REVIEW OF FISH BEHAVIOR RELEVANT TO FISH GUIDANCE SYSTEMS

BLAKE E. FEIST AND JAMES J. ANDERSON

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KEY WORDS
Hydroelectric dams, juvenile salmon, behavior, guidance, sensory systems

LIST OF ABBREVIATIONS

bls = body lengths per second
d = day
f = foot
fps = feet per second
h = hour
Hz = hertz
in = inch
L = liter
m = meter
milligrams = mg
min = minute
mm = millimeter
mo = month
s = second
SPL = sound pressure level
TL = total length
W = Watt
< = less than
> = greater than
PREFACE

Poor fish guidance at certain hydroelectric projects on the Columbia River has been a problem for some time. To date, little effort has been made to apply the principles of fish behavior when designing these fish guidance systems. The reason for undertaking this project was to review the principles of fish behavior relevant to fish bypass and apply this information to designing better bypass systems at dams on the Columbia River.

Information concerning fish behavior relevant to fish guidance systems was searched for at a variety of locations including: NMFS Montlake Library (Seattle, WA); and Fisheries-Oceanography, Fisheries Archives, Engineering, Health Sciences, Natural Sciences, and Forestry Libraries (University of Washington). Databases searched included: National Technical Information Service (NTIS), Aquatic Sciences and Fisheries Abstracts (ASFA), and Dissertation Abstracts (DISS).

The bibliography section at the end of this report is a complete listing of all references considered for this review, and is divided into sections roughly corresponding to the divisions in the review (abstracts were available only for those references downloaded from Compact Cambridge CD-ROM database). This bibliography, complete with abstracts and key words, is available on computer disk.

We would like to thank the U.S. Army Corps of Engineers for funding this research and we also thank Sidney Deering for her assistance with this project.
INTRODUCTION

Safe and efficient passage of outmigrating juvenile Pacific salmon through fish guidance systems at hydroelectric projects on the Columbia River is essential if sufficient numbers of returning adults are to be maintained. Fish guidance efficiency (FGE) is variable between dams and between years at any given dam, and the reasons for this variability are not clear. This situation exists, in part, because significant differences between the systems make it difficult to extrapolate from one situation to the other.

A large body of literature exists concerning fish behavior and ecology, and this information can be applied to understanding the behavior of fish in response to the stimuli encountered at hydroelectric projects. A set of guidelines or minimum design criteria is necessary. Although it is not possible to design optimal guidance systems, there is sufficient information to establish minimum design criteria below which a system will not work. In the context of the immediate needs of fish guidance research, minimum design criteria can help identify and thus avoid the development of inadequate fish bypass systems. In a long-term context, minimum design criteria will facilitate improved behavioral guidance systems by identifying where additional work is required to develop design criteria for optimizing guidance systems.

This literature review examines five key parameters that we feel affect FGE the most: light and vision; sound and hearing; water currents and rheotaxis; turbidity; and temperature. All five of these factors interact simultaneously at times, so it is often difficult to "tease apart" the individual effects. Therefore, the information presented will often overlap or combine (or both) one or more of the five factors. For each factor we will provide a brief background with definitions, and then we will attempt to apply what is known about each factor to fish guidance at dams and minimum design criteria.

SOUND AND HEARING IN FISH

CHARACTERISTICS OF SOUND

There are two components to sound propagation through water: particle displacement and sound pressure. Particle displacement is the to-and-fro movement (on the order of nanometers) of water molecules and is a vector quantity, whereas sound pressure is the oscillatory change in pressure above and below hydrostatic pressure and is a scalar quantity acting in all directions.

UNITS OF MEASUREMENT

In a free sound field without physical obstructions to sound transmission, and with an advancing wavefront that is essentially a plane surface, particle velocity (the first derivative of particle displacement) is proportional to sound pressure in the following manner:

\[ v = \frac{p}{\rho c} \]

where \( v \) = particle velocity, 
\( p \) = sound pressure,
\[ \rho = \text{the density of the medium, and} \]
\[ c = \text{the propagation velocity.} \]

The product \( \rho c \) is the acoustic impedance of the medium. However, sound levels are not usually expressed as particle velocity, rather the logarithmic decibel (dB) scale of sound pressure level (SPL) is used because a great range of sound levels are found in nature:

\[
\text{sound pressure level (SPL)} = 20 \log_{10} \frac{p}{p_{\text{ref}}} \text{dB}
\]

where \( p = \text{the measured sound pressure, and} \)
\[ p_{\text{ref}} = \text{the reference pressure.} \]

A reference quantity is always associated with the dB in order to place sound levels in a reasonable range. The reference quantity for SPL in water is usually 1 Pascal (Pa). Twenty \( \mu \text{Pa} \) of sound pressure is the reference (re.) pressure for the dB scale in humans, because 20 \( \mu \text{Pa} \) is the amount of sound pressure the average human requires to hear. Therefore, 0 dB re. 20 \( \mu \text{Pa} \) is the human threshold of hearing and 120 dB re. 20 \( \mu \text{Pa} \) is the threshold of pain. For each 20-dB increase in SPL, regardless of the reference pressure, the increase in actual sound pressure is tenfold. Thus, a 40-dB increase in SPL is 100 times more pressure, 60 dB is 1000 times more and so on.

Sound pressure and particle displacement are essentially the same at substantial distances from the source. However, in the near-field (\( \lambda/2\pi \) [\( \lambda \) = wavelength], from the sound source) where the wavefront is spherical rather than a plane surface, particle velocity is much higher for a given sound pressure—the “near-field effect.” The near-field can be thought of as the region where the greatest amount of bulk movement of water occurs in response to the sound source, which is not as pronounced after \( \lambda/2\pi \) distance from the sound source. This near-field effect can extend up to 50 m from the source for low frequencies such as 5 Hz, which is perceivable by many fish.

Sound propagation through water, via either the pressure or displacement component, is a logarithmic function:

\[ y = a + m \log x \]

where \( a = \text{the source-sound pressure level (y-intercept),} \)
\[ m = \text{the logarithmic slope, and} \]
\[ x = \text{the distance from the source.} \]

Therefore, rates of sound level increase close to the source are rapid compared to those far away.

**SOUND PERCEPTION IN FISH**

Literature on hearing in fish is abundant, and it is clear that fish detect and respond to sounds in their environment. Fish appear to use sound: to locate prey, evidenced by attraction to a sound stimulus (for example, sharks: Wisby et al. 1964, Nelson 1965; various teleosts and elasmobranchs: Richard 1968, and Nelson et al. 1969; rainbow trout,
Onchorhynchus mykiss: Abbott 1970; for social interactions (bicolor damselfish, Pomacentrus partitus: Myrberg 1972, and Myrberg and Riggio 1985; gudgeon, Gobio gobio: Ladich 1988); for encounters with fishing gear (Nomura 1980, Wardle 1983, Ona and Toresen 1988); and to signal the presence of danger, evidenced by fish avoiding a sound stimulus (steelhead trout, O. mykiss: Van Der Walker 1967; herring, Clupea harengus L.: Blaxter et al. 1981a, Schwarz and Greer 1984, and Blaxter and Batty 1985a and 1985b; alewife, Alosa pseudoharengus: Haymes and Patrick 1986). In addition, minimum audible field thresholds have been determined for many species of fish (Tavolga and Wodinsky 1963; Chapman and Hawkins 1973; Chapman and Sand 1974; Hawkins and Johnstone 1978; Coombs and Popper 1979; Saidel and Popper 1987). A few studies have investigated fish behavior in response to changes in SPL over time. Olsen (1971) found a positive correlation between the rate of sound pressure increase and the number of Atlantic herring that would avoid this stimulus (see Blaxter et al. 1981a). Schwarz and Greer (1984) obtained similar results on Pacific herring (C. harengus pallasi). However, these studies did not quantify rates of sound pressure increase or the fish's response to the sound stimulus.

Physiology of Hearing

Fish hearing in general is different from that of terrestrial organisms. Most fish hear with a primitive version of the terrestrial inner ear (located in the skull of fish) and with the lateral line that runs the length of each side of the fish and is often extensively routed on the head. The inner ear and the lateral line system is called the acoustico-lateralis system. The inner ear does not have a cochlea as in terrestrial vertebrates; rather there are three symmetrically paired structures with associated bony otoliths: the lagena, sacculus, and utriculus. The lagena and sacculus are directly involved with hearing, whereas the utricle is mainly for three-dimensional orientation (Platt and Popper 1981). The mechanism for hearing is the differential displacement of high-density otoliths relative to the low-density bodies of fish, resulting in bending of sensory hair cells that line the lagena and sacculus. This mechanical stimuli is then converted to electrical stimuli in the hair cell body and sent to the brain for processing.

Audiograms (threshold SPL for various frequencies) of different species of fish are variable. Families of fish with the best hearing such as cyprinids and ictalurids (Ostariophysan fish) possess a physical connection (via a series of bones, the Weberian apparatus) between the swimbladder and the inner ear. Thus, the swim bladder acts as an amplifier. The hearing ability of other fish such as salmonids and flatfish is limited in bandwidth and intensity threshold compared to other teleosts: Atlantic salmon (Salmo salar) are functionally deaf above 380 Hz (Hawkins and Johnstone 1978, Fig. 1). These fish lack the physical connection between their swim bladder and inner ear that Ostariophysan fishes possess (Hawkins 1986). Fish with this type of hearing are most sensitive to particle velocity since the otoliths in the lagena and sacculus essentially respond to particle displacement (Hawkins and MacLennan 1976).

Compared to humans, salmonids have poor hearing on the basis of perceivable frequency range and sensitivity to sound pressure (Fig. 1). Human infants are capable of detecting sounds from 20-20,000 Hz, and at SPLs much lower than that of salmonids. For example, a human would require about -80 dBs re. 1 Pa SPL to hear a 160 Hz pure tone,
while a salmonid would require about -20 dBs. Therefore, the salmonid requires close to a thousandfold increase in SPL to hear the same 160 Hz tone.

**Minimum Requirements to Hear a Sound Stimulus**

The minimum requirements for sound that will at least be audible to a juvenile salmon are as follows. First, SPL must be at least that of the minimum audible field of salmon in Figure 1 for all frequencies. Second, the ambient noise in the area where fish are to respond to the sound produced must be at least 24 dB less than the minimum audible field of the fish; otherwise “masking” will occur, and the fish will not hear the sound stimulus (Hawkins and Johnstone 1978). In addition, SPL should be at least 20-30 dB higher than ambient noise levels in order to be effective. Third, salmonids have a 183 Hz bandwidth for masking (Hawkins and Johnstone 1978). This means that any sounds within 90 Hz
above or below the stimulus frequency will mask the fish's detection of that frequency. Finally, noise or broad-band sound that is pulsed rather than continuous has been more aversive to other fish species than pure-tone continuous sound (see Hering 1968 in Olsen 1971; Olsen 1971; Blaxter et al. 1981b; Schwarz and Greer 1984).

**FISH RESPONSES TO SOUND**

The fright response of salmonids to sound is typically a “startle” or “start” behavior (Burner and Moore 1962, Moore and Newman 1956). Such behaviors involve sudden bursts of swimming that are short in duration and distance travelled. Few studies have shown that sound can attract or repel salmonids over great distances or for long lengths of time. Fish typically “habituate” to sound stimuli in their environment, evidenced by a rapid return to pre-stimulus behavior.

Most salmonids can be attracted to or repelled from sound through classical conditioning (Abbott 1973), but they habituate rapidly or do not respond at all when there is no conditioned response, regardless of SPL (Burner and Moore 1962, Moore and Newman 1956). “At no time did a sound frequency or intensity influence the action of the trout enough to be utilized in guiding young salmon into safe passages around dams and diversions” (Burner and Moore 1962). An explanation for this is that salmon have poor hearing, and the nature of the sounds presented to them in experiments has not been biologically relevant. Other species of fish with better hearing capabilities than salmon have been shown to jump out of the water or swim rapidly away from or towards sound stimuli (Moulton 1956; Hashimoto and Maniwa 1966).

Studies conducted on the response of salmonids to sound have direct application at hydroelectric projects. Fish guidance efficiency is low at certain projects, and many outmigrants pass through the project turbines (Williams et al. 1988). It is estimated that up to 33% of juvenile salmonids passing through the turbines are killed (Long et al., unpublished in Giorgi et al. 1988).

Bypass screens may produce some stimulus that fish avoid (Williams et al. 1988), and this stimulus might be sound (Anderson 1988a,b; Anderson et al. 1989). The acoustic environment at hydroelectric projects has been measured extensively (Anderson et al. 1989). However, we do not know how juvenile salmonids react to these sounds. Research on the response of salmonids to sounds analogous to those found at hydroelectric projects would be useful in assessing the impact sound has on outmigrant salmonids at hydroelectric projects. On the basis of studies concerning salmonid audition, sound is unlikely to be useful for attracting or repelling fish at hydroelectric projects.

**Salient Research on Fish Hearing**

In summary, further research directed at salmonid hearing would yield little useful information to increase bypass efficiency at hydroelectric projects. Given the turbulent hydraulics at turbine intakes, we consider that using sound to divert outmigrating juveniles is unlikely to be successful.

**LIGHT AND VISION**

**CHARACTERISTICS OF LIGHT**

Light is characterized by both intensity and wavelength. The propagation of sunlight through water can be described by the equation

\[ I = I_0 e^{-kz} \]

where \( I \) = intensity at depth \( z \),
\( I_0 \) = surface intensity, and
\( k \) = an extinction coefficient.

The intensity of a point source light at distance \( r \) from the source can be approximated by the equation:

\[ I = \mu N_0 (r_0/r)^2 e^{-a(r-r_0)} \]

where \( a \) = volume absorption coefficient,
\( N_0 \) = surface radiance-per-unit-area, and
\( r_0 \) = the radius of the source.

The values of \( a \) for distilled water are 0.04 \((1/m)\) and 0.3 \((1/m)\) for Lake Pend Oreille water in the spring.

**UNITS OF MEASUREMENT**

Light intensity measurements generally integrate light over a specific range of wavelengths for a unit length of time and area of illumination. The result is an energy flux over a unit area. Table 1 provides a conversion for some of the common light measurements. Some are approximate because the energy content of light depends on wavelength, and different measures cover different ranges of wavelength. When characterizing the response of fish to light, the problem is further complicated because fish have different sensitivities to different wavelengths, and this spectral sensitivity is different from that of measuring instruments. Tables 1 and 2 describe the relationship of different measures of light and typical light levels.

**PHYSIOLOGY OF VISION**

As in most fish, salmon have paired, image-forming eyes. Accommodation is accomplished by moving the lens relative to the retina as opposed to altering the shape as in the case of human accommodation. Adaptation to various light intensities is mainly accom
Table 1. Conversions of different measurements

<table>
<thead>
<tr>
<th>Conversion</th>
<th>Value</th>
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<tr>
<td>10.76 lux = 1 footcandle</td>
<td></td>
</tr>
<tr>
<td>1000 lux = 1 lambert</td>
<td></td>
</tr>
<tr>
<td>1 lux = 1 lumens/m²</td>
<td></td>
</tr>
<tr>
<td>98 lux ~ 1 watt/m²</td>
<td></td>
</tr>
<tr>
<td>41 lux ~ 1 mE/m²/s</td>
<td></td>
</tr>
<tr>
<td>1 µEinstein = 6.02 x 10¹⁷ photons</td>
<td></td>
</tr>
<tr>
<td>1 mwatt/cm² = 1 watt/m²</td>
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</tr>
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Table 2. Intensities of different light sources

<table>
<thead>
<tr>
<th>Condition</th>
<th>Lux</th>
<th>Watt/m²</th>
<th>mE/m²/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sky at noon</td>
<td>81,667</td>
<td>834</td>
<td>~2000</td>
</tr>
<tr>
<td>Direct sunlight</td>
<td>5.19 x 10⁸</td>
<td>5.3 x 10⁶</td>
<td>~1.3 x 10⁷</td>
</tr>
<tr>
<td>Dusk-dawn</td>
<td>5</td>
<td>0.05</td>
<td>~0.1</td>
</tr>
<tr>
<td>Starlight</td>
<td>0.03</td>
<td>0.0003</td>
<td>~0.0007</td>
</tr>
<tr>
<td>Fluorescent lamp (40 watt)</td>
<td>2100</td>
<td>21</td>
<td>~51</td>
</tr>
<tr>
<td>Mercury lamp (100 watt)</td>
<td>9.4 x 10⁷</td>
<td>9.6 x 10⁵</td>
<td>~2.3 x 10⁶</td>
</tr>
</tbody>
</table>

plished by moving the outer segments of retinal receptors relative to the pigment layer (retinomotor response). The large number of rods (18 ± 2/100 µm⁻¹) and cones (14 ± 2/100 µm⁻¹) in all Oncorhynchus spp. shows that the eye is adapted for vision in both bright and dim light (Brett and Ali 1958). However, even under optimal conditions, maximum sight distance for most pelagic fish is probably well under 50 feet (15.2 m). Less than 75% of blue-green light is absorbed by the retinas of many marine fish, compared to 30% absorption in humans (Woodhead 1966).

LIGHT AND FISH ECOLOGY

Light levels and photoperiodism can affect the ecology of fish (feeding, shelter seeking, etc.). Photoperiodism may influence smolt timing through its action on the pituitary (Hoar 1953). Minnows, Phoxinus phoxinus (L.), are more active in general at night than during the day when cover is available (Jones 1956). When there is no cover, the activity pattern is reversed. This situation held when fish were tested individually or in groups, and with or without food. The minnows avoided light intensities >0.08-0.17 meter-candles (m-c), and shoaling behavior (dependent on vision) broke down from 0.0240-0.0034 m-c. Feeding (on Daphnia) efficiency was 90% at intensities >0.008 m-c, but decreased to 40% in total darkness (Jones 1956).

Changes in photoperiod can have long term effects on salmonids. When exposed to advanced photoperiod schedules in experimental raceways, juvenile steelhead trout (O.
mykiss) exhibited initiation of migratory movements and elevated gill Na\textsuperscript{+},K\textsuperscript{+}-adenosine triphosphatase activity (Na\textsuperscript{+},K\textsuperscript{+}-ATPase) 1 mo earlier than controls (Zaugg 1981).

Level of light intensity is not a good measure of whether fish can see each other well enough to maintain schools (Whitney 1969).

Feeding efficiency of "young" coho salmon (O. kisutch) on Daphnia began to decline at intensities of 0.01 footcandles and dropped logarithmically with light intensity to no feeding in total darkness (Brett and Groot 1963). Glare from light of 9000 footcandles did not have any impact on feeding.

Steelhead trout from upper river drainages of the Columbia River may respond to changes in photoperiod analogous to that of winter steelhead trout (Zaugg and Wagner 1973; Wagner 1974).

LIGHT AND MIGRATION

Juvenile Pacific salmon (Oncorhynchus spp.) appear to migrate out of their natal streams and rivers at night. However, the time during darkness that fish migrate varies. Pink (O. gorbuscha), chum (O. keta), coho (O. kisutch), spring chinook (O. tshawytscha), and sockeye salmon (O. nerka) fry released at the head of an impoundment migrated at night, primarily from 1.5 h after sunset to 1.5 h before sunrise, and their migration velocity was much faster than the average water velocity (MacKinnon and Brett 1955). Brett and Ali (1958) found that sockeye salmon smolt evening migration peaked between 1900 and 2100 h in the Lalese River, British Columbia. The downstream migration of chum, sockeye, pink, and coho salmon was initially nocturnal and was regulated closely by light intensity (approximately 0 footcandles); migration was most active 2-5 h after dark, decreasing until dawn (McDonald 1960). Downstream movement seemed to occur when fish lost visual reference to their surroundings.

While most juvenile salmonids outmigrate in the darkness, there are instances of migration during daylight. Lengthy migrations of pink and chum salmon can extend into daylight, and chum salmon migrations can occur during daylight under certain conditions like high flow (McDonald 1960). Durkin (1981) found most coho salmon outmigration was associated with daylight hours and increased from late March to mid-May.

Outmigrating sockeye salmon exhibit pulsed movements around dawn and especially dusk. The general hypothesis on the nature of sockeye salmon outmigration is: "Celestial phenomena are used in the time-compensated orientation of migrating sockeye which, by an unknown inherited mechanism, provides a direction appropriate to the particular escaped route from the lake" (Brett and Groot 1963). Because light reflects differentially off many things, it is a good way for salmon to navigate if there is no particulate interference (Brett and Groot 1963).

Nocturnal outmigration of juvenile salmonids is thought to be partially caused by loss of visual and contact stimuli at night, which decreases their rheotactic response intensity and leads to downstream migration (Hoar 1951; McDonald 1960). Atlantic salmon seem dependent on a light-dark cycle for timing their activity patterns (Varanelli and McCleave 1974). However, using chinook salmon (1.6 in [41.1 mm] mean TL) and bluegill (Lepomis macrochirus, 2.5 in [64.2 mm] mean TL) with high (1 X 10\textsuperscript{3} footcandles) and low (<1 X 10\textsuperscript{-4} footcandles) light intensities, Hanson and Jacobson (1985) found that visual cues did not play a significant role in the fish's orientation to water currents (0-0.08
fps [0-2.5 cm/s]). Thus the nighttime seaward migration of salmon was thought not to be initiated by a loss of ability to detect and respond to water currents at night. However, the velocities used in this study were extremely slow and are not necessarily indicative of the flow conditions found in a river or stream.

Experiments on two stocks of rainbow trout (above- and below-waterfall stocks) found that both stocks had similar responses to current in the light, but the below-falls stock showed more downstream movement in darkness than did the above-falls stock (Northcote 1981). In one study, chum salmon fry preferred bright light and moved into strong currents by day (Hoar 1953). Coho and Atlantic salmon, and steelhead trout defended territories during the day, and sought deeper water and became inactive at night; this behavior is believed to facilitate seaward movement.

Coho salmon smolts adapt rapidly to current (MacKinnon and Hoar 1953). Turbulence produced no changes in distribution of fish between light and dark sides of a tank in tests of smolts and fry of coho, pink, chum, and sockeye salmon, but the presence of rocks helped fish hold position more strongly (Hoar et al. 1957).

**Attraction and Repulsion to Light**

As with sound, light can attract or repel fish. In general, fish are more affected by pulsing (strobe) rather than continuous light (Brett and MacKinnon 1953; Craddock 1956; Patrick et al. 1985). Light intensity has been examined, and minimum intensity thresholds along with attraction/repulsion behaviors have been established. The level of light to which fish are adapted, the species studied, and the developmental stage of fish seem to be three key parameters affecting fish response to light.

The level of light to which fish are adapted affects response to light. Puckett and Anderson (1988) found for trout that if part of their environment was suddenly darkened, attraction to the remaining lighted region was strongest if the light level was the same as they were previously adapted to. Light levels dimmer or brighter than their previous surrounding produced weaker attraction. Sockeye left in darkness for 4 d before exposure to a 6300 footcandle light at night were almost completely light-adapted in 20-25 min; those acclimated to the 6300 footcandle light continuously for 4 d showed a slower adaptation of 55-60 min to sudden dark (Brett and Ali 1958).

A directional light (6 Volts, 50 candle power) 3.3-9.8 ft (1-3 m) deep, was found to attract *Lateolabrax japonicus* (catch was doubled) in a trap at night, especially if the lights were in strings and lit in succession (Sasaki 1959). In the Gulf of Mexico, coastal pelagic fish have been led away from obstructions such as oil rigs (1000-W mercury vapor lamps, Wickham 1973). Sequential leading with the lamps only worked if the lamps were <32 ft (10 m) apart. A drifting lamp led 5 tons (4.5 metric tons) of *Sardinella anchovia* 0.6 miles (1 km) before being captured (Wickham 1973). If fish went out of the lamp beam in either sequential or leading strategies, they were lost. Ten (400-W) underwater floodlights were tested at Jenkins Creek on outmigrating, 0-aged coho salmon, and an average of 81% of the fish were diverted by the lights at night (Craddock 1956). However, the author felt that the results might have been different if lights were left on all night.

Response to lights varies between species or stock studied and water velocity. Anderson and Nemeth (1987) observed differences in the behavior of coho and chinook salmon smolts to strobe lights in raceways. Freshwater (alewife; smelt, *Osmerus mordax*;
and gizzard shad, *Dorosacepedianum* and estuarine (white perch: *Morone americana*, spot: *Leiostomus xanthurus*, menhaden: *Brevoortia tyrannus*) fish all exhibited avoidance behavior to strobe lights, which varied with water velocity, flash rate, and acclimation of fish (Patrick et al. 1985). Gizzard shad showed strong avoidance to lighted runways at velocities ranging from 0.5-1.0 fps (0.15-0.32 m/s), less so at higher velocities. White perch were slightly attracted to lights at the higher velocities although, like the gizzard shad, they avoided other lighted conditions (Patrick et al. 1985). Hoar et al. (1957) found that coho salmon smolts were uniformly photonegative. When sockeye salmon smolts were suddenly exposed to light (150 footcandles), they displayed the most marked negative response compared to chum, coho or sockeye salmon fry or coho salmon smolts. At sudden exposure to 1000 footcandles, all species of smolts tested (coho, chum, pink, and sockeye salmon) were photonegative, as determined by a >50% negative response.

Fish response to light is known to change with developmental stage. Sensitivity to light was found to increase during smolting in both coho and sockeye salmon, as evidenced by their seeking cover or deeper water (Hoar et al. 1957). Kwain and MacCrimmon (1969) found that until rainbow trout were 7 mo old, there were no behavioral responses to overhead light. At 10 mo, light between 0.010 and 0.005 lux was the minimum threshold for response, but by 24 mo 0.005 lux could be discriminated from total darkness, but not 0.001 lux. When given a choice between light and dark sides of a tank, at intensities from 0-500 footcandles, pink and chum salmon fry (which school) were consistently photopositive whereas coho salmon fry were indifferent to light intensities >45 footcandles (Hoar et al. 1957). This behavior in coho salmon coincides with their rapid acaptation to current (MacKinnon and Hoar 1953) and to alarming stimuli (Hoar unpublished). At 1000 footcandles, all groups in the study were photonegative, as determined by a >50% negative response to sudden light. Sensitivity to light increased during smolting in both coho and sockeye salmon, which then retreated to deeper water or cover (Hoar et al. 1957).

**EFFECT OF LIGHT AT DAMS AND STRUCTURES**

Working at McNary Dam, Fields (1966) found that ten times more salmonid migrants (all species) were caught in surface traps when the lights were on than on dark nights; the subsurface catches were not decreased in these cases. In addition, no significant difference in total number or vertical distribution of migrants occurred in the six submerged nets on light or dark nights. This suggests that the experimental guiding lights in this study attracted and concentrated migrants from all directions and did not simply pull migrants from the turbine entrance. Fields also found that significantly larger numbers of downstream migrants were recovered from lighted emergency slots than dark slots, and this number did not increase when turbines were inoperative. Slots with 200-W lamps attracted fish best; however, migrants avoided brighter 1000-W lamps in swiftly flowing water. There was no interaction between lighting conditions in the forebay and that in the slots. Chinook salmon and steelhead trout were caught more in lighted slots but sockeye salmon showed no preference. Guidance was especially effective at McNary because fish were light acclimated as they passed through the powerhouse, and the “swim towards the light response” was in effect after they entered the turbines (Fields 1966).

Collins and Elling (1960) noted that adult chinook salmon and steelhead trout swim slower in dark channels than light channels but swim faster in dark fishways (<1 foot-
candle) than light (800 footcandles). The authors felt, however, that this was probably due to the laminar flow in the channels versus the turbulence of a fishway. In the same study, light-adapted adult steelhead trout exhibited a marked preference (80%) for dark channels over light, whereas chinook salmon showed no preference. In addition, rate of ascent of fishways in the dark compared favorably with ascent during the day.

Atlantic salmon and sea trout (anadromous brown trout, Salmo trutta) ascended a tunnel 7250 feet (2208 m) long, 20 feet (6.25 m) high and 18 feet (5.50 m) wide despite the lack of lights and the very low velocity (<0.92 fps [28 cm/s], Rogers and Cane 1979).

In experiments with glass tubes and/or chains suspended vertically in the path of downstream migrating sockeye salmon, the visual response to the chain clearly was the cue for stream orientation in low light, rather than deflection of current around an unseen obstacle (glass) (Brett and Groot 1963).

Adult spring chinook salmon passage through the Bonneville Dam, Washington, ladder was tested. During the lights-on condition at Washington Gate number one (two 150-W thallium iodide lights installed on the powerhouse wall directed through the trash and ice sluiceway) the exit to entry rate was 82%; at lights-off it was neutral. Sluicegate number one had a higher net entry during dark periods (Shew et al. 1984).

When exposed to various trashrack bar spacing at an average water velocity of 1.0 fps (32 cm/s) in an oval swim tank, juvenile chinook salmon exhibited changes in rheotaxic orientation and a hesitancy to pass through bar-spacing <5.9 in (15 cm), under light intensities of 14.0 and 1.0 X 10^-2 footcandles (Hanson and Li 1983).

A reduction to about one third of the expected catch of outmigrating salmon was achieved with either a continuous or flashing light. No difference was seen in the movement of trout through similar conditions (Brett and MacKinnon 1953).

Patrick (1981), studying gizzard shad, smelt, and alewife, found that in the absence of light, most diversion barriers were ineffective. The addition of a strobe light not only reduced fish passage but kept fish from the vicinity of barriers. These barrier/light combinations were effective at water velocities of 0.5 and 1.0 fps (0.15 and 0.32 m/s) and at strobe intensities of at least 10 lux. Shad sped up upon encountering the barrier, and passage was significantly higher in the dark. In contrast to shad, smelt displayed a high order of rheotaxis. In the presence of a strobe light, alewife appeared disoriented and often ran into the wall trying to escape. For all barrier types, passage increased by a factor of 2.4, with an increase in velocity from 0.5-1.0 fps (0.15-0.32 m/s). Generally, the fish showed no evidence of behavioral adaptation to the light over a 12-h period (Patrick 1981).

It is important to determine preferred wavelengths of fish around well-lit industrial structures, so fish are not inadvertently attracted to dangerous places (i.e., intakes, etc., Sager and Hocutt 1985). Zaugg (1981) felt that in order to compensate for the migratory inhibition induced by dams, hatchery smolts should be exposed to advanced photoperiods. In addition, flood lighting of streams changed sockeye salmon behavior, and also increased predation on the concentrated schooling fish (Brett and Groot 1963).

**TURBIDITY**

Turbidity levels on the Columbia River are variable, and the effect of turbidity on fish passage at hydroelectric projects is difficult to determine. Continuous monitoring of
turbidity levels at the entrance to bypass systems is unnecessary. However, turbidity in the river tends to increase during the spring runoff, and modifications of bypass parameters might be appropriate during these times.

UNITS OF MEASUREMENT

There are three different units for turbidity used in this paper: nephelometric turbidity units (NTU), formazin turbidity units (FTU), and mg/L (milligrams per liter). No standard conversion is available between NTU/FTU and mg/L. The conversion varies with particle size and type. For example, Gradall and Swenson (1982) used 2 μm diameter particle size, and the conversion for mg/L to FTU was: \( \text{mg/L} = 0.61 \times \text{FTU} + 0.16 \). Because the references for measuring NTU and FTU are different, a simple conversion for these units is not available.

FISH RESPONSE TO TURBIDITY

Fish do respond to turbidity, and this response is a result of a combination of sensory inputs. Vision and rheotaxis are probably the most important sensory modalities affecting turbidity response. The olfactory and acoustico-lateralis systems of fish are unaffected by turbidity (Brett and Groot 1963).

*Interspecific Responses*

There are interspecific differences in response to turbidity. Creek chubs (*Semotilus atromaculatus*) prefer highly turbid water (56.6 FTU) to moderately turbid water (5.8 FTU), while brook trout (*Salvelinus fontinalis*) show no preference (Gradall and Swenson 1982). In addition, schooling behavior of the creek chubs was not affected by the above turbidity levels.

*Turbidity Acclimation*

The turbidity that fish are acclimated to has an effect on the turbidity the fish will respond to. Juvenile coho salmon that were acclimated to clear water (<0.3 NTU) initially avoided water of 70 NTU (sublethal levels) and above, but this behavior ceased after about 5 min. Such behavior was thought to occur in response to maintaining visual contact with potential food items (Bisson and Bilby 1982). Juvenile coho salmon that were acclimated to slightly turbid (2-15 NTU) water initially avoided water of 100 NTU and above, but this behavior also ceased after about 5 min. In addition to this response, some fish exhibited a "fright huddle" by darting rapidly, hiding in corners, and huddling together at times, all within the turbid areas of the experimental tank. When the "fright huddle" behavior occurred, virtually all fish were involved (Bisson and Bilby 1982). The authors concluded that juvenile coho salmon may not avoid moderate turbidity increases over low background levels, but this could not be fully justified until fish could be tested in their native streams (Bisson and Bilby 1982).

*Chronic Responses*

High turbidity or surges of turbidity seems to correspond to outmigration, however, it is often difficult to differentiate between the effects of increased water velocity and turbid-
ity. McDonald (1960) found that the largest daytime catches of young migrant pink salmon were observed during periods of increased water velocity and turbidity. However, on the Kalum River, British Columbia, where the water is always turbid, the run is essentially constant over time despite water level fluctuations. Peaks in the outmigration of chinook and sockeye salmon from the middle reaches of the Susitna River in Alaska correlated with peaks of river flow and discharge of sediment (Hale 1987). McDonald (1960) found that the daily migration period of Pacific salmon was extended if waters were turbid, and migration continued in muddy waters. All of this suggests turbidity as a factor in fish migration and movement in general.

**Acute Responses**

There are also acute effects from both sudden changes in or high levels of turbidity. Juvenile coho salmon exhibit "alarm" responses to rapid increases in turbidity, whereby they hide in the gravel, swim sporadically or head downstream (Berg and Northcote 1985). High levels of turbidity increased the rate of downstream migration in juvenile chum salmon during the day (McDonald 1960; Noggle 1978). Lake trout (*Salvelinus namaycush*) have been shown to avoid turbid water (Swenson 1978). Raising the turbidity level above 30 NTU caused juvenile coho salmon to move closer to the substrate, decreased capture success and reaction distance to brine shrimp from 11.8 to 4.7 in (30 to 12 cm), deactivated dominance hierarchies, and discontinued territorial behavior (Berg and Northcote 1985). Brook trout (*S. fontinalis*) and creek chubs exhibited decreased use of fixed overhead cover, increased activity, and reduced association with the substrate in response to increased turbidity (Gradall and Swenson 1982). Juvenile coho salmon, when given a choice, prefer "moderately" turbid water, but exhibit no preference for "slightly" (10-20 NTU) turbid water (Bisson and Bilby 1982).

The findings of turbidity effects on fish are variable, however. Noggle (1978), found that juvenile coho salmon do not avoid suspended sediment concentrations that are normally found in nature. Turbidity can be lethal if levels are high enough, but turbidity levels found in nature rarely reach lethal levels (Herbert and Merkens 1961). Avoidance in juvenile coho salmon has been observed at 4000-8000 mg/L of sediment, which is above the 96-hour LC50 (lethal concentration to kill 50% of the fish in 96 h) for coho salmon (Noggle 1978). In the same study, fish preferred low to medium (0-2000 mg/L) levels of turbidity in a laboratory setting for short periods of time, and avoidance occurred at high concentrations (4000-8000 mg/L) of suspended sediment.

**WATER CURRENTS AND RHEOTAXIS**

The response of fish to water currents (rheotaxis) in conjunction with their swimming abilities seems to hold the most promise for understanding and improving FGE's at dams. The complex hydraulic environment found at the entrance to fish bypass systems should be characterized at each project and correlated with what is known about fish response to hydraulics and swimming ability.
PHYSIOLOGY OF SWIMMING

There are a few key words and concepts regarding fish swimming that must first be defined. Swimming experiments conducted on fish typically examine three types of swimming or swimming speeds: burst, critical, and sustained. Burst swimming speed is the maximum velocity a fish can swim for 15 sec or less, analogous to sprinting in humans. Burst swimming velocities consume tremendous amounts of energy. Puckett and Dill (1984) found that the metabolic rate (based on oxygen consumption) required for burst swimming was 40 times higher than that required for sustained swimming. Critical swimming velocity is determined by increasing water velocity in experimental flumes by a constant interval every 15 min and noting the velocity at which the subject becomes exhausted. And finally, sustained swimming is the velocity a fish can maintain for an hour or more without variation in performance, analogous to walking in humans.

Fish use about 10% of their total oxygen consumed to operate their gills; this percentage is probably less in small fish than large. In contrast, oxygen use for breathing is about 3% in humans (Lindsey 1978).

Fish have two functionally different types of muscles for swimming: dark or red muscle, and white muscle. Red fibres of fish muscle are thought to be involved in aerobic, slow swimming (Bone 1966; Hudson 1973; Webb 1975; Johnston et al. 1977), whereas white fibres are associated with anaerobic, burst or fast swimming in fish. Hudson (1973) found that the white muscle may be more involved with intermediate speeds than burst swimming.

Orientation in moving water (rheotropism) is accomplished mainly with visual and tactile sensation (Lyon 1905; Dijkgraaf 1962; Pavlov 1966) along with the lateral line system. Because of this, most teleost fish (especially the young) invariably have a lower critical velocity in darkness than in light. Rheotropism is thought to be maintained in fish by an optomotor reaction that is actually an unconditioned reflex movement as a function of moving reference points in the field of vision (Lyon 1905; Jones 1963; Pavlov 1966).

UNITS OF MEASUREMENT

Swimming velocity is usually expressed in body lengths per sec (bls), where body length is total length (length from tip of head to tip of tail, TL). Body lengths per sec are used in order to standardize velocities since the length of a fish governs its ability to swim. Sometimes swimming velocity is expressed as fork lengths per sec, fork length being the distance from the tip of the snout to the fork of the caudal fin.

Tail beat frequency is the number of beats the caudal fin of a fish makes per-unit-of-time. In general, lower tail beat frequencies for a given velocity are equated with increased swimming efficiency (Flagg and Smith 1981). Tail beat frequency increases linearly with swimming velocity for a given fish at a given temperature (Bainbridge 1958).

PHYSICAL CHARACTERISTICS OF WATER

Physical characteristics of water have an effect on fish swimming. Water viscosity is the dominant factor in larval fish locomotion with associated low Reynolds numbers. Water viscosity is 30% greater at 50°F (10°C) than at 68°F (20°C, Bematchez and Dodson 1985). For large fish, inertial forces of the water are the dominant factor; thus it is more
difficult to accelerate and easier to glide. With larval fish, acceleration is less difficult, but gliding is more difficult (Lindsey 1978). For example, smaller fish (about 4 in [10 cm] TL) can attain burst speeds of 25 lbs (at 57°F [14°C]), whereas larger fish (about 40 in [100 cm] TL) can reach 6 lbs (Wardle 1977). The power needed for propulsion equals the drag that the fish has to overcome, and fish morphology and locomotion are the main factors affecting drag (Webb 1975).

**Swimming Performance**

In addition to the physical constraints of living in a fluid medium, a number of other factors contribute significantly fish's ability to swim: temperature, size or age, species, stock, ecology/behavior, and physiological status (such as smolting). Vision and the lateral-line system of fish are the key sensory inputs for a fish's response to currents. However, we will first consider the basic swimming abilities of fish, and then discuss how the aforementioned variables affect swimming.

Many studies have determined swimming “performance” of various species of Pacific salmon at various temperatures and sizes of fish. For the most part, swimming speeds of 2-3 lbs can be achieved by most fish for some time (4 lbs for salmonids, Blaxter 1969).

A current of 3 feet per sec (fps, 0.9 m/s) was believed to be too rapid to permit trout fry to swim out of a deflection zone (Brett and MacKinnon 1953). Optimal velocity for chinook salmon (1.25-1.50 in TL) was concluded to be 1 fps (92% maintained this velocity for 10 min). Kerr (1953) stated: “Even though the salmon might be impinged on screens for short periods of time, they will still survive upon release,” and impingement for 10 min was not harmful.

Maximum burst speeds of are generally on the order of 10 lbs (Blaxter 1969). Rainbow trout had burst speeds of 10 lbs, steelhead trout 7-13 lbs, adult coho salmon 6-9 lbs, adult chinook salmon burst 7-11 lbs. Burst speeds in the rainbow and steelhead trout could only be maintained for 10-20 sec, after which it dropped to 4 lbs (Blaxter 1969). Coho salmon (1.9 in [48.3 mm] TL, 59°F [15°C]) reached burst swimming velocities of 1.4 fps (43.5 cm/s) or 9 lbs, and travelled an average distance of 7.4 in (18.8 cm) during the burst (Puckett and Dill 1984). Gray (1953, 1957) found that burst swimming velocities of coho salmon (mean TL of 3.7 in and 4.0 in [9.4 cm and 10.1 cm]) at 54-59°F (12°-15°C) were 4.5-5.0 fps (140-150 cm/s), or about 15 lbs.

Blaxter (1969) noted that sustained swimming speeds for sockeye and coho salmon were 3.0 and 3.4 lbs, respectively. Recovery of an exhausted coho salmon was estimated at 5 h (Blaxter 1969). Kerr (1953) found that 1.2- to 2.0-in (3- to 5-cm) TL spring chinook salmon could swim at 1.0- to 1.5-fps velocities for up to 10 min in a flume, but would continue swimming in 1.0- to 1.2-fps velocities for an hour or more.

Brown, brook, and lake trout, and Atlantic salmon (1.6-2.0 in [40-50 mm] TL) had critical velocities >1.6 fps (0.5 m/s [Brett et al. 1958]). “Approach velocities above dams which exceed 1.0 fps will cause increased difficulty in guiding young salmon into safe bypasses if more than 20 to 30 min elapse during which the fish are forced to stem the current. Fatigue from exceeding the cruising speed is likely to occur (65-71°F [18.5-21.5°C])” (Brett et al. 1958).

In addition to swimming performance, there is information of jumping performance in salmonids. Symons (1978) found that juvenile coho and Atlantic salmon could leap water
falls at least 5 body lengths in height. There were no seasonal changes in leaping behavior, but temperatures near optimal for the species produced maximum jumping heights.

FACTORS AFFECTING SWIMMING PERFORMANCE

Temperature

Temperature has a tremendous impact on a fish's swimming ability (Figs. 2 and 3). For any given species of fish, there is an optimum temperature for swimming. In general, 59°F (15°C) is considered the optimum temperature for most Pacific salmon (Beamish 1980). However, temperature optima vary for different activities (food digestion, swimming, etc.).

The best swimming temperature for sockeye salmon was 59°F (15°C) [5.1 bls]), and swimming ability dropped off greatly outside this temperature preferendum (Blaxter 1969). The optimum temperature for sustained swimming speed in yearling and subyearling coho salmon (3.5 and 2.1 in [8.9 and 5.4 cm] mean TL, respectively) was 68°F (20°C). Maximum sustained velocities at these temperatures were 1.0-1.5 fps (30-45 cm/s). Brett (1964) and Bernatchez and Dodson (1985) also found that the cost of swimming at high, sustained speeds was independent of temperature. Fry and Hart (1948) found that the sustained swimming speed of thermally adapted goldfish (Carassius auratus) at 41°F (5°C) was about 0.7 fps (0.2 m/s), rising rapidly to 1.7 fps (0.5 m/s) at 68°F (20°C), levelling out until 86°F (30°C), above which, swimming speed decreased to 1.25 fps (0.4 m/s) at 95°F (35°C). Fish acclimated at different temperatures also gave different curves for swimming speeds at specific temperatures.

Critical swimming speeds increased by 1.6 fps (0.5 m/s) for each 7°C increase in temperature for brown, brook, and lake trout, and Atlantic salmon fry (Brett et al. 1958). Once temperature optima are exceeded, however, critical swimming velocity presumably decreases (Fry and Hart 1948; Heggenes and Traaen 1988). Change in water temperature mainly affects critical swimming velocities by altering metabolic processes. However, oxygen content and water viscosity are also affected by water temperature, thus altering swimming ability (Pavlov et al. 1972). Temperature appears to have little effect on burst swimming speed (Blaxter 1969).

Rheotaxis and migratory behavior may be influenced by temperature. Hoar (1953) found that chum salmon fry swam with the current as temperature increased. He felt that this effect might be due to thyroid stimulation, which occurs when fish are held too long in freshwater (immersion of chum salmon in thyroxine significantly alters their swimming speed [Hoar 1953]). Pink salmon are assumed to exhibit the same response. Juvenile steelhead trout, when exposed to 55.4 °F (13°C) for 20 d experienced continued migratory behavior impairment and a decrease in gill Na⁺,K⁺-ATPase activity (Zaugg 1981). In experimental raceways, migrant summer steelhead trout exposed to 55.4°F (13°C) for 20 d exhibited serious impairment of migratory behavior and a reduction in gill Na⁺,K⁺-ATPase activity (Zaugg 1981). Higher water temperatures increased gill Na⁺,K⁺-ATPase activity and inhibited downstream migration of winter steelhead trout (Zaugg and Wagner 1973).
Figure 2. Effect of temperature on cruising speed of yearling and subyearling coho salmon, adjusted to common mean lengths of 3.5 and 2.1 in (8.9 and 5.4 cm), respectively (Brett et al. 1958).

Figure 3. Relationship between yearling and subyearling coho salmon cruising speeds as a function of TL at various temperatures. On the basis of the mean slope, cruising speed increasing about 0.1 fps (3 cm/s) for each 0.4 in (1 cm) increase in TL (Brett et al. 1958).
Fish Length and Maneuverability

The ability of fish to avoid a bypass screen or other structures is a function of their maneuverability as characterized by their turning radius. Webb (1983) found that the minimum turning radius for rainbow trout (10.1 in [25.7 cm] TL) was independent of speed and acceleration. Minimum turning radius was 0.18 ± 0.2 L. The equation R/L = 2V/AL predicts minimum turning radius where R is turning radius, L is fish length, V is velocity, and A is wet surface area. Maximum acceleration was found to be 262 fps² (80 m/s²), and maximum turning speeds were 8.2 fps (2.5 m/s) (Webb 1983).

Fish Length and Swimming Velocity

The length of a fish not only governs its ability to maneuver, but also its burst, sustained, and critical swimming speed, and time to exhaustion (Figs. 2 and 3). For juvenile coho salmon (4.4-8.3 in [111-212 mm], FL) swimming in a flume with a minimum velocity of 1.6 fps (0.5 m/s) (computed velocity based on flow was 3.4 fps [1.0 m/s]), the mean difference in mean FL of fish swimming after 15 h versus fish impinged in the first 15 min was 0.75 in (19.2 mm, Fields et al. 1954a). Therefore, fish still swimming after 15 h were, on average, 13.6% longer than those impinged within 15 min. When the velocity was increased to 4.0 fps (1.2 m/s) throughout the flume, fish (3.4-10.3 in [87-262 mm] FL) were all impinged within 15 min. Fish with mean FL of 4.2 in (108 mm) were swept out in 5 min, whereas those of 8.5 in (217 mm) mean FL were swept out within 12 min.

Fish Length and Migration Status

The size of fish may indicate their tendency to migrate. Larger coho salmon tend to migrate downstream before smaller individuals do in any given season, and larger coho salmon usually come from hatcheries, while the smaller fish are usually wild (Durkin 1981). Zaugg (1981) found more migrants than nonmigrants among juvenile steelhead trout with forks lengths ≥ 6.3 in (16 cm).

Cardiovascular and Muscular Efficiency

The “physical fitness” of a fish also affects its ability to swim. Coho salmon smolts from two different stocks were exercised at 0.2, 1.0, 1.5, and 2.0 body fork lengths/s and assessed for their swimming performance changes on the basis of swimming characteristics and critical velocities; the two stocks exhibited differences in their swimming endurance (Besner and Smith 1983). Endurance increased in the exercised fish compared to controls, and this increase in stamina was maintained after a period of rest for the fish. Long-term exercise in the laboratory also increased the strength of muscular contractions in the caudal peduncle of Alaska coho salmon stock (Besner and Smith 1983).

Nahhas et al. (1982) exercised rainbow trout (2.4-2.7 in [6-7 cm] TL) in flowing water at 0, 1.4, 2.2, and 3.5 bls for a period of 46 d. The group exercised at 3.5 bls exhibited an increase in swimming ability as measured by oxygen consumption and increase in white muscle mass. White muscle mass also increased at the 2.2-blis water velocity. Training at 3.5 bls increased time to fatigue by about 420% compared to fish exercised at lower velocities, which exhibited little or no improvement. Fish trained at 1.4, 2.2 and 3.5 bls had white/red muscle ratio increases of 4.7, 35.6, and 71.7%, respectively. The standard
metabolic rate of trained fish was higher than that of untrained fish, and trained fish had lower oxygen consumption rates than untrained fish. The oxygen consumption rates were not significantly different when the training velocity dropped below 1.4 bis (Nahhas et al. 1982). Training also increases the ability of fish to resist fatigue when confronted with sudden drastic changes in water velocity (Nahhas et al. 1982).

Exercising fish increases their stamina (ability to resist fatigue, Brett et al. 1958; Hammond and Hickman 1966) and critical swimming speed (Farlinger and Beamish 1978). Prolonged training has been shown to cause hypertrophy of the skeletal muscle in fish (Greer-Walker 1971; Greer-Walker and Pull 1973; Davison and Goldspink 1977; Davison and Goldspink 1978; Greer-Walker and Emerson 1978). Exercised coho salmon achieved a higher burst swimming velocity and fatigued slower than unexercised fish (Blaxter 1969). Coho salmon (2.6 in [6.7 cm] mean TL) exercised at 0.8 fps (24.4 cm/s) exhibited increased sustained swimming speeds and were less susceptible to fatigue than unexercised fish (Brett et al. 1958).

The implications of fish exercise is that hatchery-reared fish are not as "physically fit" as wild stocks; hence, compared to wild stocks, hatchery stocks are: less able to avoid high currents, exhibit decreased stamina in a given flow, and are generally less able to successfully navigate through a bypass system. When designing new, or modifying existing bypass systems, the decreased swimming abilities of hatchery raised fish must be accounted for.

Stock

Different stocks of fish have been shown to have different swimming abilities. Above falls stocks of rainbow trout were shown to have a more efficient lactate dehydrogenase (LDH)—that is, better at lactic acid conversion under acidic conditions—than the below falls stock (Northcote et al. 1970). According to Tsuyuki and Williscroft (1977), this better LDH confers greater swimming stamina for the above falls stocks to maintain their position. Taylor and Larkin (1986) studied two different populations of juvenile chinook salmon: those that migrate straight to sea in their first spring and those that reside in their natal streams for over a year. The latter group had more positive rheotactic responses and were more aggressive.

Smolt Stage

Predicting how fast and how long a juvenile salmon can swim is confounded by smolt stage (Fig. 4). Numerous physiological and endocrine changes associated with smolting affect fish behavior, swimming ability, ecology, etc. Elevated thyroxine (T₄) levels are associated with smoltification (Dickhoff et al. 1981). Zaugg (1981) found that coho salmon released in June and July, following an increase and subsequent decrease in gill Na⁺,K⁺-ATPase activity in a laboratory, began a rapid migration with elevated ATPase levels. Zaugg (1981) concluded steelhead trout actively migrating seaward possess elevated gill Na⁺,K⁺-ATPase levels. Giorgi et al. (1988) concluded that smolting juvenile chinook salmon have elevated gill Na⁺,K⁺-ATPase levels.

Pink, chum, coho, spring chinook, and sockeye salmon exhibit a remarkable reduction of swimming ability with the onset of smoltification (Fig. 4), with wild smolts collapsing at water velocities above 2 bls; this collapse does not seem to be due to fatigue (Thorpe and
Morgan 1978). Coho salmon smolts characteristically show an increase in tail beat frequency (TB) at any given velocity, which is assumed to be a result of decreased swimming stamina at smolting (Flagg and Smith 1981). This swimming deficiency disappears once the fish have fully smolted. The decrease in swimming proficiency at 4 bls based on increase in tailbeat frequency (from 275 to 390 TB/min) for coho smolts was 40%. During smoltification, coho salmon experience a decrease in swimming proficiency reflected in increased tail beat frequency that is hormonally induced (Flagg and Smith 1981).

**Secondary Effects of Smolting**

Smolt stage affects swimming secondarily via alterations in behavior (Fig. 4). During the parr-smolt transformation, fish become less bottom-oriented and more surface-oriented, exhibit more pelagic and active territorial behavior, have a migratory disposition, and perhaps school (Schreck 1981). In addition, smolting fish exhibit increases in general activity, drinking behavior, feeding behavior, and especially learning by motivational or appetitive means (Schreck 1981). Parr-smolt transformation turns a bottom-dwelling parr into a more pelagic-oriented, migrating smolt, and the decrease in swimming proficiency associated with this change may make the fish incapable of maintaining its position in the stream, thus giving an impetus for outmigration (Flagg and Smith 1981).

**THE RESPONSE OF FISH TO WATER CURRENTS**

As with light, water movement has been shown to affect fish behavior. Craddock (1956) found that greater currents attracted greater numbers of outmigrating fingerlings.
Andrew and Green (1960) suggest a minimum velocity for attraction of 3.9 fps (1.2 m/s). Surface turbulence was found to attract Atlantic salmon parr and protected them from predatory birds (Gibson and Power 1975). When exposed to a choice box with different water velocities in a laboratory, young coho salmon sought out lower velocities, although they preferred slow-moving water to that of still water, and they had no preference for up- or downstream portions of the apparatus when both areas had identical water velocity (Carney and Adkins 1955).

A behavior of juvenile salmonids that complicated behavioral studies is the tendency of the fish to seek zones of lower water velocity in both experimental and *in situ* situations (Brett 1965). Thus one cannot assume that outmigrating fish will seek high current velocities necessarily. Fausch and White (1981) suggested that salmonid seek low water velocity areas so as to minimize swimming energy, yet maintain close proximity to fast currents thus maximizing access to invertebrate drift. Juvenile coho salmon, and steelhead and cutthroat (*Salmo clarki clarki*) trout were observed to exhibit habitat preferences in a stream in terms of velocity and depth. Coho salmon generally stayed in pools with low current velocities, in line with usual feeding of surface invertebrates (Bisson et al. 1988). Steelhead trout were more tolerant of higher velocities and tended to be bottom feeders. Cutthroat trout had intermediate preferences. Kalleberg (1958) and Everest and Chapman (1972) observed that territoriality of salmon decreased as water velocity decreased in the laboratory. Fish living in weir basins (low flow rates) change position more frequently, occur at greater densities, and swim greater distances than fish residing in faster moving water; they also left their positions more often than the fish in running water (Heggberget and Heggberget 1986).

When given a choice, adult coho and chinook salmon, and steelhead trout preferred high velocity (4-8 fps [1.2-2.4 m/s]) over low (2-6 fps [0.6-1.8 m/s]) (Collins and Elling 1960). The chinook salmon preferred water that was too fast for them in some cases. Young coho salmon in a water velocity choice box did not maintain their positions in still water as much as they did in areas of some velocity, except when the only alternative was water moving 1.7 fps (0.5 m/s) or more (Carney and Adkins 1955). In addition, the fish tended to maintain their position in low velocity areas better when visual cues were present (i.e., light was on); velocity can also be a point of reference for maintaining position.

**MINIMUM VELOCITY THRESHOLDS**

A number of studies have determined the minimum water velocities fish are capable of detecting. Both blind and seeing fish face into a current (Gregory and Fields 1962). Low velocities detected in the lab could probably be pushed even lower in the field where vision could play a role. Young salmon migrants can discriminate water velocities much lower than those which must be maintained in order to not delay them at dams (Gregory and Fields 1962). In darkness, wild chinook salmon (mean TL 2.9 in [73.7 mm], water temperature 55-58°F [12.8-14.4°C]) could discriminate flows of 0.017 fps (0.52 cm/s). Unblinded hatchery coho salmon could discriminate 0.013 fps (0.39 cm/s) (mean TL 4.7 in [118.5 mm], water temperature 46°F [7.8°C]). The controlling factor in setting the velocity in a reservoir is not what the salmon can detect, but how much delay can be imposed (Gregory and Fields 1962). Hanson and Jacobson (1985) concluded that chinook salmon
are capable of detecting and responding to constant velocities <1.0 in/s (2.5 cm/s) under high and low light conditions.

several species of roach (Rutilus rutilus L., and R. rutilus capicus L.), sturgeon (Acipenser gilddensäti B., and A. stellatus P.), rudd (Scardinius erythrophthalmus L.), stone-loach (Nemachilus barbatulus L.), and perch (Perca fluviatilis) were tested to determine the effects of light intensity and water temperature on current velocities critical to fish. As reference points moved in their field of vision, the fish exhibited an optomotor response. Reduction of the number of visual reference points from 50 to 0 per 3.28 feet (1 m) in the path of the verkhovka (Leucaspius delineatus Heck.) caused a reduction of the critical velocities by 25% (Pavlov et al. 1972).

**SWIMMING BEHAVIOR AND ECOLOGY**

Swimming behavior of outmigrating fish can be affected dramatically by their ecology. Many studies show that fish compete for areas in streams and rivers where there are eddies in the current and swift-moving currents nearby. Therefore, fish in this behavioral stage may seek out slower moving water (i.e. any eddy in or near a bypass system) and try to feed or compete for space; they do this to optimize their growth rate while expending as little energy as possible doing so.

The relationship between specific growth rate and resources is hyperbolic and fixed by two key points: the resource threshold or maintenance level at which no growth occurs, and the maximum specific growth rate expressed at high resource levels. So a fish in optimal stream positions that give maximum energy gain should also grow at maximum specific rates (Fausch 1984). The energy available to fish as drift is a linear function of water velocity:

\[ E = m \cdot V \]

where \( E \) = the drift energy (calories per hour per square centimeter), and
\( m \) = the slope of the drift versus velocity relationship.

The available drift energy

\[ D = \frac{1}{8\pi r^2} a e^{-bx} \cdot V \]

is a function of fish body length (1/2r), distance downstream from the food source (x), and water velocity (V), the last being the maximum velocity within two body-length radii (Fausch 1984).

Dominant fish defending areas with the highest resource level had the highest specific growth rates, and the hierarchy of subordinates defending less desirable areas corresponded to their dominance ability (Fausch 1984). The salmonids in this experiment chose stream positions with respect to food supply, flow, and the dominance hierarchy. The author hypothesized that fish that compete best for the resources available to them are able to maximize potential profit and thus maximize fitness.
Prolonged swimming at rapid velocities can lead to stress and death in fish. Mortality due to swimming fatigue in smolting coho salmon from non-acute stress usually occurred at least 3 d following the stress induced by swimming fatigue (Flagg and Smith 1981).

CASE STUDIES

There have been numerous case studies that examined different types of “fish sorting” and diverting devices. We will briefly touch on some of these studies.

One type of metal conduit covering (resembling a cheese grater with the holes facing downstream) reduced flow near its surface, thus allowing fish to remain in the conduit longer (80% evacuation over 1 h compared to 5 min for fish exposed to a smooth bottom) (VanDerwalker 1970). The author noted that “Migration routes of juvenile salmon moving through an inclined conduit were influenced by flow patterns along the boundaries of the conduit.”

An underwater size separator at Little Goose Dam relied on two behaviors of smolt salmonids: orienting into a water flow and diving as an avoidance reaction. Water jets shooting up between separator pipes allowed smolts to swim downward into separate chambers as the gap between pipes increased (Gessel et al. 1985). Separator pipes were 0.87-in (22.2-mm) metal tubes covered with plastic. Space between separator pipes was 0.50-in (12.7-mm) in the first chamber and 1.25-in (31.7-mm) in the second.

When nets were compared based on number of migrants caught per cubic feet of water screened, surface nets caught 16 times more migrants at 8000 cfs and 11 times more at 12,000 cfs (Fields 1966).

Fish guiding screens with the greatest porosity (one layer of webbing) worked best (87% of migrants, dark conditions, velocity 5.9 fps [1.8 m/s]) (Marquette and Long 1971).

Field et al. (1954b) found that 3.3-in (85-mm) Pacific salmon exposed to a 1-min pulsed square wave direct current voltage of 1 Volt/cm (frequency 16 Hz, 35% duty cycle) were immobilized in 5-15 sec with no mortality. The fish-guiding efficiency of an electrical field generally decreased with increased water velocity. The use of electricity to guide juvenile trout and salmon may be feasible if water velocities do not exceed 1 fps (30 cm/s), but it does not appear practical for most streams (Pugh et al. 1970).

The lateral distribution of outmigrating pink and sockeye salmon was closely related to current speed above a threshold of 1.3 fps (0.4 m/s) (McDonald 1960).

TEMPERATURE

Pacific salmon are considered stenothermal and are intolerant of low temperatures in general. Spring chinook salmon are the least resistant to low temperatures of all Pacific salmon. Spring chinook and coho salmon have the greatest tolerance to high temperatures of all Pacific salmon (Brett 1952). The resistance time to a high temperature in salmon is lengthened by acclimation at a higher temperature, but a given temperature will still be lethal. None of the species of juvenile Pacific salmon can tolerate temperatures above 77.2°F (25.1°C) for 1 week (Brett 1952).

Brett (1952) determined the preferred temperature of juvenile Pacific salmon in laboratory aquaria. The preferred temperature of spring chinook salmon was 53.6-55.4°F (12-13°C) when acclimated to 68°F (20°C) (Brett 1952). Preferred temperature of coho,
sockeye, chum, and pink salmon was 53.6-57.2°F (12-14°C) when acclimated to 68°F (20°C).

One way of determining if stress is related to temperature is to measure plasma cortisol levels. Increased plasma cortisol levels is a primary response of vertebrates, including Pacific salmon, to stress (see reviews by Schreck 1981, 1982; Thomas et al. 1986). Out-migrating juvenile Pacific salmon are stressed from passage through fish guidance structures at hydroelectric projects. One measure of stress in fish is their blood cortisol levels: the higher the cortisol concentration the greater the stress level. Bjornn et al. (1984) found that mean plasma cortisol concentrations were usually below 10 ng/ml for undisturbed spring chinook at Eagle Creek National Fish Hatchery. After simulated bypass procedures, levels rose to 53-72 ng/ml. (Results were three- to fourfold smaller than seen at Snake River Dam [Congleton et al. 1984]).

TEMPERATURES ENCOUNTERED IN MAINSTEM COLUMBIA

The range of temperatures encountered in the Columbia River, especially by distant upriver migrating smolts, is believed to pose a threat to the immigrants (Zaugg 1981). Temperatures at Bonneville Dam are usually 54°F (12°C) by mid-May (5/5/73 and 4/28/77), but these temperatures can occur earlier during years of low water flow (Zaugg 1981). In addition, thermal gradients exist in the forebays of hydroelectric projects on the Columbia, and there may be some correlation between temperature and FGE. At McNary Dam, temperature levels were inversely related to the theoretical estimate of FGE from the vertical distribution. Higher surface water temperatures during the later period of the study may have caused the deeper distribution of salmon observed (Swan and Krcma 1984).

RATES OF TEMPERATURE CHANGE

Rates of temperature change are of concern for salmon, and outmigrating juveniles are certain to experience temperature changes as they pass through a project. In general, fish have specific temperature preferendum for different physiological processes, but out-migrating salmonids cannot control their temperature by moving into different temperature environments as they move through a dam: the bypass systems limit the range of temperatures available to the salmon.

Various studies have established ranges of temperature extremes that juvenile Pacific salmon can tolerate (Fig. 5). Figure 5 gives a guideline for the maximum instantaneous change, and the minimum/maximum temperatures tolerable for any period of time for chinook and coho salmon. For example, if a coho is acclimated to 37°F (3°C), that fish could withstand an instantaneous temperature increase to about 73°F (23°C). Conversely, if acclimated to 73°F (23°C), the fish could withstand a decrease to 37°F (3°C). It is important, however, to point out that these temperature changes can certainly affect behavior, swimming velocity, stress levels, etc. In general chinook and coho thermal tolerances are similar: no significant difference exists in their response to upper lethal temperature levels when acclimated to 50°F (10°C) and above (Brett 1952). Juvenile chinook salmon (1.25-1.50 in [31.75-38.10 mm] TL) can withstand instantaneous temperature changes of 25°F (no mortality over next 24 h), and maximum temperature tolerance is 83°F (28.3°C) (Kerr 1953). Juvenile spring chinook salmon (.6-2.0 in [4-5 cm] TL, about 0.035 oz [about one
Acclimation temperature and the change in temperature that is not lethal for coho and chinook salmon (Brett 1956).

On a long-term scale, young spring chinook salmon have been cultured successfully at 75.2°F (24°C), and can survive at that temperature for 1 week. Age-0 and age-2 presmolt coho salmon can withstand a 41-73.4°F (5-23°C) temperature cycle. Age-0 and age-2 presmolt coho salmon starved for 22 d did not die over a 19-d exposure to diel temperature fluctuations of 43.7-68.0°F (6.5-20°C), nor did they exhibit common symptoms of stress such as flashing, disorientation or gasping at the surface (Thomas et al. 1986). Age-0 and age-1 presmolt coho salmon exposed to various temperature fluctuations had no significant difference in mortality or growth. However, there may have been chronic stress during the 19-d study as evidenced by slightly elevated plasma cortisol (Thomas et al. 1986).

**LETHAL TEMPERATURES**

Death can be caused either by extreme temperatures (high or low) or by extreme temperature changes. In a laboratory, fish will swim into lethal temperatures to feed or in response to the stimulus that feeding was about to commence (Brett 1952); however, fish will not expose themselves to lethal temperature changes for a time period sufficient to cause mortality. Lethal temperature for young spring chinook salmon in culture was 77.2°F (25.1°C), and 77.0°F (25.0°C) for coho salmon (Brett 1952). Age-0 and age-2
presmolt coho salmon acclimated to 51.8°F (11°C) water exhibited LT50 (lethal temperature at which 50% of subjects died) at 75.2°F (24°C), while those acclimated to 50-55.4°F (10-13°C) cycle showed LT50 at 82.4°F (28°C) for age-0, and 78.8°F (26°C) for pre-smolts (Thomas et al. 1986). No age-0 and age-2 presmolt coho salmon survived a 35.6-84.2°F (2°C-29°C) cycle (Thomas et al. 1986). Age-0 and age-2 presmolt coho salmon did not die from thermal stress until diel temperature fluctuations were 39.2-77°F (4-25°C) (Thomas et al. 1986).

**FACTORS AFFECTING TEMPERATURE TOLERANCE**

*Acclimation Temperature*

Acclimation temperature has an effect on temperature tolerance in salmonids. Three- to 5-mo post-hatch spring chinook and coho salmon were most resistant to high temperatures when acclimated between 41-75°F (5-24°C) (Brett 1952). Acclimation to a given temperature is a function of metabolic rate, with acclimation rates being slowest at low temperatures and fastest at higher temperatures (Brett 1946).

*Fish Size/age*

There are size differences that must be taken into account when determining a fish’s ability to withstand temperature changes and extremes. The size of the Pacific salmon does not seem to affect heat tolerance, but it is a factor for cold tolerance (Brett 1952). Smaller fish die more often than larger fish at lower temperatures (Brett 1952). In the same study, there were two different rates of mortality for the cold-tolerance determinations, with a considerable delay to the second wave of mortality.

**CONCLUSIONS**

In order to design fish bypass systems, an underlying understanding of fish behavior is important. Fish bypass systems to date have largely been designed with little emphasis on the interaction of fish behavior and guidance systems. This literature review considered five aspects of fish behavior that could significantly affect fish guidance efficiency: hearing, vision, turbidity, rheotaxis, and temperature. There are several key issues to consider for each of these aspects when designing fish bypass systems.

The key characteristics of fish hearing and sound to consider are as follows. A sound stimulus must be within the frequency range of juvenile salmon hearing and have a sufficient sound pressure level (SPL) in order to be audible. In addition, the SPL must be at least 24 dB above ambient noise. Finally, pulsed or random bursts of sound are more effective at eliciting a response in fish compared to continuous sound. Sound generally will not alter fish behavior for long periods of time.

Pacific salmon can certainly see under starlight conditions (0.03 lux). It is important to consider the equations for light propagation in this review when designing light attraction/diversion systems. Fish subject to diversion must have adequate time and distance to respond to lights; this is a function of propagation, source intensity, and water velocity. Like sound, pulsed rather than continuous light is more effective at altering fish behavior.
Turbidity affects fish reaction and perception by altering visual acuity and rheotaxis. The level of turbidity must be considered for light propagation, range of vision, and response to currents. Salmon can respond rapidly to sudden changes in turbidity. While it is unlikely salmon will encounter lethal levels of turbidity at dams, it is possible they will encounter changes in turbidity that could slow their swimming rate or depth in the water column.

Of all the topics covered in this review, rheotaxis and water currents are the most important for successful fish bypass. Maximum burst swimming speeds for a 4-in (10-cm) pre- or post-smolt juvenile salmon would be 3.3-4.9 fps (100-150 cm/s). Water velocities above this at a bypass intake will certainly exceed the fish's swimming capacity. However, smolting fish often fatigue rapidly above 2 bls or 0.67 fps (20 cm/s) for a 4-in fish. Where fish fatigue is a concern, a “safe” maximum water velocity to target in fish bypass systems is 1 bls or 0.33 fps (10 cm/s) for a 4-in (10-cm) fish.

Temperature, like turbidity has an effect on the other topics considered in this review. As for sudden temperature changes, a general rule of thumb is that fish acclimated to 41°F (5°C) can be immediately exposed to up to 68°F (20°C [and vice versa]) without mortality. However, it is important to point out that temperature changes will induce stress in fish, and the amount of stress is not easily predicted. Thus sudden temperature changes should be avoided in a bypass system. In general, 59°F (15°C) is an optimum swimming temperature for Pacific salmon. Temperatures above 73°F (23°C) and below 37°F (3°C) are usually lethal for any period of exposure.

For all five topics discussed in these review, it is important to remember that fish behavior is highly variable even for a given fish in a given scenario. Pacific salmon have complex life histories and their perception and response to sound, light, turbidity, water currents, and temperature does change with their developmental stage. In addition, steelhead trout, and coho and chinook salmon are the three predominant species to consider for fish bypass on the Columbia River. These three different species react differently to stimuli in their environment. These general considerations are paramount in designing efficient fish bypass systems.
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Hanson, C.H., and E. Jacobson. 1985. Orientation of juvenile chinook salmon, Oncorhynchus tshawytscha and bluegill, Lepomis macrochirus, to low water velocities under high and low light levels. Calif. Fish Game Notes:110-113


COLLECTED BIBLIOGRAPHY FOR REVIEW OF FISH BEHAVIOR RELEVANT TO FISH GUIDANCE SYSTEMS

GENERAL BEHAVIOR


Fourteen species of freshwater fish were trained to execute a simple conditioned response in a shuttle box - to move in response to light to avoid an electrical shock. There was no relation between learning ability and phylogenetic position. Better learners included striped bass (Morone saxatilis), bigmouth buffalo (Ictiobus cyprinellus), common carp (Cyprinus carpio), and channel catfish (Ictalurus punctatus). Bluegill (Lepomis macrochirus) and northern pike (Esox lucius) were poor learners. Yellow perch (Perca flavescens) and redbelly tilapia (Tilapia zilli) could not be trained. Some fish retained their learned behavior for months, although performance deteriorated with time. Older channel catfish learned better than juveniles, but there was no difference between juvenile and older largemouth bass (Micropterus salmoides).


Larval Atlantic herring, C. harengus harengus L., are known to change their vertical distribution by day and night. Two experiments were designed to test whether herring larvae would respond to imposed pressure changes by making appropriate compensatory vertical movements and whether such ability could be related to the development of the bulla system (stage I, bulla absent; stage II, bulla liquid-filled; stage III, bulla gas-filled). In the first experiment, pairs of larvae were exposed to a fixed sequence of pressure changes (ΔP) ±13 cm H2O to ±66 cm H2O. Members of simultaneously tested pairs tended to be influenced by one another when responding to pressure change. A second experiment tested the response of individual larvae to randomized sequences of pressure changes. Stage-III larvae moved most frequently to compensate for the pressure changes, but stage-I and stage-II larvae also responded to changes in pressure. Both experiments show that herring larvae of all three stages compensate for applied pressure changes by moving up when pressure is increased and down when it is decreased, but that they rarely move sufficiently far in the vertical plane to full compensate.


To study the factors influencing S. salar fry survival in the Sainte-Anne-des-Monts River and to learn more about the dispersion of planted fish, experimental fry stockings have been done from 1973 to 1987. The fry were planted at an initial density of 160 * 100 m^-2. Variable losses (28-95%) occurred during the 40 to 80 days after stocking. River water temperature and fry weight have been identified as important factors affecting survival at this stage. From then on to one year old parr, mortality rates are less variable (69-99%), being function of parr population density during their first summer of life. Fry and parr did not tend to disperse extensively so that maximum dispersion should be given at stocking time in order that all available habitat is utilized. Fry should be released, in this river, at a density of 40-60 * 100 m^-2 to avoid heavy undue losses and at water temperature about 10°C.


Coho, O. kisutch, length measurements reveal large individuals tend to migrate downstream first and small individuals later. Based upon size most Columbia River coho smolts are hatchery rather than natural spawning origin. The principal
prey organisms utilized by smolts appear to be insects in the river, amphipods in the middle estuary, and amphipods with marine organisms near the mouth. Timed release experiments show rates of coho downstream movement increased from late March to mid-May. The results of beach seine catches suggest most migratory movement is associated with daylight. Marked coho recoveries within the estuary indicate an association with water exceeding 4 m depth and the absence of a distinct migratory route through the estuary.


Juvenile Atlantic salmon, Salmo salar, changed their foraging strategy markedly after a brief exposure to a model trout predator, in ways that reduced their conspicuousness and hence risk of being preyed upon. After seeing the predator, the salmon were less likely to orientate to passing food particles, and having orientated, were less likely to attack them. They also reduced the extent of their movements, by only attacking those food particles that came close to them, and by delaying attacks until the food had reached its closest point.

GENERAL ECOLOGY


Coho, salmon (Oncorhynchus kisutch) eggs were incubated and fry were reared at ambient and elevated temperatures to determine at what stage an increase in rate of growth became apparent, and whether faster growth rate was sustained after the fry were returned to ambient temperature. It was found that a significant increase in developmental rate at 15.6°C was apparent even at the hatching stage and that in general increased growth was positively correlated with cumulative°days and that growth rate after the temperature was lowered was not sustained, a possible exception being provided by fish which had been accelerated up to hatching.


Early research efforts begun in the 1950s and continued to the present to address the problems of environmental degradation on anadromous fish were centered mainly on fish behavioral work designed to provide solutions to fish passage problems. Information leading to solutions to passage problems for both adult and juvenile salmonids caused by dams and impoundments in the Columbia River was the highest priority of this research. Research on various fisheries enhancement measures was also begun in the late 1960s to increase production of Columbia River salmon. The main conclusions, remedial actions recommended and future research needs that were derived from this research are summarized.


Changes in common indices of parr--smolt transformation were compared with the timing of outmigration of juvenile steelhead trout (Salmo gairdneri) from Cole Rivers Hatchery on the Rogue River, Oregon. Numbers of fish with silver coloration became maximal before the time of maximum migration. Nearly 80% of the migrating fish were entirely silvery (smolts) throughout the migration period, suggesting that silverying was associated with the migration process. Gill Na+,K+-ATPase activity reached a peak in non-migrant fish nearly 2 weeks before a peak in migrant fish was reached. Neither silverying nor gill Na+,K+-ATPase activity correlated well with maximum migration. Results suggested a number of physiological changes which occur in steelhead trout in the spring do not occur coincident with the onset of migration tendency.


Brown trout (Salmo trutta), Atlantic salmon (Salmo salar), brook trout (Salvelinus fontinalis) and lake trout (Salvelinus namaycush) fry entering the free-feeding stage, were tested for overhead cover preferences in stream channels at different temperatures and water velocities. Atlantic salmon showed strong preferences for overhead cover, brown trout moderate preferences, whereas lake trout had preferences only at high temperatures, i.e. 12.4-19.2°C. Brook trout showed no cover preferences. Temperature influenced cover preferences of Atlantic salmon and brown trout considerably. The fry tended to seek more cover at low temperatures, i.e. 6.0-8.3°C.


Summer and winter habitat utilized by age-0 spring chinook salmon Oncorhynchus tshawytscha was assessed in the Red River, an Idaho stream heavily embedded with fine sediment. During summer 1985, chinook salmon used habitats with water velocities less than 20 cm/s, depths of 20-80 cm, and close associations with cover (undercut banks). Densities were greater than 60 fish/100 m². As the fish became larger they selected faster, deeper water. Eighty percent of the chinook salmon emigrated from the study sites in October when stream temperatures were 4-8°C, apparently because suitable winter habitat was not available.


**Light and Vision**


The behavior of juvenile herring (Clupea harengus L.) feeding on Artemia sp. nauplii in both light and dark was recorded using an infra-red-sensitive television-recording technique. In the light, two modes of feeding were observed, particle biting and filtering, but in the dark only filtering was observed. Marked differences in swimming behavior were seen between light and dark. In the light, the fish continued to school while feeding in both modes; in the dark, the school dispersed, the fish swam slower in tight circular paths and fed only by filtering. In the dark filtering fish swam faster (0.11 m s\(^{-1}\)) than non-filtering fish (0.07 m s\(^{-1}\)). In the light, no difference in speed was measured between filtering and non-filtering fish (0.34 m s\(^{-1}\)). Owing to the lower filtering speeds in the dark, the removal rate of nauplii from the water was much lower than in light.


Vision is vital for feeding of many near-surface teleosts. The visual threshold for feeding of about 0.1 lux is similar to the light intensity at which dark-adaptations of the retina takes place. The time available for feeding per 24-h day depends greatly on the seasonal changes of day length in high latitudes. In light-adapted fish, feeding efficiency depends on the shape and size of the visual field, the distance covered during searching, the feeding drive, and on characteristics of the prey such as its size, conspicuousness, and density. The visual axis, acuity, and contrast perception of predators are discussed together with camouflage of prey and the reaction distances for prey perception and volumes searched while feeding. Information on volumes searched per unit time and visual thresholds allows an estimate to be made of volume of water searched for food per 24-h day. This gives some insight into whether available prey biomass is adequate to support the predator population.


The stress responses of migrating smolts of chinook salmon *Oncorhynchus tshawytscha* and steelhead *Oncorhynchus mykiss* (formerly *Salmo gairdneri*) to passage through three flumes (small baffled, large baffled, and unbaffled with corrugations) were determined by assaying plasma cortisol concentrations before and after fish passed through each flume. Flume design significantly affected post-passage cortisol concentrations in steelhead but not in chinook salmon smolts; concentrations were lowest in steelhead smolts that passed through the corrugated flume. In daytime tests, cortisol concentrations were significantly lower in chinook salmon smolts that passed through completely darkened flumes than in those that passed through partly darkened flumes. The cortisol response (post-passage minus pre-passage concentration) of both species to passage through darkened flumes was smaller in day tests than in night tests.


Hanson, C.H., and E. Jacobson. 1985. Orientation of juvenile chinook salmon, Oncorhynchus tshawytscha and bluegill, Lepomis macrochirus, to low water velocities under high and low light levels. Calif. Fish Game. 71(2):110-113

A series of experiments was conducted to determine the influence of light intensity on the orientation response of juvenile chinook salmon, Oncorhynchus tshawytscha , to low water velocities. The orientation response of juvenile bluegill sunfish, Lepomis macrochirus , was also determined for comparison with the orientation response of juvenile chinook salmon. Bluegill were chosen for comparison since they are so ecologically different in their habitat preferences and, presumably, their behavioral response to low-velocity water currents.


In an experiment designed to test color constancy, goldfish were trained to approach a particular color within a richly colored but variable "Mondrian" background. They retained the ability to identify colors accurately even when the spectral composition of the illuminant was radically altered in generalization tests. Since the behavior of fish resembles that of human beings in these tests, Land's retinex theory seems to apply to a relatively primitive vertebrate as well as to humans.

Six experiments were conducted for five kinds of marine fishes to clarify the possibilities of using a 'frame screen' to provoke rounding movements of fish and of using it in the sea to concentrate fish for fishing purposes. The frame screen, which was made from a wire cylinder of diameter 1.2 m and height 0.8 m was set in the center of a pond and rotated at about 40 cm/s by hand. Two experimental ponds were used one was an outdoor pond (4 x 5 x 1.2 m) and another, an indoor pond (1.5 x 1.5 x 0.5 m). When the size of the pond was larger than that of the screen, the screen gained successful effects for oval filefish, Novodon medestus, and parrot bass, Oplegnathus fasciatus. For sardine, Sardinops melanosticta, anchovy, Engraulis japonica and mackerel, Pneumatophorus japonicus japonicus, it showed no effects. When the pond was not much larger than the screen, the screen was effective with anchovy.


Both ayu (Plecoglossus altivelis) and pale chub (Zacco platypus) lay their eggs on spawning beds in rivers with similar conditions of water flow and bottom sediments, the former migrating down-stream after hatching and the latter remaining in the river after emergence from the spawning bed. To find an explanation for these different behavior patterns, the eyes and neuromasts of the larvae were morphologically examined. At hatching, the larval ayu already have morphological well-developed free neuromasts with cupula and eyes with pure cone retina, while the larval pale chub have no developed sensory organs. After hatching, the eyes and neuromasts of the chub develop fast, and after exposure to water flow at 4 days old, the sensory organs are developed almost as well as those of ayu. Both sensory organs of the two larvae are considered sufficiently functional to enable the larva to respond to water flow visually and mechanically. It is therefore suggested that there might be an active behavioral process governing the downward migration of the ayu, such as choice of downward water flow or active downward swimming.


Rods have been reported to develop later than cones in the retina of many teleosts, increasing its sensitivity and leading to change in the visual behavior of the fish. The change in the visual threshold in ayu, Plecoglossus altivelis, with the development of rods is reported. Development of the retina with growth was examined histologically, and visual thresholds were determined by the light intensity at the extinction of rheotaxis. Rods appeared in the retina of 19-day-old larvae first, and increased in number afterward. The visual thresholds for 14, 22, 43, 74 day-old ayu were 7 x 10⁻¹, 7 x 10⁻¹, 1.2 x 10⁻² and 8.4 x 10⁻⁴ lux respectively. An inverse relationship was seen between the visual threshold and the development of rods with age in this species.


The efficacy of a strobe light and a combined strobe light/bubble curtain system was evaluated under turbid water conditions as a fish avoidance scheme. Three estuarine species commonly impinged at electric generating facilities along the Atlantic coast of the United States were tested: Atlantic menhaden (Brevoortia tyrannus), spot (Leiostomus xanthurus), and white perch (Morone americana). The strobe light/bubble curtain combination was the most effective system studied in all cases. An interesting phenomenon was that fish avoidance to strobe light systems increased with turbidity over the range tested (clear, 39-45 and 102-138 NTU).


Manipulations of the duration and direction of light did not substantially alter the movement or emergence behavior patterns of embryonic rainbow trout Salmo gairdneri within artificial substrate redds. Phototactic responses do not appear to control embryonic rainbow trout behavior. Movement and emergence patterns are suggested to be primarily due to geotactic behavior.


The responses of selected freshwater (Alosa pseudoharengus, Osmerus mordax, Dorosoma cepedianum) and estuarine (Morone americana, Leiostomus xanthurus, Brevoortia tyrannus) species to air bubbles alone, strobe light alone, and a combined strobe light/air-bubble barrier were investigated under laboratory conditions. Gizzard shad, alewife and smelt avoided an air-bubble barrier. Avoidance response varied with air-bubble spacing and illumination. All species tested exhibited avoidance behavior to strobe lights, which varied with current velocity, strobe flash rate, and acclimation of fish. Increased avoidance was evident for most species when strobe lights were combined with air bubbles as an exclusion barrier.


Evidence is presented supporting the idea that the human visual system has several specific sensitivities to different kinds of relative motion. These specific sensitivities include: sensitivity to a velocity difference between two different points A
and B on one eye's retinal image, the two velocities being directed along the line AB; sensitivity to the velocity difference at A and B between velocity components perpendicular to the line AB (i.e., shearing motion); sensitivity to rotary motion; sensitivity to the ratio between the velocities of the left and right retinal images of an object that is moving in depth. These specific sensitivities can be attributed to relatively hardwired neural filters that are "tuned" to different retinal image correlates of the three-dimensional structure and motion of solid objects in the environment. Such filters may be of use in distinguishing rigid non-rotating objects from nonrigid or rotating objects. They may also be of use in recovering information from the two-dimensional retinal image, including information about object boundaries, the three-dimensional structure of the environment, self-motion and object motion in depth. An alternative way of regarding certain of these specific sensitivities is that they might provide rough physiological equivalents of the values of div V and curl V at every point in the instantaneous velocity field of the retinal image and thus crudely analyze the retinal image flow pattern in terms of mathematical quantities that have the useful property of being relatively invariant against bodily translations of the whole retinal image caused by eye rotation.


Activity rhythms and light intensity preferences of largemouth (M. salmoides) and smallmouth (M. dolomieu) black basses were investigated in laboratory experiments designed to elucidate aspects of niche separation between these sympatric congeners. Both species exhibited crepuscular activity, but M. salmoides also showed a mid-day activity peak. M. dolomieu avoided bright light, and their peak activity periods occurred at the beginning and end of the dark periods. Activity of M. salmoides was much more depressed during the dark periods, and rose sharply at the onset of light periods. Activity records in constant light conditions showed these activity rhythms to be endogenous.


Recordings were made of cardiac and ventilatory responses of goldfish to the onset of 10 sec illumination presented at 2 min intervals. These responses were measured by increases in cardiac interbeat interval, ventilatory interbreath interval and by reductions in ventilatory amplitude. Four groups of fish were subjected to intensities of 52, 78, 90 and 160 lux. It was found that the more intense the stimulus the greater was the magnitude of the initial physiological response and correlated with this the number of stimulus presentations required for habituation. The relationship between stimulus intensity, initial response magnitude and resistance to habituation was consistent for cardiac responses.


This study examined strobe lights and strobe light/bubble-curtain combinations as behavioral guidance systems for estuarine fish. White perch (Morone americana), spot (Leostomus xanthurus) and Atlantic menhaden (Brevoortia tyrannus) were tested in a behavior experimental tank for avoidance to strobe lights, bubble curtains and strobe light/bubble-curtain combinations at different water flow rates, strobe flash frequencies and light acclimations. Avoidance of strobe light ranged from 8 to 36% for white perch, 8 to 100% for spot and 8 to 68% for menhaden. Chi-square analyses indicated significant avoidance rates by the three species at varying flash rates and flow rates. All species showed little avoidance of bubble curtains. Avoidances of 3-58% for white perch, 21-85% for spot and 9-81% for menhaden were obtained with the strobe light/bubble-curtain combinations. Chi squared analyses indicated avoidance rates for the three species at varying flow rates and conditions. The strobe light and strobe light/bubble-curtain combinations elicited best avoidance results at flash rates of 300/min or greater and low flow rates. Strobe lights show promise as a guidance system for estuarine fish.


A group of 18 young chinook salmon *Oncorhynchus tshawytscha*, trained to orientate in the direction 270 degree, showed a unimodal orientation of 264 degree and a mean bimodal axis of orientation of 25 degree /078 degree (magnetic) within confidence limits of 218 degree arrow right 285 degree: 0.38 degree arrow right 105 degree when tested under controlled conditions in Auckland. Two year later 12 of these fish were transferred to a new test area in Christchurch, south (7 degree latitude) of the original location, for individual re-testing at night in a light-proof room and also in sunlight in the absence of "local" Auckland cues/clues. These fish had been kept in artificial light but six fish were exposed to sunlight in Auckland 2 weeks before moving to Christchurch. At night each fish showed consistent non-random orientation and nine out of 10 fish showed a mean bimodal orientation that fell within the confidence limit established in Auckland the mean of means axis of orientation for 10 fish was 270 degree /090 degree. In sunlight each individual fish showed a consistent, non-random mean bimodal orientation that fell outside the confidence limits established in Auckland and, at night, in Christchurch. The principal findings in this study are given.


**M I G R A T I O N**


The hypothesis that juvenile anadromous salmonids which are migrating to sea have higher levels of gill [Na+ K+] ATPase activity than nonmigrants was examined for wild and hatchery spring and fall chinook salmon (O. tshawytscha) from the Rogue River, Oregon [USA]. Although migrant juvenile chinook salmon captured at river km 173 had elevated gill (Na+ K+)- ATPase activity, migration from the more upstream portions of the Rogue River occurred without significant changes in gill (Na+ K+)- ATPase activity. High water flows stimulated migration without increasing gill (Na+ K+)- ATPase activity. Tributary-to-main-stem migration of juvenile fall chinook salmon did not result in elevated gill (Na+ K+)- ATPase activities. Juvenile spring chinook salmon released from Cole Rivers Hatchery (km 254) migrated rapidly to km 18 on the Rogue River without changes in gill (Na+ K+)- ATPase activity. Although the relationship between seaward migration and elevated gill (Na+ K+)- ATPase activity is demonstrable in chinook salmon in many cases, such elevated ATPase activity may not be a prerequisite for seaward movement of juvenile chinook salmon.


During the spring of 1980, a total of 21 spring chinook salmon and steelhead smolts were tagged with the new miniature tags, released into the Columbia River about 6 miles upstream from John Day Dam, and tracked in the forebay as they approached the dam. The routes they swam during spill and nonspill periods as well as their general swimming behavior were monitored. Five of the smolts were tracked to the dam, and all went downstream through the turbines. No smolts were tracked over the spillway, although some appeared to be influenced by the currents created by the spill. One tagged fish was eaten by a seagull. Another fish turned upstream and was followed for 6 hours.


Tinbergen (1963) pointed out that in order to understand behavior patterns it is necessary to study how the behavior adapts the organism to its environment, how the behavior evolved, how the behavior develops within the organism's own lifetime and what mechanisms underlie that behavior. Crews (1980) has recently attempted such an integrated study of reproductive
behavior in anoline lizards. The present short and selective review is an attempt to approach the subject of salmonid migrations at the juvenile freshwater stages from these four directions.


Behavioral and physiological mechanisms postulated for the control of downstream migration of Atlantic salmon smolts are reviewed briefly, and some new evidence is presented for their refusal to undergo sustained swimming. Although these mechanisms imply passive displacement as the primary means of emigration, it is likely that active components must also exist as the rates of travel of smolts through loch systems are only slightly slower than those recorded for river systems. The timing of these movements within 24 h periods is reviewed and it is shown that the predominantly nocturnal emigration pattern is evident on occasions in alevin, fry and parr stages also. Thus at migration the diel periodicity probably represents a seasonal locomotor rhythm which, under changed behavioral and physiological circumstances, results in downstream displacement.


Ultrasonic telemetry was used to follow the movements of two groups of smolts in the estuaries of two small Scottish rivers. Hatchery reared smolts released into a typical wedge flow, partially mixed estuary had movements which were dominated by the influence of tide on the direction of water flow. The net movements of wild native smolts in a two layer flow estuary, in which freshwater flow dominated, was downstream but were intermittent consisting of short steps and numerous long pauses. The hatchery reared smolts escaped from the estuary within a tidal cycle, moving out on an ebb tide. The wild smolts remained in the estuary for periods up to 108 h, none escaping within one tidal cycle.

RHEOTAXIS AND SWIMMING ABILITY


The logarithm of stamina for each of Sardinops sagax (4 to 6,600 s), Scomber japonicus peruanus (16 to 27,000 s) and Odontesthes regia (7 to 9,900 s), adjusted to a length of 10 cm, decreased linearly over swimming speeds of 31 to 82, 25 to 78 and 24 to 75 cm s⁻¹, respectively (19°C). The regression coefficient was -0.064 for both S. j. peruanus and O. regia and -0.049 for S. sagax. Critical swimming speed (60 min, 5 cm s⁻¹) for S. sagax (10 cm), 32 cm s⁻¹, is within the range found for other species of similar length. The suggestion of a change in regression coefficient as swimming speed increased from prolonged to burst was not supported by the results of this study.

Juvenile lake trout, *Salvelinus namaycush*, of similar size were fed one of three isocaloric diets, each differing in protein and lipid content. Oxygen consumption for a given speed did not differ significantly throughout the feeding trial nor among the diets implying a similarity in the quality and quantity of substrate catabolized for energy. Basal metabolism (0 cm/s) was also independent of diet and feeding interval. Critical swimming speed increased with dietary and carcass protein content to suggest a direct association with muscle mass and number of myofilaments.


A stamina tunnel was used to determine the prolonged swimming performance of age-0 humpback chubs, *Gila cypha*, bonytail chubs, *G. elegans*, and Colorado squawfish, * Ptychocheilus lucius* and of subadult Colorado squawfish. The "fatigue velocity" in body lengths per second at which 50% of the test fish were fatigued (FV50) was determined at 14, 20, and 26°C. The ranges of FV50 values for the three fishes (average total length in parentheses) were: humpback chubs (95 mm), 4.4-5.7; bonytail chubs (99 mm), 4.7-5.8; small Colorado squawfish (104 mm), 4.0-4.5; large Colorado squawfish (432 mm), 2.0-2.3. Absolute speed of large Colorado squawfish was about 2.4 times that of small Colorado squawfish. Swimming ability of the subyearlings increased with increased water temperature. These rare fish had prolonged-swimming abilities similar to other fish species.


Coho salmon (*Oncorhynchus kisutch*) smolts from two different stocks were exercised continuously for 40 d at water velocities of 0.2 (control), 1.0, 1.5, and 2.0 body fork lengths per second. Their critical velocities and swimming characteristics were determined using a Blazka-type respirometer-stamina swimming chamber immediately after training and after 2 mo of rest. Endurance increased in exercised fish compared with control groups and the improvement was maintained after the period of rest. Swimming modes in freshwater differed between the two stocks, and it is suggested these were adaptations resulting from differing genetic backgrounds. Continuous moderate exercise modified swimming modes in sea-water. Long-term low water velocity regimes before release in the ocean might be a profitable rearing strategy for the survival of coho salmon because it allows an economy of energy during their oceanic migrations and improves their homeodynamic capacity.


Habitat use by juvenile coho salmon *Oncorhynchus kisutch*, steelhead *Salmo gairdneri*, and the coastal subspecies of cutthroat trout, *Salmo clarki clarki*, in small streams in western Washington was influenced by hydraulic characteristics of different types of channel units. Coho salmon preferred pools with average velocities less than 20 cm/s. Steelhead occurred in riffles and also utilized deep pools with relatively high velocities. Cutthroat trout were intermediate between coho salmon and steelhead in their use of swiftly flowing habitats. Variation in body shape and fin size among the three species generally fit the predicted morphologies that would be favored in different locations within the channel. The cutthroat trout's lack of morphological adaptation to either fast or slow water may help to explain why this species is dominated by coho salmon and steelhead in areas of sympathy.


Prolonged swimming speeds of female pink salmon (55 cm, 1879 g) were determined in a 27-cm diameter steel tunnel at 20 ±1°C. The speeds were corrected for cross-sectional blocking effect of the fish by comparing tailbeat frequencies for the same velocities in the tunnel and in an open flume. The mean maximum sustained speed (10-hr test time) was 1.12 m/sec (2.04 L/sec). Compared with sockeye salmon, pink salmon could only perform at about 80% of the level of prolonged speed achieved in the same tunnel by sockeye of comparable size.


The reaction to different water currents of the cave salamander Proteus anguinus and his epigean relative Necturus maculosus has been tested in a choice chamber. Both species showed a positive reaction which started in P. anguinus with a current of 35 cm/min and in N. maculosus 60 cm/min. These thresholds are within the range measured for different species of fish in the absence of visual stimuli.


The swimming performance, as judged by maximum sustained swimming speed, of rainbow trout from a fish farm in S.W. England, is low when compared to previously published values for this species. This may be a localized peculiarity resulting from hatchery selection and rearing procedures.


The dispersion of salmon and trout of 0+, 1+ and 2+ age classes was examined by electrofishing 12 sections of a stream in Perthshire, Scotland at the end of the growing season in September to October in 1972 and 1976. In 1972 sections ranged in surface area from 21 to 122 m² and had volumes of 5 by 0-17 by 3 m³ and when surveyed in 1976 surface areas were 15-106 m² and volumes 2 by 1-6 by 7 m³. In 1976 widths and areas of sections were 63 - 87% of the values for 1972, depths were 39-68% and volumes 28-52% of the earlier values. These differences were due to 1976 being drier and warmer. In both years, all sections contained 0+ and 1+ age classes of salmon and trout and some sections contained 2+ age salmon and trout. The total density of fish in a section ranged from 1 by 9 to 3° 9 m⁻² in 1972 and from 3° 72 to 6 by 08 m⁻² in 1976. There was an inverse relationship, significant in 1972 only, between the density of 0+ salmon and that of 1+ trout in the different sections. Densities of both 0+ and 1+ salmon in the sections were inversely correlated, and those of 0+ and 1+ trout were directly correlated, with area of water deeper than 10 cm.

The vertical distribution and swimming direction of 2-year-old smolted Baltic salmon *Salmo salar*, kept in circular tanks containing either fresh or brackish water, was monitored for a year. Fish in both groups were distributed in the upper part of a water column and moved with the current during the first part of the experiment, May to August. Salmon kept in brackish water continued this behavior throughout the year whereas fish maintained in fresh water changed their behavior drastically. From September, freshwater fish were distributed close to the bottom and tended to swim against the current. The following spring (April-May), fresh water kept fish again started to swim high in the water column. Apparently, there is an interaction between alternative circannual programs in Baltic salmon.


The movements of 23 northern squawfish, *Ptychocheilus oregonensis*, were monitored by radiotelemetry below a Columbia River hydroelectric dam during the out-migration of juvenile anadromous salmonids in 1984 and 1985. The work was done as part of a study to relate predator abundances and distribution to juvenile salmonid mortalities associated with dams. Northern squawfish remained in protected shoreline areas in spring and early summer, when discharge rates were high, but moved close to the dam and the juvenile bypass outflow area in mid to late summer, when discharge rates were low. Trends in northern squawfish movements were similar during abrupt changes in discharge rate. Modification of structures to maintain high water velocities around bypass outflow areas should reduce potential predation on juvenile salmonids by northern squawfish.


Physical conditioning at swimming speeds of 2 and 3 body lengths per second for periods up to 30 days increased critical swimming speed by as much as 15% over that found for unconditioned fish. Haemoglobin increased significantly with conditioning, suggesting an enhancement of aerobic capacity. Conditioning did not, in general, increase the production of lactate dehydrogenase in blood serum. Following periods of swimming at critical speeds, blood volume decreased in unconditioned bass but with conditioning remained relatively stable.


A model is developed to predict potential net energy gain for salmonids in streams from characteristics of water velocity and invertebrate drift. Potential net energy gain, or potential profit, is calculated for individuals of three species of juvenile salmonids in a laboratory stream aquarium, based on the energy available from drift minus the cost of swimming to maintain position. The Michaelis-Menten or Monod model is used to describe the relationship between potential profit and specific growth rate. Potential profit was a better predictor of specific growth rate for coho salmon (*Oncorhynchus kisutch*) than for brook trout (*Salvelinus fontinalis*) or brown trout (*Salmo trutta*). Coho salmon always achieved higher specific growth rates than either brook trout or brown trout in concurrent experiments, and maintained growth to lower resource thresholds. In each experiment, fish established intraspecific hierarchies and dominant fish held positions affording maximum potential profit.


Zebradanios, *Danio rerio*, 3-39 long, were studied to quantify ontogenetic changes in routine (spontaneous) swimming. Swimming speeds and mean acceleration rate increased during the larval period with the most rapid changes occurring when fish were between 5 and 15 mm long. At larger sizes, the rate of increase in performance was small. This pattern presumably resulted from morphological changes which also proceeded rapidly in larvae and levelled off towards adulthood. The implications of ontogenetic changes in swimming performance for the development of foraging and anti-predator behavior are discussed.


The agonistic behavior of smolts, of *S. salar* was compared with that of parr in stream tanks over the normal migration time of the smolts. Smolts had similar agonistic behavior to that of the parr. There was no migratory behavior observed, and smolts remained as aggressive as the parr. Diminished aggression appears not to be responsible for the downriver migration of smolts, and the change from territorial to schooling behavior observed in natural conditions is likely due to the change in buoyancy and the associated change in preferred water velocity.


Pink salmon fry exhibited, on the average, an irregular daily pattern of swimming activity, and swam near the water surface at night (nocturnal rhythm of vertical distribution) during the first week after gravel emergence. The nocturnal rhythm of vertical distribution indicated a relative negative response of the fry to high light intensities. A shift from an irregular pattern to a diurnal rhythm of swimming activity occurred 7 to 13 days after emergence. Coincident with this shift was an increasing tendency of the fry to swim in the upper half of the water column during daylight. This suggested a gradual weakening of the fry's negative response during the Second week. Thereafter, daily rhythms of swimming activity were diurnal, whereas rhythms of vertical distribution remained nocturnal. Periodogram analysis revealed that these behavioral rhythms were synchronized strongly with the artificial daily light-dark cycle. The onset of light appeared to synchronize the diurnal swimming activity rhythms, whereas the onset of darkness synchronized the nocturnal patterns of fish rising toward the water surface.


The circadian rhythm of swimming activity and the role of the daily illumination cycle in the synchronization of this rhythm were studied in individual juvenile pink salmon *O. gorbuscha*. Sixty eight percent of all fish examined (*n* = 38) were day-active when exposed to a 12 h L:12 h D cycle the remaining fish were nocturnally active. One half of the fish tested under laboratory conditions of continuous, constant light intensity (LL) and constant temperature showed unambiguously endogenous activity rhythms with circadian periods for up to 10 d. The remaining fish were arrhythmic. Mean period length of the free-running activity rhythms for diurnal fish in LL shortened with constant light intensity increasing from 6 to 600 lux, as predicted by the circadian rule. In contrast, mean free-running period for nocturnal fish did not vary significantly with similarly increasing constant light intensity. Mean swimming speed (activity level) of both diurnal and nocturnal fish increased significantly with increasing light intensity. This is suggestive of a positive photokinetic response. When subjected to a phase-delayed LD cycle, the fish resynchronized their daily rhythms of activity with this new LD cycle after only one transient cycle in most instances.


At times corresponding to their juvenile coastal and pelagic ocean phases, groups of juvenile pink salmon exhibited diel rhythms of generally diurnal swimming activity and nocturnal vertical movement in response to simulated seasonal variations in photoperiod and water temperature in the laboratory. Diurnal swimming activity was synchronized with the daily light cycle throughout most of the year, but not with ambient daily temperature cycles. On average, fish were increasingly more active during the day than at night with increasing duration of the photophase. Results are related to the migratory behavior of pink salmon, and it is concluded that photoperiod may be an important proximate factor in the timing of their seasonal migratory behavior.


Rainbow trout were trained for 3-4 weeks in a flume at swimming speeds of 1, 2 and 3 Ls⁻¹. For each experiment growth rates were estimated and by measuring the hypertrophy of red and mosaic skeletal muscle fibres their function was described at particular swimming speeds and compared with earlier experiments on coalfish using the same technique. Maximum growth, compared with controls in still water, occurred at swimming speeds of 1 Ls⁻¹. At this speed the trout mosaic muscle fibres hypertrophied by 40% but the red muscle fibres showed only a 25% hypertrophy. It is suggested that natural swimming speeds are close to 1 Ls⁻¹ and the trout mosaic fibres are better adapted for use at this speed in comparison with coalfish white muscle fibres.


Through ultrasonic tagging, fish living in running water and in slow-flowing water in man-made weir basins were tracked over a period of 3-6 days. Results showed that the fish living in the weir basins changed position more frequently and moved over larger areas than fish living in running water. As a consequence of the different behavioral patterns of fish in rapids and in weir basins, densities of salmon are lower in the weir basins than in the rapids. Therefore, weirs creating large areas of slow-flowing water should not be established in rivers where an optimal production of Atlantic salmon is the goal.


Fry of brown trout, Atlantic salmon, brook trout and lake trout were tested for downstream migration and critical velocities with a method of stepwise increasing water velocities. Critical velocities for fry entering the free-feeding stage, were between 0.10 and 0.25 m/s, varying among individuals and depending on species and water temperature. Downstream displacement started at lower velocities. Lake trout had the lowest critical velocity. Temperature influenced swimming performance. On average, a 7°C increase in temperature resulted in a 0.05 m/s increase in critical velocity. Flow-sensitivity gradually decreases with fry development; when the fry had reached a length of 40-50 mm they were able to tolerate water velocities higher than 0.50 m/s.


The differentiation of myotomal muscles in the brook trout (Salvelinus fontinalis Mitchill) has been investigated using p-phenylene diamine stained semi-thin sections and cytochemical and quantitative determinations of enzyme activities. Evidence is presented that the range of fibre size in white muscle represents stages in growth rather than distinct fibre types. 3. Electromyography shows that both red and white muscles are recruited for sustained swimming. The threshold swimming speed for recruitment of white fibres is around 1.8 body lengths/s (L/s). 4. White muscle citrate synthetase and cytochrome oxidase activities are 25-35% that of red muscle. Hexokinase, phosphorylase and phosphofructokinase activities are 2, 4 and 2 times higher in white than red muscles. It is considered that the aerobic capacity of white muscle is sufficient to support sustained swimming, and that blood glucose could be an important fuel source. 5. Endurance exercise training has been investigated in fish swimming, continuously, for 21 days at 3 L/s. This training regime restricts spontaneous high-speed swimming activity and resulted in a general decline of white muscle glycogenolytic enzyme activities. Red fibres underwent hypertrophy relative to non-exercised controls (530 ±64 μm² non-exercised, 901 ±63 μm² trained). Aerobic enzyme activities in red muscle and the fraction of fibre volume occupied by mitochondria (30.2 ±0.8%) did not change in response to the training programme, but glycolytic enzyme activities were elevated. 3-OH Acryl CoA dehydrogenase activities increased in both red and white muscles indicating an enhanced capacity for fatty acid catabolism with training. 6. Plasma and muscle lactate levels were not statistically different between tank-reared and trained fish swimming a 3 L/s. 7. Adaptations of fish muscle to endurance training are discussed and compared with results for other vertebrates.


The aim of this work was to investigate the relationship between shoal size and vigilance. The behavior of minnows (Phoxinus phoxinus) foraging on an artificial food patch during the simulated stalking approach of a model predator (pike: Esox lucius) was recorded for shoals of 20, 12, 6 and 3 fish. Minnows in large shoals reduced their foraging sooner but remained feeding on the patch longer than in small shoals. The relatively late reaction of small shoals to the model and the rapid cessation of feeding once the predator was detected, indicates that small shoals were less vigilant than large shoals.


Pink salmon, Oncorhynchus gorbuscha , sockeye salmon, O. nerka , and chum salmon, O. keta are essentially ecological equivalents in their use of riverine habitat. These Oncorhynchids are stream spawners that deposit their eggs in the early fall. The eggs incubate through winter, and emergence and outmigration of the juvenile salmon occur in early spring. Although these fish are transient in the riverine environment, the stream plays a critical role in controlling their production and year-class strengths by significantly influencing egg and alevin survival. In these early stages, survival is primarily a function of the quantity and quality of instream flow during the fall and winter in conjunction with redd superimposition and streamed oversieving. A model is proposed to explain the relationship between abiotic and biotic factors upon Oncorhynchid recruitment, based on our knowledge of pink salmon in the Great Lakes and a review of literature pertaining to early-outmigrating Oncorhynchids.


Ecological observations of ascending behavior of juvenile masu salmon (Oncorhynchus masou) under various hydraulic and light conditions were carried out using a small-scale experimental fishway. In tests on the effect of pool depth below the weir, a 10 cm pool depth, approximately equal to body length of the fish, resulted in the most successful passage over weir. The general tendency was not evident in the relation between waterflow supplied into the channel and ascending rate. However, under inadequate flow conditions of higher or lower discharge, ascent form of the fish changed from "swimming-type" to "jumping-type" and jump failure coincided with the change.


The specific growth rate of rainbow trout (Salmo gairdneri R.) (7-8 cm length) was investigated at 0.5, 18 and 32 ppt. salinities for a period of 28 days. Fish growth at 18 ppt. was less than that at 0.5 ppt. but growth at 32 ppt. was much impaired and mortality at this salinity reached 92% by the end of 21 days of the experiment. Exercise training of fish in fresh water at water velocities of 0.0, 1.4, 2.2 and 3.5 L s\(^{-1}\) showed that the growth of exercising fish was considerably greater than that of the controls. Exercise training of the fish at 18 ppt. was not successful, and negative growth rates resulted.


Groups of 6-7 cm length rainbow trout, Salmo gairdneri were simultaneously trained at four water velocities (0, 1.4, 2.2 and 3.5 L s\(^{-1}\)) for a period of 46 days. Oxygen consumption and swimming ability (fatigue time) were then measured. Only training at 3.5 L s\(^{-1}\) increased the swimming ability of the fish. A study of the relative proportion of the white and red muscles indicated that the white muscle was increasing its mass at velocities in excess of 2.2 L s\(^{-1}\). The oxygen consumption rate of the trained fish was lower than that of the untrained fish when considered over the whole velocity range.


Young rainbow trout were propagated from adults collected from above and below a waterfall, impassable to upstream fish migration on Kokanee Creek, tributary to Kootenay Lake, British Columbia. The two stocks of young (above and below waterfall) were reared in a hatchery under identical temperature, light and food conditions. Their directional response to water current was tested in a laboratory migration channel during their first summer and autumn, as well as the following spring. During tests in light, both stocks of young trout showed similar current responses, but in darkness the below falls stock showed much more downstream movement in the autumn than did the above falls stock. In addition, below falls trout had a higher growth rate, were slightly heavier at the same length and matured earlier than the above falls stock. The adaptive significance of these differences are discussed in relation to maintenance of trout populations above waterfalls and to selective pressures faced by migratory below waterfall populations.


Direction of current flow did not affect the movement patterns of rainbow trout (S. gairdneri) embryos maintained in artificial substrate systems. Embryos successfully emerged from the substrate in total darkness, although light has previously been implicated as necessary for emergent behavior. Neither phototactic or rheotactic behavior appears necessary for "normal" movement and emergence of salmonid embryos. Movement patterns appear to be primarily due to geotactic-geokinetic behavior.

The downstream movement of young trout and salmon in relation to water velocity was studied in simulated river channels. The results are interpreted as showing that these young salmonids pass through a short period when they are very vulnerable to downstream displacement by flow. Behavioral differences between the two species are considered with the influence on fish movement of changing rate of water velocity, light and temperature.


Trout eggs were planted in four experimental stream channels, each channel being run at a different but constant discharge. Survival of the eggs to hatching was low and apparently unrelated to surface water velocity. However, movement of young trout out of channels was affected by water velocity, the higher the velocity the greater the proportion of trout that were lost. Virtually all fry moved out of a channel with a mean surface water velocity of 0.73 m s⁻¹. The rate of loss was not constant over the experiment but increased as the young trout entered the free-feeding stage. At the end of the experiment, loss of fry, after abrupt increases in discharge, was demonstrated in the lower velocity channels.


The relationship between oxygen consumption rate (milligrams per kilogram per hour) and sustained swimming speed (calculated from tailbeat frequency) was determined for 1.2-g juvenile coho salmon (O. kisutch) at 15°C. The data are best described by the following equation: log oxygen consumption rate = 2.2 ±0.13 (body lengths per second, bls). This relationship is very similar to that extrapolated for sockeye salmon (O. nerka) of the same size, thus potentially enabling researchers to utilize the extensive sockeye data base to predict metabolic rates of coho. The oxygen consumption rate during burst swimming (9 bls) was also determined. The burst swimming metabolic rate (38,000 mg O₂ * kg⁻¹ * h⁻¹) is nearly 40 times greater than the maximum sustained swimming metabolic rate.


Comparison of typical water velocities in the Columbia River system with observed migration rates for salmon and steelhead smolts previously has been interpreted as evidence for passive migration during part of each night. Recent research, however, has shown that coho salmon experience reduced swimming proficiency and fatigue levels during
smolting, particularly when smolts are transferred directly into seawater. Reexamining the migration times in light of the new swimming proficiency data suggests that smolts may swim mostly head first upstream during outmigration thus drifting downstream tail first.


Regarding the swimming behavior of test fish in a 1985 experiment, swimming direction showed a notable eastward element, and the mean horizontal swimming speed was faster than Ichihara's estimated value. The trend of vertical movement showed that the test fish swam comparatively deep before and after noon, just below the sea surface without vertical movement at mid-night, and with notable vertical movement at sunrise. As the results of experiments conducted in and after 1982, the migration of chum salmon (Oncorhynchus keta) was assumed to be as follows: chum salmon migrated to Kitamiyamato Bank along the East Sahalin Current, and diverged to east and west at an area from Kitamiyamato Bank to Cape Notoro or off-shore Monbetsu.


Juveniles of coho (O. kisutch) and Atlantic salmon (S. salar) proved capable of leaping falls at least 5 body lengths in height. No species differences were apparent: both species leapt lower falls (12 cm) more readily than higher ones (27 and 57 cm) and proportionately more leaps occurred on days with temperatures between 14.0 and 17.0°C than on days with lower temperatures.


In Slim Creek, a tributary to the upper Fraser River east of Prince George, B.C., chinook salmon (Oncorhynchus tshawytscha) fry summer and overwinter in their natal stream before migrating seaward as yearlings; they are "stream-type" in juvenile life history pattern. From the Harrison River, a tributary to the lower Fraser River, chinook fry migrate to the Fraser River estuary sometime during their first spring or early summer; they are "ocean-type." Differences between Slim Creek and Harrison River Chinook fry are in a direction consistent with their different patterns of length of freshwater residence as juveniles, since aggressive behavior, positive rheotaxis, and bright fin coloration are important components of extended stream residence in salmonids.


The distribution, social behavior, and feeding behavior of juvenile Atlantic salmon were studied in a selection of stream and river habitats in northern Scotland using Scuba diving techniques. The results are discussed with respect to food acquisition and choice of feeding site. It is concluded that juvenile salmon feed predominantly on drifting material and that their daytime distribution reflects the current velocity related abundance of drift.


Speed, acceleration rate and turning radius were measured for rainbow trout (Salmo gairdneri; length 25.7 cm) and smallmouth bass (Micropterus dolomieu; length 23.6 cm) attacking live minnows. The observations sampled a range of values for each kinematic variable up to the limits of maximum performance. Minimum turning radius was independent of speed and acceleration rate. Expressed as a ratio of total length, L, minimum radii were 0.18 ±0.2 L for trout and 0.11 ±0.02 L for bass* (±2 S.E.). Differences in minimum turning radius, R, between trout and bass were attributed to differences in the volume of the body and entrained water, V, and projected lateral surface area of the body and median fins, A. For subcarangiform swimmers, the dimensionless minimum specific turning radius R/L = 2V/AL.


Critical swimming speeds were determined for male and female pink salmon (Oncorhynchus gorbuscha) captured from the Fraser and Thompson rivers and Seton Creek, British Columbia. The fish were categorized into two basic groups. Lower river fish were captured from the Fraser River at Fort Langley and Yale, and up-river fish were captured from the Thompson River at the Canyon and at Ashcroft and from Seton Creek near Lillooet, British Columbia. The critical swimming speeds of males and females in various stages of maturation were compared. In general, the up-river fish were stronger swimmers than the lower river fish. Gravid fish were stronger swimmers than spawning fish, which in turn were stronger swimmers than fish which were spawned out.


SMOLTING


The purpose of this review is to provide fishery biologists and fish culturists with a summary of those published reports relating to the morphological, behavioral and biochemical changes associated with smoltification and seawater adaptation in anadromous salmonids.


Literature concerned with the appearance of smolts (silvery color, streamlined body form), their physiology (salinity relationships, endocrinology), and their behavior (territorial and schooling) is discussed in relation to possible key steps in the evolution of the parr-smolt transformation and seagoing behavior. It is assumed that Salmonidae evolved in fresh water, that the genus Oncorhynchus originated in a large area of brackish water such as the Sea of Japan, and that schooling on Oncorhynchids (e.g. O. gorbuscha and O. keta) are the most specialized of the seagoing salmonids while species of char (Salvelinus) and trout (Salmo) are more primitive.


**SOUND AND HEARING**


In 1974 and 1975 a series of trials were made to investigate the effectiveness of sound as a deterrent to marauding seals at salmon netting stations. A feasibility trial was followed by experimental work on a captive juvenile common seal. A wide variety of sounds including pure tones, killer whale calls and recorded loud noises were transmitted and responses were recorded on videotape. While one sound appeared to elicit an alarm reaction, habituation was rapid. Field trials were carried out at netting stations at the mouth of the River Tweed which frequently suffer damage from Grey seals. Although the frequencies used spanned the entire hearing range of seals, no sound was consistently effective in scaring seals from the nets. It is concluded that the prospect of an acoustic deterrent is remote.


Startle responses of shoaling herring (*Clupea harengus* L.) to various well-defined sound stimuli were investigated. A sound consisting of only one cycle of a sine wave was as effective a stimulus as a sound of the same amplitude lasting many cycles. The variability of response to a given stimulus was small. If a wave train took several cycles to reach its maximum amplitude the threshold was raised considerably. If measured as pressures the amplitudes of single-cycle stimuli needed for
constant responses were almost independent of the duration of the stimuli (range tested: 2-40 ms). The authors conclude that herring can receive, in a transient sound, sufficient information to determine the amplitude of the sound and the general direction from which it comes. They argue that, while the directional sense demands information on particle velocities and pressure, responses are triggered by pressure alone.


Vital staining with Janus Green, Phase contrast and scanning electron microscopy were used to map the distribution of free neuromast organs from first hatching, 10 mm long larvae to 100 mm long juveniles of herring (Clupea harengus L.), with some further observations on juvenile sprat (Sprattus sprattus (L.)). Neuromasts are sparsely distributed on the head and trunk at hatching but soon proliferate on the trunk where, but a length of 13-15 mm, they occur one to every segment. Near metamorphosis there are at least three rows of neuromasts on the anterior trunk region, 6-9 single neuromasts on the caudal fin and as many as 50 on the head. The scales develop at about 40-50 mm and the neuromasts are then found singly or in groups of 2 or 3 on the surface of the scales of the anterior trunk. The lateral line develops at 22-24 mm and appears to incorporate existing free neuromasts on the side of the head. Unlike the cupulae of the free neuromasts, which are cylindrical, the lateral-line cupulae are thin erect plates lying along the axis of the canals.


Herring (Clupea harengus L.) show a characteristic "startle" response when subjected to vibrational stimuli from a diaphragm in the wall of their tank. Threshold measurements on fish from 2.8 to 17 cm total length tested at frequencies from 70 to 200 Hz showed that the response was elicited by sound pressures between 2 and 18 Pa, the most sensitive fish being in the length range from 8-11 cm. Intermediate-sized fish of 12-13 cm also responded to sounds from a loudspeaker in air above the tank, the mean threshold being about 5 Pa. The stimulus was thought to be the sound pressure rather than the particle velocity component of the stimulus, the gas-filled pro-otic bulla acting as part of the pressure detecting system. Decoupling of this link by cutting window over the lateral recess did not affect the response much, nor did treatment of the lateral line by methylene blue or streptomycin as blocking agents.


The behavior of herring subjected to stationary and vibrating obstacles in their swimming path was recorded in daylight and darkness using an infra-red sensitive TV system. The herring avoided stationary obstacles using visual stimuli and usually collided with such obstacles in darkness. They showed strong avoidance to a continuously vibrating sound source in darkness but the speed of turning was relatively slow and there was no evidence for habituation. As they approached the source they usually responded when the sound pressure reached 10-20 Pa, about 70 dB above the threshold. Particle velocity within the lateral line canals was calculated and was 40-60 dB above threshold. Herring seem to be able to adapt their avoidance behavior to suit the urgency of the situation.


Fast-startle responses were found in herring larvae soon after hatching. Young larvae of 10-12 mm body length responded to tactile stimuli and to contact with medusae with escape speeds of 5.8 and 10.1 BL (body length)/s respectively. These larvae did not respond to acoustic stimuli. Older larvae, of 22-36 mm body length, responded to acoustic stimuli, but only if the otic bulla contained gas. The latency averaged 27 ms, the threshold of sound pressure was about 10 Pa and the escape speed about 12 BL/s. The older larvae did not make directional responses away from the sound source until the head lateral line, and its coupling with the bulla, were developed.


Comparisons of the behavior of herring (Clupea harengus L.) were made in the light and dark by means of an infra-red sensitive TV system and video recording. Herring, which were schooling in the light, became less active in the dark, their
swimming speed decreased, they tended to disperse and the proportion of gliding compared with swimming fish increased. Herring which were not schooling in the light increased their swimming speed in the dark. When subjected to transient sound stimuli herring made fast-startle responses. The proportion of fish responding was lower in the dark. The directionality of the response (the proportion turning away from the sound source) was the same in the light and dark suggesting there was no visual component in the response.


The responses of A. lineatus to water surface waves were investigated. A. lineatus responds to surface waves from 10 Hz to at least 250 Hz. Reaction time to clicks within a target angle of 70 to 100° varies between 128 ms 24 at 8.9 m and 242 ms 67 at 0.06 m amplitude. The distance the fish swims toward the wave source decreases with increasing stimulus frequency.


The ability of cod (Gadus morhua L.) to discriminate between sound waves coming from opposing directions was studied by means of cardiac conditioning in approximately free field conditions under a raft in a Scottish sea loch. The sound sources were positioned at 0° (frontal), 60° or 120° in the fish's median vertical plane, or at 60° or 90° in the transverse plane, other sources occupying diametrically opposed locations. Radial distances varied between 3.05 m and 4.20 m. It is concluded that the detection of sound propagation direction is based on the characteristic phase relationship between particle motion and sound pressure. Cues resulting from sound propagation itself are irrelevant, and do not appear to be perceived.


It was noticed that the blind Mexican Cave Fish repeatedly passes along objects new to it at a short distance. Observations and experiments are reported which support the hypothesis that water movements occurring between the stationary object and the fish as it passes by convey information about the location and possibly the shape of the object, which is detected by the lateral line organ of the fish. Water movements of the expected type were recorded with the help of a model fish equipped with a mechanoelectric analogue of a free neuromast.


Auditory sensitivity as a function of frequency has been behaviorally determined for 2 species of fish from the teleost family Holocentridae which is characterized by marked variation in peripheral auditory structures. Best sensitivity measured for *Myripristis kuntee* was -50 dB re: 1 dyne/cm SUP-2 for frequencies between 300 and 2,000 Hz, while best sensitivity measured for *Adioryx xantherythrus* was 28 dB at 500 Hz. Both species can detect sounds at 100 Hz while the high frequency end of the auditory range extends up to 3,000 Hz for *M. kuntee* and to 800 Hz for *A. xantherythrus*. It is hypothesized that these differences in auditory capabilities are related to differences in sound transmission characteristics of the peripheral auditory system.


Behavioral methods were used to determine psychophysical tuning curves for three teleost fish species (*Notopterus chitala*, *Adioryx xantherythrus*, and *Osteoglossum bicirrhosum*) for 300- and 500-Hz signals. Simultaneous masking techniques revealed that 300-Hz curves were similar for all species, with peak masking occurring when the frequency of the masker equaled 300 Hz. In contrast, there were considerable interspecific differences in simultaneously masked 500-Hz curves. The 500-Hz curve for *Adioryx* was a broadly tuned, V-shaped function with peak masking occurring in the frequency region of the signal, whereas the curve for *Notopterus* was a sharply tuned, multi-peaked function with peak masking occurring for both 500- and 300-Hz maskers. Comparisons of tuning curves obtained with both forward and simultaneous masking techniques for *Notopterus* revealed little or no difference between 300-Hz curves, but substantial differences between the 500-. These results suggest that there are interspecific and frequency-dependent differences in the frequency selective processes of fish auditory systems.


The ability of goldfish to detect the presence of amplitude modulations (AM) impressed on 200, 570 and 800 Hz tones was measured under stimulus conditions producing intermittent, short-term adaptation and continuous, long-term adaptation. Sensitivity to AM under intermittent conditions increased as a function of modulation rate, with thresholds of AM detection occurring between 10 and 25% modulation at 10 Hz and around 2% modulation at 100 Hz. The results show that adaptation affects AM detection and that phase-locking to the AM envelope is the most likely basis for behavioral detection.


Various functions have been attributed to the lateral line organs of fish, including those of detecting touch and sound and flow past a swimming fish. It is generally agreed that lateral line neuromasts are excited by liquid within the canal moving
relative to the canal walls. For the sprat, such movements are proportional to local differences in motion between the fish and the surrounding seawater. The authors describe the motions of fish and seawater at various positions around vibrating sources. It is shown that fish are rigid longitudinally. Local differential movements between fish and seawater occur. Predictions based on these results suggest that when a fish is close to a source of vibration, the amplitudes, signs and patterns of stimulation along the lateral line system change with the position of the fish relative to the source.


The output from some pulsed ultrasonic transmitters commonly used in fish movement studies is faintly audible to humans. This study was undertaken to determine if the output from these and some other transmitters is detectable by Atlantic salmon (Salmo salar) parr. Classical conditioning of cardiac deceleration was attempted using the transmitter's output as the conditioned stimulus. The results from 29 experimental and 14 control fish suggest that the parr were unable to detect the output from these transmitters.


The psychophysics and neurophysiology of sound detection in quiet and under noise masking were studied in goldfish Carassius auratus. Psychophysical masking is a linear function of masker level. For long duration signals, signal-to-noise ratios (S/N) at threshold are 15.5, 19, and 22.5 dB for 200, 400 and 800 Hz signals, respectively, and is -5 dB for a noise signal. Threshold declines with signal duration to about 700 ms. The slopes of the masked temporal summation functions are about unity, indicating that energy is constant at threshold. In quiet however, the slopes are generally less than 0.5, indicating that shorter signals are detected at lower energy. Neural correlates of the masked S/Ns and the slopes of temporal summation functions were sought in the response patterns of single saccular neurons. Rate- and synchronization-intensity functions were obtained for tone and noise signals in quiet and in noise. S/Ns at behavioral threshold correspond closely to those required to raise spike rate just above that evoked by the masker alone, but are well above those required to cause clear synchronization. Therefore, sound detection is probably based on spike rate and not synchronization criteria.


The capacities of the goldfish (*Carassius auratus*) auditory system for encoding and processing periodic temporal patterns were characterized using behavioral and neurophysiological analyses. Animals were classically conditioned to detect changes in the rates (20 to 200 Hz) at which tonal and noise signals were amplitude-modulated, at a variety of modulation depths (3 to 100%). For the same stimulus set, the variability with which saccular neurons represent envelope periodicity in inter-spike-intervals was measured. The just discriminable change in envelope period (ΔP) is approximately equal to the variance which spikes in saccular neurons are phase-locked to modulation envelopes. The error made in detecting changes in modulation rate is highly correlated with the error with which inter-spike-intervals in saccular fibers represent envelope periodicity at a wide variety of modulation rates and depths. This is evidence that the goldfish estimates the duration of acoustic inter-pulse-intervals through information contained in neural inter-spike-intervals.


Averaged evoked responses from multiple electrodes in the goldfish midbrain (torus semicircularis) area were recorded in response to acoustic stimulation by loudspeaker and to direct vertical vibration of the head. Relative pressure and displacement sensitivity was such that in the far field, the response to sound pressure would dominate the response to particle motion by 40-90 dB. Swimb bladder deflation caused a flat (70-1000 Hz) loss in pressure sensitivity ranging from 20 to over 50 dB, and led to an enhanced response to vibration at low frequencies. The goldfish midbrain is not homogeneous with regard to relative pressure and motion sensitivity.


Methods of investigating the hearing abilities of fish are outlined and the hearing capacities of fish are discussed, considering audiograms, auditory masking, the relevant stimuli, hearing and sound duration and discrimination of sound quality.


Communication by means of sound appears to be widespread in fish, low-frequency calls being produced in a variety of social contexts including competitive and aggressive behavior and courtship. Fish are acutely sensitive to sounds, though their hearing abilities are confined to low frequencies. They are able to discriminate between sounds of different amplitude and frequency, and between calls that differ in their pulse patterning - an ability that seems to be particularly important in enabling them to distinguish their own calls from those of other species. Fish are also able to determine the direction and even the distance of a sound source.


Directional characteristics of single units from the ear of the cod (Gadus morhua) were examined. Units from the utriculus and sacculus were studied with the fish stimulated by vibration at different angles in the horizontal plane. Results show that the sacculus and utriculus both contain bi-directional units which might provide a basis for vector weighing. The utriculus and lagena, as well as the sacculus, may play a vital role in determining the direction of sounds.


Experiments to test the effectiveness of low-frequency, high-intensity sound in excluding alewife, Alosa pseudoharengus, from an experimental net structure were conducted on Lake Ontario near Pickering, Oni. Sound was generated by modified seismic devices called pneumatic poppers. The number of alewife entering the experimental structure was reduced by 71-99% when the poppers were operating. Sonar evidence from one test suggested that another species which was not caught in the collection nets was less influenced by the acoustic deterrent. The results suggest that low-frequency, high-intensity sound may be effective in reducing losses of adult alewife at water intakes.


The swimbladder-acoustico-lateralis system of the Atlantic menhaden, Brevoortia tyrannus, is described and compared with that of the Atlantic herring, Clupea harengus. The system develops in the larva at a much earlier stage than the herring,
being functional by about 2 mm TL. The volume of the gas-filled pro-otic bullae is five times that of the herring, and the gas ducts to the swimbladder, instead of being short and separate, are three times the length and join to form a common duct well in front of the swimbladder. The menhaden swimbladder is baggy and totally compliant when subjected to pressure changes. There is no toughened anterior end as in the herring, but the swimbladder is steeply angled in the body cavity, causing gas to collect at the anterior end after a pressure increase, unless the fish is diving very steeply.


The auditory sensitivity of the red sea bream, *Pagrus major*, was determined by heart-beat conditioning using a sound coupled with a delayed electric shock. Sufficient care was taken in order to obtain a stable acoustic condition. Sound was projected from an air-speaker in a sound-proof chamber in which the experimental tank was placed on an air spring. The audible range of the red sea bream extended from 50 to 1000 Hz with a peak sensitivity of -14.2 dB (0 dB = 1 μbar) at 200 Hz. On the basis of its responses to unconditioned sounds, it is suspected that the red sea bream is able to distinguish sound quality.


The startle response of the red sea bream (*Pagrus major*) was examined in order to clarify the development of behavioral change upon application of audio-stimulation. Pre-larvae did not respond to the audio-stimuli even at the maximum amplitude attainable by apparatus. After metamorphosis from pre-larval to larval stage, however, the startle response appeared and was found to depend on the amplitude of the stimulus. The threshold was between 55 and 60 dB at the examined frequencies.


The behavioral changes of the young red sea bream (*Pagrus major*) were examined experimentally in a tank to clarify the effect of sound stimulus on the fish. Sound stimuli applied were pure tones which were generated electrically, and projected from an underwater speaker set in the tank. Sound pressures ranged from 40 to 70 dB. The fish responses were obtained by eye observation and by feeding activity recorded electrically. The rate of the occurrence of fish threatened increased with increasing sound pressure and the response was most sensitive at 200 Hz. Feeding activity was also disturbed at higher sound pressure and at the frequency of 200 Hz. However, the response was not so sensitive as behavior disturbance. Duration of sound projection had little effect on the behavioral disturbance.


While ascending streams from the sea to the upper river, the fry of ayu (*Plecoglossus altivelis*) has a strong anadromous character and shows jumping response not only to water falls but also to underwater sound. Generally, the auditory sensitivity of fish has been studied with electrophysiological or psychophysical experiments. It may also be possible to study it by the behavioral observation of the jumping response of the fish to underwater sound. From these observations,
the following results were obtained: (1) The most sensitive frequency of the fish to underwater sound was about 200 Hz. However, the sensitivity of the fish was not clear above 600 Hz. (2) The lowest threshold level of underwater sound for jumping response was 72 dB (re 1 μPa) at a frequency of 200 Hz. (3) The numbers of fish responding to the sound pressure were distributed following a normal curve in the range of 70 to 80 dB (re 1 μPa).


Acoustic signals emitted by the gudgeon (Gobio gobio) are described and the context of sound production is considered. In aquaria, gudgeons produce creaking sounds of differing duration, which are always built up of single bursts. Each burst is composed of a series of rapidly repeated short pulses. Vocalization is correlated with the level of activity: it increases at higher temperatures and decreases when fish are disturbed. After acclimatization to the aquarium, fish which formerly showed a diurnal pattern of activity became active at all times of the day and night. Gudgeon called as a reaction to digging by other members of the group and a variety of disturbances.


The averaged auditory evoked response of roach, (Rutilus rutilus) was monitored, in the acoustico-lateralis region of the medulla, in response to sounds of frequencies between 60 and 1000 Hz. When the fish was held in air, the responses were greater than when held in water. Deflation of the swimbladder reduced the magnitude of the evoked response, an effect reversed by reflation. Hyperinflation also reduced the response, especially to sounds of low frequency. It is suggested that the swimbladder of fish of this species is normally in the optimum condition for sound reception and it is the swimbladder wall which acts as the primary resonator, not the gas column within it.


The averaged evoked responses of the medullary and anterior tectal surfaces of roach (Rutilus rutilus) were recorded to 64 "click" stimuli. The medullary response of five peaks and the single tectal peak showed no change in latency or duration when non-auditory stimuli were presented. The medullary response amplitude was increased by presenting a moving shadow or dilute chemical solutions to skin or nares, yet reduced by water similarly applied, vibration or a flashing light. Tectal response amplitudes increased with the presentation of a moving shadow, flashing light or chemical solutions. The adaptive functions of cross-modality inhibition and facilitation were discussed.


The habituation of fright and arousal responses of goldfish (Carassius auratus) and roach (Rutilus rutilus) to the repeated operation of a plunger in the water was studied. The early response was of fright, which habituated, and the response characteristic of arousal appeared, which then habituated as well. Longer intervals between stimuli required more presentations of the stimulus for habituation to occur in goldfish. Roach required more presentations of the stimulus than goldfish for the responses to habituate, and telencephalic ablation severely impaired habituation of arousal, though not fright responses, in this species. The results are discussed in relation to recent work on arousal, habituation, and telencephalic function in fish.


Behavioral arousal and fright and their physiological correlates have been extensively studied in domesticated cyprinids. In these fish arousal is associated with slight changes in orientation or an increase in stabilizing movements. Novel stimuli may elicit arousal or the more violent response of fright. This escape response consists in cyprinids of a rapid lateral flexion of the tail or tail-flip. Both arousal and fright habituate in cyprinids, and if the initial responses are of fright then these habituate to be replaced by arousal, which itself habituates. Halichoeres bivittatus is a diandric protogynous hermaphrodite, its reproductive biology has been extensively studied. The labrids are extremely active and alert fish and
this makes them ideal subjects for testing the generality of descriptions of behavioral arousal and fright, and the motor components of these responses.


The acoustic startle response in rats shows both short-term habituation, which recovers in seconds or minutes, and long-term habituation, which is effectively permanent. Lesions of the cerebellar vermis significantly attenuated long-term habituation without affecting the short-term process or altering initial response levels. In this response system the cerebellar vermis is part of an essential circuit for long-term habituation.


Calls of the scorpaenoids fish, Sebasticus marmoratus, were classified into single knock sound and a train of knock sounds each of which lasts for about 100-160 msec followed by a silent period of 200-500 msec. Each knock sound was made of a frequency component of less than 1 kHz. The fish emitted vigorous calls for about one or two h at dawn and dusk. Little remarkable seasonal variation in the occurrence of the sounds emitted was observed. The calls which were used mainly to threaten away invaders, were made by a contraction and relaxation of the sonic muscle, and amplified by the swim-bladder. The peak frequency of a call was decided mainly by the cycle of contraction and relaxation of the sonic muscle and secondly by the length of the swim-bladder.


The suitability of the lateral line system of fish and aquatic amphibia for the detection of planktonic prey was examined in the Antarctic fish Pagotenia borghrevinki (family Nototheniidae). The best response of primary afferent lateral line neurons to waterborne vibrations were recorded at frequencies within the range of those produced by swimming crustacea. Simultaneous recordings from a swimming zooplankter held close to the fish and from primary afferent neurons provided direct confirmation that swimming movements of crustaceans are a potent natural stimulus of the lateral line system.


The authors propose a method for determining the resonance frequencies of sound-scattering layer (SSL) fish swimbladders based on the ratio of the acoustic signal spectrum scattered by the sound-scattering layer to the sounding signal spectrum. Results are given for an experiment undertaken in the northeastern Tropical Pacific Ocean. Resonance frequencies for SSL fish swimbladders have been determined, the volume of the fish swimbladders has been calculated, fish lengths and concentration have been estimated, and three size groups of resonant scatterers have been distinguished. A decrease in the scatterer resonant frequency was recorded just before the morning descent of the SSR, apparently caused by the fish "pumping" their swimbladders. One group of fish migrated in the "constant volume" regime and another in the "constant mass" regime.


Following a definition of communication, a framework is presented upon which analyses of communication could develop in the future. Application of the framework to sound communication in fish is discussed, considering signalling predators, signalling prey, signalling prospective mates, signalling companions and signalling competitors; application to sound interception is also discussed.


Acoustically mediated individual recognition has been demonstrated in the field by males of the bicolor damselfish Pomacentrus partitus Poey. Playbacks of non-resident sounds from a given fish's territory elicited a greater response from its nearest neighbour than playbacks of the resident's sound - in accordance with the predictions of the "dear-enemy" effect. Testing also included switching the sounds of the two nearest neighbors relative to each respective male's territory. Results demonstrated that all males in the colony individually recognized the sounds of their two nearest neighbors.


Field evidence has demonstrated that free-ranging females of the bicolor damselfish, Pomacentrus partitus, use the courtship sounds of conspecific males to locate male nest sites during the spawning period. Evidence is also provided that females can distinguish, not only between such sounds and similar sounds on the reef, but also between courtship sounds of different conspecific males, the latter indicating a role in mate assessment by the acoustical modality.


The calls of the Japanese parrot fish, Oplegnathus fasciatus consist of a pulse or a series of pulse sounds. The calls were divided into three patterns by the method of pulse sound projection, namely single popped call, complex popped call and repeated popped call. Each pulse sound was made of a frequency component from less than 30 Hz to about 1 kHz. The duration of the pulse sound was usually 13-20 msec. In the complex popped call, the interval between each pulse sound was 11-367 msec. In the repeated pulse call, the repetition rate of each pulse sound was from 0.5 to 1.4 per second. The frequency of sound emitting became high before and after sunrise and sunset. Vigorous calls were emitted during the spawning period. The calls, which are mainly used for threatening invaders, are made by the rapid movement of the operculum and amplified by the swim-bladder.


The authors provide a general outline of what is known about hearing in fishes, and to identify what they consider to be some of the most interesting and pressing questions that could occupy their research efforts for the next several years. While it is tempting to form generalizations concerning fish audition, it is likely that there is no such thing as "the" fish ear or hearing capabilities in "the" fish. Furthermore, it is not even clear that individual otolith organs have the single roles ascribed to them in the earlier literature.


This paper considers various aspects of the anatomy and ultrastructure of the actinopterygian ear and makes a number of suggestions on the possible adaptive significance of the structural specializations. The focus of the arguments is based upon the substantial inter-specific variation in teleost auditory systems as measured anatomically, behaviorally, and physiologically. It is potentially of considerable significance that the major points of inter-specific variation in the teleost ear are associated with the gross morphology and ultrastructure of the otolithic organ most often implicated in sound detection, the sacculus.


In order to determine unambiguously the bearing of a sound source, a fish must be able to resolve acoustic pressure and the components of the acoustic displacement vector from the signals detected by the otolithic organs. A new hypothesis for the processing of acoustical information by bony fish is presented. It is demonstrated that much of the processing required to do this may be implicit in the structure of the ear and its associated neural innervation.

Saidel, W.M., and A.N. Popper. 1983. The saccule may be the transducer for directional hearing of nonostariophysine teleosts. Exp. Brain Res. 50:149-152.


A review is presented of experiments investigating the functions of the lateral line in fish. Sensitivity to local water movements, surface waves and low frequency sound is considered. Results confirm electrophysiological data showing the trunk lateral line to be an extremely sensitive vibration detector.


In order to construct models of fish acoustic localization systems the principle is used that the mechanism for acoustic localization must be adapted to take advantage of the modes of wave propagation in the fish's environment. Before examining models of wave propagation in the environment of the fish, a summary of the important concepts and results of the model building is presented. How the sound reaches the fish in the habitat and subsequently how the external sound variables relate to the internal vibratory quantities that activate the hair cells are considered.


The authors describe the behavioral responses of net-penned Pacific herring (Clupea harengus pallasii) to a variety of tape-recorded sounds. Sounds recorded in the field from a herring fishing fleet included moving and stationary (idling) vessels, sonar, echo sounder, and deck gear. Natural sounds included rain on the water surface, gull (Larus spp.) cries, killer whale (Orcinus orca) vocalizations, barks of Steller's sea lions (Eumetopias jubatus), and sounds made by herring themselves. Sounds of more uniform structure were created with an electronic synthesizer and played back to herring to determine the relative effectiveness of various combinations (triads) of amplitude and frequency (increasing, decreasing, constant) and temporal pattern (continuous, regularly, or irregularly pulsed tones).


To identify the neurotransmitter released by sensory hair cells, as well as to find other substances that might influence neural function of the inner ear, the authors have prepared extracts from inner ears of fishes (which have large numbers of hair cells), fractionated the extracts, and studied the effects of the fractionated extracts on the discharge rate of afferent fibers innervating hair cells in the lateral line organ of the African clawed frog Xenopus laevis. The extracts contain active substances. Some extracts also contain a high-molecular-weight inhibitory substance.


Blind Mexican cave fish were trained to discriminate between grids of vertical bars placed at various distances from each other. Discrimination was possible only if the freely swimming fish was allowed to glide past the grids in close proximity.


TEMPERATURE


The authors tested the influence of temperature and water velocity on metabolic rate and swimming performance of lake whitefish (*Coregonus clupeaformis*) and cisco (*C. artedii*) using respirometry techniques. Tests were conducted at 5, 12, and 17°C (speed range 20-102 cm s\(^{-1}\)) for lake whitefish and at 12°C (speed range 20-63 cm s\(^{-1}\)) for cisco. The net aerobic cost of swimming, obtained by subtracting standard from total oxygen consumption, was twice as high for cisco as that for lake whitefish at any swimming speed. However, the standard metabolic rate of lake whitefish was almost the double that of cisco acclimated to the same temperature. Results support the hypothesis that the combined effect of high water velocities and low ambient temperature on cisco's metabolism and swimming performance may be a more important factor than specific spawning temperature in the timing of the early reproductive migration of anadromous ciscoes.


Feeding and growth experiments on Nechako River and Big Qualicum River Chinook juveniles were conducted for 28 days at temperatures from 16°C to 24°C (Nechako) and 14°C to 25°C (Big Qualicum). On maximum daily ration, optimum temperature for growth was approximately 19°C, above which feeding and growth decreased particularly above 22°C. Mortalities reached 64% at 25°C, in agreement with earlier studies on lethal temperatures. In comparison with Qualicum chinooks, Nechako juveniles had a lower growth rate and food conversion efficiency at all but the highest temperatures.


Zebrafish Danio (*Brachydanio rerio*) were spawned and their eggs and larvae were reared in a simulated natural thermal regime, increasing from 21 to 30°C for 7 h and decreasing to 21°C for 17 h, daily. Burst-swimming performance was provoked by electrical stimulation of larvae. Distance travelled in a specified time (S\(_i\)), maximum velocity, and maximum acceleration increased with temperature. Size-specific maximum velocity was considerably higher than previously reported for larvae. A predictive model relating S\(_i\) to temperature was developed.


Atlantic salmon parr and brook trout were observed in stream tanks at the Matamek Research Station, Quebec. In the autumn, at 10°C Atlantic salmon parr began sheltering in rubble, and at 9°C the majority had disappeared into hiding.
Brook trout also had this tendency to hide at cold temperatures, but not as strongly as the salmon. In slow water flows (<5 cm/s), Atlantic salmon parr tended to hide in the rubble substrate at any temperature, and aggression decreased. In both slow and faster water velocities during summer and autumn the commonest agonistic act by Atlantic salmon parr was 'charge and chase.' Brook trout in July showed 'nip' as the commonest agonistic act, but in September and October 'approach' and 'charge and chase' were more common, possibly due to aggression associated with spawning. Shade was attractive to both species in shallow water, but given the choice of a shallow (30 cm) tank with a shade cover, and a deeper (50 cm) tank with no shade, the majority of brook trout and Atlantic salmon selected the deeper tank. In one experiment in a shallow-water tank, turbulent water surface was more attractive to Atlantic salmon parr than shade.


This paper presents a modified electronic shuttlebox for studies of behavioral thermoregulation in fish. The apparatus incorporates continual water replacement, the water temperature being controlled by the fish. Such a design facilitates long-term studies, with or without a chemical agent. Additionally, the absence of a temperature gradient permits strict response-conditioning experimentation. Fingerling rainbow trout (Salmo gairdneri) maintained a mean temperature of 18.1 ±0.6°C, thermoregulating with a degree of regularity and precision similar to the findings of other workers using different devices. Fish have been able to successfully thermoregulate in this apparatus for periods of up to 6 weeks.


Growth and survival of chinook salmon (O. tshawytscha) during the transition to active feeding were examined in relation to the timing of initial food presentation at 6, 8, 10 and 12°C. The transition to active feeding in these salmon involved a period of "precocious feeding" during which ingestion of food had no effect on fish size, growth rate, or survival. Initial utilization of food for growth and survival did not coincide with any specific stage of development, but rather it occurred earlier and at a less mature stage of development at higher temperatures. Delays in initial food presentation beyond this point reduced fish size and survival. Temperature and the timing of initial food presentation interacted to create a zone of optimum feeding. Biomass production was maximized when alevins began to feed within this zone, independent of the precise time of initial food presentation or temperature. This optimum feeding zone existed at temperatures below 12°C, between 905 thermal units (TU) postfertilization and a point (F, TU) which varied with temperature (T, °C) as F = 1201.1 - 20.3 T.


Clear-cut logging of 41% of the basin of Carnation Creek, British Columbia, resulted in increased stream temperatures in all months of the year. Increases above prelogging temperatures ranged from 0.7°C in December to 3.2°C in August. Earlier emergence of coho salmon (Oncorhynchus kisutch) fry associated with temperature increases lengthened their summer growing season by up to 6 wk. Fingerlings were significantly larger by the fall in the years after logging compared with the years before logging. The increased size of fingerlings was associated with improved overwinter survival. Following logging, yearling smolt number doubled, although 2-yr-old smolt number decreased. The life history model is used to quantify the effect of stream temperature changes related to logging on the population size of adult coho salmon. The predicted effect of those temperature changes was a 9% increase in adult coho numbers prior to the fishery.


Using multiple regression models, the authors tested water temperature, water flow, cloudiness, and lunar cycle for significant correlation with the timing of the yearly descent of Atlantic salmon (Salmo salar) smolts in the Norwegian Imsa River, 1976-1983. Water temperature between 9 April and 16 May explained 91, 95, and 89% of the yearly variation in date of 25, 50, and 75% cumulative smolt descent, respectively. The regression models were not very sensitive to variations of
the date of the start or stop of recording of temperature. The start of the yearly smolt run was not triggered by a specific water temperature or a specific number of degree-days, but was controlled by a combination of temperature increase and temperature level in the river during spring. There was no significant correlation between smolt descent and any of the other environmental variables tested.


A mathematical model relating mean survival times of samples of fish at lethally high temperatures was developed. It permits the estimation of upper incipient lethal temperature (UILT, °C) from the results of short-term experiments. Application of the model to data sets obtained from the literature yields "predicted" UILTs usually within 0.5° and almost always within 1 degree of observed values. The model was also applied to determine threshold toxicities (LC50, 144 h) of copper ion from tests of shorter duration.


The authors determined the time of adjustment of buoyancy of juvenile hatchery-reared Atlantic salmon (S. salar) and investigated whether if their higher position off the substratum, compared with wild fish, might better result from a higher buoyancy. In flowing water, hatchery-reared Atlantic salmon adjust their buoyancy within 24 h. No difference in buoyancy exists between juvenile hatchery-reared and wild Atlantic salmon in still water. However, juvenile hatchery-reared Atlantic salmon are more buoyant in flowing water than wild Atlantic salmon. Even after 3 mo in a stream, the buoyancy of juvenile hatchery-reared Atlantic salmon did not change. Acquired hatchery behavior appears to be responsible for their difference in buoyancy.


The ability of wild and hatchery yearling Atlantic salmon (Salmo salar) to hold a position against water currents was tested in relation to water temperature and season. This species would not swim, but held positions on the bottom of the test apparatus. Their performance was, therefore, rated on the basis of critical holding velocity instead of critical swimming velocity, often used for other species. Qualitatively, the relationships of critical holding velocity with both temperature and season were similar for wild and hatchery fish. However, wild fish were consistently more able to hold positions against water currents so that the mean water velocities at which they were unable to stem water currents were 25-84% greater than those for hatchery fish. The sharp decrease in performance at 8°C explains the previous observation that this species suddenly moves into the stream bed when temperature falls during the autumn.


Effect of temperature and growth on smoltification of underyearling masu salmon (Oncorhynchus masou) was studied using six different temperature regimes. Fertilized eggs were placed at three different temperatures, 9°C, 12°C, and 15°C till hatching in late September, and the hatched-out fry were reared under the same conditions until late March, and then each treatment group was divided into blocks. Fish of the first blocks were reared at 9°C and the second blocks were reared at about 15°C until early July. The percentage of smolt observed in these groups by the end of the rearing period were as follows: 9-9°C, 0% 12-9°C, 57% 15-9°C, 79% 9-15°C, 0% 12-15°C, 0% 15-15°C, 12%. Average body length of smolt in 15-15°C was largest, followed by that of 15-9°C and of 12-9°C in decreasing order. These results indicate not only that growth is stimulated by rearing at a high temperature in the early stage, but also that other factors such as cold water treatment may be necessary for more efficient smolt production.


Lower and upper lethal temperatures and measurements of volitional swimming speeds were determined for Scomber japonicus subjected to a progressive temperature change of 1 °C * d⁻¹. The mean lower and upper lethal temperatures were approximately 6 and 29°C, respectively. S. japonicus showed a significant positive relationship between temperature and swimming speed, within its range of thermal tolerance. There were no significant differences in swimming speed from 12 - 23°C. Significant differences were observed in swimming speeds between mid-day and late afternoon.


The physiological basis for well-known correlations between summer air temperature indices and year-class strength in northern smallmouth bass (*M. dolomieui*) populations was examined. Field and laboratory studies demonstrated the existence of 2 critical stages in early life when smallmouth bass are particularly vulnerable to features characteristic of many natural water temperature regimes. The first stage extends from fertilization until the young leave the nest; high mortality results from exposure to extreme temperatures. The second stage extends over the first winter, when the young subsist on accumulated energy reserves. Because the ratio of energy stored to basal metabolic rate increases with size, large fish can withstand winter starvation better than small fish. The results from these and other studies were incorporated into a deterministic model of the relations between temperature and 1st-yr survival of smallmouth bass. Analysis of water temperature time series data from many locations led to the development and parameterization of a stochastic model capable of simulating variations in water temperature characteristic of the littoral zones of typical North American lakes. The stochastic physical and deterministic biological models were used together to assess the effects on 1st-yr survival of changes in climate and of realistic changes in the magnitude and frequency of short-term temperature fluctuations. The model successfully predicted the observed northern limit of the species' range. It also generated approximate environmental criteria for judging when year-to-year variation in survival, over one or both of the critical life history stages identified, is likely to reach a level sufficiently great to determine the pattern of year-to-year variation in recruitment to the adult stock. The combined model was also used to assess the effects of thermal loading from a nuclear power plant on a particular population.


The relationship between temperature and standard metabolism in young Pacific salmon (*Oncorhynchus*) was studied. The temperature dependence of metabolism of young fish, long acclimatized to temperatures from 2 to 24°C, is well approximated by the exponential dependence $Q_{w} = Q_{0}e^{b_{1}T}$ and by the Arrhenius equation. For practical purposes, it is more appropriate and convenient to use the exponential relationship. The temperature coefficient $Q_{10}$ for juvenile fish of varying body weight is constant at 2.29 in the entire temperature range. The nature of temperature dependence in different species with varying body weight is similar. The dependence of oxygen consumption rate on temperature and body weight is approximated by the equation $Q_{10u} = 0.035W^{0.755} \pm 0.01e^{0.083 \pm 0.003}$ with the multiple correlation coefficient of 0.99. The published data on temperature dependence of metabolism in salmon and the reasons for various contradictions are discussed.


In an artificial stream channel, the distribution of juvenile coho salmon *Oncorhynchus kisutch* and chinook salmon *O. tshawytscha* at various water temperatures and average water velocities was monitored with respect to use by the fish of water velocities, cove objects, and a simulated side pond area in two successive years. Low water temperatures and, to some extent, increases in water velocity may be important stimuli for microhabitat shifts often reported in stream observations of juvenile salmonids during the fall-winter transition.


The effects of fluctuating diel temperature cycles on survival, growth, plasma cortisol and glucose concentrations, liver weight, and liver glycogen of juvenile coho salmon *Oncorhynchus kisutch* were determined. Temperature cycles (10-13°, 0-15°, 8-17°, and 6.5-20°C) were selected to simulate observed temperatures in clear-cuts of southeastern Alaska. Different levels of feeding, including starvation, were used in each of the tests. LT50s (peak temperature within a cycle producing 50% mortality) were 28°C for age-0 fish (350 mg) and 26°C for age-II fish (22-g presmolts). Cyclic temperatures for 40 d, averaging 11°C daily, did not influence growth of age-0 fish on any food ration as compared to controls held at a constant 11°C. Plasma cortisol and glucose concentrations were significantly greater in fish maintained for 20 d in the 6.5-20°C cycle but not different in fish in 10-13° and 9-15°C cycles or a constant 11°C. These elevated concentrations may be indicators of long-term stress.

Under raceway conditions, an advanced photoperiod schedule caused migratory movements and elevation in gill Na⁺-K⁺ adenosine triphosphatase activity (Na⁺-K⁺ ATPase) to occur about 1 month earlier than normal in yearling summer steelhead (Salmo gairdneri) from Dworshak National Fish Hatchery (Idaho). Exposure of migrants to 13°C for 20 d resulted in serious impairment of continued migratory behavior and a reduction of gill Na⁺-K⁺ ATPase activity. Migrants outnumbered nonmigrants at fork lengths of 16 cm and longer. It is proposed that the potentially detrimental effects of warming river temperature during the normal migratory season and delayed migration caused by dams and impoundments might be partially overcome by inducing early smolt transformation and migration with the use of advanced photoperiods.

**TURBIDITY**


The territorial, gill-flaring, and feeding behavior of juvenile coho salmon (Oncorhynchus kisutch) in a laboratory stream was disrupted by short-term exposure to suspended sediment pulses. At the higher turbidities tested (30 and 60 nephelometric turbidity units (NTU)), dominance hierarchies broke down, territories were not defended, and gill flaring occurred more frequently. Only after return to lower turbidities (0-20 NTU) was social organization reestablished. The reaction distance of the fish to adult brine shrimp decreased significantly in turbid water (30 and 60 NTU) as did capture success per strike and the percentage of prey ingested. Implications of these behavioral modifications suggest that the fitness of salmonid populations exposed to short-term pulses of suspended sediment may be impaired.


Some water quality standards established by the states permit only minor increases in suspended sediment when background turbidity is low, allow greater absolute increases as background levels rise, and do not consider acclimation of stream biota to high turbidity. Juvenile coho salmon (Oncorhynchus kisutch) were subjected to experimentally elevated concentrations of suspended sediment and did not avoid moderate turbidity increases when background levels were low, but exhibited significant avoidance when turbidity exceeded a threshold that was relatively high (> 70 NTU) and was varied according to previous suspended sediment exposure.


Striped bass, Morone saxatilis, breed in water often affected by human activities that increase turbidity. Laboratory experiments were conducted to examine the effect of turbidity on the numbers and sizes of prey consumed by striped bass larvae during 25-min feeding trials. Larvae feeding on natural prey assemblages, primarily composed of copepods, consumed approximately 40% fewer prey in suspended solids concentrations of 200 and 500 mg L⁻¹ than in 0 or 75 mg L⁻¹. In contrast, larvae feeding on Daphnia pulex captured the same average number of prey at all suspended solids concentrations tested. Turbidity also had no effect on the size of copepods or D. pulex eaten.


The influence of red-clay turbidity on behavior and distribution of brook trout, Salvelinus fontinalis, and creek chubs, Semotilus atromaculatus, was measured in the laboratory. Creek chubs preferred highly turbid water (56.6 formazin turbidity units-FTU) over moderately turbid water (5.8 FTU) but brook trout did not show a preference. In moderately turbid water, both species were more active, and used overhead cover less, than in clear water. The results indicate turbidity may represent an important isolating mechanism that promotes production of creek chubs.

During 3 years of study of juvenile salmon outmigration from the middle reach of the Susitna River, a correspondence was noted between peaks of river discharge and peaks of outmigration. Two large hydroelectric dams proposed for a region above the salmon-rearing areas would markedly change the downstream discharge, temperature, and turbidity regimes. Box-Jenkins models were developed for the 1983 and 1984 time series of river discharge, turbidity, outmigration rates of *Oncorhynchus tshawytscha* and *O. nerka* fry to better understand the forces that shape the series and to statistically describe natural conditions. About 74% of the variance in discharge and 85% of the variance in turbidity for one day were explained by the values of each on the previous day. This percentage was 44% for chinook salmon outmigration and 43% for sockeye salmon outmigration the lower numbers indicated the effect of behavioral decisions on biological time series.


Chronic turbidity in streams during emergence and rearing of young anadromous salmonids could affect the numbers and quality of fish produced. The authors conducted laboratory tests to determine the effect of chronic turbidity on feeding of 30-65 mm long steelheads *Salmo gairdneri* and coho salmon *Oncorhynchus kisutch* in straight and oval channels. Fish subjected to continuous clay turbidities grew less well than those living in clear water, and more of them emigrated from channels during the experiments.


**CASE STUDIES**


Anonymous. 1977. Snake and Columbia are horrible example. Western Fisheries. 94(5):1927-29.

Before dams were constructed on the Snake and Columbia rivers, juvenile chinook salmon and steelhead trout migrated to the ocean in early spring and summer under natural conditions. Water flow was high, water temperatures were favorable, turbidity sufficient for protection from predators, and there was little slow-moving water to delay the migration. This environment has been changed drastically by the construction of the dams. Fingerlings on their journey are subject to high mortality from passing through turbines, predation in tailraces and nitrogen supersaturation resulting from spilling at the dams. Delay is also caused by reduced water velocity. This paper examines some data on quantities of salmon and trout migrating in the river over the past 6 years, and briefly considers some work in progress intended to minimize losses at turbines, the use of intermediate dams and by-pass systems. Flow control is also discussed. It is recognized that there are conflicts between users of this water system, particularly from irrigators and fishery scientists.


The annual Smolt Monitoring Program is the result of implementation of Section 304(d)(2) of the Northwest Power Planning Council Fish and Wildlife Program. This is the second year of the annual systemized program conducted by the Fish Passage Center (formerly Water Budget Center). Index reaches have been established. Travel time indices are calculated for year to year comparison. Marked groups of steelhead, spring chinook, fall chinook, and summer chinook are monitored at sampling points throughout the system. Because this program is intended to be representative of the juvenile migration, marked groups represent major hatchery production stocks. Arrival time and duration of marked groups are reported. Annual travel time indices are reported from Rock Island Dam to McNary Dam, and from Lower Granite Dam to McNary Dam. Hatchery and brand release information is reported.


This report presents the results of post-seasonal analyses including timing and relative magnitude of the outmigration, travel time for marked hatchery releases, and survival in mid-Columbia and lower Snake River index reaches. Travel time of marked yearling and sub-yearling chinook salmon (Oncorhynchus tshawytscha), sockeye salmon (Oncorhynchus nerka), and steelhead trout (Salmo gairdneri) is measured between specific sampling points in the system. Marked groups usually represent major hatchery production stocks. Survival estimates are computed for specific spring chinook and steelhead marked groups. Arrival time and duration of outmigration of the chinook, sockeye, coho (Oncorhynchus kisutch) and steelhead runs are reported at key sampling points. Hatchery and brand release information for 1986 is also listed.


Smolt Monitoring Program Annual Report, 1986, Volume I, describes the results of travel time monitoring and other migrational characteristics of yearling and sub-yearling chinook salmon (Oncorhynchus tshawytscha), sockeye salmon
(Oncorhynchus nerka), and steelhead trout (Salmo gairdneri). This volume presents the data from Fish Passage Center freeze brands used in the analysis of travel time for Lewiston, Lower Granite, Lower Monumental, Rock Island, McNary, and John Day dams. Summary of data collection procedures and explanation of data listings are presented in conjunction with the mark recapture data. Data for marked fish not presented in this report will be provided upon request. Daily catch statistics (by species), flow, and sample parameters for the smolt monitoring sites, Clearwater, Lewiston, Lower Granite, Lower Monumental, Rock Island, McNary, John Day, and Bonneville also will be provided upon request.


The stress response of chinook salmon and steelhead trout smolts to passage through three different flumes was tested by assaying plasma cortisol concentrations before and after flume passage. In addition, de-scaling of fish was recorded before and after flume passage, and the ability of the flumes to pass adult chinook salmon and debris was determined. The three flumes were a corrugated metal flume (CMF), a 4-foot wide baffled flume (BF4), and a 2-foot wide baffled flume (BF2). Each flume was tested under conditions: 1) at night, 2) during the day with a perforated metal cover, which reduced the amount of light entering the flume by about half (partially darkened), and 3) during the day with the perforated cover and additional double layer of black plastic (completely darkened). Plasma cortisol concentrations were not significantly elevated in chinook salmon smolts after passage through any of the flumes (P>0.2, ANOVA). In daytime tests of partially and completely darkened flumes cortisol concentrations were consistently decreased following flume passage. We attribute this to pre-test stress (holding of fish in small tanks) and to the absence of a strong stress response to flume passage. Flume design did not have a significant effect on cortisol concentrations (P=0.9). Total darkening of the flumes during daytime was beneficial: cortisol concentrations were lower (P=0.03) in chinook salmon smolts passing through completely darkened flumes than in smolts passing through partially darkened flumes.


Juvenile salmonids collected at dams on the Snake and Columbia Rivers (Oregon and Washington USA), require separation by size prior to transportation. A method of separating most of the smaller downstream migrating juvenile Pacific salmon, *Oncorhynchus* spp., from the larger steelhead, *Salmo gairdneri*, at hydroelectric dams is described. The device utilizes behavioral responses that allow fish to remain in water during the separation process. This system is presently being installed at collector dams on the Columbia and Snake River.


Several hydroelectric dams in the Snake-Columbia river system are equipped with submersible traveling screens that project into the turbine intakes. The screens are designed to divert juvenile migrant Pacific salmon *Oncorhynchus* spp. and steelhead *Salmo gairdneri* from the intake upward into gatewells and the adjoining central bypass system. Assays of gill Na$^+$-K$^+$-ATPase were performed on yearling chinook salmon *O. tshawytscha* collected during several routine fish guidance efficiency tests in 1985 and 1986. Data suggest there is a relationship between the physiological status of smolting yearling chinook salmon and their susceptibility to guidance by traveling screens. Assessments of salmonid out-migrations may be biased if they are based on samples from traveling-screen guidance systems.


This study was initiated to determine the extent of predation by resident populations of native and introduced fish on juvenile salmonids in main stem Columbia River Reservoirs. The John Day Reservoir and tailrace was selected as the study area. Results indicated that juvenile salmonids were consumed by all four predatory fish species studied: northern squawfish (*Ptychocheilus oreognenesis*), walleye (*Stizostedion vitreum vitreum*), smallmouth bass (*Micropterus dolomieu*), and channel catfish (*Ictalurus punctatus*). However, degree of predation varied among predators as a function of spatial distribution, apparent abundance size, and temporal feeding behavior.


The behavioral response of juvenile chinook salmon, *O. tshawytscha*, to vertical trash racks having interbar spacings ranging from 5.1 to 30.5 cm is reported. Experiments were conducted in a laboratory channel with an average water velocity of 32 cm/sec under light intensities of 14.0 and 1.0 x $10^{-2}$ footcandles. Transit times were not significantly different between light levels, but differences between bar spacings were significant. Observed changes in rheotaxic posture and
hesitancy to pass through a trash rack with bar spacing less than 15 cm would increase the susceptibility of juvenile fish to predation.


In 1977 the River Skjoma was regulated in such a way that the elevated parts of the water shed were eliminated, which caused increased water temperatures and reduced silt transportation in summer. After reduction of the water flow, the density of presmolt salmonids increased from approximately equals 8 fish/100 m² to approximately equals 30 fish/100 m². The increase of the proportion of salmon from 40 to 60 in the period from 1976 through 1980 is likely due to method used. The productive area of the river was reduced by approximately equals 2/3 in the same period. In the weir magazines, trout (Salmo trutta) became the dominating species, while salmon (S. salar) dominated at the river stations. The growth of presmolt salmon and trout increased by 1.5-2.0 cm for each year-class in the period from 1978 through 1980. This was mainly due to the increased water temperatures, which were caused both by the hot summers in 1978 and 1979 and the elimination of the elevated, cold tributaries.


Juvenile salmonids were monitored on their seaward migration at Lower Granite, McNary, and John Day Dams: sampling at these sites provided data primarily for evaluation of smolt survival, travel time, and migrational timing. At Lower Monumental Dam catch data was to provide a general indication of smolt passage and comparison with the hydroacoustics passage index.


The 1986 smolt monitoring project provided data on the seaward migration of juvenile salmon and steelhead at Lower Granite, Lower Monumental, McNary, John Day, and Bonneville Dams. The number of fish sampled by species, brand recaptures, and pertinent flow data were provided for the purpose of evaluating smolt survival, travel time, and migrational timing.


A study of wild spring chinook salmon was conducted in the John Day River, Oregon: (1) recommend harvest regulations to achieve escapement goals in the John Day River; (2) recommend adjustments in timing of fish passage operations at Columbia River dams that will increase survival of John Day migrants; (3) recommend habitat or environmental improvements that will increase production of spring chinook salmon; (4) determine escapement goals for wild spring chinook salmon in the John Day River; and (5) recommend procedures for hatchery supplementation in the John Day River in the event it becomes necessary to artificially maintain the run of spring chinook salmon. Juveniles were captured as smolts during migration and as fingerlings during summer rearing. Juveniles were coded-wire tagged, and recoveries of tagged adults were used to assess contribution to ocean and Columbia River fisheries, timing of adult migrations through the Columbia River in relation to fishing seasons, and age and size of fish in fisheries. Scoop traps and seines were used to determine timing of smolt migrations through the John Day River. In addition, recoveries of tagged smolts at John Day Dam, The Dalles Dam, and Jones Beach were used to determine migration timing through the Columbia River. We examined freshwater life history of spring chinook salmon in the John Day River and related it to environmental factors. We looked at adult holding areas, spawning, incubation and emergence, fingerling rearing distribution, size and growth of juveniles and scales. Escapement goals for the John Day River as well as reasons for declines in John Day stocks were determined by using stock-recruitment analyses. Recommendations for hatchery supplementation in the John Day River were based on results from other study objectives.


Vertical swimming responses of 2-year-old rainbow trout Salmo gairdneri were tested with air saturated and air supersaturated water in tank experiments. The level of supersaturation varied between 115 and 125% total gas pressure. No consistent vertical avoidance response was observed in the fish tested, but the mortality of fish restricted to the upper 30 cm of the tanks was significantly greater than fish free to sound to the whole depth of the tanks. It is concluded that the Norwegian stock of rainbow trout do not avoid air-supersaturation at levels from 115 to 125% TGP by active hydrostatic pressure compensation.


Emigrating juvenile salmonids are collected at McNary Dam on the Columbia River and transported past the three downstream dams to avoid mortalities caused by passage through power-generating turbines. During the 1982-1984 seaward migrations of juvenile fall and spring chinook salmon Oncorhynchus tshawytscha, authors used an array of physiological measurements (plasma cortisol and glucose, white blood cell counts) and challenge tests (saltwater challenge, secondary stress, and swimming endurance) to identify the stressful elements in these activities. Although there were no significant differences in responses of fish collected at various times during the migrations, apparent differences between the responses of fall and spring chinook salmon suggested that the latter were more sensitive to the stresses of collection.


The report describes the travel time of marked yearling and sub-yearling chinook salmon (Oncorhynchus tshawytscha), sockeye salmon (O. nerka), and steelhead trout (Salmo gairdneri) between points within the system, and reports the arrival timing and duration of the migrations for these species as well as coho salmon (O. kisutch). A final listing of 1984 hatchery releases is also included.


The effects of instream river flow on the passage time, survival, and migrational behavior of juvenile fall and summer (O-age) chinook salmon in John Day Reservoir is being studied. In 1983, the final year of juvenile sampling in the reservoir, research activities continued to refine flow/travel time relationships and distributional behavior of O-age chinook salmon. Fifteen groups (72,559 fish) of marked O-age chinook salmon were wire-tagged, branded, and released into the tailrace at McNary Dam, and thirty-two groups (22,206 fish) were branded and released into the reservoir at various other sites. Sampling at John Day Dam, utilizing the airlift pump system in the B and C slots of Turbine Intake Unit 3, captured 82,698 subyearling chinook salmon including 640 mark recoveries. Additional marks (458) were recovered from purse seine samples taken at various sites throughout the reservoir. Weekly mean fork lengths of O-age chinook salmon captured at McNary and John Day Dams and in the reservoir by purse seine ranged from 103 mm in mid-June to 166 mm in mid-December. Fish captured at the John Day Dam monitoring facility and by purse seine throughout the reservoir were in excellent condition. Preliminary analysis of stomach samples taken in 1982 and 1983 from purse seine catches indicates active feeding is taking place. The average passage time of the fastest moving marked O-age chinook salmon from McNary Dam to John Day Dam was 11 days (based on 25th percentile of mark recaptures). The average reservoir residence time was 22 days. Regression analysis was used to develop a description of the relationship of river flow to the rate of downstream movement of O-age chinook salmon in John Day Reservoir in 1983. The slope of this line and the correlation coefficient (R) were not significantly different from zero. (ERA citation 10:045152)


As part of a study to define the effects of instream flows on the passage time, migration behavior, and survival of chinook salmon migrating through John Day Reservoir from June through August juvenile fish were tagged and released below McNary Dam in 1981. This report discusses adult returns through 1984.


Juvenile fall chinook salmon, Oncorhynchus tshawytscha, were freeze branded, coded wire tagged, and released into the Columbia River in the tailrace below McNary Dam during the summers of 1981-1983. The objectives of the study were to examine the effects of river flow on the passage time and migrational behavior of the juveniles and to subsequently assess any relationship to adult survival. This report details adult recovery data to June 1987.
During the fall of 1984 and spring of 1985, 362,428 chinook salmon (Oncorhynchus tshawytscha) and steelhead trout (Salmo gairdneri) juveniles were freeze branded for Water Budget Center - Downstream Smolt Monitoring Studies. Of these, 106,361 fish received a coded wire tag. Release of the freeze brand groups began March 20, 1985 and were completed by June 4, 1985. After brand loss and mortality, there were 133,025 spring chinook, 25,630 summer chinook, 33,850 fall chinook, 65,125 A-run steelhead, and 62,400 B-run steelhead released with brands.


A review and synthesis of existing information were used to develop a Habitat Suitability Index (HSI) model and instream flow suitability curves for pink salmon (Oncorhynchus gorbuscha). The model consolidates habitat use information into a framework appropriate for field application, and is scaled to produce an index between 0.0 (unsuitable habitat) and 1.0 (optimum habitat).


Modes of downstream passage (penstock, spillway, diversion chute) by Atlantic salmon (Salmo salar) smolts were monitored using radio telemetry to assess the effectiveness of an angled trash rack/fish bypass structure at a small hydroelectric dam on the Boquet River, New York. Telemetry of 170 Atlantic salmon smolts and visual observations of stocked smolts were used to determine aspects of Atlantic salmon outmigration behavior. Smolts initiated mass migrations after river temperatures reached or exceeded 10 °C. Many radio-tagged smolts interrupted movements upon reaching ponded waters and/or the dam. River flow did not (P > .05) affect the frequency of migratory movements, passages, or rate of movement. Migrations were of approximately 30 days duration. Passages at the dam occurred primarily at night (61%) with diurnal passages (17%) and crepuscular passages (17%) of secondary importance. Timing of 5% of the passages was undetermined. All passages which occurred when angled trash racks were in place were through the bypass or over the spillway. Six (6) passages occurred when trash racks perpendicular to the penstock were in place: 3 of these were penstock passages. The angled trash rack and bypass structure served to reduce entrainment.


The downstream migration of salmon and steelhead in spring 1984 at Wells Dam on the mid-Columbia River was monitored using hydroacoustics. The primary objective of this research was to document run timing and describe the distribution of smolts at the dam. The study occurred from April 2 to June 15, 1984. Four transducers were deployed at the bases of pier noses at Turbines 3, 5, 7, and 9 and aimed up 24° into the forebay. They were sampled once every hour, 24 hours per day, for 75 days. An index of fish passage was reported daily to the Water Budget Center in Portland, Oregon. This index was computed as follows. For each 24-h period, separate fish passage rates (number/time) at each of the four sampling locations were estimated by dividing the sum of the "weighted" fish detections by total sample time. These four values were then averaged to produce the daily index (number/day/location). The first substantial increase in fish passage occurred on April 25, 1984 due to the chinook released from the Winthrop hatchery on April 23. During May, run timing was fairly uniform except for peaks on May 2, 14, 18, and 22. The unexpected peak in run size that occurred from May 29 to June 2 could have been caused by juvenile mountain whitefish. Although the proportion of each species varied, chinook passage probably peaked in late April, and steelhead in the first two weeks of May; sockeye passage was variable throughout the study. The data indicated that most downstream migrants were distributed high in the water column and toward the western end of the dam. Average hourly passage rates for day and night were similar, but more fish passed the dam during the longer period of daylight than the shorter period of darkness.


Trends in abundance of spring and summer chinook salmon Oncorhynchus tshawytscha and steelhead Salmo gairdneri returning to the Snake River and mid-Columbia River above Priest Rapids Dam were determined by analyzing the percentage of adults returning from the smolt-out-migrations of 1962-1984. Runs declined as a result of hydroelectric development of the river; the main cause for the decline was the mortality of juveniles migrating downstream through as many as nine dams and impoundments en route to the ocean. Enhancement measures to offset dam-related mortality of smolts began in 1970 on the Snake River and in 1975 on the mid-Columbia River. These measures included increased numbers of smolts released from hatcheries, spillway deflectors to reduce dissolved gas saturation, fingerling bypasses at dams, transportation of smolts around dams, supplemental river flows to minimize delay for smolts passing through reservoirs, and supplemental spill at dams to minimize turbine mortality of smolts at dam without fingerling bypasses. These actions have reversed the decline of steelhead but not of salmon.


After conversion of a lake, previously a part of a river system in Gwynedd, North Wales, to a pumped storage reservoir, salmon will be faced with a 2.2 km long diversion tunnel in order to reach parts of their former spawning grounds. The unlit tunnel is described, with notes on water velocities under various discharge conditions. A fish counter, mounted at the peak of the fish pass in the upstream (intake) weir of the tunnel, has indicated that, in the first spawning season following construction of the tunnel, numbers of adults have succeeded in negotiating tunnel and weir, despite the hitherto-assumed unattractive conditions of low velocity and complete darkness.

Consumption of migrating juvenile Pacific salmon Oncorhynchus spp. and steelhead Salmo gairdneri by gulls was estimated below the turbine area of Wanapum Dam on the Columbia River in 1982. The number of salmonids consumed by gulls ranged from 50 to 562 fish/h. Multiple-regression analysis indicates that the number of salmonids consumed by gulls is significantly affected by the passage rate of fish through the turbines and spillgates, and by light intensity. The number of salmonids consumed by gulls foraging below the turbines during 25 d of peak salmonid migration was approximately 111,750 to 119,250 fish or 2% of the estimated spring migration.


Proliferation of water withdrawals and new pump intake and screen designs had occurred with the growth of irrigated agriculture along the Columbia and Snake Rivers. Concern for the protection of anadromous and resident fish populations resulted in formulation of a survey of the water withdrawal systems. The survey included distribution studies of juvenile fish near pump sites and field inspection of those sites to determine adequacy of screening for protection of fish. A total of 225 sites were inspected in 1979 and 1980, with a follow-up inspection of 95 sites in 1982. Results indicated a definite trend toward lack of concern for the condition of fish protective facilities. Only 4 out of 22 sites not meeting criteria in 1979 had been upgraded to acceptable conditions. Of more concern, 13 of the sites meeting criteria in 1979 were below criteria when reinspected in 1982.


MISCELLANEOUS


A new tracking method of biotelemetry is described. The apparatuses used were composed of an acoustic transmitter (pinger), three sonobuoys, wireless receivers and two time-interval counters. The sonobuoys were designed to relay acoustic pulses from the pinger to a base station on land by wireless. These buoys were moored several hundred meters apart so as to form a triangle on the surface of the water. A fish carrying the pinger was tracked in the circumscribed circle of the triangle. The wireless signals from the buoys were caught with three receivers at the base station. The successive positions of the fish were calculated from the differences in the received times of the signals. The results of the tests showed that this method gives good positional information. It is possible to plot the successive positions of the fish on a X-Y plotboard with a computer.


The authors have developed a flexible, moderately priced, behavioral analysis system that has been used to determine the response of salmonids to certain olfactory stimulants. The system, which is called ITS for interactive computer-video tracking system, consists of a 128K Apple IIe computer with software, a video camera and videocassette recorder, and a special-effects generator. Experiments are video taped and then, during playback, the special effects generator is used to simultaneously display the video image and the graphics output of the computer on a monitor. The user tracks the animal of interest using an electronic pen, and the position of that animal in the test chamber, in the form of x-y coordinates, is determined by the computer at user-defined time intervals. In this paper the authors describe ITS and then demonstrate how it can be used to demonstrate that changes in ambient pH alter the behavioral response of juvenile Atlantic salmon to olfactory stimuli.