

Effects of Dams on Pacific Salmon and Steelhead Trout

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INTRODUCTION

The need for salmon, sea-run trout, and other anadromous fish to spawn in fresh water has made them particularly vulnerable to many of the activities of man. Forestry, farming, road building, growth of cities, industry, and pollution have all taken their toll. However, none of these developments has had more impact on the survival of salmon than the construction of dams. The watershed of the Columbia River presents a critical illustration of the effects of dams on salmon, reflecting events in progress in the entire Pacific Northwest.

The earliest dams in the Columbia River Basin were relatively small. They appeared on tributary streams in the 1840's, constructed to divert water for irrigation, for logging, and for the operation of sawmills. Their numbers were few and their total effect was relatively minor. In the 1880's dams for hydroelectric power were constructed on larger streams, such as the Spokane and Willamette Rivers, seriously affecting the Pacific salmon, *Oncorhynchus* spp., and steelhead trout, *Salmo gairdneri*, populations in those streams. In the 1930's major hydroelectric dams were built on the mainstem Columbia River (Fig. 1), initiating the large-scale development of the water resources of the Columbia River Basin for electrical power, irrigation, navigation, and flood control. For the next four decades construction of many large dams proceeded on the Columbia River and its major tributaries producing sudden, enormous changes in the environment of anadromous fish. Great dams barred passage to the sea; huge lakes replaced swift-flowing rivers; spawning grounds were inundated; water temperatures were modified; predator, competitor,

and disease relations were upset; food supplies were affected.

The necessity for providing safe passage over the physical obstructions of dams was an obvious reality. Of equal importance was the need to protect the fish when the changes made by dams in the basic environment were too severe. Because there were many dams (Fig. 2) the cumulative effect of small losses, injuries, or delays at each dam became serious. Failure to solve fish passage problems at high dams with large impoundments (i.e., Grand Coulee and Brownlee Dams) resulted in a complete barrier to migrating fish in the upper reaches of the Columbia and Snake Rivers (Fig. 3). This barrier denied, to anadromous fish, access to a substantial portion of the entire Columbia River watershed.

PASSAGE OF FISH

Adult Fish Passage at Dams

As dams were constructed on the Columbia River, fishways were provided to permit adult fish to swim over the dams to continue their upstream migration toward their spawning

grounds. These fish "ladders" consisted of a long series of pools (Fig. 4), starting from the water level below the dam (tailrace) and ascending approximately 1 foot in elevation at each succeeding pool until reaching the water level behind the dam (forebay). Water flowed from pool to pool and fish could ascend by swimming over the weirs that separated each pool or through holes in the weirs provided for that purpose.

Although fishways of this general design had been in use for many years, the large scale of fishway construction necessary on the Columbia River and the variety of new situations that had to be faced required more information on fish behavior and abilities than was available.

Some of the questions that needed to be answered were surprisingly simple, such as: At what rate do fish ascend fishways? What is the maximum water velocity through which fish can swim? How does light affect the rate of ascent



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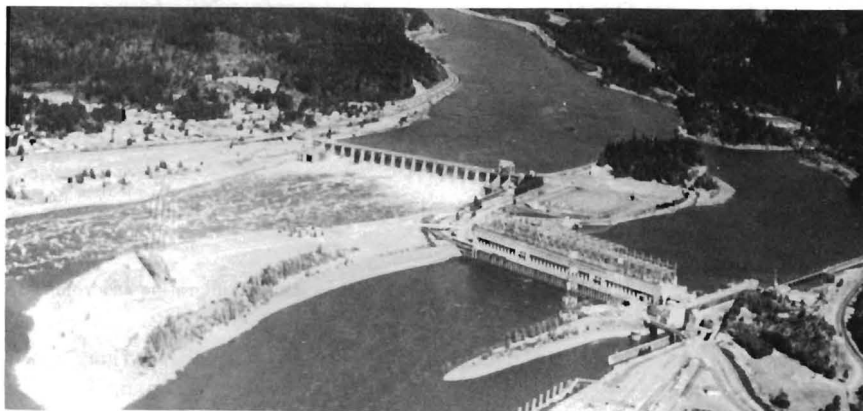


Figure 1.—Bonneville Dam, the lowermost dam on the Columbia River, was constructed in 1938. A second powerhouse will be constructed on the north shore (left side), reducing the need to spill large amounts of water.

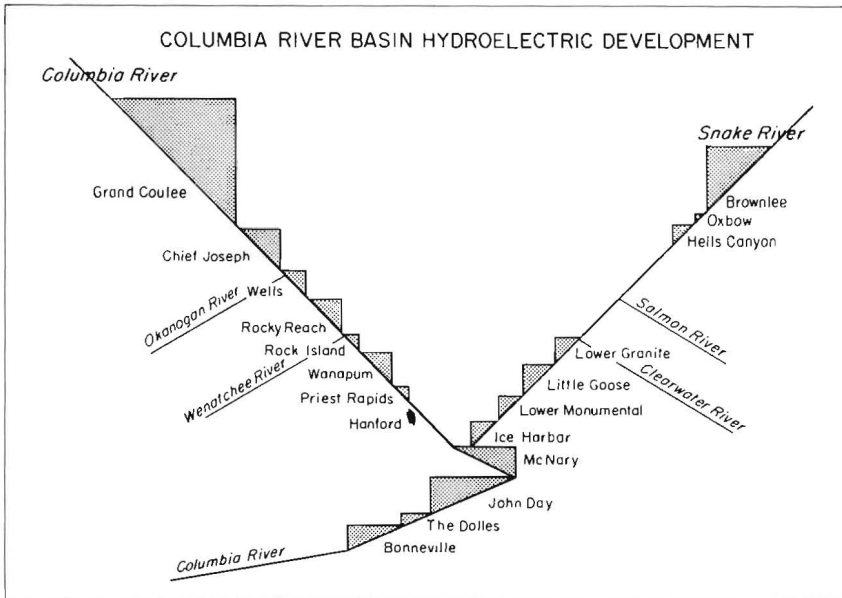


Figure 2.—Diagram showing the sequence of major dams on the Columbia and Snake rivers.

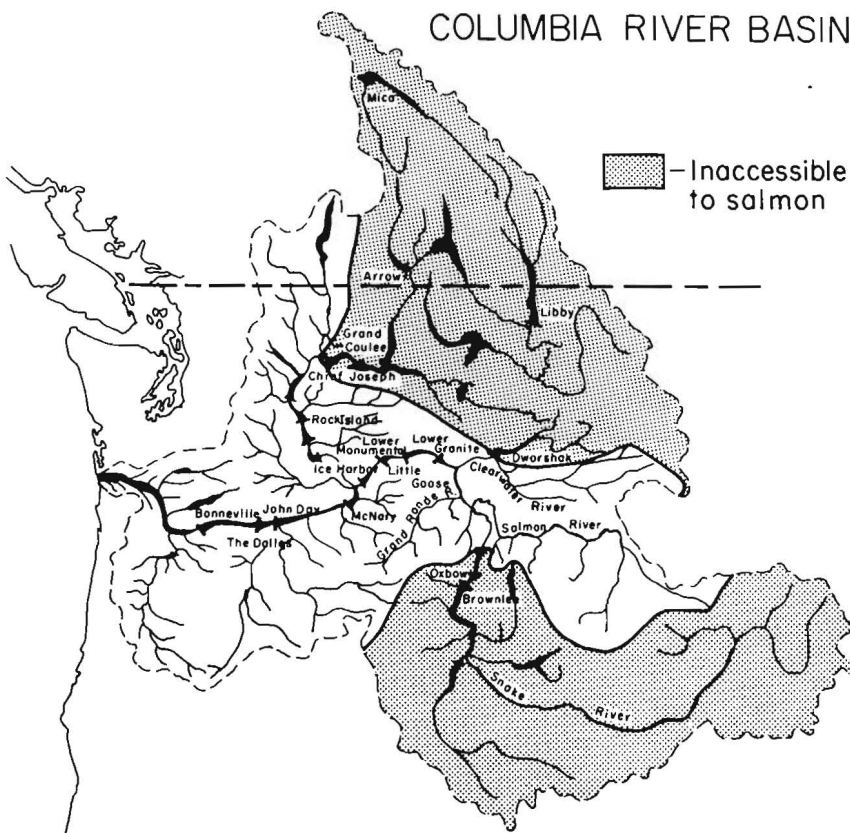


Figure 3.—Areas in the Columbia River Basin no longer accessible to migrating anadromous fish because of dams.

in fishways? Other questions had a direct bearing on the cost of fishways, such as: How large a fishway is needed for a given number of fish? How steep can a fishway be without causing fish to

tire or fail to ascend? How long can a fishway be without fatiguing fish? To gain answers to these and similar questions, an intensive research effort was undertaken in which State and

Federal fishery agencies, universities, and a major dam constructing agency, the U.S. Army Corps of Engineers, participated.

A special laboratory for fishery-engineering research was constructed at Bonneville Dam in which it was possible to measure the reactions of anadromous fish under controlled experimental conditions while the fish were actually migrating. Fish were diverted from one of the major fishways into the laboratory (Figs. 5 and 6), where their responses to full-scale fishway situations were observed and recorded. Fish then swam out of the laboratory to continue their migration upstream.

Experiments conducted at the laboratory provided data on the spatial requirements of salmon in fishways, on rates of movement of fish ascending fishways, and on the effect of fishway performance and physiological indices such as blood lactate and inorganic phosphate could find no evidence of fatigue from ascending fishways when proper hydraulic conditions were obtained. It was concluded that the ascent of a properly designed fishway was only a moderate exercise for fish, possibly similar to swimming at a "cruising" speed that can be maintained over long periods of time.

Tests to measure swimming abilities (Fig. 7) indicated that the critical velocity of water was between 8 and 13 feet per second (fps). Velocities above this range proved to be an obstacle to a significant number of fish, although some individual fish had a much greater ability. The maximum observed swimming speed was 26.7 fps by a steelhead.

Examination of fish preferences for light conditions revealed marked differences in species. Steelhead, given a choice of light and dark channels, selected a dark channel. Chinook salmon, *O. tshawytscha*, appeared indifferent under the same conditions and moved randomly into both light and dark channels. Steelhead moved more quickly through fishways that were darkened (Fig. 8), yet—in passing through pipes and open channels—showed an increase in speed when light was added. Presented with a choice of

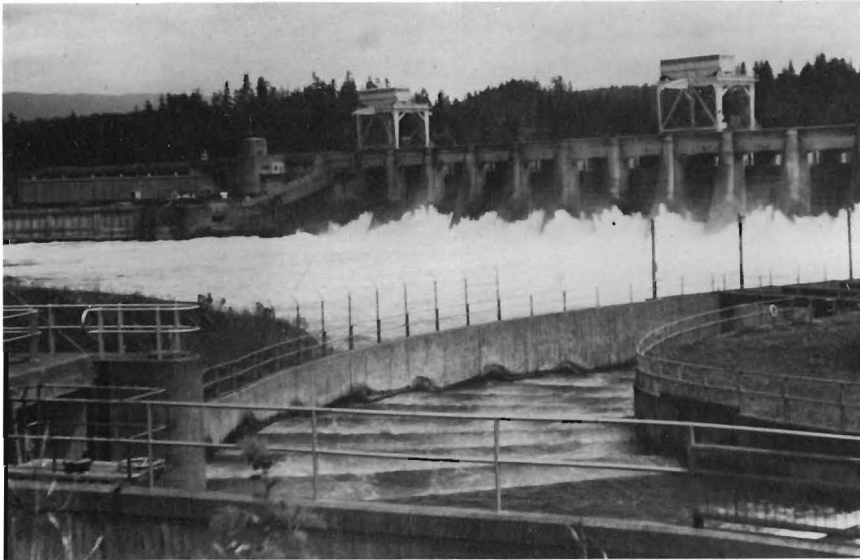


Figure 4.—Pool type fishway (foreground) at Bonneville Dam. The long, windowless building on the opposite shore is the Fisheries-Engineering Research Laboratory.

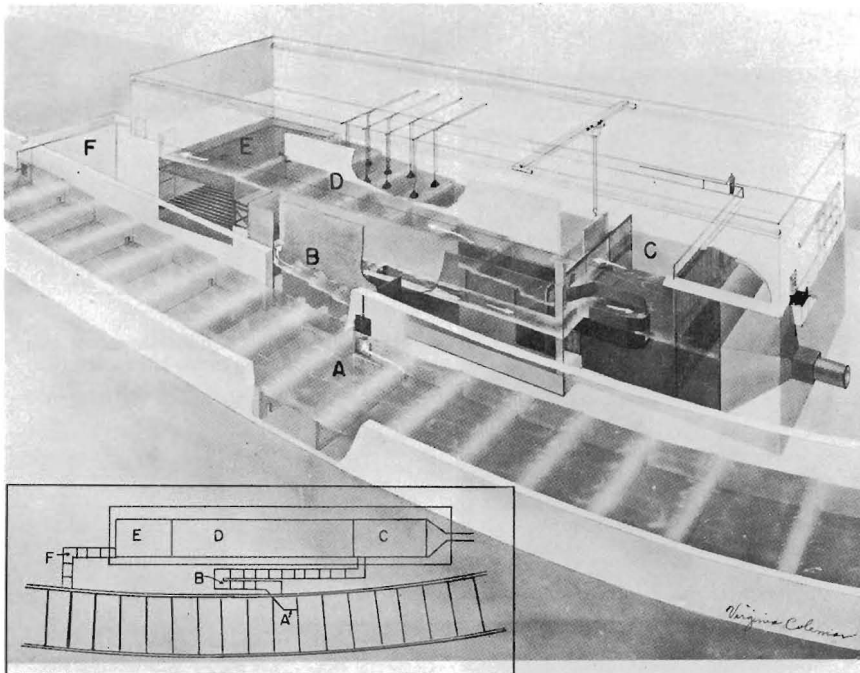


Figure 5.—Sketch of Fisheries-Engineering Research Laboratory at Bonneville Dam showing its relationship to fishway. Fish are diverted from the main fishway by a picketed lead (A) and ascend the entrance fishway (B) to a collection pool (C) in the laboratory. After release they pass through an experimental area (D) to the flow introduction pool (E) and then out the exit fishway (F) where they return to the main fishway. (Insert shows plan view of laboratory.)

channels with a high velocity (13 fps) and a low velocity (3 fps), both salmon and steelhead showed a strong preference for the high velocity.

These are but examples of the types of information gathered at this unique laboratory for use in designing fishways that would be effective and efficient. Full-scale models of complete

fishway designs (Fig. 9) were then tested in the laboratory before being put into use at a dam. Even after being constructed at a dam, new fishway designs were carefully evaluated in actual operation (Fig. 10).

The search for information on the behavior of adult fish was also extended into river situations. Individual

fish were tracked by means of sonic and radio tags (Figs. 11 and 12) to determine their patterns of movement approaching dams under a variety of flow conditions for improving the design and placement of fishway entrances. Tracking studies of fish movements after leaving fishway exits showed the importance of the proper location of fishway exits because of the possibility of the fish being swept back downstream over the spillway of a dam.

Adult passage at dams is measured at counting stations in each fishway. Trained observers enumerate individual species of anadromous fish as they migrate through the fishway. At some dams migrating fish are directed by picketed leads over a white counting board (Fig. 13) where they can be easily seen and tallied by an observer. At more recently constructed dams, fish counts are made through large viewing windows (Fig. 14) set in the side of a fishway. The data are used in estimating total populations, assessing spawning escapements, and determining effects of changing ecological conditions at dams. Counting is now being done at 12 major dams on the Columbia and Snake Rivers with counting stations in operation from early spring to late fall. When the dam construction phase in the Columbia River Basin has been completed and river flow patterns have been stabilized, however, migrating fish will probably be counted only at a few index dams.

In addition to counting stations in each fishway, most dams have special viewing facilities for the public. The surge of hundreds of thousands of salmon, steelhead, and American shad, *Alosa sapidissima*, passing through the fishways of the Columbia River dams has become a national pride as well as the visible index of the health of a fishing industry and a recreational resource. More visitors come annually to watch salmon and steelhead at the dams on the Columbia River than visit Yellowstone Park or the Grand Canyon (Fig. 15).

Juvenile Fish Passage at Dams

Young salmon migrating to the sea in the Columbia River may have to pass over as many as nine major dams on

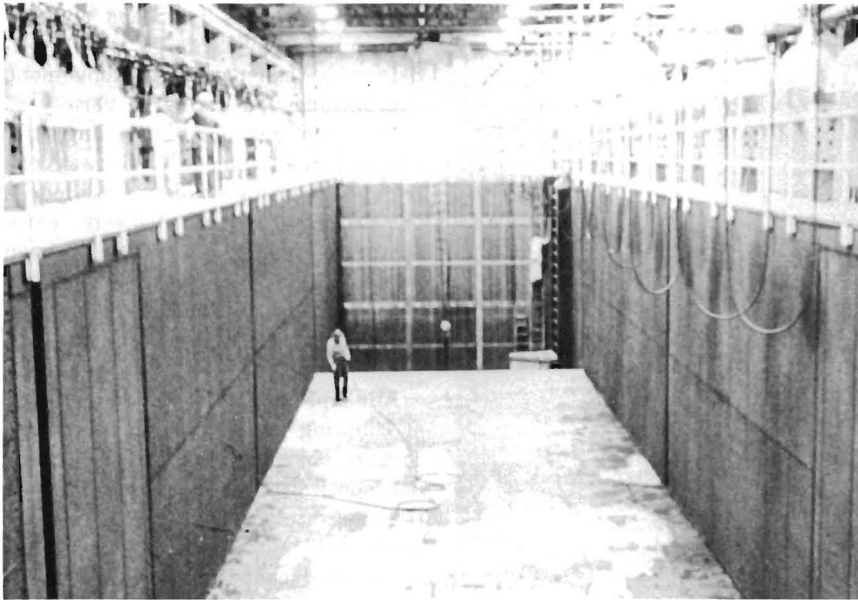


Figure 6.—Interior of Fisheries-Engineering Research Laboratory when empty and unwatered. Experimental area (center) is 104 feet long, 24 feet wide, and 17 feet deep. Fish collection pool at far end is 50 feet long and 24 feet deep.

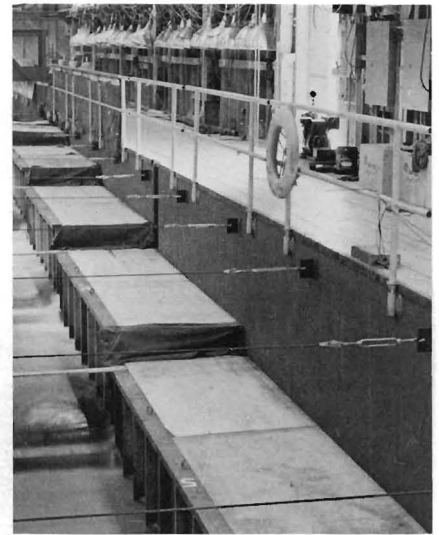


Figure 8.—Covered fishway used in darkened passage experiments. All laboratory lights were turned off during dark tests.

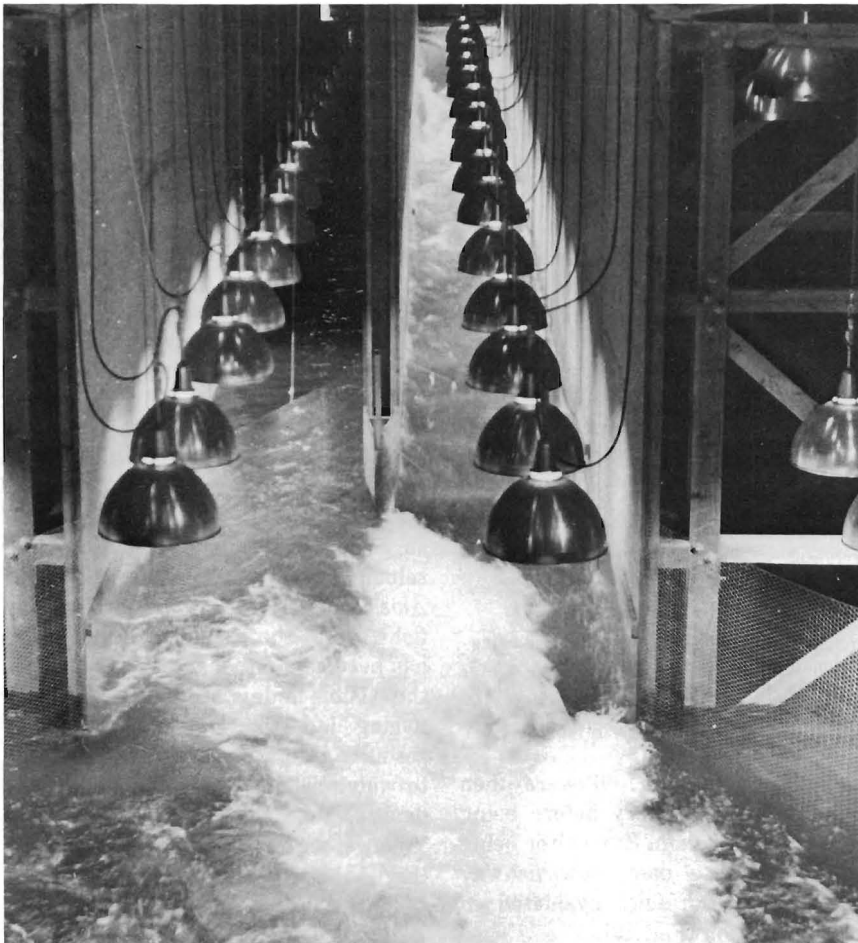


Figure 7.—Experimental channel with a water velocity of 16 feet per second appears on right. Entrance to channel on left is screened to prevent access during swimming ability tests.

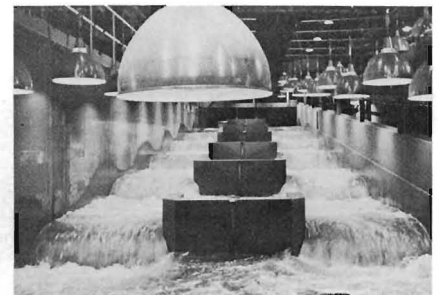


Figure 9.—Test of a full-scale model of a new fishway design in the laboratory.

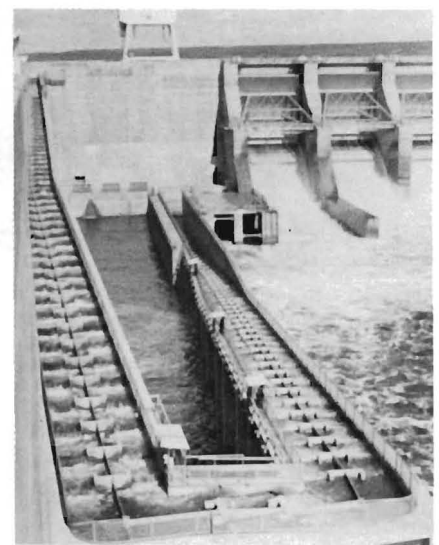


Figure 10.—New fishway design being evaluated at Ice Harbor Dam. Note four observer stations for measuring rates of fish movement.



Figure 11.—Radio fish tag being inserted into the stomach of an adult chinook salmon.



Figure 12.—A fish tracking team member taking a bearing on a radio-tagged salmon below Lower Monumental Dam. Simultaneous bearings taken by two or more team members will be used to establish the location of the fish by triangulation.



Figure 13.—Adult salmon passing over a white counting board which aids observer in identifying species.

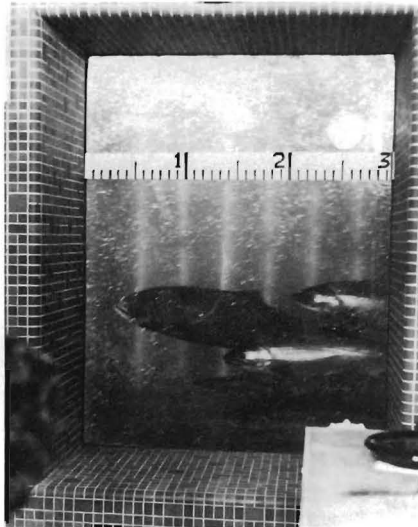


Figure 14.—Adult fish are counted as they pass a viewing window set in the side of a fishway.

their journey downstream. Those that are carried over spillways at each dam pass without injury; those that move with flows through turbines are less fortunate, however. Some are killed outright by turbine blades, high turbulence, shearing flows of high velocity, and sudden pressure changes. Others are injured or temporarily stunned and are easy prey for predators such as sea gulls or northern squawfish, *Ptychocheilus oregonensis*, feeding in the eddies of the tailrace below the dam.

Mortality rates at each dam differ with the relative amounts of water passing through powerhouse and spillway; with the size, species, and condition of the fish; with the type of turbine; with the operating load; etc., but an estimate of 15 percent loss per

dam is generally considered to be conservative. With the development of upriver storage reservoirs and increasing water control, a greater percentage of the water (and a higher percentage of the fish) will be passing through turbines so that mortalities might even be expected to increase in the future. These losses are compounded, of course, by the number of dams through which the young fish have to pass.

In response to these critical circumstances, studies were undertaken to develop practical methods of protecting the young migrants at dams.

An investigation of the distribution of young fish in turbine intakes showed that 70 to 80 percent of the migrants were concentrated in the upper 15 feet of water (Fig. 16). The investigation also showed that many of the young migrants entered the gateway (where the gates that can close off the intake for unwatering the turbine are stored) through a gate slot in the ceiling of the turbine intake. These fish had to leave by the same route or remain trapped in the gateway. Efforts were focused on a system that enabled the juvenile migrants to bypass the turbines by being diverted through the gateway and into a passageway leading to the tailrace.

An inclined traveling screen (Fig. 17) was installed that diverted most of the migrants into the gateway, and holes (labeled "orifice" in Fig. 16) were cut in the gateway wall, enabling the fish in the gateway to pass into a channel that connects with the tailrace. This system does not protect all of the migrants entering turbine intakes and it would be expensive to install and maintain in

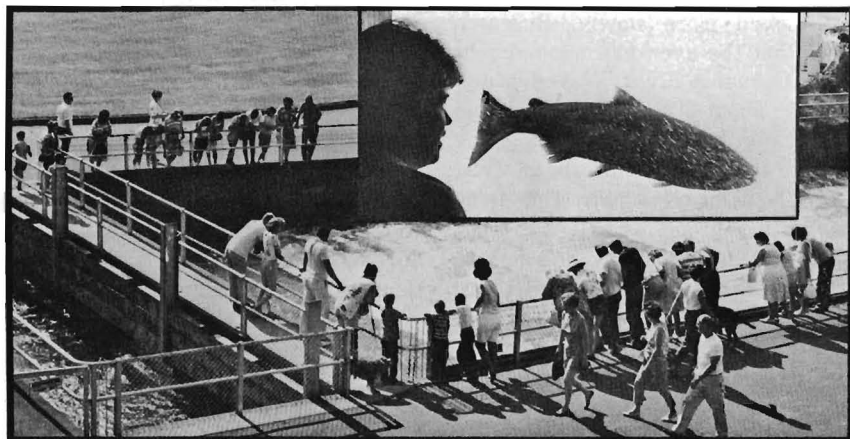


Figure 15.—"Salmon Watching" at Bonneville Dam.

all of the dams of the Columbia River. It does, however, provide an alternative to excessive mortalities in turbines.

CHANGING ENVIRONMENT OF FISH AND COUNTERACTIVE MEASURES

Dams Bring Change

Vast changes in the environment of salmon have been brought about by the construction of many dams in the Columbia River Basin. Long Chains of lakes now exist where once were rushing rivers, complete with rapids and gravel bars ideally suited for the incubation of salmon eggs. Hundreds of miles of spawning areas were flooded with nearly disastrous effects on fish populations. To replace the loss of so much area critical to salmon reproduction, large scale programs of artificial reproduction were begun by State and Federal fishery agencies. A major share of this effort was begun in 1949 when Congress appropriated funds for the Columbia River Fishery Development Program. This program finances the operation and maintenance of 21 fish hatcheries that produce over 86 million juvenile salmon and steelhead annually in compensation for those that were produced in the wild before dams were constructed.

To fish that had been adapted for thousands of years to existing seasonal patterns of water flow and temperature, the construction of many dams created other environmental stresses. Freshets and floods that had carried young fish swiftly down to the sea were now controlled. In the impoundments behind the dams the water (and the fish) moved more slowly. Research shows that the average impoundment on the Columbia River delayed young migrants about 3 days. Fish from the upper river have been reaching the estuary almost a month later than before the dams were built. This delay in migration through the river extended the exposure of the young fish to hazards such as disease and predation. Temperatures in the river, because of the greater surface area of the impounded waters, increased during the summer at a time when high water temperatures can become critical to salmonids. The habitat of many of the

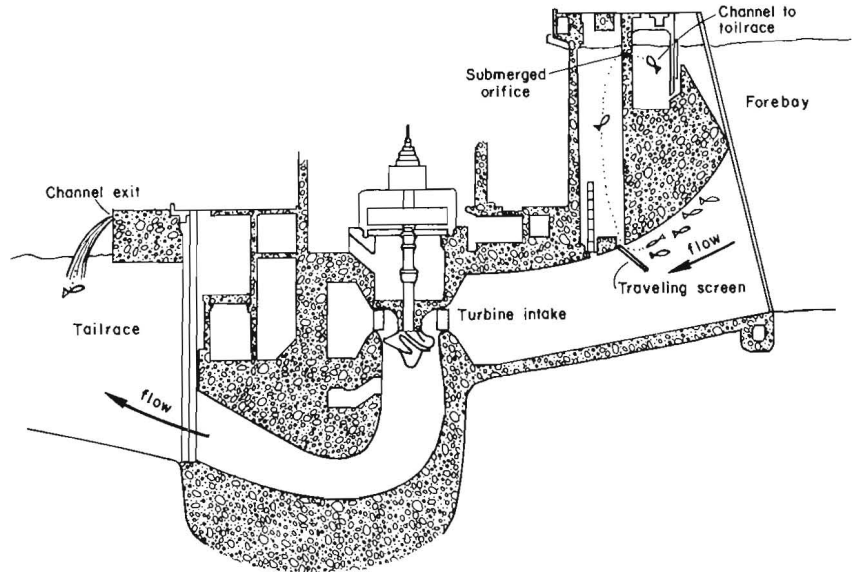


Figure 16.—System to bypass juvenile migrants around turbines. Young fish entering a turbine intake concentrate near the ceiling. Approximately 75 percent of the fish are diverted by traveling screens into the gatewell, then the fish pass through submerged orifices into a channel connected to the tailrace. With this system fish may be bypassed around the turbines of a single dam or the fish may be collected and transported around many dams.

salmon's competitors and predators was increased and improved.

Research on the effects of impoundments on salmon migration showed that the degree of passage success related to the length and volume of the impoundment, to the relative volume of flow through the impoundment at the time of migration, and to both the physical and biological environment in the impoundment. Migration through the impoundments created by the "river run" dams—all about 100 feet high, on the Columbia and Snake Rivers—appears to be generally successful for both adults and juveniles. However, the large impoundments created by dams (i.e., Grand Coulee, 343 feet; Brownlee Dam, 277 feet) proved to be more serious obstacles. Studies made in the Brownlee impoundment showed that while adult fish were able to migrate through the 57-mile long reservoir successfully, the young fish found conditions too severe. A high degree of thermal stratification develops in the reservoir with surface temperatures reaching levels lethal to young salmon while the cooler sub-surface water becomes deficient in oxygen. The impoundment, for all practical purposes, is an impassable barrier for juvenile salmon and steelhead.



Figure 17.—Traveling screen shown in operating position on the deck of Little Goose Dam. Hydraulically operated arm is withdrawn to permit lowering of screen through gatewell slot.

Dams are also responsible for creating a condition under which the water becomes supersaturated with gases. Frequently referred to as "nitrogen supersaturation" because air is nearly four-fifths nitrogen, the condition is lethal to fish at high levels of gas pressure. Large volumes of water discharging over a spillway plunge into a deep pool below the dam forcing entrapped air into solution with the water. Under the hydrostatic pressures prevailing at depths of 40 feet or more in the spillway basin, the gases are continually dissolved and added to the water as long as spilling continues. In free-flowing rivers, where riffles and cascades provide for a quick release of dissolved gases, supersaturation rarely becomes a problem because gas pressures in water rapidly return to atmospheric level. In a series of impoundments such as now exist on the Columbia and lower Snake Rivers, there is not sufficient circulation to provide for a rapid release of gases. As a result, gas pressures remain above atmospheric levels.

Fish trapped in supersaturated water suffer from so-called "gas bubble disease." This relates to the physical damage caused by creation of gas bubbles in the tissues and blood vessels (Fig. 18). Dissolved gases are absorbed in the bloodstream and embolisms are formed when the gases leave solution. The symptoms are analogous to the "bends" in human divers when they move too quickly from a high-pressure to a low-pressure environment.

Mortalities created by supersaturation have been high for adult and juvenile fish in high-flow years, in which large volumes of water were surplus to power generation use and were passed over spillways. The most critical circumstances occurred when new dams were completed and a high flow occurred before the turbines could be put into operation. At such times, the entire river flow plunged over the spillway. Saturation levels have reached a deadly 145 percent (100 percent is normal; over 110 percent begins to be lethal to fish).

In an effort to reduce supersaturation, the U.S. Army Corps of Engineers, after an intensive search of alternatives, developed a spillway flow deflector (Fig. 19) that creates a

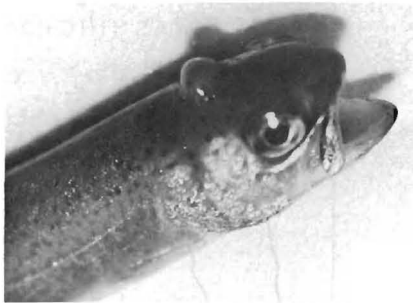


Figure 18.—Gas bubbles beneath the skin on the head of a young chinook salmon. When bubbles burst, infections may set in and kill the fish. Dissolved gases absorbed into the bloodstream form bubbles when the gases leave solution. These embolisms may block the circulatory system and cause death.

surface flow below the spillway instead of permitting the deep plunging action that is responsible for most of the supersaturation. With the installation of the deflectors at all of the dams on the river, it is hoped that major problems with supersaturation will be solved.

Collection and Transportation

To avoid the cumulative hazards of a long series of dams and impoundments to upriver stocks of fish, a system is being evaluated that would collect young migrants at the uppermost dam and transport them to the estuary. Under this procedure, losses—from turbines, from predation, from supersaturation, and from other adverse environmental effects in many miles of impoundments—would be eliminated. Collection would be by the use of turbine intake traveling screens and gatewells. Instead of the bypassed fish being released to the tailrace, they would be diverted temporarily into

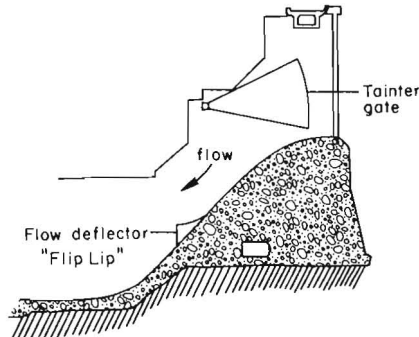


Figure 19.—Cross section of a spillway showing flow deflector (Flip Lip) installed to reduce supersaturation. Deflector creates a surface flow instead of permitting the plunging action responsible for supersaturation.

holding ponds, then trucked and released at appropriate locations in the estuary (Fig. 20).

Research is now in progress with fish marked as juveniles by the insertion of a tiny piece of magnetic wire in the snout. Initially some of these fish (test fish) were transported around the dams (Fig. 21); some (control fish) were released to find their way down the long series of dams and impoundments. When these fish return from the sea as adults and ascend the fishway at Little Goose Dam, a detector will recognize the magnetic tag and automatically shunt the fish into a holding tank where they can be examined to determine which treatment they received. When the data are analyzed scientists hope to have the answers to many questions. For example, will the homing of the fish to its native stream be affected by its capture and "rerouting"? What will be the losses associated with collecting, holding, trucking, and releasing fish in



Figure 20.—Tank trucks transport fish from collection and marking area around the hazards of seven dams and six impoundments for release below Bonneville Dam, about 350 miles downstream from Little Goose Dam. Studies are also being carried out at Lower Granite Dam in which eight dams and seven impoundments are being bypassed.

comparison with allowing them to proceed downstream on their own volition? Will the system be economically feasible?

It will be several years before a final judgment can be made, but sufficient information is already available for optimism. Theoretically, by reducing losses of young fish, the system has the potential for increasing the number of adult salmon and steelhead to the Columbia River Basin by 60 percent. The degree to which reality can match this potential remains to be seen.

CONCLUSION

Despite the many problems that complicate the maintenance of salmon runs when rivers are interrupted by dams, our runs of salmon can be maintained. Problems of reproduction, passage, temperature, delay, and supersaturation all can be solved if

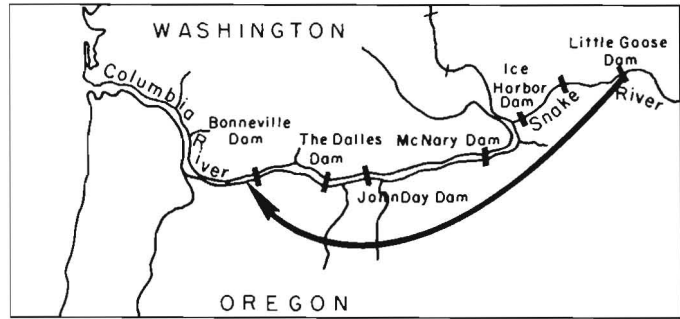


Figure 21.—Transportation route from Little Goose Dam to below Bonneville Dam.

enough effort is made. Even the "impassable" large impoundments can be bypassed. With sufficient determination, there will always be salmon in the "Salmon" River—and all of the other salmon streams of the Northwest.

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MFR PAPER 1223

Effects of Water Diversions on Fishery Resources of the West Coast, Particularly the Pacific Northwest



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INTRODUCTION

Man has found it necessary to divert water from its natural courses to enhance his existence and insure his survival. In the United States, for example, the Rio Grande River no longer flows into the sea, and all water of the Colorado River is being used—except for 1.5 million acre-feet, which is allocated to Mexico. The Missouri and Mississippi rivers have been affected by man's water diversion practices. Another example, which has altered the environment of Delaware Bay, is the diversion of Delaware River water

to New York City. In 1922 the total water storage capacity in the United States was 33 million acre-feet; in 1962, it was about 300 million acre-feet; and by the year 2,000, an estimated 600 million acre-feet will be stored. By 1980 approximately 50 percent of our stream and river flow will be diverted. By the year 2000, this will increase to more than 80 percent. As we carry out vast programs of water storage and use, we will greatly curtail river flow into the sea (Stilwell, 1962). Even though less than 1 percent of the world's water supply is now diverted or stored (Armstrong, 1972), the manipulation of this

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seemingly insignificant portion can have a profound effect on the survival of fish species.

In the United States today, the primary water uses are: 1) electrical power production, 2) irrigation, 3) flood control, 4) navigation, 5) industrial, 6) mining, 7) domestic, and 8) recreation. These uses are not listed in order of importance because any one use on any body of water may take precedence over all others; each plays a part in contributing to water diversion problems.