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Mitigating the effects of high-head dams on the Columbia River, USA: experience from the trenches

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Abstract Worldwide, humans have tremendously altered freshwater ecosystems and arguably, construction of dams has had the greatest effect. Maintaining natural ecological processes and developing mitigation strategies that will maintain species while retaining dam benefits is challenging. In the Columbia River, USA, over the last 30 years more than US$7 billion has been spent on efforts to save historically large runs of salmon. These efforts have included improving passage conditions at dams through construction of efficient fish ladders for adult salmon, effective fish passage facilities for downstream migrating juvenile salmon, voluntarily spilling water to decrease the number of downstream migrants that pass through turbines, modifying dam operations to provide more constant flow and providing additional flow from storage reservoirs to create more natural flow through areas inundated by dams. Construction of hatcheries to offset losses in habitat for wild fish has also occurred. Further, for salmon from the Snake River, the largest tributary to the Columbia River, a large percent of juvenile salmon smolts are collected at upstream dams and transported in barges to the lower river to avoid passage through dams, turbines, and reservoirs. Experiences in the Columbia River suggest that the sum of all of these actions may keep salmon stocks from going extinct, but the technological fixes will not likely provide complete mitigation for altered freshwater ecosystems.

Keywords Dams · Mitigation · Salmon · Freshwater ecosystems

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Hydropower, Flood Control and Water Abstraction: Implications for Fish and Fisheries

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Background

Globally, humans have caused tremendous change to freshwater ecosystems. With expected future population increases, limited freshwater habitats will be affected to an even greater extent in the future (Postel et al., 1996; Jackson et al., 2001; Foley et al., 2005). Of the many impacts, construction of dams has arguably caused one of the greatest alterations. Worldwide, there now exist more than 45,000 dams that exceed 15 m in height (World Commission on Dams (WCD), 2000). Yet, despite the clear benefits to humans from dams that store, use, and divert water for consumption, irrigation, flood control, transportation, power production, and recreation, the lack of effective mitigation measures to maintain ecological processes has led to serious discussions about dam removal

(World Commission on Dams (WCD), 2000; Babbitt, 2002; Doyle et al., 2003; Stanley & Doyle, 2003).

In recent decades, efforts to understand and improve ecological conditions created by large, high-profile hydropower dams in the United States have occurred in the Tennessee Valley (Bednarek & Hart, 2005), at Glen Canyon Dam on the Colorado River (Patten et al., 2001; Petersen & Paukert, 2005; White et al., 2005) and, most notably, in the Columbia River basin (Fig. 1) (National Research Council, 1996; Northwest Power and Conservation Council, 2003; Williams et al., 2005). Despite efforts to stem losses of wild salmonids, 13 of 16 salmon (*Oncorhynchus* sp.) evolutionarily significant units (ESUs) (Waples, 1991) in the Columbia River basin are currently listed as threatened or endangered under the U.S. Endangered Species Act (ESA). Thus, the attempts to minimize or mitigate the effects of dams and their reservoirs on these fish may provide some lessons on the difficulties others may face in river systems altered by dam construction.

The Columbia River historically had the largest runs of Chinook salmon (*O. tshawytscha* (Walbaum)) in the world (Netboy, 1974). In the early 1880s, spring and summer Chinook salmon provided commercial fisheries in the lower Columbia River with average annual catch of 17.7 million kg (Craig & Hacker, 1940). Heavy exploitation by these fisheries caused a substantial depletion of the dominant summer stock; the fisheries then concentrated on the spring and fall stocks. In addition, beginning in the early part of the twentieth century, construction of dams in headwaters of tributaries to the Columbia River further depleted runs as the dams were often constructed without adult fish passage facilities. In the 1930s, concern about salmon losses led to insistence that all future dams (<30 m of head) constructed on the mainstem of the river and its major tributary—the Snake River—must have adult passage facilities.

The Snake River, the major tributary Columbia River, historically produced the majority of salmon in the Columbia River basin. Here, we use the construction of Snake River dams to illustrate the effects of dams on salmon and ecosystems. We discuss how large dams initially affected salmon stocks, the evolution of strategies to mitigate the effects, along with evolution of techniques to measure success, and uncertainty about the extent that the hydropower system presently limits salmon stock recovery. We also note where measures to lessen impacts on salmon stocks have not worked for some other fish species.

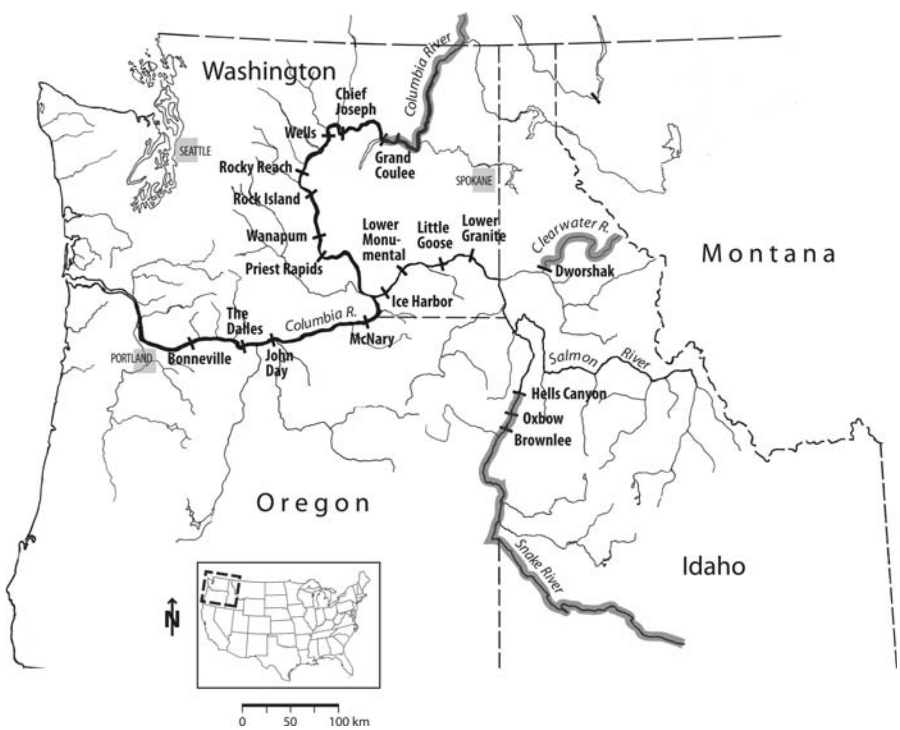

Fig. 1 Map showing the Columbia River Basin with its major tributary the Snake River. Large mainstem dams are noted on the lower Snake and Columbia Rivers. Shaded areas indicate historic salmon spawning areas now blocked by dams

Initial effects of dams on fish

In 1958, the construction of Brownlee Dam in the upper reaches of the Snake River blocked all access to anadromous fish (Fig. 1). The dam created a 92-km long reservoir with a depth of 92 m at full pool, and it contained no adult fishways. Concurrent to its construction, studies at the Fisheries Engineering Research Laboratory at Bonneville Dam determined that adult Chinook salmon and steelhead (*O. mykiss* (Walbaum)) could easily pass well-designed fishways of hundreds of meters in height (Collins & Elling, 1960). Fishways were not, however, subsequently installed at Brownlee Dam, nor at other high-head dams in the Columbia River basin—most notably Grand Coulee Dam on the upper Columbia River—because research on juvenile salmonids determined that insufficient numbers of smolts negotiated Brownlee reservoir, and of those that did, few could find and pass the deep turbine intakes (Krcma & Raleigh, 1970; Sims, 1970). Although research would occur over the next 30 years to evaluate adult fishways at dams, large numbers of adult fish passing dams indicated generally successful passage, thus, few changes were made to adult fishways.

In 1962, Ice Harbor Dam, with a head of approximately 30 m was completed on the lower Snake River. With four additional mainstem dams of similar height slated for construction in the next decade, efforts turned toward evaluating survival of juvenile salmonids through the free flowing sections of the Snake and Salmon (tributary to the Snake) Rivers down to Ice Harbor Dam. Simultaneously, efforts were directed toward development of strategies for decreasing the expected lower survival that would occur once the additional dams were in place. Over the next two decades, mark-recapture studies using freeze-branded smolts (Mighell, 1969) determined that juvenile fish travel time substantially increased while survival decreased after construction of the additional dams (Raymond, 1979; Raymond, 1988) (Figs. 2, 3).

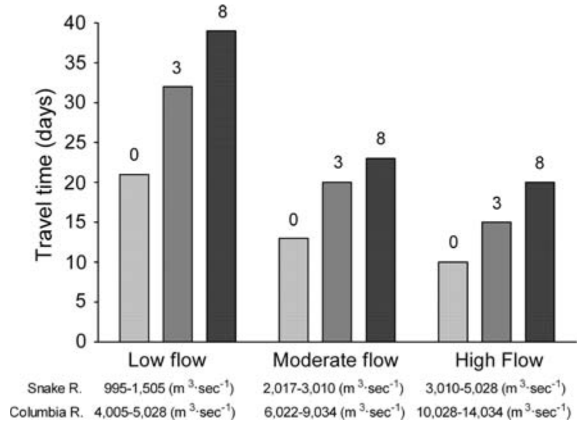

Fig. 2 Estimated travel time of Snake River juvenile Chinook salmon through the lower Snake and lower Columbia Rivers with 0, 3, and 8 mainstem hydropower dams

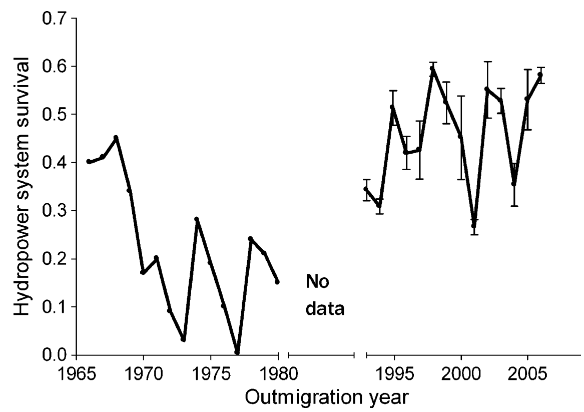

Fig. 3 Estimated juvenile Chinook salmon survival through the lower Snake lower and Columbia Rivers, 1964–1980 and 1993–2006. Juvenile fish migrated through 4 dams from 1964 to 1967, five dams in 1968, six dams in 1969, seven dams from 1970 to 1974, and eight dams since 1975

Early strategies to mitigate dam effects

Screening turbine intakes and transportation

Research in the 1960s and 1970s to mitigate these losses was initially directed toward developing screening systems to divert juveniles away from turbines into effective juvenile bypass systems that routed the diverted fish to a collection area. From there, two options existed: (1) route fish back to a release point in the tailrace of the dam, or (2) put them into trucks and barges and transport them to a safe release site below Bonneville Dam.

The transportation option was developed because it was recognized that the massive change in ecological conditions and cumulative effects to migrants from passing through eight reservoirs and dams might cause the demise of stocks. As initial transportation research found that transported fish returned at higher rates than nontransported fish (Ebel et al., 1973;

Ebel, 1980), in 1977 the region decided to collect and transport as many fish as possible from upper Snake River dams. By the mid- to late 1980s, more than 85% of the salmon smolts migrating from the Snake River basin were collected at Lower Granite and Little Goose dams, barged 400- to 460-km downstream through reservoirs and locks at dams, then released into the lower Columbia River below Bonneville Dam. Despite continued evaluations using batch-marked, freeze-branded fish that indicated higher returns of transported fish compared to nontransported fish, returns of wild adult spring–summer Chinook salmon to the Snake River continued to decline (Fig. 4). Nonetheless, the transportation strategy continued because research indicated that transportation provided more adult returns than the alternative, and it held the promise of allowing considerably more power production. Some fishery agencies, however, questioned the strategy because of concern about experimental design of the studies and the lack of positive increases in adult fish (Ward et al., 1997). With the listing of Snake River salmon stocks under ESA in the mid-1990s, and concern that the transportation program did not mitigate sufficiently for dams, in 1995 spill was implemented at Lower Granite and Little Goose dams in order to "spread-the-risk" during any parts of a year with flows above a minimal level (approximately 1,600 $m^3 s^{-1}$). Even with the large spill program implemented to pass fish (Fig. 5), the improvements in screening at these dams resulted in the transportation of greater than 65% of salmon from the Snake River Basin.

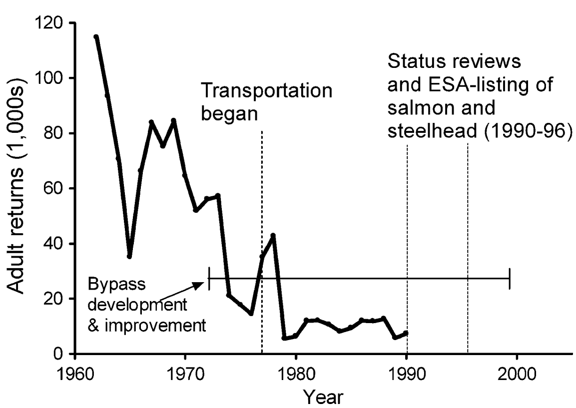

Fig. 4 Estimated wild Snake River spring–summer Chinook salmon adult return to the Snake River (includes escapement plus lower river catch), 1962–1990

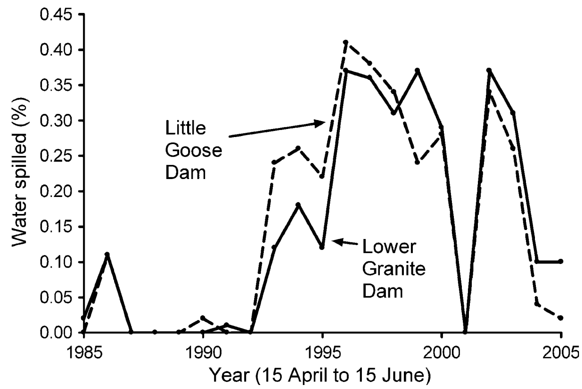

Fig. 5 Percentage of river flow spilled at Lower Granite and Little Goose Dams, 1985–2005. Directed spill (mandated spill that did not exceed powerhouse capacity) began in 1993 to decrease the numbers of juvenile fish collected for transportation

Support for the transportation strategy required the continued development of systems to divert fish from turbines at upper Snake River dams, and also the development of systems at lower Columbia River dams to divert fish away from turbines where transportation did not occur. For example, protection was needed for stocks migrating from the upper Columbia River and all other tributaries downstream of the Snake River. Without specific knowledge of juvenile smolt behavior, studies to improve old or develop new screening systems in turbines and other parts of juvenile bypass systems relied to a large degree on trial and error. As a prime example, a new powerhouse was constructed at Bonneville Dam in 1980–1981. It included turbine intake screens and a juvenile bypass system with a design based on successful systems developed and tested at upstream dams. However, the turbine intakes at the new Bonneville Dam powerhouse did not have exactly the same dimensions as at upstream dams. Initial evaluations of the system found that the turbine intake screens worked very poorly. Research over the next 7 years attempted to determine causes for the lack of success and develop new strategies for increasing the number of fish diverted from turbines, but did not attain the initial design criteria (Gessel et al., 1991). The evaluations relied on recapture of fish in nets above and below screens. Evaluations of other parts of the bypass system components relied on measuring changes in descaling rates on individual fish and recaptures of fin-clipped fish. These testing methods were used not only at Bonneville Dam, but throughout the 1970s through the early 1990s at all of the other dams. The capability of directly measuring smolt movement or behavior did not exist. Thus, the studies could not provide needed information to inform, a priori, engineers on designs that would likely provide the best chance of successful passage. Engineers, with biologists looking on, could, at best, use dye traces in models run in hydraulic laboratories. Results of field testing would often clearly indicate that the fish did not "go with the flow" as identified by the dye traces.

In spite of the lack of good juvenile behavioral data, years of field testing of turbine intake screens with many different configurations led to increased guidance of juvenile salmonids away from turbines, and changes to the screens and bypass system components decreased injury and delay of migrant fish at each dam. It was not possible to design a good functioning screening system for any dam without some prototype testing and certainly complete evaluations after installation (which often led to the need for further modifications). Between 1981 and the mid-1990s, no system-wide evaluations of how these efforts affected overall survival of migrant fish were made because of concerns that mark-recapture studies of batch-marked branded fish were not reliable (see Burnham et al., 1987).

Flow and spill

In 1980, the U.S. Congress passed the Pacific Northwest Electric Power and Conservation Act. It included the provision to create the Northwest Power and Conservation Council (Council) with two representatives each from the states of Oregon, Washington, Idaho, and Montana. The Council had (and continues to have) the charge to develop an efficient and reliable energy supply in the Pacific Northwest while restoring anadromous fish resources damaged by the development of the Columbia River hydropower system (Williams & Tuttle, 1992). In 1982, the Council developed a Fish and Wildlife Program (F&W Program) that created a water budget, a volume of water stored during the winter usable by fishery agencies to increase flows during the following spring or summer. Although no longer referred to as such, the current federal biological opinions (the directives for how to operate the Federal Columbia River Power System to avoid jeopardy for ESA listed

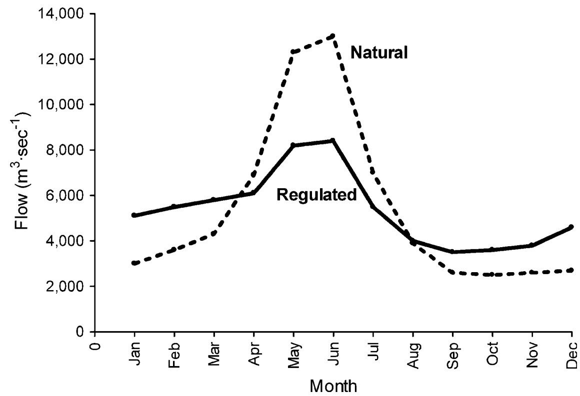

Fig. 6 Change in the natural hydrograph in the lower Columbia River as a result of water storage at upstream reservoirs used to regulate flow for flood control and power production

salmon) have set annual volumes of stored water for fish that range from 7.2 to 8.5 cubic kilometers, or about 6–10% of total annual flow, depending on the water year. Despite these efforts, water stored for prevention of flooding events has considerably changed the natural river hydrograph (Fig. 6).

The Council's F&W Program also called for spilling water at dams to decrease the number of fish passing through turbines during the development period for screening systems at lower river dams. By 2000, the Council had amended the F&W Program to call for specific recommendations for each mainstem dam to determine the most efficient level of bypass spill in order to maximize passage efficiency (percentage of fish not going through turbines) and fish survival with the goal to preserve water for hydropower generation when not needed for spill for fish.

Spill, however, is not entirely benign. In the 1970s, high levels of spill in the Snake River caused high levels of atmospheric gas supersaturation that caused substantial mortality to fish (Ebel & Raymond, 1976). The States of Washington and Oregon set a 100% limit on atmospheric gas supersaturation. After an evaluation gas bubble trauma disease (the cause of mortality) in juvenile migrant fish (Backman et al., 2002), annually fisheries agencies have requested a waiver of the gas supersaturation limit to allow levels to reach 115% in the forebay of dams and 120% in the tailrace. At this level, very little evidence of gas bubble trauma is observed in migrant fish.

The Council's prescriptions for flow and spill were made without empirical evidence about the extent to which they would increase return rates of adult fish, but with expectations that they would produce better passage conditions for juvenile fish than had previously existed. The costs of the Council's F&W Program for spill have grown substantially over the years as foregone costs for power not produced by spilling water over dams, and providing water for flow in the spring and summer rather than using it in the winter for power production have increased. The Bonneville Power Administration markets power produced by the federal dams. Their analyses indicate high value for water used in the winter when natural flows are low, and much less during spring melt when excess water exists. During summer periods, water used for spill also has high value if used for power production. For the 2007–2009 rate periods, the Bonneville Power Administration estimates their annual revenues at approximately $2.35 billion. Their estimates of annual costs for fish and wildlife (combined costs of direct expenditures for research; construction, operation, and maintenance of fish facilities and hatcheries; and "lost revenue" from power foregone that results from flow manipulation and spill) at approximately $700 million, or nearly 30% of total revenue. All costs for the F&W Program are borne by the region's ratepayers who use power produced by the federal dams.

River levels controlled for spawning fish

Historically, river levels below dams fluctuated with power demand. By the early 1980s, this condition clearly adversely affected some fish populations as often salmon spawned at high river levels and redds became dewatered as levels receded. This led to agreements by dam operators to limit water releases for power production during spawning periods. The operators have agreed to keep water levels at consistently low levels during spawning so fish will spawn in areas that will remain covered under subsequent power operations until all eggs have hatched and alevins have left the gravel.

New techniques to measure hydropower system effects

PIT tags

In the late 1980s, passive integrated transponder (PIT) tags were developed by researchers at the Northwest Fisheries Science Center (NWFSC) for implantation into juvenile salmonids, along with means to detect the juvenile fish as they passed through bypass systems at Columbia River dams (Prentice et al., 1990a, b). The uniquely coded tags allow the identification of each individual fish. In order to address criticisms about control fish used to compare against transported fish (Ward et al., 1997), NWFSC scientists also developed systems that provided the capability of separating PIT-tagged fish from the untagged population collected by juvenile bypass systems at Snake River dams, then selectively returning the PIT-tagged fish to the river while the untagged population was sent to barges for transportation (Marsh et al., 1999). Serendipitously, this led to the ability to use maximum-likelihood statistical techniques to accurately estimate survival of juvenile migrants (Skalski, 1998), as well as the ability to characterize travel time under different hydropower operations (Zabel, 2002).

The initial PIT-tag systems were only installed at the upper Snake River dams, but after determining that it was possible to make accurate estimates of survival, over the next several years, PIT-tag detection systems were progressively installed in the juvenile bypass systems at downstream dams. In order to make a survival estimate using the maximum-likelihood technique requires detection capability of tags at two points. Thus, to make a hydropower system survival estimate to Bonneville Dam (the lowest dam on the river) required the ability to detect tags downstream of Bonneville Dam. In order to do this NWFSC researchers developed an underwater PIT-tag detection device placed within the cod end of a surface trawl towed by two boats and operated in the Columbia River estuary (Ledgerwood et al., 2004).

Initial releases of PIT-tagged fish were small because each tag cost approximately $3.00 and small numbers were sufficient to determine timing of fish. However, numbers of tags increased from 2 to 3,000 per release group when it became clear that accurate survival estimates with high precision were possible to obtain. By 2000, analyses of PIT-tag data indicated that efforts during the 1980s and 1990s to screen turbine intakes, install or improve juvenile bypass systems at mainstem dams, increase flow, and provide spill at dams led to increases in juvenile survival such that levels were equivalent to or higher than levels that existed in the 1960s when only four mainstem dams existed (Fig. 3) (Williams et al., 2001). Based on PIT-tag detections for spring migrants, data analyses also indicated that the provision of spill and flow may decrease travel time of Chinook salmon by as much as 2 days from their average travel time of 17 days.

In 1995, the decision to use PIT-tags to evaluate transportation was made and approximately 250,000 PIT tags were inserted into juvenile fish at Lower Granite Dam. PIT-tag detectors installed in the Lower Granite Dam adult sampling facility subsequently detected returning adults. The huge increase in PIT-tagged fish in 1995 and in subsequent years for this study and others at hatcheries, traps, or other dams has provided the capability to determine differences in adult return rates of transported fish and nontransported fish and to characterize how different juvenile migration histories, such as seasonal downstream timing or number of juvenile bypass systems passed (based on detections at dams of PIT-tagged juvenile fish during their migration to the sea) related to adult returns (Zabel & Williams, 2002; Williams et al., 2005; Zabel et al., 2005). For the first time, data indicated that spring–summer Chinook salmon juveniles transported early in the season did more poorly than juveniles transported later, and that the earliest transported Chinook actually fared poorer than fish that migrated through the entire hydropower system.

Based on results from earlier transportation studies, transportation was hypothesized to decrease overall adult returns because it caused stress which increased susceptibility to disease or predation (Congleton et al., 2000; Mesa et al., 2000; Budy et al., 2002; Schreck et al., 2006). Now, with recent information on temporal, seasonal changes in adult return rates, the past physiological hypotheses of mortality do not explain return rates as well as hypotheses on differential rates of predation in the estuary and ocean based on size of fish predators and juvenile salmonids (Muir et al., 2006).

Radio tags

In recent years, miniaturization of radio tags has provided the ability to tag smaller natural juvenile migrant salmonids. With antennas placed in the forebays, tailraces, turbines, spillways, and bypass systems at dams, researchers can determine the approach patterns of juvenile fish as they approach dams, how they react to flows through different passage routes, and which routes they chose to pass (Johnson et al., 2005). Due to the high cost of spill at dams, efforts are now underway to develop alternative means to attract fish to spillways and pass them in much lower volumes of water. Presently, removable weirs installed in single spillways at dams are under evaluation with radio-tagged fish at several Snake River dams to determine if surface flow can attract and pass large numbers of fish in much lower volumes of water than through the spillways (which have tainter gates that open 10 or more meters below the water surface). Based on initial successes of a prototype spillway weir installed at Lower Granite Dam in 2002, research using radio tags to determine the effectiveness of spillway weirs is scheduled to occur through at least 2010 as new systems are developed for other mainstem dams.

In addition to determining the general approach patterns of juvenile fish at dams, researchers expanded on the success of maximum-likelihood survival techniques used with PIT tags, and now have installed radio-telemetry receivers downstream of dams. Multiple-detection capabilities provide data usable to make survival estimates of the radio-tagged fish passing the dams (Skalski et al., 2002). Radio tags, however, typically have a 15–20 cm-long trailing antenna that exceeds the length of the tagged fish. The antennas may affect juvenile fish behavior and survival, which has led to advances in acoustic technologies.

Acoustic tags and evaluation

In recent years, small acoustic tags have been developed for surgical insertion into the abdominal cavity of juvenile salmonids >90 mm. They have the advantage of no external antenna and are effectively detected in seawater; whereas, radio tags are not. For example, one such tag weighs 0.62 g in air, with a residual mass of 0.35 g in water. It is 5.5 mm wide, 17 mm long and 4.0 mm high (thick). Each tag transmits a uniquely coded 31-bit binary phase-shift keyed signal at a frequency of 416.7 kHz and a source level of 150 dB (relative to 1 μPa and 1 m). Specially designed detectors have been installed at the mouth of the Columbia River and allow survival through the hydropower system and river below the dams to be estimated. These technologies are so new they have not been reported in the peer-reviewed literature. Another alternative uses underwater acoustic arrays to determine 3-D locations of fish as they approach dams. These data combined with computer modeling of flow dynamics has provided a basis for models that predict smolt behavior under varying flow conditions (Goodwin et al., 2006).

Modeling effects of the hydropower system on fish stocks

Adult returns of Snake River Chinook salmon increased substantially beginning in 2001. For the 5-year period 2001–2005, the total run of adult spring–summer Chinook salmon (hatchery and wild combined) into the Snake River averaged 104,800 fish versus to 25,800 fish from 1996 to 2000. Compared to the 1960s when only wild fish existed, total returns exceeded those of earlier years, but now rather than wild fish, most came from hatcheries. Nonetheless, the large increase in PIT-tagged juvenile fish released, and the large numbers of adult fish that have returned, has provided the ability to conduct much more sophisticated modeling. Analyses of recent adult data indicate that smolt-to-adult return rates of wild fish in recent years were nearly the same as in the 1960s (total numbers of wild fish were lower because juveniles produced from depressed populations were lower) when only four dams existed in the hydropower system (Fig. 7). This appears to have resulted from a change to favorable from unfavorable ocean conditions (Scheuerell & Williams, 2005). Modeling analyses on a large sample of PIT-tagged fish has also uncovered length-related survival relationships and the importance of knowing juvenile migration histories when observing differences in adult returns (Zabel et al., 2005).

Lessons learned and discussion

The progression of actions to change Columbia River dam configurations and hydropower system operations to improve conditions for migrant salmon has taken decades and proven difficult, as well as costly; however, several important lessons have been learned. First, only in recent years have data and analyses become available that suggest that low adult

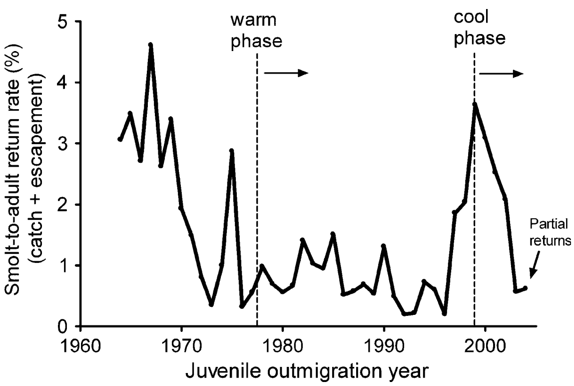

Fig. 7 Estimated smolt-to-adult return rate (escapement to the Snake River plus lower river catch) of wild spring–summer Chinook salmon from the 1964 to 2003 juvenile outmigration. The graph shows the switch to a warm phase of the Pacific Decadal Oscillation (PDO) in 1976/1977 and back toward a cold phase in 1998/1999 [Salmon production is related to the PDO (Mantua et al., 1997; Hare et al., 1999; Mantua & Hare, 2002)]

returns observed over decades were a result of poor ocean productivity, and not simply the direct result of hydropower system construction and operation. This suggests that actions taken in freshwater to improve conditions for fish need evaluation in the context of the life cycle, and for anadromous species, this would include effects of variability in ocean productivity.

Second, reliance on "trial and error" methodologies conducted over decades to develop effective bypass systems for juvenile salmonids likely delayed solutions. In contrast, fishways and passage systems developed for adult salmonids were based on extensive laboratory observations of adult fish behavior and performed well once installed, requiring little adjustment or modification. Thus, whether for upstream or downstream migrants, development of effective fish passage facilities at dams requires detailed knowledge of the behavior of the fish of interest relative to hydraulic flow patterns.

Third, efforts in the Columbia River have focused almost entirely on salmonids and at the expense of other species. Laboratory research determined how to modify adult salmonid fishways to effectively pass shad (*Alosa sapidissima* (Wilson)—a nonnative species) (Monk et al., 1989). However, recent radio-telemetry research has now determined that these fishways do not effectively pass adult Pacific lamprey (*Lampetra tridentate* (Richardson)) (Moser et al., 2002). Video movies taken of Pacific lamprey show that they have a difficult time entering collection channels because of the 90-degree edges at the entrances where water velocities of 2.5 m s^{-1} exist. Laboratory and field studies are currently in progress to determine lamprey preferences for different configurations to fishway entrances and to develop new bypass alternatives. Also, knowledge and possible solutions for effective passage facilities for white sturgeon (*Acipenser transmontanus* Richardson), essentially does not exist. Therefore, studies of all fish species are required to completely mitigate for the effects of dams on riverine ecosystems.

Fourth, it is easy for people to develop "belief systems" that something works, and these can easily become "institutionalized." Once "institutionalized" and in place it is difficult to change solutions such as flow, spill, and transportation, even if data do not show great benefits from them. Thus, prescriptions for solutions to low adult returns should be based on an empirical-based knowledge of their benefits. Often, this will require development of specialized equipment and procedures for testing dam mitigation alternatives.

Fifth, experiences in the Columbia River basin clearly demonstrate the difficulty in developing mitigation strategies to offset changes in ecological processes as a result of dam construction. For example, fish transported around all the dams arrive below the lowest dam in less than 2 days and hence at the Pacific Ocean earlier than they did historically, while nontransported fish arrive later. However, given that transported fish avoid the mortality of passing eight dams, they do not return at levels suggested by the early research. Trying to unravel this mystery has taken decades. Another mitigation tool is the use of hatcheries to augment salmonid productivity. However, we now see evidence that releases of hatchery fish may, in fact, decrease wild fish returns (Levin et al., 2001; Levin & Williams, 2002). The effects of hatcheries in the Columbia River Basin is a topic of ongoing research (Berejikian & Ford, 2004), and the role that hatcheries should play in the recovery of stocks listed under the ESA is currently under active debate and review.

Finally, the Columbia River has one of the highest levels of fragmentation and flow regulation of any large river system in the world (Nilsson et al., 2005), returning it to predam conditions is not possible, and the provision of more spill or flow for the fish will not likely change outcomes significantly. For example, recent modeling exercises suggest that changes in direct hydropower system survival will have little effect on overall adult returns (Kareiva et al., 2000; Wilson, 2003). Barring removal of Snake and Columbia River dams–a very contentious and controversial proposition heavily debated in the Pacific Northwest–complete restoration of historical ecological processes will not occur. Juvenile salmonids will continue to encounter migratory conditions unlike those under which they evolved. While these are difficult issues to address and there are no easy solutions, modifications to dam operations, habitat improvements, changes to hatchery production, and continued limits on harvest are all underway and may keep stocks from going extinct. Clearly, taking an "all-H" approach to these issues, where all anthropogenic causes of salmon decline including habitat, hatcheries, harvest, and hydropower are considered, is an important step in recognizing the total impact humans have on fish species. Development of cost effective strategies to mitigate for fish declines requires these types of holistic efforts, both in the Columbia River basin and elsewhere in the world. Otherwise, ineffective and costly piecemeal mitigation strategies may result.

Additional resources to obtain information not cited here:

The U.S. Army Corps of Engineers (COE) (built the majority of mainstem Columbia River dams), and the Bonneville Power Administration (BPA) (markets the power produced by the dams) contract for US$ 10s millions per year in research related to the hydropower system. Contract reports have a wealth on information on fish passage that has not been published in the peer review literature. Reports submitted to the COE for the last approximately 10 years are available at:

http://www.nwp.usace.army.mil/pm/e/afep_docs.asp
http://www.nww.usace.army.mil/planning/ep/fishres/newmain.html

Reports submitted to BPA are available at:
http://www.efw.bpa.gov/reports.aspx

Acknowledgments Although the author has over 30 years of experience, it pales in comparison to the efforts expended by staff over the last 45 years to gain knowledge on anadromous fish in the Columbia River. The majority of research to determine effects of Columbia River dams on upstream and downstream migrating anadromous salmonids was conducted by our organization at the Northwest Fisheries Science Center, part of the National Marine Fisheries Service within the

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