish and Wildl., Michigan State Univ., 166 p.

Lowenstein, O. 1957. The sense organs: the acoustico-lateralis system, p. 155-209. *in* M. E. Brown (ed.) The Physiology of Fishes. Academic Press, New York.

Mackay, H. H. 1963. Fishes of Ontario. Publ. Ontario Dept. Lands Forests.

Madison, D. M., R. M. Horrall, A. B. Stasko, and A. D. Hasler. 1972. Migratory movements of adult sockeye salmon (*Oncorhynchus nerka*) in coastal British Columbia as revealed by ultrasonic tracking. J. Fish. Res. Board Can. 29: 1025-1033.

Marlborough, D. 1970. The behavior of common carp (*Cyprinus carpio* L.) and crucian carp (*Carassius carassius* L.) as indicated by angling records. Lond. Nat. 49: 69-76.

McCleave, J. D. 1967. Homing and orientation of cutthroat trout (*Salmo clarki*) in Yellowstone Lake, with special reference to olfaction and vision. J. Fish. Res. Board Can. 24: 2011-2044.

McCleave, J. D., and R. M. Horrall. 1970. Ultrasonic tracking of homing cutthroat trout (*Salmo clarki*) in Yellowstone Lake. J. Fish. Res. Board Can. 27: 715-730.

McCleave, J. D., and K. A. Stred. 1975. Effect of dummy transmitters on stamina of Atlantic salmon (*Salmo salar*) smolts. J. Fish. Res. Board Can. 32: 559-563.

McCrimmon, H. R. 1968. Carp in Canada. Bull. Fish. Res. Board Can. 165: 93 p.

Paulik, G. J., and A. C. DeLacy. 1957. Swimming abilities of upstream migrant silver salmon, sockeye salmon and steelhead at several water velocities. Univ. Wash. Scool Fish. Tech. Rept. 44: 1-40.

Peterson, D. C. 1975. Ultrasonic tracking of three species of black basses, *Micropterus* spp., in Center Hill Reservoir, Tennessee. M.S. Thesis, Tennessee Technological Univ., Cookeville. 142 p.

Radcliffe, R. W. 1950. The effect of fin clipping on the cruising speed of goldfish and coho salmon fry. J. Fish. Res. Board Can. 8: 67-73.

Reimers, N. 1956. Trout stamina. Progr. Fish-Cult. 18: 112.

Robbins, T. W., and D. Mathur. 1976. The Muddy Run Pumped Storage Project: a case history. Trans. Amer. Fish. Soc. 105: 165-172.

Scholz, A. T., J. C. Cooper, D. M. Madison, R. M. Horrall, A. D. Hasler, A. E. Dizon, and R. J. Poff. 1973. Olfactory imprinting in coho salmon: behavioral and electrophysiological evidence. Proc. 16th Conf. Great Lakes Res. 1973: 143-153.

Schoumacher, R. 1976. Biological considerations of pumped storage development: introductory remarks. Trans. Amer. Fish. Soc. 105: 155-157.

Scott, W. B., and E. J. Crossman. 1973. Freshwater fishes of Canada. Bull. Fish. Res. Board Can. 184: 966 p.

Shepherd, B. 1973. Transmitter attachment and fish behaviour. Underwater Telemetry Newsletter 3: 8-11.

Sigler, W. F. 1968. The ecology and use of carp in Utah. Utah State Univ., Agr. Exp. Sta. No. 405: 62 p.

Spoor, W. A. 1941. A method for measuring the activity of fishes. Ecology 22: 329-331.

Stasko, A. B. 1971. Review of field studies on fish orientation. Ann. N. Y. Acad. Sci. 188: 12-29.

Stasko, A. B. 1975. Underwater biotelemetry, an annotated bibliography. Fish. Mar. Serv. Res. Dev. Tech. Rep. 534: 31 p.

Stasko, A. B., R. M. Horrall, and A. D. Hasler. 1976. Coastal movements of adult Fraser River sockeye salmon (*Oncorhynchus nerka*) observed by ultrasonic tracking. Trans. Amer. Fish. Soc. 105: 64-71.

Stasko, A. B., R. M. Horrall, A. D. Hasler, and D. Stasko. 1973. Coastal movements of mature Fraser River pink salmon (*Oncorhynchus gorbuscha*) as revealed by ultrasonic tracking. J. Fish. Res. Board Can. 30: 1309-1316.

Tracy, H. C. 1910. Annotated list of the fishes known to inhabit the waters of Rhode Island. Fortieth Ann. Rept. Comm. Inland Waters Rhode Island: 354-360.

Warden, R. L. Jr., W. J. Lorio. 1975. Movements of largemouth bass (*Micropterus salmoides*) in impounded waters as determined by underwater telemetry. Trans. Amer. Fish. Soc. 104· 696-702.

Webb, P. W. 1975. Hydrodynamics and energetics of fish propulsion. Bull. Fish. Res. Board Can. 190: 158 p.

Young, A. H., P. Tytler, F. G. T. Holliday, and A MacFarlane. 1972. A small sonic tag for measurement of locomotor behaviour in fish. J. Fish. Biol. 4: 57-65.