Fish Passage and Entrainment Protection 2

PART 1: ISSUES AND CONTROVERSIES

This chapter focuses on the need for fish passage and entrainment protection at Federal Energy Regulatory Commission (FERC)-licensed hydropower dams (see box 2-1). Hydropower-related habitat changes, habitat accessibility, and predation are discussed where they directly relate to the passage or protection needs of various fish species.

It is often unclear to what extent fish populations are affected by the impacts of blockage, entrainment, and turbine mortality associated with hydropower (71). Theoretically, considering the great diversity of fish species, hydropower dam designs, and river basin types involved, fish mitigation should be highly site-specific. In addition, the lack of information regarding the biology of some target fish may add further uncertainty to mitigation decisions (215).

This study focuses on two categories of obligatory freshwater fish, since these are the most common fishes that come in contact with hydropower facilities. The first category is the **riverine fishes** (the so-called *resident* or *non-migratory* species[1]) that cannot tolerate long-term exposure to salt water (108). These fishes include all of the freshwater species that use the river or stream as residence for their entire life. Such fish include the sunfishes, catfishes, minnows, suckers, perches, and many other families. The second category is the **anadromous fishes**, which are born in freshwater streams and rivers, migrate to saltwater for their adult phase, and return to freshwater to spawn (see box 2-2).

This chapter is divided into two parts. Part 1 is a discussion of the controversial issues concerning the need for fish mitigation at hydropower projects. The emphasis is largely on passage and protection for the riverine fishes, because at present this is where the most controversy is. Part 2 provides more technical information regarding experimental design for entrainment and turbine mortality studies.

Anadromous Fish Protection

The significance of delaying or blocking fish movements within rivers and the possibility of

[1] These two terms are highly controversial. The terms "non-migratory" and "resident" are often misinterpreted to mean that these fishes do not engage in biologically significant movements within the river basin. As a matter of biological terminology, these fish are perhaps best described as "freshwater dispersants." This term is used by zoogeographers to describe fish that have evolved in freshwater and that cannot disperse via marine routes due to their low tolerance for high-salinity water.

BOX 2-1: Chapter 2 Findings—Fish Passage and Entrainment Protection

- The need for entrainment protection and passage for riverine fish is very controversial. There is a growing body of evidence that some riverine fish make significant movements that could be impeded by some hydropower facilities. The need for passage for riverine fish is most likely species- and site-specific and should be tied to habitat needs for target fish populations. This will be difficult to determine without establishing goals for target species.
- The acceptability of turbine passage for anadromous fish is site-specific and controversial. There is major concern when anadromous fish must pass through multiple dams, creating the potential for significant cumulative impacts. Passage of adult repeat spawners is also a major concern for most Atlantic Coast species.
- The effects of turbine passage on fish depend on the size of the fish; their sensitivity to mechanical contact with equipment and pressure changes; and whether fish happen to be in an area near cavitation or where shearing forces are strong. Smaller fish are more likely to survive turbine passage than larger fish. Survival is generally higher where the turbines are operating with higher efficiency.
- Riverine fish are entrained to some extent at virtually every site tested. Entrainment rates are variable among sites and at a single site. Entrainment rates for different species and sizes of fish change daily and seasonally. Entrainment rates of different turbines at a site can be significant.
- Turbine mortality studies must be interpreted with caution. Studies show a wide range of results, probably related to diversity of turbine designs and operating conditions, river conditions, and fish species and sizes. Turbine mortality study design is likely to affect results. Different methods may yield different results.
- Methods for turbine mortality study include: mark-recapture studies with netting or balloon tags, and observations of net-caught naturally entrained fish, and telemetry. Methods for entrainment studies include: netting, hydroacoustic technology (used especially in the West), and telemetry tagging. These methods have advantages and disadvantages depending on target species and site conditions. Hydroacoustic technology and telemetry tagging can provide fish behavior information (e.g., tracking swimming location) useful for designing passage systems and evaluating performance.
- Early agreement on study design would help minimize controversies between resource agencies and hydropower operators. Lack of reporting of all relevant information makes it difficult to interpret results. Standardized guidelines to determine the need, conduct, and reporting of studies could help overcome this limitation.
- Mitigation by financial compensation is very controversial. The degree of precision necessary for evaluation studies and how fish should be valued are items of debate.

SOURCE: Office of Technology Assessment, 1995.

fish being injured or killed in turbines was rarely considered when hydropower dams were initially designed and built. However, stocks of some high-profile anadromous fish species such as Pacific salmon (157,162), Atlantic salmon (152,154,155,166), and American shad (155) have severely declined. These declines have been linked to a combination of environmental impacts, including hydropower dams, water diversion projects, cattle grazing, water pollution, and over-fishing. It is unknown which of these has had the greatest impact on fish stocks. However, it is widely agreed that the recovery of many of these socially and economically important fish species is in part dependent on providing safe and efficient passage around dams that have excluded them from historically critical habitat (155).

BOX 2-2: Fish Terminology and Life History Notes

Fishes Found At Hydropower Dams

Many different species of fish may come into contact with hydropower dams at various stages in their life cycles. Depending on the site, the species may range in size from a few centimeters to a few meters and display an astounding plethora of behaviors and life histories. Some species complete their life cycles entirely within the boundaries of freshwater rivers, streams, and associated lakes (riverine), while others move between marine and fresh water (diadromous).

In this report, fish that spend their entire lives in freshwater are referred to as **riverine**. This group includes sunfish, perch, gar, catfish, minnows, suckers, trout, paddle fish, bowfin, some sturgeon, herring, lamprey, and many others. The terms *resident* and *non-migratory* have also been applied to these fish, but can be misinterpreted to mean that such species do not engage in biologically significant movements within the river basin. The term riverine was specifically chosen for this report because it does not group fish together based on their movement patterns.

The hundreds of fish species included in the riverine category have such extremely diverse life histories that no generalizations concerning their propensity to make biologically significant movements can be made. Some riverine fish species may be quite mobile and others highly sedentary. In addition, their movement patterns may change from site to site (i.e., a species may be mobile in one river, and sedentary in another).

Some of the riverine fish may exhibit spawning migrations between lakes and rivers, or from one area of a river to another. This migratory pattern is referred to as **potamodromy**. Some common examples of fish that engage in potamodromous migrations include trout, sauger, mooneye, some redhorse, some suckers, some sturgeon,[a] some lamprey, etc.

Some fish exhibit specialized migratory patterns involving regular, seasonal, more or less obligatory movements between fresh and marine waters. This strategy is generally referred to as **diadromy**, and there are three distinct forms.

First, in some species, sexually mature adults migrate from the sea to spawn in freshwater streams/rivers and associated lakes. This migratory pattern is called **anadromy**. Examples of fish that engage in anadromous migrations are Pacific and Atlantic salmon, American and Hickory shad, Atlantic sturgeon, alewife, searun lamprey, etc.[b]

Second, sexually mature adults of some species migrate from freshwater streams/rivers and associated lakes to spawn in the sea. This migratory pattern is called **catadromy**. The most notable example of species that make catadromous migrations is the American eel.[c]

Third, some species make seasonal movements between estuaries and coastal rivers and streams. This migratory pattern is called **amphidromy** and is typically associated with the search for food and/or refuge rather than reproduction (149). Examples of fish that engage in amphidromous movements include striped mullet and tarpon.

Diadromy is relatively rare, represented by less than 1 percent of the world's fish fauna. Of the diadromous fish, anadromy (54 percent) is most common, followed by catadromy (25 percent), and finally amphidromy (21 percent). In the United States, anadromy is by far more common than catadromy or amphidromy.

As with every artificial classification scheme for organisms, some species will not fit neatly into the groups. Some species may have populations that would be classified as riverine and other populations that make anadromous migrations. For example, steelhead, rainbow, and Kamloops trout are three different types of the same species. Steelhead stocks are anadromous, rainbow stocks are riverine, and Kamloops stocks are lake-resident.

(continued)

BOX 2-2: Fish Terminology and Life History Notes (Cont'd.)

Life History Details

Riverine

The riverine fishes are an incredibly diverse freshwater group represented by nearly 1,000 species from over 40 families. The various species exhibit a multitude of life styles, and within its scope, this chapter could not begin to describe all of the diversity. The different species occupy virtually every kind of riverine habitat.

Unlike the diadromous fishes, the riverine species do not require a marine phase to complete their life cycles. The various kinds of habitats in the river (and associated lakes and streams) must meet all of the biological needs of these fishes. For instance, the river must provide habitats to hunt prey, hide from predators, engage in courtship, build nests, spawn, and over-winter. Quite often fish must use very different areas within a river to accomplish these activities. In addition, habitat requirements of most riverine fish species change with their size, age, and with the season. In order for their populations to survive, they must be able to access sufficient quantities of each important habitat type. For example, some species prefer deep pools with muddy bottoms and slow-moving water to feed and/or to seek refuge in, but require shallow riffles with pebbly bottoms in which to spawn.

Because of the sheer diversity within the riverine fish group and the unique (site-specific) conditions created by the interplay of different rivers with different hydropower designs, very few useful generalizations can be made concerning the potential impacts from hydropower dams on riverine fish populations. However, the distribution and abundance of the various riverine fish species in a given river reach can be altered by changes in the quantity and quality of macro- and/or micro-habitat. These changes will likely favor some species while selecting against others that lose access to crucial habitat.

Hydropower dams do alter the natural riverine environment to varying degrees and, in the process, often replace the original habitat types with different habitat types. For example, many hydropower dams create reservoirs which provide pool-type habitat. Bluegill, crappie, and largemouth bass which may have been rare or even absent in the river reach prior to damming, may become the dominant species in these reservoirs.

On the other hand, the populations of some species may be diminished, displaced, or even extirpated from a given river reach due to the changes in the environment up- and downstream of a hydropower dam. For example, fish species that prefer or require riffle-type habitat may disappear from reservoirs.

Some hydropower dams have turbine intakes that draw cold and clear water from near the bottom of their head ponds (hypolimnetic releases). These releases often change the pre-dam water flow, temperature, and turbidity patterns, as well as changing the topography of the river bottom. These tailwater conditions may support productive trout fisheries, even in a river reach where trout are not native and probably could not have survived prior to the hydropower facility.

Anadromy

Fish that exhibit anadromous migrations are born in freshwater streams and rivers and spend a period of time in their natal stream. At some point they begin a migration toward the ocean and then spend one to several years there. After a period of growing in the marine environment they migrate back to a river where they will ultimately spawn, thus completing the life cycle.

Various species of anadromous fish home in on their natal streams and rivers with different degrees of precision. There is also a great deal of variation in the distance upstream that they migrate and the kinds of freshwater spawning habitats they utilize, both within and among species. In addition, while some species, or some individuals within a species, may repeat the cyclic migration several times, others will die after one completed migration cycle.

(continued)

BOX 2-2: Fish Terminology and Life History Notes (Cont'd.)

Even with the incredible diversity and variation within this life style, these fishes all have at least one important thing in common: a need to enter freshwater to spawn and return to saltwater to feed and grow. This biological requirement is the reason that such species are highly vulnerable to impacts related to hydropower dams.

Hydropower dams may alter the quantity of spawning habitat for anadromous fishes. Adult upstream migrations are blocked by hydropower dams unless fishways are in place. If fishways are present, they must be designed to accommodate the biology of the target species and must be maintained properly, or migrations can be delayed. Juveniles and adults that are migrating downstream toward the ocean may be delayed in slack-water reaches of reservoirs or if they cannot locate a route past the dam. If the turbines are used as the migratory route, some fish will be injured and killed.

Catadromy

Catadromy is less common than anadromy in North America. In the United States, the American eel is the only catadromous species that has been well documented. In general, fishes that exhibit catadromous migrations require a fresh- and saltwater phase to complete their life cycles. They are known to migrate hundreds and even thousands of miles between their fresh and salt water habitats and, thus, are highly likely to encounter dams and other blockages. Catadromy is essentially the ecological opposite of anadromy.

These fishes migrate out of lakes and rivers into estuaries and finally to offshore marine waters where they will spawn. The juveniles migrate from the ocean to an estuary and eventually swim up the river. They grow and mature for several months or years in freshwater until they reach sexual maturity and begin to migrate back to the ocean to complete the life cycle.

Adult fish migrating downstream may be injured or killed in turbines. They may also be delayed in slack-water reaches of reservoirs. Juvenile fish migrating upstream can be blocked by hydropower dams unless fishways are in place. Fishways must be designed to accommodate the biology of the target species and must be maintained properly, or migrations can be delayed.

Amphidromy

Amphidromous migrations are much less studied and understood than anadromous and catadromous migrations. Fish species that spawn in freshwater (freshwater amphidromy) and in the sea (marine amphidromy) can exhibit this migratory pattern (149).

Amphidromy is not directly related to spawning and may occur at many life stages. Some species may not necessarily require a freshwater or saltwater phase to complete their life cycle, and thus amphidromous migrations may be less obligatory than catadromous and anadromous migrations. However, coastal weirs, which are used to control water levels in fresh- and saltwater marshes, may block some amphidromous movements, effectively eliminating or limiting important rearing habitat. Hydropower dams located in proximity to estuaries could also block amphidromous movements, but at the time of this report, we could not find an example in the United States of a request for fish passage at a hydropower dam for a fish species classified as amphidromous (i.e., movements between rivers and marine waters for purposes other than spawning).

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[a] See box 2-5 for more detail on lake sturgeon.

[b] Some salmon and sturgeon have become "landlocked," either naturally or due to human intervention. These fishes may now migrate from lakes into rivers and streams to spawn. This migratory pattern (either between a lake and a river/stream or entirely within a river/stream), which is also adopted by many riverine species, is referred to as **potamodromy**.

[c] In North America, the anadromous strategy is more common than the catadromous pattern. However, the catadromous migratory strategy is more prevalent than the anadromous pattern in Australia (149).

SOURCE: Office of Technology Assessment, 1995.

In addition, hydropower dams are also known to kill fish that pass through their turbines. However, the percentage of fish that die from turbine exposure is a matter of debate and also a great deal of research. Prior to the 1950s, fish protection efforts were focused on establishing upstream fish passage facilities at hydropower plants. By the middle of that decade there were growing concerns about the potential hazards of turbine passage for some fish, especially those that migrate between the sea and inland streams. Since the 1950s there has been extensive research on fish turbine mortality. Even with this considerable base of research, there is still some disagreement over the risk to various kinds of fish that pass through turbine designs.

Fish Passage for Anadromous Fish

Fish passage is widely accepted as necessary for anadromous fish. This may be due to the fact that anadromous fish migrations are conspicuous and have been observed and studied extensively. Although there is a great deal of variation in the seasonal timing, duration, distance, and homing accuracy, etc., it is widely known that anadromous fishes must migrate upriver to their spawning grounds to complete their life cycle. In addition, it is also known that anadromous juveniles and some anadromous adults must migrate downstream to the ocean. Consequently, there is general consensus that anadromous fish need safe and efficient passage routes around the dams that are located between their marine and freshwater habitats.[2]

The catadromous migrations of eels have also been studied. Adults must return to the ocean for spawning and juveniles must migrate upriver to their rearing habitat. Logically, fishes that have catadromous migratory patterns (American eels are the most conspicuous example in the United States) need safe and efficient passage around dams just as much as the anadromous fish. However, at least in this country, there is very little knowledge as to how to provide this passage. Consequently, resource agencies more commonly request passage for anadromous fish than for eels (see box 2-3).

BOX 2-3: Eel Biology and Protection

The American eel (*Anguilla rostrata*) is native to the North Atlantic and may be found in the United States along the Atlantic coast and throughout the Gulf of Mexico. They do not occur on the Pacific Coast of North America. The American eel is catadromous, migrating from inland freshwater lakes, streams, and rivers to spawn in the open ocean.

American eels spawn in the southwest part of the North Atlantic Ocean, at a location known as the Sargasso Sea. The adults spawn at great depths and die after spawning. Unlike most fish, eels have a true larval stage (called leptocephalus larvae), in which the young eels do not resemble the adults. Rather, they are transparent ribbon-like creatures with very conspicuous eyes.

The eels spend several months growing in the ocean and arrive in coastal waters about one year after birth. The larval eels metamorphose at about 2.5 inches, which typically takes place during the winter months just prior to entering, or while swimming in coastal waters. Metamorphosed eels look more like the adult eels and gradually become pigmented as they grow. When they become entirely pigmented, which generally happens by the time they move into the streams and rivers, they become known as elvers. As they grow and become better swimmers they are referred to as "young" or "small" eels.

(continued)

[2] There is often argument over what constitutes "safe and efficient passage routes."

BOX 2-3: Eel Biology and Protection (Cont'd.)

Elvers often occur in great numbers and may be fished along the shores of some rivers and streams with stationary nets. The elvers make their way upstream, where they may live in shallow streams or deep rivers or even associated lakes and ponds. They typically bury themselves in muddy or silty areas or hide beneath large rocks during the daylight hours and generally feed at night, consuming a wide variety of fish and invertebrates.

Very little is known of the early life history of this species. Females generally grow to 25 to 40 inches in length, while males seldom exceed 24 inches. Little is known concerning their age at reproduction, although it is likely to be between six and 12 years. During their freshwater stay, they are generally yellow or orange in color, leading to the term "yellow eel." However, when they reach sexual maturity and begin their downstream migration, they take on a metallic shine and are known as "silver eel." Adults migrate all the way back to the Sargasso Sea (reportedly, as far as 5,600 km) where they will complete the life cycle (158, 208).

The European eel (*Anguilla anguilla*) also migrates to the Sargasso Sea to mate. The two species are exceedingly similar and differ mainly in the number of vertebrae (103 to 111 for American eels and 110 to 119 for the European eels) and adult size (American eels are bigger). European eels apparently take three years on average to get to coastal waters, as compared to one year for American eels. However, most arrive as elvers at about the same size (2.5 inches) as the American eels and thus it seems that the European eels grow considerably slower, at least during the early life stages in the ocean. They are similar in that they migrate long distances upstream in many stream and rivers. Like American eels, they are often found in great numbers and may make a significant contribution to the biomass of certain ecosystems.

The predatory habits, long stay in freshwater, large numbers, and migratory habits have caused some authors to speculate that the decimation of the American and European species could have a considerable impact on the nutrient cycles and energy relationships within lakes, streams, rivers and associated terrestrial habitats (212). Hydropower dams may affect eels in a variety of ways, including killing or injuring some eels as they pass through turbines (92), as well as blocking elvers from migrating upstream (183).

Some biologists, especially in Europe, have explored new technologies to protect eels at hydropower dams and cooling-water intakes (92). For example, lights, air bubbles, and electrical screens have all been tested to keep eels from being entrained. While most of these methods did not work, the experiments with lights were promising. In these tests, eels tended to avoid areas that were illuminated with either incandescent or high-pressure mercury vapor lamps (or both). More research will be needed to determine the efficacy of such technologies to protect eels from entrainment at hydropower dams.

Other scientists have been working on providing upstream fishways for elvers. They are relatively small (10 to 40 cm) and are poor swimmers, thus some traditional fishway designs used for salmon, etc., may not be appropriate. In addition, fishways for elvers may need to accommodate millions of fish in a brief time period. Specially designed fishways for young eels are being developed, mainly in France, where this species is of considerable economic importance (183).

SOURCE: Office of Technology Assessment, 1995.

Turbine Mortality

If a dam has no downstream bypass, every individual of an anadromous fish population reaching the dam must either pass by the turbines, sluiceways, or spillway during their seaward migration. If fish migrate at times when sluiceways are closed and during times of no spill, the majority (or all) of the fish must use the turbine channels as their migratory route (56,193). Therefore, the question of whether these anadromous fishes are being entrained is often moot. However, the question of whether the fish are injured or killed during turbine passage is still somewhat controversial.

Scientists began studying turbine mortality in the United States in the late 1930s. Nearly all of this research was focused on juvenile anadromous salmon (19,199,224). Beginning in 1980 the experimental effort expanded somewhat to include other anadromous species, especially American shad and alewives (18,87,135,206,222).

There is much variation in the data gathered from these experiments. In fact, turbine mortality has been estimated anywhere from 0 to 100 percent (19,46). This wide variance is probably due to the great diversity of turbine designs and operating parameters, as well as the different river conditions and fish species where the mortality tests were done. However, in some cases there may be large differences in turbine mortalities estimated by different studies at the same turbine, and using the same or similar fish species (55).

Studies of turbine mortality have identified four potential categories of dangers to fish: mechanical damage, pressure changes, cavitation damage, and shearing damage.

Mechanical damage is caused by contact with fixed or moving equipment, and is a function of the characteristics of the turbine (number of blades, revolutions per second, blade angle, runner diameter, hub diameter, and discharge) and the size of the fish. Models have been developed to estimate the number of fish of various size that will come into contact with the turbine machinery. Among other things, these models predict that fish size is positively correlated with the potential for physical strikes (35).

The pressure changes that entrained fish experience are a function of the turbine design and flow rate, as well as the location of the fish in the water column prior to entering the intake. Fish that are swimming at depth will be acclimated to relatively high pressure and will experience little change in pressure when entering a submerged turbine intake. Surface swimmers will be acclimated to near atmospheric pressure and will experience an increase in pressure as they "dive" to locate the intake. Just on the downstream side of the turbine blades, fish will experience a region of subatmospheric pressure and then quickly be returned to atmospheric pressure in the draft tube and tailwaters. The region of subatmospheric pressure will only be slightly less than the pressure that a surface swimmer was adapted to, but may be a substantial decrease for bottom swimmers. The amount of pressure damage may depend on the depth of the intake, net head, as well as the pressure tolerance and the acclimation pressure of the target fish species or life stage.

Cavitation is caused by localized regions of subatmospheric pressure (on the trailing edges of runner blades). Air bubbles form when the hydrostatic pressure decreases to the vapor pressure of water. These air bubbles, which can be relatively large, are then swept downstream into regions of higher pressure, which causes them to collapse violently, creating localized shock waves that are often strong enough to pit metal runner blades. The shock wave intensity dissipates rapidly with distance from the center of collapse. Undoubtedly, if fish are passing near a region of collapse, they will be damaged or killed. However, it is difficult to predict how many fish will pass nearby such regions. Cavitation is an undesirable and costly condition for hydropower operators and fish alike. The interplay between turbine setting (centerline of the runner in relation to tailwater elevation) and net head affects turbine efficiency, and often measures can be taken to increase this efficiency. The incidence of cavitation decreases with increasing turbine efficiency, and therefore it is desirable to maintain high turbine efficiency to reduce fish mortality.

Shearing occurs at the boundaries of two adjacent bodies of water with different velocities. Passing through such a zone can spin or deform a fish, which could lead to injury or death. Shearing is most pronounced along surfaces, like walls or runner blades, but is extremely difficult to quantify in a turbine. Therefore it is difficult to determine what percentage of fish deaths from turbine exposure are caused by shearing forces.

It is often difficult to ascertain which type of damage caused the visible injuries to the fish, as they are often manifested similarly (205). In general, there appears to be a positive correlation between turbine efficiency (less cavitation with higher efficiency) and fish turbine passage survival and there is generally a negative correlation between fish size and fish turbine passage survival (64,55).

Early studies of turbine mortality typically only estimated immediate mortality. In other words, investigators focused on fish that were collected dead or dying after passing through the turbines. However, some biologists assert that delayed mortality is also possible and as a result, some investigations have attempted to estimate total mortality by studying both immediate and delayed mortality (62,205). Bell has suggested that, for salmon smolts, 72 hours is an acceptable time period to judge total mortality (17). Delayed turbine mortality estimates are often difficult because of problems associated with maintaining the fish for a period of time after turbine exposure. For example, if control fish have a high mortality level (or a highly fluctuating mortality level among control replicates) due to stress caused by various parts of the experimental apparatus, it becomes difficult to test for statistical significance of test fish mortality (62,64,203,206).

Resource protection agencies also suggest that turbine mortality studies probably underestimate the number of fish that die from turbine passage, because many study designs do not take predation into account. They suggest that as fish emerge from draft tubes they are often subjected to high predation in the tailwaters (or even in the draft tubes). This is due to a variety of tailwater conditions, including the supposition that fish are disoriented after turbine passage, fish getting caught in hydraulics that detain them in the tailwater, increased predator habitat, and the general concentrating nature of turbine passage. Some study designs may be able to include predation in their estimate of turbine mortality, but they may suffer from low re-capture rates, which require using very large sample sizes and may confound statistical comparisons of control and test fish.

Scientists have also been concerned with the general stress, shy of immediate physical injury or death, that could be acting on fish that pass through turbines. The hypothesis is that all fish that are exposed to turbines are affected to some degree. This hypothesis suggests that different individuals react to turbine exposure to varying degrees, and thus even though many fish may survive the initial passage, their chances of future survival are reduced by the exposure. However, in a review of the salmon turbine mortality literature, Ruggles concluded that "... fish that survive passage through turbines without physical injury, by and large, do not have their chances for subsequent survival reduced" (205). However, some studies have shown that even minor de-scaling can reduce the ability of fish to cope with other environmental stress (24).

In general, the experimental design used to study turbine mortality is likely to affect the results considerably (62). A good example is the controversy over turbine mortality estimates for the American shad, blueback herring, and alewife juveniles. Using standard netting techniques, scientists have estimated mortality rates for American shad and blueback herring juveniles at between 21.5 and 82 percent in a Kaplan turbine at Hadley Falls Hydropower Station in Holyoke, Massachusetts, on the Connecticut River (18,222). However, several studies using a different collection technique (balloon tags) estimated turbine mortalities much lower, 0 and 3 percent on average, for these same species at the same (144) and similar (103) Kaplan units.

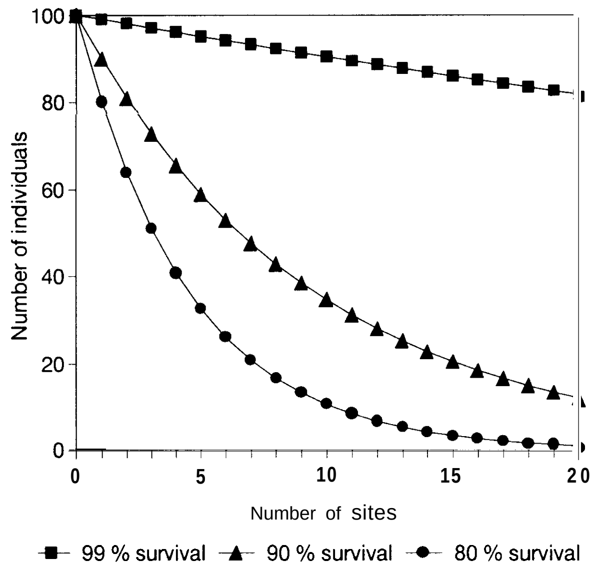
In addition, other aspects of experimental design may also affect results. For instance, the way the experimenter defines "dead" is critical. Some experiments have included fish that are swimming "normally" but that are noticeably damaged (i.e., scrapes, cuts, bruises, loss of scales) in the "dead" column. If another experimenter included that type of fish in the "live" column, the same study results may estimate considerably different mortality rates (see Part 2 of this chapter for more details on turbine mortality studies).

Despite some controversy over the extent of turbine mortality, it is still widely believed to be a significant factor in the reduction of many anadromous fisheries around the country. The concern is greater when there are multiple dams in a system, because of the potential cumulative impact (193). If there is only one dam to pass, mortality rates lower than 10 percent may not seem so alarming. However, when fish must pass multiple dams, as is often the case with anadromous fish, the cumulative impact of several distinct low mortality rates can result in severe losses (35). For instance, a group of salmon smelts migrating downriver will be decreased by half after passing seven dams, each with a 90 percent survival rate (see figure 2-l).

Therefore, downstream protection to reduce entrainment and also some measure of safe downstream passage is often sought for anadromous fishes (i.e., fish bypass, spill measures, trap and truck, etc.). However, all bypass systems are not harmless to fish. Some fish may be killed in bypasses, and thus the mortality rate from the bypass should be compared to the mortality rate of other possible routes (i.e., turbine, spill, sluiceway) (78). In some cases hydropower operators have tried to establish that turbine mortality on anadromous fishes is minimal, suggesting that turbine passage is a viable migratory route for some species at some sites (103). For example, the Federal Energy Regulatory Commission (FERC) has approved turbines as the preferred passage route for juvenile American shad at Safe Harbor hydropower facility on the Susquehanna River in Pennsylvania and for juvenile blueback herring at Crescent hydropower facility on the Mohawk River in New York. The United States Fish and Wildlife Service (FWS) has supported the conclusion at Safe Harbor and is contesting the Crescent case (29,30).

However, accepting turbine passage as a migratory route is still highly controversial and will certainly be highly site-specific. In addition, many anadromous fish have repeat spawners. These fish migrate back to the ocean after

FIGURE 2-1: Cumulative Mortality



SOURCE: Office of Technology Assessment, 1995.

spawning and return the following year to reproduce again. In fact, on the Atlantic Coast, every anadromous fish species, except the sea lamprey, has repeat spawners. Therefore in addition to providing safe passage for down-migrating juveniles, many projects must also provide safe downstream passage for adult repeat spawners (32). Since turbine mortality is more severe with increasing fish size (62,64), presumably turbine passage would not be an acceptable route for adults of most species (18,134).

■ Entrainment Protection for Riverine Fish

The relatively new interest in riverine fish at hydropower dams has mainly been concerned with entrainment and turbine mortality. Research has focused on determining the magnitude and the species and size composition of entrainment and turbine mortality. Hydropower operators may have the option to forgo these studies and develop and implement an enhancement plan for minimizing the entrainment of fishes at their project(s).

Entrainment Studies

A wide array of study designs and methods has been employed to study entrainment at hydropower dams. The diversity in experimental design may be partly linked to site-specific logistical constraints or safety concerns. Dam and powerhouse design, as well as river hydrology, hydraulics and geo-morphology, may limit the methods that can be used. In addition, study goals, experimenter preference, and financial constraints may also play a role in determining what methods are employed.

Unfortunately, the diversity in study methods limits our ability to compare entrainment results from site to site. Two major reviews of recent entrainment studies have been done. Both reviews focused on studies done at sites east of the Mississippi river, primarily Michigan and Wisconsin. The Electric Power Research Institute (EPRI) contracted Stone and Webster Environmental Services (SWEC) to prepare a review of entrainment (and turbine mortality) studies (62). The Federal Energy Regulatory Commission also contracted SWEC to prepare an assessment of fish entrainment at hydropower projects (71).

The following findings regarding entrainment of riverine fish are largely drawn from the FERC 1995 review *Preliminary Assessment of Fish Entrainment at Hydropower Projects* (unless otherwise cited). In general, riverine fish of various species are entrained to some extent at virtually every site that has been tested. Entrainment rates are extremely variable among sites. Smaller fish tend to be entrained at higher rates (62,71). For example, more than 90 percent of entrained fish in several studies were less than 20 cm in length (62). However, the entrainment of large fish is not uncommon.

The location of the intakes relative to fish habitat may be a key factor in determining how many and what types and sizes of riverine fish species are entrained. Penstocks that are located far from shore in open water may tend to entrain different kinds (and quantities) of fish than intakes that are located near the shoreline.

The species, size, and number of entrained fish may differ significantly between units at the same site. The operating time, flow volume, and relative location of the various units may be important in determining the entrainment rate of each. In general, the longer a unit is operated and the greater the flow volume per unit time, the more fish are entrained. Intakes that are positioned near areas where fish like to spawn or feed may entrain more of these fish than units that are further away. Therefore, extrapolation of entrainment data from one unit to another is often controversial. State and federal agencies generally do not like studies that attempt to sample entrainment from a subset of turbines and extrapolate these values to other untested units. In addition, the efficacy of extrapolating entrainment rates will depend on how similar the sites are in fish composition, powerhouse and dam design, as well as on many physical characteristics of the river.

Research concerning the entrainment of fish eggs and larvae at hydropower projects is very rare. Studies that collect fish eggs and larvae are expensive and difficult. However, it is well established that the egg and larval stages represent a critical period that often determines the strength of a given year-class of many fish species (2,129,138). Some studies have suggested that entrainment of larvae and eggs at hydropower facilities can be very high and can affect the abundance of some species (256). Similar results have been obtained at pumped-storage facilities (184,214). However, at least one study found no direct link between entrainment of larvae and population size (48).

Several models have been developed to estimate the impact of egg and larval entrainment at nuclear power plants on fish populations, and they may be applicable to hydropower dams (116). This seems to be an area that deserves more attention in the hydropower arena, but will be difficult and costly. In addition, a recent report on the potential for mortality of fish early life stages (i.e., eggs and larvae) suggested that turbine mortality may be low (35).

Some state and federal resource agencies have drafted specific guidelines on how entrainment and turbine mortality studies should be done

(35,264). Some argue that studies should be conducted over a period of at least three years, and in some cases five, because of changing weather patterns (which affect river flow, etc.) and natural fluctuations in fish population levels (264). Presently studies are generally one year in duration and are relatively expensive. For example, the mean cost of seven different 12-month entrainment studies (using nets to capture fish) was reported to be $273,006 (71). Extending studies for three to five years would substantially escalate these costs, especially when the costs of a turbine mortality study are included.

Standardizing the types of experimental designs that can be used would help in attempts to compare data from several studies. Agreement on study designs between resource agencies and hydropower operators could minimize controversies about how to interpret results. Such comparisons could also be important in identifying trends that might help to guide fish protection mitigation. Suggested guidelines for determining the need for entrainment studies, as well as for conducting studies (e.g., defining target fish and sizes, the appropriate use of hydroacoustic and netting studies, sampling schedules) and reporting results (e.g., the type of information to include, such as sampling times and frequencies, entrainment rates and flows for different hydroplant units, appropriate information on environmental variables, methods used to account for unsampled periods, statistical methods) are provided in the FERC 1995 *Preliminary Assessment of Fish Entrainment at Hydropower Projects.*[3]

Turbine mortality

Estimates of turbine mortality specifically for riverine fishes were rare until recently, and they are still less common than for anadromous species. However, a number of recent studies suggest that smaller fish experience less mortality than larger fish, similar to findings for anadromous fish discussed above (62). Cada reviewed the scientific literature pertaining to the kinds of stresses that fish are exposed to in turbines (i.e., shear, cavitation, subatmospheric pressure, physical strikes) (35). The review suggested that mortality rates may be low for fish eggs and larvae. However, direct measurements of turbine mortality for fish eggs and larvae have never been done.

It is simply too early to make any generalizations about turbine mortality of riverine fish. Resource agencies currently prefer that turbines run at or near peak efficiency to reduce cavitation damage. More research is needed to better determine the risk of death from turbine passage for various sizes and species of riverine fish. Guidelines for turbine mortality studies would also help to standardize results.

Population perspective

Most research on entrainment and turbine mortality has not attempted to determine the fishery impacts at the population level. The entrainment and turbine mortality rates for riverine fishes, which have been gathered now at many hydropower facilities, only represent part of the picture. While entrainment (risk of injury or death) is obviously significant to the individual fish, it is not necessarily significant to the population. For instance, entraining 100,000 fish per year with a 30 percent mortality rate may represent a tragic consequence for one species, while the exact same rates may represent a lesser impact for another. The severity of the impact will depend on many aspects of the population biology of the fish species being entrained. Such parameters include the size of the population, the length, weight and age structure of the population, the reproductive potential of the population, and the natural survival rates (unrelated to entrainment) of the population.

It would be ideal to know the effects of entrainment and turbine mortality on fish populations. However, studies designed to determine these impacts would be very time consuming and expensive, if not impossible. The FERC has recently issued a statement concerning the need for proving population impacts when requesting mitigation at hydropower projects (71).

[3] The Electric Power Research Institute is also currently preparing such guidelines (219).

> Ohio Power's argument appears to be that an effect on fish population as a whole is necessary before any mitigation may be required, and that no such effect has been demonstrated here. However, there are many other environmental variables that influence fish populations, particularly in a large system like the Ohio River. *Consequently, it would be very difficult, if not impossible, to isolate the effects of turbine mortality on fish populations in the vicinity of the Racine Project.* Clearly, there is the potential for an effect on a fish population when a large number of its individuals are removed. These effects can range from the dramatic, such as a reduction in numbers sufficient to affect the long-term viability of the population, to the subtle, such as changes in the average size of fish or their growth rates. *Mitigation can be required even if it cannot be proven that project operation threatens the long-term viability of the entire population* (emphasis added).

There is disagreement on who should bear the "burden of proof" (36). The agencies feel they are often asked to prove that fishes are being negatively affected by dams, and the dam owners feel they are obligated to show that the project does not have a negative impact on the fish. Neither objective is easy.

Controversy concerning entrainment

In general, the industry views entrainment and turbine mortality as a minimal risk to the riverine fish since the bulk of entrainment consists of small fish (primarily young of the year) and the turbine mortalities associated with these small fish are low (35,62). In addition, in some cases there are viable fisheries above and below dams (48). They argue that any negative effects on the population due to fish being entrained will be countered over time by "compensatory mechanisms" at the population level. This theory suggests that as the population gets smaller due to entrainment, the competition over limiting resources between the remaining individuals decreases. Those fish that are not entrained will benefit from the decrease in competition for important resources and this benefit may lead to increased reproductive potential and/or survival. Thus the positive impact of the "compensatory mechanism" could counteract the negative impact of the entrainment.

On the other hand, the resource agencies and conservation groups view entrainment as a significant and chronic source of fish loss. Regardless of turbine mortality, entrainment decreases the populations of upstream fisheries that cannot be replenished by downstream stocks because of the blockage created by the dam. The resource agencies generally disagree with the "compensatory mechanisms" theory. They suggest that individuals in many fish populations are not limited in reproduction, growth, or survival by intense competition over limited resources with other members of the population (88,259). Thus, eliminating "x" number of fish from a population may free up "y" amount of resource, but if the individuals were not limited by that resource in the first place, they are not likely to benefit appreciably from the additional amount. While the compensatory mechanism may occur in some populations for some animals, there has been no research to date that shows that it does (or does not) work for riverine fish species at hydropower projects.

Financial compensation for fishery losses

At some sites, hydropower operators may have to pay a fee equivalent to the value of the fish that are killed by turbine passage. This is known as "compensatory mitigation" and has also been referred to as "fish for dollars" mitigation. This type of mitigation is controversial for several reasons as discussed below.

Techniques that can be used for environmental mitigation have been identified and prioritized by the President's Council on Environmental Quality (CEQ) (40 C.F.R. S 1508.20) as follows:

- avoiding the impact altogether by not taking a certain action or parts of an action;
- minimizing impacts by limiting the degree or magnitude of the action and its implementation;
- rectifying the impact by repairing, rehabilitating, or restoring the affected environment;

- reducing or eliminating the impact over time by preservation and maintenance operations during the life of the action; and
- *compensating for the impact by replacing or providing substitute resources or environments* (emphasis added).

Thus, financial compensation is an acceptable form of mitigation when all of the other preferred forms of mitigation are deemed impossible or inappropriate. The United States Fish and Wildlife Service (FWS) defines "compensation" as "full replacement of project-induced losses to fish and wildlife resources, provided such full replacement has been judged by the FWS to be consistent with the appropriate mitigation planning goal." It defines "replacement" as "the substitution or offsetting of fish and wildlife resource losses with resources considered to be of equivalent biological value" (253).

The hydropower operators pay a yearly financial compensation to the state resource agencies, which is said to be equivalent to the estimated yearly amount of fish killed by a project. Unlike screens, monetary compensation does not directly protect the fish that are being entrained and killed, but rather the monies can be used to support other fishery enhancement projects (habitat restoration, artificial production, etc.).

Compensatory mitigation is becoming more common for projects that entrain riverine fish, but it is controversial. For instance, there is disagreement over the degree of precision that should be required for the entrainment and turbine mortality studies that are used to determine the compensation amount. In general the utilities believe that order-of-magnitude estimates are adequate while resource agencies contend that a higher degree of precision is required to ensure that the level of mitigation is equivalent to the fish loss. FERC discussed study precision in an order issued concerning Ohio Power's 40-megawatt Racine Project, on the Ohio River at a Federal Dam in Meigs County, Ohio, and Mason County, West Virginia (71).

> In this case, we understand that the Commission staff sought to calculate a compensation amount that is roughly equivalent to the replacement cost of the fish lost. 44/ However, we think that the parties misapprehend the nature of the undertaking to the extent they believe that the defensibility of the amount to be set aside for compensatory mitigation turns on the precision of the estimates of lost fish and their associated replacement costs. No such precision is called for; rather, the goal is to establish a reasonable expenditure with which to compensate for the project impact on fish....
>
> 44/ The Division Director referred to the "value" of killed fish, but clarified that the "value" reflected only the cost of hatchery production of the different species and size classes of fish (71).

There is also debate over how to value the fish that are killed. The American Fisheries Society (AFS) Handbook on the Valuation of Fish Kills is often used to determine the value of the turbine-killed fish. This publication values fish based on the cost to replace the fish with hatchery-raised fish of equivalent size (5). The agencies claim that this is not appropriate and that this type of valuation ignores the other intrinsic and economic values of the fish (264). They claim that the AFS replacement values underestimate the "true" value of the fish by as much as 90 percent (see chapter 5).

Passage for Riverine Fish

Though some resource agencies are beginning to make an issue of it, fish passage has rarely been requested for riverine species (relative to the number of requests for anadromous species). Some argue that the fish populations that became established after a hydropower dam was constructed (often 30 to 100 years ago) have been relatively sustained without the existence of fish passage. This argument would apply to fish passage requests during FERC relicensing. However, it is also argued that since the riverine fishes spend their entire lives within freshwater, they may not necessarily need to move past a dam to complete their life cycles.

Some resource agencies have begun to argue that some riverine fish species do make significant movements within the river. Depending on habitat availability at a given river segment and the biological needs of the target fish species, dams may (or may not) separate certain riverine fishes from critical habitat (e.g., spawning areas) that could be important for enhancing or sustaining their populations. Some scientists have also speculated on the ecosystem level impacts of providing or denying fish passage (see box 2-4). The assumption that riverine fish do not require passage may reflect a lack of knowledge of the magnitude and significance of their movements.

Methodology and fish movements

Though the paradigm is beginning to change, the predominant thinking has been that riverine fishes have restricted movements (i.e., "sedentary").[4] The theory that riverine fishes are largely sedentary is partially attributable to the methods used to study their movements (89). The vast majority of studies since the 1940s used the "Mark-Recapture" technique which involves capturing fishes, tagging them, releasing them, and then attempting to recapture them. In many of these studies those fish that were recaptured apparently remained very near the initial capture site, causing the investigators to conclude that these fish are relatively sedentary. However, only a small percentage of fish were recaptured in many of these studies and thus conclusions concerning the amount of fish movement ignore the portion of fish that are not recaptured.

There are several ways that mark-recapture studies may bias results about fish movements. First, there is no information about the movement patterns of the fish that are not recaptured, and in many cases this is the majority of the tagged fish. This could mean that these fishes have moved beyond the boundary of the study or that they may have evaded recapture for some other reason (e.g., mortality, large population size, etc.).

Second, by setting the spatial and temporal boundaries of the study the investigator is presupposing how far and when the fish will move. For instance, if the study concentrates recapture effort on a small region of the stream and a tagged fish ventures beyond the study boundaries, it will not be recaptured and thus its movements cannot be known or included in analyses. To alleviate the bias, researchers can focus recapture efforts over a larger area (e.g., by including angler returns). Recapture efforts should also have a broad temporal focus, so that seasonal fish movements can be detected.

Third, fish that are recaptured in the same stream reach where they were initially caught are assumed to have been there all along. This could considerably underestimate the propensity of a species to move if the fish had left and returned to the area between the two capture events.[5] Mark-recapture studies can provide useful data concerning fish movements and populations size when they are designed to alleviate these potential bias problems.

Other studies have attempted to use radio telemetry to study fish movements. This technology allows the investigators to track individual fish from a population over long distances from the point of initial capture. These studies do not pre-suppose how far the fish move and thus are less likely to bias the results. However, logistics and cost may limit the number of fish that can be followed, which has sometimes led to basing conclusions about fish movements on data from a relatively small number of fish. In addition, transmitter life-span limits the length of time a fish can be followed.

Telemetry and mark-recapture studies can provide data on where a fish is at a particular

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[4] The theory that most stream (i.e., riverine) fish are "sedentary" originated in 1959 with a paper entitled *The restricted movement of fish populations* (86).

[5] A fish may be captured and released at "point A," swim some distance to "point B" and then swim back to "point A" and be recaptured. This fish would be incorrectly counted as not having moved. For example, a walleye was captured, fitted with a radio transmitter, and released at Prairie du Sac dam in Wisconsin. The walleye was then radio tracked for 10 months and found to have traveled a distance of 40.6 miles during that period. Three years later, the same fish was caught by an angler behind Prairie du Sac dam. Had there been no radio-tracking data this fish would have appeared (incorrectly) to have restricted movement.

BOX 2-4: Ecosystem Perspective for Fish Passage

The need for fish passage can be considered at the population and ecosystem levels. Most research has focused on the need for passage as it relates to the sustainability of a particular fish population or species. However, some scientists have theorized about the potential ecosystem level impacts related to fish passage. In other words, hydropower dams can preclude fish from migrating or moving to a given river reach. This may or may not have a negative impact on that particular fish population, but it could have a negative impact on other organisms that depend to a greater or lesser extent on the presence of those fish (146).

For instance, many species may depend on fish resources in a given stream reach. Some mammals, birds, reptiles, amphibians, fishes, and invertebrates may prey on fish eggs, larvae, juveniles, or adults. These predator-prey relationships may in some cases represent important ecological interactions between aquatic and terrestrial ecosystems, or within the aquatic ecosystem. Such interactions can be affected (interrupted, decreased, or severed) if some fish can no longer swim to a historic portion of their range.

In addition, many species of anadromous fish die after spawning and their carcasses provide energy to some of the organisms that live in the area. Studies have shown that the carbon from salmon, shad, and lamprey is recycled in the local stream environment and may make a significant contribution to the energy flow of the local ecosystem (261).

Thus, hydropower dams may affect the natural flow of energy through the river basin by impeding natural fish movements, thereby fragmenting the environment and having a negative impact on the entire ecosystem (140,261). Even though the movements of a particular fish population may not always be critical to its own sustainability, the movements may still be critical for other species and thus overall ecosystem health and stability.

These ecological interactions may be more profound in certain river basins and less important in others. Most of the current empirical evidence relates to anadromous fish movements, but the same concept would apply to the riverine and catadromous fishes as well (212,261). More research is needed to examine the significance of ecosystem fragmentation at a level that can guide mitigation.

SOURCE: Office of Technology Assessment, 1995

time and the minimum distance it moved within a given time frame. However, these data must be carefully analyzed before making judgments concerning the biological significance of the observed movement patterns. Fish may move within a body of water for many reasons (see table 2-1). Studies of movement patterns using telemetry or mark-recapture may provide little evidence to draw conclusions about the reasons for the observed movement patterns. Other experiments and natural observations regarding the fish and their habitat may provide supporting evidence to help formulate such conclusions.

Sedentary and mobile hypothesis

Telemetry studies (as well as some mark-recapture studies) have shown that some fish move long distances, while others remain very near the point of initial capture. Some scientists believe there may be a “sedentary” and a “mobile” portion of many fish populations (84,95,102,104,148,216,218). The proportion of the population that is “sedentary” or “mobile” seems to vary from species to species, population to population, and even year to year (89). Individual fish may be either “sedentary” or “mobile” for their entire lives or a fish that is sedentary at one point may become mobile at another time (89).

The significance of having mobile and sedentary subpopulations is not always well understood. However, some case studies have shown that the mobile portion of the population benefited substantially from roaming. For example, individual Arctic char that migrated from their

TABLE 2-1: Some Widely Recognized Riverine Fish Movements
Dispersal
Passive fry dispersal with water flow
Active fry or juvenile dispersal, possibly mediated by competition
Specialized dispersal with patchy resources
Habitat shifts
Shifts in microhabitat related to life stage (age or size)
Seasonal movements between summer and winter habitat
Daily movements between feeding and resting positions
Spawning migrations
Potamodromous migrations between lakes and rivers
Movements in all directions when spawning and rearing habitats are interspersed
Homing movements
Following displacement (floods, capture and release, etc.)
Home Range Movements
Daily movements related to territory defense
Daily movements related to feeding

SOURCE: Office of Technology Assessment, 1995.

home lake to a more highly productive lake 5 km upstream grew faster and reached sexual maturity two years sooner than their sedentary counterparts that remained in the home lake (160,161).

Study examples

Lower Connecticut River Catfish and Perch: An intensive mark-recapture study of several species of riverine fish was done as part of a major ecological investigation of the Lower Connecticut River (1968 to 1972) (143). Thousands of fishes (9,817) were captured, tagged, and released. For all the years that data were taken, recapture rates ranged between 3.8 and 10.7 percent (918 total recaptured; 9.4 percent). The data indicated that the recaptured fishes of some species were far from stationary and that some individuals occasionally traversed the entire 85.3 km of the lower Connecticut River from Old Saybrook to Enfield Dam. White catfishes (range: 23 km downstream and 61.2 km upstream; average of 15.4 km from tagging site) and yellow perch (range: 23.3 km downstream and 54.7 km upstream; average of 13.5 km from tagging site) moved the furthest from the point of initial capture and the brown bullhead catfish (average 3.6 km from tagging site) moved the least.

Smallmouth Bass (Wisconsin and New York): Mark-recapture and telemetry were used to study smallmouth bass movements between winter and summer habitat in the Embarrass and Wolf rivers in east-central Wisconsin. It was concluded that decreasing water temperature at the summer habitat in the Embarrass River caused smallmouths to travel 40 to 60 miles downstream in search of deep pools for over-wintering in the Wolf River. The following spring with increasing water temperatures the bass returned to the Embarrass River, most to the same three-mile reach of river where they were found the previous year (137). The extensive migration pattern observed in this study may be linked to wide spatial separation between prime summer and winter habitat.

In contrast to this example of long-distance directed movements by smallmouth bass (i.e., migration), other studies have concluded that smallmouths are less mobile. For instance, McBride, using mark-recapture, found smallmouth bass in the Mohawk Watershed in New York to be highly sedentary (148). Ninety-one percent of the bass were recaptured within the same sub-reach of the river that they were initially caught and tagged. However, seasonal migrations, if they occurred, may have been missed because sampling was concentrated in one month only. Recaptures occurred from one to 22 days after initial tagging. McBride interpreted these data to mean that Mohawk River smallmouth bass populations had a relatively large "sedentary" and a smaller "mobile" component, similar to earlier findings about smallmouth bass movements in Missouri streams (84,148).

Largemouth Bass: Largemouth bass movements have also been extensively studied. Most studies (mark-recapture) indicate that adult largemouth bass exhibit limited movement showing a high degree of fidelity to home areas. For example, one study recaptured 96 percent of the tagged fish within 100 m of their respective release sites (139). However, radio telemetry studies on Florida largemouth bass indicated that adults moved out of home areas to locate suitable spawning habitat (44,151).

A mark-recapture study of largemouth bass in Jordan Lake, North Carolina, focused on the movements of juveniles (young-of-the-year and yearlings). Researchers tagged 1,619 fish over two years and recaptured 87 (5.4 percent) of these from one to 133 days after initial release. The vast majority of recaptured juveniles (young-of-the-year and yearlings) were caught in the same cove or area where they were initially captured and released. A few fish (eight; or 9.2 percent of recaptured fish) did move beyond the point of initial release. Unfortunately nearly 95 percent of the fishes were not recaptured and no data is available about their movement patterns (45).

Yellow Perch: Yellow perch from Lake Winnebago in Wisconsin migrate into the Fox River in search of spawning habitat and travel as far Eureka Dam, 40 km upstream from the mouth of the river. After spawning they return to Lake Winnebago and repeat the migration the following year, with the majority (85 percent) homing to the same spawning sites that were used in the previous year (258). In the Chesapeake Bay region, yellow perch migrate from downstream stretches of tidal waters seeking spawning habitat in upper reaches (less saline) of feeder streams and rivers. The migration distance depends on the location and availability of spawning habitat (83).

Shortnose Sturgeon: Annual movements of shortnose sturgeon were studied in the Connecticut (31) and Merrimack (125) Rivers in Massachusetts. In the Connecticut River shortnose sturgeon exhibited two distinct migration patterns prior to spawning. Some of the sturgeon (estimated 25 to 30 percent) spent the latter part of the summer, the fall, and the winter about 24 km downstream of their spawning grounds. In the spring this portion of the population migrated the 24 km and eventually spawned. Following spawning, the spent sturgeon moved back to downstream feeding and overwintering sites. The majority of the sturgeon (estimated 70 to 75 percent) spent the winter at the spawning grounds, thus requiring no spring spawning migration. However, after spawning these fish migrated downstream to two distinct summering sites (23 to 24 km or 54 to 58 km). These sturgeon leave the summering sites in fall (August to October) and migrate back upstream to the spawning/overwintering sites.

In contrast, all of the sturgeon in the Merrimack River overwintered downstream of the spawning site and made a spring migration to those areas. The different movement patterns observed for these populations of shortnose sturgeon are probably related to the availability and the location of the critical habitat. If the spawning areas are far removed from feeding areas, the fish may conserve energy by making an early migration during the fall to coincide with low river flows. On the other hand, if feeding and spawning sites are in close proximity, spring migrations are not as energetically costly.[6]

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[6] Shortnose sturgeon are anadromous in southern rivers (e.g., Savannah River), spending the summer, fall, and winter in saltwater. They make long-distance upstream spawning migrations in the spring (between 175–275 km), traveling as many as 30 km a day. Shortly after spawning they return downstream and enter brackish waters by two weeks post spawning (93).

Implications of riverine fish movements for fish passage mitigation

The need for passage for riverine fishes is most likely site- and species-specific. An excellent illustration of site variation is the biology of the Colorado squawfish. Colorado squawfish have been extensively studied in the Green, White and Yampa Rivers in Colorado and Utah and results indicate that adults make seasonal long-distance migrations upstream (65 to 160 km) to locate spawning habitat. After spawning the adults return downstream, often homing within a few miles of where they were prior to the spawning migration. Squawfish larvae in these rivers drift to nursery areas far downstream of the spawning sites (as far as 100 to 160 km) (225,226,227,228,260).

However, McAda and Kaeding studied the same species in the upper Colorado River and found that adult squawfish had much shorter spawning migrations (< 50 km; mean = 23.2 km) than those described for populations in the Green, White and Yampa Rivers (65 to 160 km) (147). The availability of spawning habitat may help explain the difference in the movement patterns of these populations. Spawning habitat was abundant and widely distributed in the upper Colorado River and consequently the fish did not require long-distance spawning migrations to locate suitable areas. In contrast, in the Green River spawning habitat was less common and was highly clumped, requiring fish to swim long distances to locate acceptable areas.

These studies underscore the point that mitigation concerning fish passage will have to be site- and species-specific and should be tied to the specific habitat needs for target fish populations in a given river reach. Seasonal habitat types (e.g., rich feeding habitats v. spawning sites) are sometimes widely spatially separated and may require extensive migrations of some riverine species (169). Goals concerning the target species' population sizes as well as size and age class structure, etc., will be important in determining whether fish passage is needed.

Some riverine fish may need to make long-distance movements past one or more dams to locate critical habitat (e.g., spawning, overwintering, etc.). Some species that make long potamodromous migrations from lakes into streams or rivers may need safe passage routes around hydropower dams to allow access to spawning habitat (see box 2-5).

BOX 2-5: The Lake Sturgeon

The lake sturgeon, *Acipenser fulvescens,* has one of the widest geographic ranges of all freshwater fish. It is found in three major drainage basins: the Mississippi, the Great Lakes, and the Hudson Bay. This species, which once ranged so widely throughout North America, is now nearly decimated throughout most of its native range (110,118). Lake Michigan in 1880 produced a commercial catch of over 3,800,000 pounds of lake sturgeon (15a). A combination of overfishing, dam construction and pollution nearly eliminated these vast populations, to the point that today they are considered threatened or endangered species throughout most of their range. The Menominee River, a boundary water between Wisconsin and the upper peninsula of Michigan, is currently the only tributary to Lake Michigan that still contains a fishable lake sturgeon population. This same scenario has been played out numerous times throughout the historic range of these fish. The lake sturgeon is included on the U.S. Fish and Wildlife Service's list of candidate species being considered for listing as endangered or threatened. It is considered a "Category 2" species which comprises taxa for which information now in possession of the Service indicates that proposing to list it is possibly appropriate, but for which conclusive data on biological vulnerability and threat are not currently available to support proposed rule making.

(continued)

BOX 2-5: The Lake Sturgeon (Cont'd.)

Lake sturgeon are considered living fossils. They have many primitive characteristics which have been lost on most of our modern-day fish. These include a large cellular swim bladder, a heterocercal tail, a cartilaginous skeleton and a notochord, instead of bony vertebrae. These fish are long-lived and often reach a large size. On average females do not reach sexual maturity until they are 25 years old and approximately 50 inches long, while males generally mature around 15 years of age when they are around 45 inches in length. There are records of these fish living over 100 years and attaining lengths in excess of six feet and weights over 200 pounds.

Lake sturgeon are generally found in large river systems or in lakes connected to these rivers. They often move long distances, over 100 miles, to reach suitable spawning habitats. Seasonal movements of lake sturgeon outside of spawning time are not well documented. Lake sturgeon spawn in the spring or early summer. Most spawning occurs in rivers below falls or in rapids. High-velocity water with a rock rubble substrate is preferred. Eggs adhere to these bottom substrates prior to hatching in 7 to 10 days after deposition.

Dams have impacted lake sturgeon populations in a number of ways. Lake sturgeon have been blocked from obtaining their traditional spawning areas by dams that are located at or near the mouths of rivers (15a,96). Brousseau and Goodchild describe how fluctuating flows in a spill channel can adversely impact lake sturgeon populations (28). Low and/or fluctuating flows immediately after spawning will affect spawning success as eggs experience variable water temperatures, low oxygen concentrations and exposure to the atmosphere. Fry become trapped in shallow pools and are subjected to heavy mortality through predation, temperature stress, and oxygen depletion. Water level fluctuations between dams, both seasonal and periodic, have caused decreased production and loss of species such as lake sturgeon from some reaches (173). In addition Altufyev et al. (4), Khoroshko (124), Voltinov and Kasyanov (255) and Kempinger (122) have all shown that changes in magnitude and timing of river flows below hydroelectric dams have affected the reproduction and early life stages of several sturgeon species. Auer has documented significant changes in behavior and population characteristics in the spawning run of lake sturgeon when a project was converted from peaking to run of the river (8,9,10,11). The following changes were documented: 1) an increase in the average size of the lake sturgeon; 2) an increase in spawning readiness; 3) a decrease in the amount of time the spawning fish remained in the area of the spawning grounds, thus decreasing their exposure to adverse conditions and poaching; and 4) an increase in the overall size of the spawning run. Lake sturgeon are adversely impacted by daily flow instability like that created by peaking hydroelectric projects, thus run of the river flows in the main channel and stable spillway flows are critical to the rehabilitation and restoration of lake sturgeon populations.

A key component to lake sturgeon restoration is to provide a means for fish to return upstream to suitable spawning, summer, and winter habitat. By allowing adult sturgeon to pass these dams, historic spawning, nursery and foraging habitat could be utilized by these fish. This could be accomplished by installation of upstream fish passage facilities. Upstream passage of lake sturgeon at dams with heads higher than five to 10 feet has not been successfully accomplished with traditional-style fish ladders. Resource agencies in the Midwest and Ontario are currently working on developing the technology to safely and effectively pass lake sturgeon over these dams. Research is currently being conducted by the National Biological Survey and researchers in Canada on swimming speeds of adult and juvenile lake sturgeon and behavioral response of lake sturgeon to various fishway types. This information is critical to designing an effective upstream fishway for lake sturgeon.

SOURCE: Thomas Thuemler, Area Fisheries Supervisor, Wisconsin Department of Natural Resources, August 1995.

Other fishes may find adequate habitat within the dammed portion of the river. For example, hydropower dams often change the habitat upstream by creating head ponds (i.e., reservoirs) which provide different habitat than the original flowing environments that they replace. There is often a change in species composition favoring fish species that prefer lake-like or pool-type habitat. Such species include some sunfishes like bluegill, largemouth bass, and crappie. Some of these fish are generally structure oriented and may not need to leave the reservoir to locate critical habitat.

PART 2: STUDY METHODS

Entrainment and Turbine Mortality Studies

Entrainment studies quantify the numbers, sizes, and species of fish that pass through the turbines at hydropower facilities. Turbine mortality studies (which are often done in conjunction with the entrainment studies) determine the risk of death caused by passing through a given turbine for the various species and sizes of fish. Prior to 1980, nearly all of the research on entrainment and turbine mortality examined anadromous juvenile salmon (17,19,199,224). Between 1980 and 1990 the experimental effort expanded somewhat to include other anadromous species, especially American shad and alewives (18,87,135,206, 222).

Since 1990 there have been intensive efforts to study entrainment and turbine mortality at sites that primarily or solely support riverine fish. Many of these studies were requested by state and federal resource agencies during the Federal Energy Regulatory Commission (FERC) relicensing process. The results of these studies are used to determine what level of mitigation and what kinds of mitigation are appropriate.

Entrainment Study Methodology

Netting

Netting is the most common method used to measure entrainment. Full tailrace nets (most preferred netting technique) are anchored to the exit of the draft tube and sample the entire discharge from one or several turbine units. Floating mesh boxes of various sizes and types (i.e., "live cars") are often attached to the end of the net to reduce mortality caused by fish scraping and entangling in the net (i.e., net impingement). Partial tailrace netting may be used where full tailrace netting is impossible or prohibitively expensive or even dangerous due to the physical and hydraulic conditions of the tailrace. These nets are usually anchored in the tailrace on a metal frame held in place by guy-wires, or some other anchors, and they sample some portion of the discharge from one or several turbines. Nets may also be deployed some distance downstream of the tailrace and may cover the entire width of the stream.[7]

The main problem with full and partial tailrace netting is contamination of the sample by fish that did not pass through the turbine (i.e., residing in the draft tube or the surrounding areas of the tailrace). This is particularly true for partial nets because they do not completely isolate fish that reside in the tailrace from swimming into them. In addition, fish may be able to escape partial nets. This is the primary reason that full tailrace nets are preferred. However, tailrace and draft tube intrusions may also occur in full net deployments, due to gaps between the draft tube and net frame, gaps between the net frame and the net itself, or ripped portions of the net. Obviously, gaps or rips may also allow entrained fish to escape. These problems can be minimized by careful net anchoring to avoid large gaps and frequent net inspections to locate rips which may develop.

[7] In general such deployments suffer from low recapture rates of entrained fish because the fish can reside in the tailrace upstream of the net for considerable time, where they may suffer from other sources of injury or death (e.g., predation). There is also high incidence of capturing non-entrained fish that were naturally residing in the tailrace prior to the study.

Intrusions may also occur if the net is raised allowing some fish to swim into the draft tube, and later be captured when testing resumes. Most studies guard against this type of intrusion by running the turbine for a period of time without the net in place so that the draft tube will be flushed of fish when netting begins. However, the effectiveness of this technique is unclear.

Nets may be deployed within the turbine intake. Intake collection nets are relatively short so as not to interfere with turbine function, and usually several smaller nets are used rather than one large net. This is accomplished by anchoring the nets onto a frame which slides down into the gatewell. Problems of intake netting include the possibility that some of the fish that are sampled in intake nets may not have been committed to passing through the turbine, as well as the possibility of injury to collected fish because live cars cannot be used. In addition, nets that come apart from the frame may become lodged in the turbine, which could cause considerable damage.

Partial netting techniques, whether located in the tailrace or intake, assume that there is equal distribution of fish throughout the sampled area and that fish cannot avoid the nets or netted areas. These assumptions are not always, and probably rarely, tested in the field or based on any supporting evidence. Estimates of entrainment using partial netting techniques are only as good as these assumptions.

If both tailrace and intake netting are ruled out, nets may be deployed in the power canal entrance. Fish that enter the canal are assumed to be bound for turbine passage, but this may not always be the case, as there are often resident populations of fish within the power canals, or groups of fish that frequently move between a reservoir and its associated power canal. This method may be acceptable for downstream migrating anadromous fishes or when other methods are ruled out.

One of the most critical features of netting studies is "net efficiency." Since sampling nets are almost never 100 percent efficient, good entrainment studies (even with full tailrace nets) should include net efficiency tests. Testing is typically done by introducing marked fish of various sizes and species into the turbine intake at a point where they are committed to passage through the unit. Good net efficiency studies should test with both live and dead fish. In some cases, it may not be possible to introduce fish at a point in the intake where the fish are committed to turbine passage. In such cases, fish may be directly introduced into the collection nets. However, the distribution and behavior patterns of specimens entering the net from the introduction apparatus may be different than fish entering from the draft tube.

There is some argument concerning the net efficiency level that is acceptable for entrainment studies. EPRI suggests that 85 to 100 percent net efficiency is required to demonstrate the efficacy of a full-flow recovery net (62). Low net efficiency may result from rips or gaps in the net apparatus which allow fish to escape. In some cases, strong-swimming fish may be able to maintain positions within, or near, the draft tube, thus avoiding capture. Finally, the net mesh size may allow certain fish shapes and sizes to escape.

Partial flow collection nets will have much lower net efficiencies, the range of which may depend on the fish size and behavior, net size and location, and the flow conditions. Net efficiencies less than 10 percent are common. As previously discussed, net efficiency is assumed to be proportional to flow (i.e., even distribution of entrained fish) and often entrainment rates from partial-flow nets are extrapolated to the full plant flow. In these cases net efficiency testing should be repeated to test the reliability of the estimates, especially given the possibility of intrusions of non-entrained fish and avoidance behavior of entrained fish.

Hydroacoustic Technology (HAT)

Hydroacoustic technology (HAT), also known as SONAR, has been widely used to estimate fish entrainment at hydropower facilities, especially on the West Coast. This technology involves using a transducer to alternately transmit sound waves of a known frequency, usually between 40 and 500 kHZ, into the water and then monitor for any returning sound waves that may bounce off of an object.[8] Most of the newer systems require state of the art computers to decode the data and may rely on various software packages or human judgment to determine whether signals are from debris or from fish.

For entrainment studies there are basically three methods of HAT sampling: echo integration, echo counting, and target tracking. Echo counting and target tracking count individual fish, allowing a direct estimate of fish abundance. These methods are often preferred over echo integration, which is used to get an estimate of fish biomass over time. Echo integration is usually used when fish are swimming in large, tight schools, and individual fish cannot be recognized by the system. Echo integration is more susceptible to background noise levels and errors in estimates of target strength, especially when schools are not of homogeneous species or size.

The major advantage to this technology is that it is often cost effective over the long run as compared to netting. HAT sampling can operate 24 hours a day for months at a time with very little labor cost. HAT counts all fish (within chosen size limits) that swim into the ensonified region without harming or delaying the animal. In comparison, nets may detain, injure, or kill fish and are subject to avoidance behavior.

Recent HAT equipment, in addition to providing size and abundance of entrained fish, can also determine the temporal distribution of entrainment and the spatial distribution of fish as they enter a power canal, forebay, or intake. Information on important fish behaviors like swimming velocity and trajectory is also available. These data can help experimenters detect when, how, and where fish enter turbine intakes and thus may provide assistance in designing mitigation. Real-time data analysis is available, which may be used to alert plant operators when fish are passing the plant in large numbers.

The major disadvantages include the initial cost of the system, which is generally much higher than nets. The technology is also very complex and requires experienced personnel or considerable training (months or years). By design these systems collect a tremendous amount of data, much of which may not be relevant to the study (detection of debris or entrained air). In addition, fish that lie on the bottom or swim very close to a boundary (like a retaining wall, etc.) are very difficult, if not impossible, to detect with HAT. HAT studies should not be conducted in areas with electrical interference or turbulent water flow with entrained air bubbles. No (or little) information can be obtained concerning the species of the fish being detected, and fish which are milling around rather than actively migrating are likely to be counted more than once.

HAT has been used to study entrainment on the West Coast since about 1976. There have been more than 100 HAT entrainment studies (mainly targeting juvenile downstream migrating salmonids) on the Columbia River alone. Several sites have had multiple-year studies (e.g., Wells Dam has had more than 10 consecutive years of HAT entrainment sampling). In many cases, the study objectives went beyond simply quantifying the size and number of fish that were entrained. Studies have been used to evaluate different bypass alternatives (e.g., submerged spill orifices v. surface sluiceways (191) and the efficacy of vertical inclined traveling screens and other structural devices) which have led in some cases to increased bypass efficiencies (130).

HAT has also been applied at some sites in the Midwest and on the East Coast, but has been far more limited in scope. Early HAT studies in the Midwest (especially Wisconsin and Michigan) were not very successful, leading resource agencies in that area of the country to be very skeptical of the applicability of HAT to entrainment studies. Many factors may have limited the results of these early studies. HAT investigations

[8] Typically, the technique involves a pulsed cycle of alternating “transmitting” and “listening” sequences that may be repeated as many as 50 or 60 times per second.

in the Columbia Basin are usually done with state-of-the-art equipment and multiple transducers. This allows full coverage of intakes, etc., and increases the likelihood of gathering statistically useful data. The initial cost of these systems is relatively high, as compared to older HAT technologies and to using fewer acoustic samplers. Cost may not be a limiting factor at many Columbia River sites where adequate budgets allow state-of-the-art research. However, in the Midwest there is generally less money available to fund entrainment studies, and therefore HAT studies tended to use cheaper technologies and designs.

There are several substantial differences between the Columbia River sites and the Midwest sites, including fish fauna (size range, species richness, behavioral diversity), hydropower designs and operations, and overall scale. For example, most studies on the Columbia River have targeted juvenile downstream migrating salmonids which are generally of uniform species, size, and behavior. Studies in the Midwest must typically contend with numerous species with a broad size and behavioral range. These differences result in more complexity that must be addressed in the early design phase of HAT studies. However, these challenges can often be met with the proper experimental design and adequate technologies. The efficacy of HAT, like other methods to study entrainment, is highly site-specific. At some sites HAT may be impractical, while at others it may be highly feasible. If budgets (or logistical constraints) do not allow for adequate HAT equipment, then other study methodology should be sought.

Netting studies are often used in concert with HAT. This can be useful if species identification is important. In addition, the entrainment rates estimated from each method can be compared to one another, which may give a good idea of study accuracy. Comparisons of HAT and net-catch estimates of entrainment have been done at several sites (e.g., Tower and Kleber dams in Michigan (119); Ice Harbor, Rocky Reach, Lower Granite, and Wanapum dams on the Columbia River (192)) and have generally compared favorably.

Telemetry Tagging Technologies

Telemetry tagging technologies, including radio tags, sonic tags and Passive Integrated Transponder (PIT) tags, can be used to study the behavior of fish that are approaching or swimming in the neighborhood of a dam. While these types of studies cannot be used to quantify natural entrainment, they can provide valuable information that can aid in the interpretation of the potential for a problem. For instance, such studies can be used to estimate the percentage of fish that use various routes past a dam (spill, log sluice, bypass, turbine, etc.) or to estimate the risk of entrainment for different species of riverine fishes that are caught, tagged, released and then monitored in various parts of a reservoir.

Radio tags have been developed to transmit both pulsed and continuous signals. Continuous signals are easier to distinguish from background noise and are perceptible from greater distances. Pulsing systems use less energy, so batteries last longer, and individual fish can be distinguished by adjusting the length, rate or interval between pulses.

Transmitters can be attached externally, or placed in the stomach, or implanted surgically. Thus the size of the fish will determine the size of the transmitter. A small whip antenna sends the signal. Prior to attachment, transmitters are covered with a variety of substances to protect them from corrosion during operation.

The signal is stronger when the tagged fish is closer to the surface. Turbulent as well as saline water may disturb the signal quality. Radio transmitters are best suited for surface-oriented fish that are swimming in calm freshwater. Lower frequencies are transmitted further than higher frequencies, but require larger batteries and receiving antennae.

The receiver unit must be able to detect the bandwidth and exclude ambient noise. Wider bandwidths are easier to detect, but will include more background noise. Receivers may be mounted on boats or airplanes, or may be portable. Radio tags are comparatively expensive, often leading to relatively small sample sizes.

Sonic tags are used less frequently than radio tags because they operate over a more limited range, underwater hydrophones must be used, and fewer unique signals can be simultaneously monitored. The tags operate from 30 to 70 kHz, and therefore do not work well in areas of high background noise in overlapping frequency range (e.g., waterfalls, spillways, underwater movable machinery, etc.).

PIT tags have been developed over the past 10 years and allow billions of different codes. They have no internal power source and are only activated in the presence of an electromagnetic field. They are thus suited to monitor longer term migrations of adult salmonids, because the devices can be implanted during downstream migration and still be functioning when the fish return. Since the returning adults must pass through confined areas to get past dams, PIT monitors, when installed in a series of dams, can provide information on many fish passage questions. These include rate of passage, mortality during upstream migration and success rate of individual bypass facilities. The principal drawback of the technology is the need for the fish to be within a highly confined area to be detected. Depending on the transponder, the range of detection is 7 to 33 cm.

Turbine Mortality Study Methodology

Turbine mortality may be assessed using three basic types of studies: mark-recapture studies (e.g., tailrace netting, balloon tags), observations of net-caught naturally entrained fish, and telemetry techniques.

Mark-recapture studies are preferred because they allow for the use of control groups. Currently there are several methods of marking and recapturing the fish. The most common marking techniques include one or a combination of mutilation (fin clipping, branding, etc.), painting, external tags (physical items attached to the fish), and internal tags (e.g., coded wire tags). Fish may be recaptured in the tailrace with various net designs, or in some cases for anadromous fish they may be captured when they return as adults. If the latter method is used, careful control groups must be used and a very large sample size is required. However, it does have the advantage of taking predation on turbine-passed fish into account. Another recapture method involves attaching "balloon tags" to the fish that inflate after a given time and cause the fish to be buoyed to the surface where they can be captured by personnel working from a boat.

Observations of naturally entrained fish have also been used. Fish that are captured in tailrace nets (partial or full flow netting) can be retained in a live car and observed over a given time frame to check for mortality. Advantages of testing naturally entrained fish include sampling fish species and sizes that actually are entrained at the project, elimination of stresses associated with handling, holding, tagging, and introducing fish, and elimination of any potential bias associated with the placement of the introduction pipe. Disadvantages include inability to control for the number, size, and species of the fish, the occurrence of pre-existing injuries on fish, and the unpredictable nature of the timing of fish turbine passage. These problems often lead to meager statistical analyses of turbine mortality risk and therefore resource agencies do not recommend them.

Mark-recapture—Tailrace Netting

Partial or full tailrace nets are the most frequently used system for estimating turbine mortality. Full tailrace netting is preferred where feasible.[9] Experimentally introduced fish should be released at a point where they cannot avoid being entrained. This usually means using a section of pipe (usually PVC of four to six inches in diameter) to introduce the fish. A funnel may be attached to the top of the pipe and fish are usually flushed out with water, compressed air, or by

[9] See section on entrainment netting methods for a critique of net designs.

a physical plunger. There is some possibility that the introduction apparatus may bias the results if it introduces fish in a non-optimal location within the intake or if fish are disoriented when they exit the pipe thus altering their behavior in the turbine. It is also possible that the results could be biased by the number of fish introduced at one time. In other words, fish introduced in sequence may suffer different mortality rates than those that pass in large groups.

The most common problems with tailrace netting studies are intrusion of non-entrained tailrace fish into the net,[10] escape of some entrained fish causing less than 100 percent net efficiency, and injury and/or stress caused by handling or subsequent capturing and holding of entrained fish.

The intrusion of non-entrained fish should not typically be a problem for most mark-recapture studies, because the non-entrained fish should be unmarked. However, the escape of some entrained fish can be a problem. If injured and non-injured fish are caught at different rates, mortality estimates will be compromised. To alleviate this problem, experimenters try to maintain nets so that rips are not allowed to form. In addition, net mesh size must be smaller than the smallest target fish, and gaps between the net and frame (and the frame and draft tube) should be minimized.

The third problem—handling, holding and net capture stress—is one of the most controversial aspects of mark-recapture turbine mortality studies. Test fish typically must be transported to the study site, held in various types of pens, cages, and/or tanks, and physically handled while transferring, measuring, tagging, and finally injecting them into the turbines. To counter the problem, studies must include control groups that expose fish to all of the associated stresses besides turbine passage. These control groups should theoretically be able to identify the expected mortality due to handling, holding, or collecting stresses, and this amount of mortality can then be factored out of turbine mortality estimates of the test groups.

However, some scientists have argued that control groups may not be capable of factoring out all of the mortality associated with handling stress. The concept is that the stresses of handling and turbine passage are synergistic rather than discrete, thus the mortality caused by the combination is greater than the sum of the individual effects. In other words, test fish (passing through turbines) that survive turbine passage may be stressed to some degree and may be killed by a level of handling stress that would not kill a "normal" fish. In other words, control fish are not previously stressed by turbine passage, and may be more able to survive the handling. Thus, the mortality rate calculated for the control fish would not properly account for the synergistic effects on the test fish. In such cases, an overestimate of turbine mortality may result (202,203,206).

Mark-recapture—Balloon Tags

The balloon tag technique involves attaching a self-inflating tag to the test fish, introducing the fish into the turbine, and recovering the fish in the tailrace after the balloon inflates and forces the fish to the surface. This method eliminates the need for tailrace nets (which can be very expensive at large projects) and thus eliminates the stresses associated with net capture. However, recovery can be difficult as personnel must use boats to locate and capture fish, and thus radio tags are often used to help locate the floating fish. Fish recovery is typically better than 85 percent (62), and predation on floating fish and evasion by floating fish have been identified as contributing factors to the percentage of fish that is not recovered. The treatment of these non-recovered fish is one of the most controversial issues concerning this recapture technology. Presently, most studies simply include all non-recaptured fish in the dead column, which might slightly overestimate turbine mortality. How-

[10] See section on entrainment netting methods for a critique of tailrace intrusions.

ever, professional judgment may sometimes be used to determine whether non-recaptured fish are “dead” or “alive” (29).

This method has been identified as useful for frail species that are easily harmed or stressed by net capture (e.g., shad, herring, and alewife). The balloon tags themselves have not been found to kill the fish. The main disadvantage of this technology is the cost of labor-intensive fish recovery. Therefore sample sizes are usually low (total samples less than 200 are most common). If multiple species and size classes of fish need to be tested at more than one operating scheme, netting techniques are more practical.

Telemetry

Radio tagging has been used with limited success to study turbine mortality, but is less common than netting. This approach compares the movements of live and dead fish that are implanted with radio transmitters after turbine passage. In general, fish are counted as living if they move beyond the point where dead fish typically settle to the bottom. This technique assumes, among other things, that any fish that moves beyond the typical settling point of dead fish will survive (i.e., no delayed mortality), fish that settle are dead and not just stationary, fish that are counted as having moved beyond the settling point have not been ingested by another fish and taken downstream, and no fish regurgitate tags. Results may also be confounded by the loss of signals related to fish moving to areas beyond the reach of the transmitter device. In general, resource agencies prefer netting or balloon tagging methods over telemetry for turbine mortality studies.