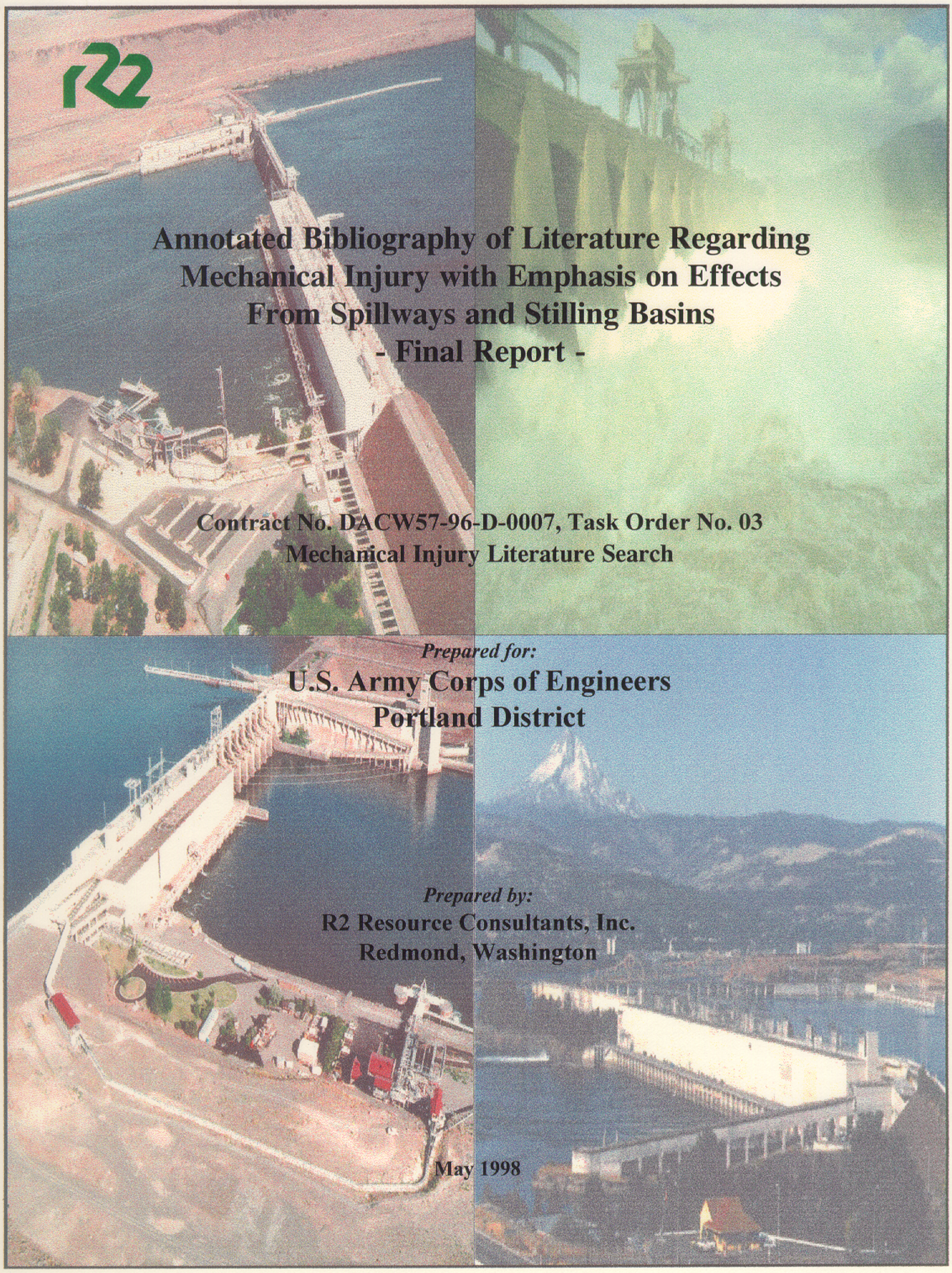

Annotated Bibliography of Literature Regarding Mechanical Injury with Emphasis on Effects From Spillways and Stilling Basins
- Final Report -

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1. INTRODUCTION

The U.S. Army Corps of Engineers (USACE) is in the process of identifying and comparing alternatives for minimizing the impacts of spills at hydroelectric dams in the Snake and Columbia rivers on downstream migrating fish, including juvenile salmon and steelhead. Originally, spillways were only used when river discharges exceeded the capacity of the powerhouse, or when regional power demands were substantially lower than the generating capacity of the Snake and Columbia river dams. The duration and magnitude of spilling has increased as a result of experimental flow measures which have been implemented to improve the downstream passage of juvenile fish in these lower Columbia and Snake rivers (NMFS 1995). These spills are intended to increase survival by decreasing the passage time of downstream migrating fish, and by passing more fish over spillways instead of through powerhouse turbines where injury and mortality rates are thought to be relatively high.

Unfortunately, these spills have also increased the potential for injury and mortality to fish resulting from total dissolved gas (TDG) supersaturation. For this reason, the National Marine Fisheries Service (NMFS) requested the USACE to identify and evaluate potential structural and operational changes to Columbia and Snake river dams which could be used to reduce TDG levels occurring under the current spill program (NMFS 1995). A Gas Abatement Workshop was held during October 1996 by the USACE Portland and Walla Walla districts to review potential alternative gas abatement measures which could be used to improve fish survival during spill events at Columbia and Snake River dams (USACE 1997). Two areas of concern were identified regarding fish survival and spillway passage: 1) achieving reductions in TDG levels which would effectively reduce injury and mortality due to gas bubble trauma (GBT); and 2) mechanical injury and mortality directly or indirectly resulting from passage through a spillway and stilling basin, including those resulting from proposed gas abatement measures. The expert panel attending the Gas Abatement Workshop identified the need for estimating and comparing the mechanical injury of fish in spillways and stilling basins which could result under a number of gas abatement alternatives, including:

- Installation of flow deflectors;
- Installation of flip buckets;
- Raising the elevation of the stilling basin;
- Raising the elevation of the tailrace;
- Construction of submerged passageways; and
- Construction of auxiliary passageways or a side channel.

The USACE is currently pursuing three avenues for gas abatement. These include: reduction in the mass of total dissolved gas produced (deflectors, raised stilling basin), minimize new gas production (submerged passageways, submerged gates, turbine flows), and flow degassing (raised tailrace). Flow (spillway) deflectors, which are concrete sills positioned along the lower end of a spillway, minimize plunge depth by focusing water released from a spillway into a horizontal jet. These devices have been found to be an effective method for reducing TDG levels, and for this reason have been installed at a number of dams on the lower Columbia and Snake rivers (USACE 1996). Their effectiveness, however, is limited to a design operating range. Outside their design range, flow overshoots the deflectors and plunges into the tailrace entraining air and producing high dissolved gas levels.

The purpose of this report is to provide a better understanding of the mechanical injury of fish passing through spillways and stilling basins based upon the data and information provided in the current literature. This literature review is intended to: 1) describe the types of injuries sustained by fish passing through spillways and stilling basins; 2) compare injury and mortality rates observed at different dams which have been directly or indirectly attributed to spillway passage, including those with gas abatement structures such as flow deflectors; 3) identify the physical factors and conditions occurring within the spillway and stilling basin environment which have been reported to injure and kill fish; and 4) describe the relationships between these physical variables and injury and mortality rates.

This report includes a summary review of literature directly or indirectly related to the mechanical injury of fish in spillways and stilling basins (Section 2), a synthesis of the literature which describes the relationships between physical variables and fish injury (Section 3), and a list the references cited (Section 4). Also included in this report is an analysis of the hydraulics of submerged jets and the potential impacts of these jets on fish injury (Appendix A), and an annotated bibliography which includes all of the documents found to date which are relevant to understanding the mechanical injury of fish in spillways and stilling basins (Appendix B).

The annotated bibliography (Appendix B) provides a review of 67 documents which directly or indirectly pertain to the mechanical injury of fish in spillways and stilling basins. Literature pertaining only to the injury and mortality of fish passing through turbines of hydroelectric dams, or to gas supersaturation, were not included in this bibliography. Each bibliographic citation includes the author's abstract, the reference type (e.g., journal article, technical report), the relevance of the citation regarding the mechanical injury of fish in spillways and stilling basins (i.e., primary, secondary, and tertiary), the type of injury addressed (e.g., abrasion), keywords useful for describing the content of the citation, and notes which summarize the key findings of the citation regarding mechanical injury. Injury was partitioned into three types: immediate mechanical injury of fish in the spillways and/or stilling basin, short term delayed injury occurring somewhere within the spillway environment, and long term delayed injury that impacts the fish once they leave the spillway and/or stilling basin. The notes section was intended to provide specific information regarding the study, including: objectives, location, spillway type, discharge in the river, discharge through the spillbay, hydraulic head, species and age of fish tested, and estimated injury and mortality (or survival) rates. A reference was considered to be of primary relevance if it contained data which quantified injury rates of fish. A reference was considered to be of secondary relevance if it described the types of injuries occurring to fish while passing through spillways, or provided estimates of total downstream survival through dams as attributed to multiple factors (including spillway mortality). Finally, a reference was considered to be of tertiary relevance if it provided information that was useful for understanding the impacts of spillways and stilling basins on fish, but that did not directly pertain to mechanical injury in spillways.

2. LITERATURE REVIEW

Water passed through the spillways of dams into stilling basins can produce total dissolved gas supersaturation (TDGS) conditions. Fish and other aquatic organisms exposed to TDGS can develop GBT (Alderdice and Jensen 1985). This condition occurs when dissolved gases diffuse into microscopic nucleation sites or hollow cavities and form bubbles. Gas bubble trauma is the biological consequence of a physical process, the formation and growth of bubbles *in vivo*. These bubbles can form in all body compartments and disrupt neurological, vascular, respiratory, and osmoregulatory processes. Bubbles may form embolisms under the skin of fish, resulting in bacterial, viral, and fungal infections (Weitkamp and Katz 1980). Injury and mortality can also result in fish and aquatic invertebrates from increased buoyancy caused by gas bubble formation.

Gas supersaturation was observed below newly completed spillways of dams in the lower Columbia River in the late 1960s (USACE 1996). Gas bubble trauma resulting from TDGS conditions first became evident on the Columbia River at the McNary spawning channel in 1962 (Westgard 1964), and became more evident in the Columbia River system during the mid-1960s (Weitkamp and Katz 1980). Spilling is currently being employed to provide an alternative passage route to turbine passage for movement of downstream migrants past Columbia and Snake river dams. Spilling at federal dams is in response to the National Marine Fisheries Service Biological Opinion (NMFS 1995). Originally, spillways were only used when river discharges exceed the capacity of the powerhouse, or when regional power demands were substantially smaller than the generating capacity of the Snake and Columbia river dams. The duration and magnitude of spilling has increased as an experimental measure to improve juvenile fish survival by passing more fish in spill and fewer through powerhouse turbines. Turbines have been operated using special operating rules in recent years to reduce injury and mortality of fish passing through turbines (NMFS 1995). Increased spilling has also been used to increase discharge as a strategy for reducing the travel time of smolt passing through the federal hydropower system (NMFS 1995).

A number of different operational and structural alternatives are being investigated to reduce the impacts of GBT on migrating juvenile and adult salmonids passing through hydroelectric dams located on the Columbia and Snake rivers. The two factors most responsible for elevated total dissolved gas (TDG) levels are discharge and plunge pool depth (USACE 1994, 1996). The use of deflectors or alternatives such as reducing the depth of the stilling basin decreases air entrainment. Changes in spill operations are also being evaluated to reduce TDG levels. Perforated bulkheads in "skeleton bays" (bays without turbines installed) were tested in the early 1970s to alleviate gas supersaturation problems on the Columbia River. This method was successful in lowering TDG levels, but high velocities emanating from the bulkheads were suspected as a factor in mortality to migrating salmonids (Long et al. 1975). Total dissolved gas abatement alternatives involving structural and operational modifications to Columbia and Snake river dams currently being evaluated by the USACE include: spillway deflectors; raised stilling basins; raised tailwaters; flip buckets; revised spillway shape; submerged sluiceways; covered spillways; and auxiliary passageways (USACE 1996). Of these structural alternatives, spillway deflectors are the only structural gas abatement measure implemented on a wide scale by the USACE. However, a variety of operational gas abatement measures have been implemented such as reduced spilling at John Day and increased spilling at The Dalles.

Spillway deflectors or "flip lips" were added to several USACE dams, including Bonneville, McNary, Lower Monumental, Little Goose, and Lower Granite dams, during the mid-1970s to reduce gas production during periods of spill (USACE 1996). Within their design operating range, these devices direct spill into a horizontal plume near the surface of the stilling basin. Depending on a variety of factors, this plume may be characterized by turbulent conditions and shear zones (i.e., extremely high water velocities near the surface moving adjacent to lower water velocities) near the upstream end where a roller or hydraulic jump forms (Copp 1968). Entrainment and/or impact in the roller at some stilling basins on the Columbia River is likely to occur (Copp 1968; Normandeau 1996). It is important to note that deflectors are designed to perform under controlled spill conditions. None of the deflectors installed within the basin are functional during flood conditions when spill levels can no longer be controlled.

Reduction in GBT related injury and mortality to juvenile and adult salmonids resulting from gas abatement measures may be offset by mechanical injury and mortality to fish resulting from conditions created in the near dam environment by implementation of the alternatives. Gas abatement measures, in addition to impacts on downstream migrants, may produce hydraulic conditions which delay the upstream passage of adult fish (e.g., inability to locate fish passageways) (Bjornn and Peery 1992; USACE 1994; NMFS 1995).

For the purposes of consolidating the potential impacts of gas abatement measures on fish, three zones where injury may occur have been identified in the spillway basin:

- *Immediate Mechanical Injury.* Injuries from abrasion, strike, and related mechanical mechanisms that occur as fish pass over the spillway and during retention in the stilling basin (i.e., events that occur in the first 10 seconds or less following passage through the spill gate).

- *Short Term Delayed Injury.* Injuries that occur after fish have passed over the spillway, but prior to leaving the spillway and stilling basin environment (i.e., events that occur in the first 3 minutes or less following passage).

- *Longer Term Injury.* Injuries that occur after fish leave the spillway and stilling basin environment, but which can be attributed to physical impacts and modifications in behavior occurring from exposure to conditions in the spillway, stilling basin, and tailrace.

A summary of literature reviewed to date for injuries following passage in spill will be provided in the following sections of this report.

2.1 IMMEDIATE MECHANICAL INJURY

Immediate mechanical injuries and mortalities to fish resulting from abrasion, strike, and related mechanical mechanisms that occur as fish pass over the spillway and during retention in the stilling basin (i.e., events that occur in the first 10 seconds or less following passage through the spill gate). Injury and mortality can also result from exposure to highly turbulent conditions including back-roll in the stilling basin, and exposure to shear velocities or high velocity jets immediately downstream of the spillway in the stilling basin (Copp 1968; USACE 1996).

The first spillway survival tests of juvenile salmonids passing through spillways were conducted in 1955 and 1956 at McNary Dam on the Columbia River with juvenile chinook salmon (*Oncorhynchus tshawytscha*) (Schoeneman et al. 1955; Shoeneman and Junge 1956; Schoeneman et al. 1961). The average survival rate for 1955 and 1956 combined was 100 percent (95% CI 94 – 100%) at McNary Dam. River discharge and flow through the spillbay for the test periods were not included in the aforementioned documents. The ogee of the spillbay being tested (bay #21) was set to 5 feet to simulate typical late-spring spill conditions. Adjacent bays (bay #20 and bay #22) were opened 4 feet to provide confinement of the discharge into the tailrace.

In more recent experiments at Bonneville Dam, subyearling chinook passed through a spillbay (bay #5 fitted with a flow deflector) had a significantly higher relative survival than fish passing through turbines or the bypass system (Ledgerwood et al. 1990). Relative survival rates for fish passing through the spillway, as indicated by downstream recoveries of coded-wire-tagged (CWT) chinook, averaged 96 percent (SE 2.2%) in 1989. Total discharge through the spillway (53 kcfs) was set to approximate tailrace conditions which are similar to adult attraction flows. Total discharge in the Columbia River downstream from both Powerhouse 1 and Powerhouse 2 tailraces was approximately 130 kcfs during test conditions.

Using paired-releases of yearling chinook salmon smolts, Iwamoto et al. (1994) estimated survival rates of fish passed through the spillbay #3 (with a deflector) of Little Goose Dam that ranged from 96 to 105 percent (SE 3.7% - 7.5%). During the experiments which were conducted on 6, 8, and 14 May 1993, all conditions except spill and turbine discharge remained the same at Little Goose Dam. Spill was similar on 6 and 8 May (approximately 26 kcfs) but increased drastically on 14 May to 67.9 kcfs. Although not statistically different, it is interesting to note that survival was greatest on 6 May (101%) and 8 May (105%) when spill was the lowest.

Normandeau et al. (1996) tested the effects of spillway passage on the relative survival of juvenile chinook salmon at the Dalles Dam, October-November 1995. Specifically, their objectives were to estimate the immediate (1 h) and 48 h survival of juvenile salmon introduced into a spillbay modified with a bulkhead forming an I-slot, an unmodified spillway, and a spillway modified to an overflow configuration. Secondly, Normandeau et al. (1996) wanted to identify the nature and the magnitude of injury/mortality of juvenile chinook passing through the spillbays at The Dalles Dam.

The spillway at The Dalles Dam contains 23 spillbays, each are 50 ft wide. Tainter gates at each test spillbay were raised approximately 7 ft, providing a discharge of 10.5 kcfs through spillbay #4 (modified to an I-slot) and spillbay #3 (unmodified). Spillbay #6 (modified to an overflow configuration) was originally to be tested at 10.5 kcfs, but vibrations in the tainter gate caused discharge to be lowered to 4.5 kcfs. Juvenile chinook salmon (128-132 mm TL) were tagged with HI-Z Turb'N Tags and a miniature radio tag to allow for immediate observation of fish survival and condition. The immediate survival (1 h) at spillbay #3 (unmodified) was estimated at 95.5% (90% CI 92.4 – 98.3%). Juvenile chinook passing through spillbay #4 (modified to an I-slot) had an immediate survival estimate of 99.3% (90% CI 97.2 – 102%) while the survival through spillbay #6 (modified to an overflow configuration) was estimated at 99% (90% CI 95.1-100%). Survival estimates for 48 h remained the same for all spillbays as no mortality occurred during this period.

Juvenile chinook salmon passing through The Dalles spillway suffered the following injuries: eye wounds; bruise/cuts to the body; hemorrhaged, cut, and scraped gills; head bruises; and descaling (Normandeau 1996). Injuries relative to controls (test – control) were 0.5% (unmodified spillbay), 1.5 (modified to an I-slot), and 2.5 (modified to an overflow configuration) during the testing procedure. The lowest survival (95.5% at the unmodified spillbay) was largely due to an unusually large number of fish becoming "entrapped" downstream of the spillbay in the baffle area. The highest survival (99% at the spillway modified to an overflow configuration) was attained at a much lower discharge (4.5 kcfs) than the other spillway bays (10.5 kcfs).

Studies of spillway mortality have been used to establish a spill mortality estimate for Columbia and Snake River dams ranging from 4 to 5 percent (Johnsen and Dawley 1974; Muir et al. 1995).

The effects of spillway flow deflectors on juvenile fish survival were first evaluated on the Columbia River during late-March, late-April, and mid-May 1974 at Bonneville Dam (Johnsen and Dawley 1974). Discharge in the Columbia River averaged 316 kcfs throughout the study period and 180.5 kcfs through the spillway. The objective of the study was to compare juvenile fish survival between spillway bays with and without flow deflectors (i.e., "flip-lips") at Bonneville Dam. The data collected during this study suggested that survival was not significantly different between "test" groups of fish passing through spillways possessing flow deflectors (bay #14) and groups passing through spillways without deflectors (bay #11). This study suggested that spillway survival could be 4 percent lower in spillways with deflectors although this difference was not statistically significant. Four groups of marked fish were released for the study. Three of these were at Bonneville Dam, one group through a standard spillway, one through a spillway with experimental deflectors installed, and one in the tailrace. The fourth group was released near Rainier, Oregon, 127 km downstream of Bonneville Dam. Recovery was made at Jones Beach near Puget Island, approximately 160 km downstream of Bonneville. Assuming a 100% survival of the fourth group of fish, the authors computed mean relative survivals of 43.7%, 39.6%, and 45.6% for the standard spillway, deflector spillway, and tailrace releases respectively. Based upon the results of their statistical analysis (suggesting that a significant difference could not be detected with the data set), the authors concluded that spillway deflectors were not detrimental to juvenile salmon survival and called for the installation of flow deflectors at all 18 spillbays at Bonneville Dam.

Muir et al. (1995) conducted a similar paired test at Lower Monumental Dam during the May through June 1994 spill period using juvenile chinook salmon. Statistical analysis of data collected from PIT-tagged fish suggested there is no difference in survival rates of fish passing through spillways with deflectors (bay #7) and those of fish passing through spillways without deflectors (bay #8). A 98.4 percent survival (SE 3%) at a spillbay without deflectors was computed compared to 93 percent survival (SE 2%) at a spillbay with flow deflectors. Discharge in the Columbia River, as determined by total spill and turbine discharge, ranged from 50.9 kcfs on 17 May to 91 kcfs on 13 May, with 4.4 to 4.8 kcfs flowing through each spillbay.

On the other hand, Long et al. (1975) found that higher survival rates occur in a spillway bay fitted with a flow deflectors (bay #7) compared to an adjacent bay without deflectors (bay #8). By testing the survival of juvenile steelhead from 27 April through 5 May, 1974 at Lower Monumental Dam, Long et al. (1975) found steelhead survival between spillbays equipped with a flow deflector and without a flow deflector was 97.8 and 72.5 percent (no estimate of variation), respectively. Survival was determined through comparisons of recovery rates for test and control fish releases. Control fish were released in the tailrace downstream of spillbay #8 and fish were recovered at Ice Harbor and McNary Dams. During testing, both spillbays were set to discharge 4.8 kcfs during the release procedure. Total river flow and spill levels during testing were not reported. The authors reported no statistical error bounds for the mortality estimates, but our evaluation of the data suggests that there are no statistical differences between the control release and either of the spillway bay releases at the 5% significance level. Regardless, the authors conclude that the addition of flow deflectors to the spillways at Lower Monumental would increase survival of juvenile steelhead passing the project.

Relevant data can be found in the literature regarding immediate injuries to fish, which are caused by factors including rapid deceleration, pressure differentials, striking impacts, shearing effects, and turbulence. After conducting a comprehensive review of existing data, Bell and DeLacy (1972) estimated that survival rates range from 93 and 98 percent for fish passing through spillways. Bell and DeLacy (1972) suggested that survival rates are primarily a function of tailrace hydraulics, especially as related to the presence of shear zones in the spillway basin. Shear zones result from high velocity waters passing in near proximity to low velocity water. Injuries to fish in shear zones may be equivalent to those under free-fall conditions (Bell and DeLacy 1972).

Shear zone injuries occur when fish move from very high velocity to lower velocity layers in the water column. This situation can occur when a fish moves from the rapidly moving water of spillway into the slower waters of a stilling basin, or when a fish migrates upstream from the deeper waters of the stilling basin into the velocity jet emanating from the flow deflector. Studies conducted by Groves (1972) indicate that salmon fry can be injured by hydraulic shear when injected into a jet having velocities exceeding 30 fps. Injury resulting from hydraulic shear was related directly to the position of the fish relative to the high velocity jet. Initial contact made in the head region resulted in the greatest damage. These tests are not directly applicable to the hydraulic shear experienced by juvenile fish moving with high velocity water into slow moving water, but provide supporting data to the general effects of fish entering regions with high spatial variability in water velocity.

Juvenile salmon were shot into relatively calm water by a submerged high velocity jet of water by Johnson (1970a, 1970b, 1970c, 1972). Injury occurred when the velocity of the jet exceeded 55 fps. Even higher mortality rates were observed above 75 fps. Studies of free-falling juvenile fish indicate that survival is very high (i.e., 97-100%) at estimated velocities less than 50 fps at Alder Dam (Schoeneman [1956] as cited in Bell and DeLacy [1972]). Hamilton (1955) reported that survival, corrected for delayed injury and capture probabilities, for sockeye (*O. nerka*) and coho (*O. kisutch*) was 63.5 and 54 percent, respectively. Schoeneman (1956) and Hamilton (1955) did not compute confidence intervals for their respective estimates.

Injury may also take the form of abrasion when fish contact gas abatement structures in a spillway such as flip buckets (USACE 1997). For example, fingerling coho and chinook were introduced through a 4-inch nozzle at 80 fps into a 6-inch wide segment of full size 50-foot radius curve. The bucket roughness was varied by the application of enamel, sand, and gravel. Delayed mortality (12.3%) and the percentage of descaled fish (34%) both increased with high roughness when compared to smooth bucket surfaces (1.3% delayed mortality and 0% descaling). No estimates of confidence intervals are included in the study. It should be noted that the thickness of the jet for these experiments was small (<4 inches), greatly enhancing the probability of contact with the boundary compared to the flow conditions in a field scale spillway.

2.2 SHORT TERM DELAYED INJURY

Short term delayed injury includes injuries that occur after fish have passed over the spillway, but prior to leaving the spillway and stilling basin environment (i.e., events that occur in the first 3 minutes or less following passage). This type of injury is thought to be more likely as the area affected by turbulence increases, a function of discharge as well as the energy dissipation characteristics of the stilling basin. Unfortunately, very little information is available concerning the relative impact of short term delayed injury on fish, especially as related to gas abatement measures such as flow deflectors. The largest problem in evaluating this type of injury is isolating it from other types of injury, such as that occurring during passage over the spillway

One method of reducing TDG levels, raising the stilling basin, essentially reduces the plunge depth of the water that is spilled. By raising the stilling basin (potentially reducing the energy dissipation ability of the stilling basin), operators may inadvertently compromise the stability of their spillway structures (USACE 1996). Dawley et al. (1998) conducted survival studies at the Dalles where the spillways are shorter and shallower than others on the Columbia River. The studies suggest lower survival (87%-92%) at the Dalles than has been reported at other Columbia River dams. The highly turbulent conditions created because of augmented energy dissipation in the stilling basin may lead to conditions in which fish are more susceptible to short term delayed injury. Good survival conditions may be provided in stilling basins as long as highly turbulent conditions are controlled (USACE 1996). Ruggles and Murray (1983) reported that Atlantic salmon smolts did not suffer significant injury or delay when passing a raised stilling basin. Here Atlantic salmon smolts in the East River, Sheet Harbour, Nova Scotia must pass through a bedrock gorge downstream of Anti Dam. However, no quantified injury or variation of injury was reported.

2.3 LONGER TERM DELAYED INJURY

Longer term delayed injuries occur after fish leave the spillway and stilling basin environment, but which can be attributed to physical impacts and modifications in behavior occurring from exposure to conditions in the spillway, stilling basin, and tailrace. Examples of this type of injury include abrasion and descaling of fish during spillway passage which later result in disease and mortality, disorientation of juvenile and adult fish during migration, and changes in behavior which increases susceptibility to predation.

Recent understandings of fish behavior and statistical design considerations suggest the need for new evaluations of spill survival, including those examining delayed mortality and physical injury (USACE 1994). Increased turbulence in the spilling basin caused during "real" spill events (compared to those occurring during "test spills" employed in some survival tests) may result in types of delayed mortality and long term physical injury not addressed in earlier studies (Fields 1966).

Disorientation and delayed adult migrant upstream passage may be one of the most important types of long term impacts caused by gas abatement measures associated with spill. Factors associated with spill (e.g., increased turbidity) may result in the inability of fish to navigate the river channel and locate fishways downstream of the spillway (Bjornn and Peery 1992). Survival of upstream migrating adult salmon and steelhead may not be able to benefit from reductions of TDG resulting from installation of flow deflectors because flow deflectors may affect passage behavior and reduce entry success of adult fish into fishways by producing turbulent flow conditions in the vicinity of these fishways (USACE 1994). Prolonged passage times caused by the inability of adult fish to locate and navigate fishways could result in increased exposure to elevated TDG levels, potentially reducing or outweighing the benefits of deflectors. For example, spillway modeling of Ice Harbor Dam suggest that upstream passage could be hindered by "poor hydraulic conditions" at fishway entrances as a result of proposed flow deflectors, and that these conditions might impede or block the upstream passage of migrating adult salmonids (USACE 1994). Alternatively, the USACE (1994) reported that seasonal fish passage time estimates for Snake River dams in 1993 were similar regardless of spill duration or deflector installation. The median days to pass Snake River dams were: 0.78 for Ice Harbor (spill all season), 0.85 for Lower Monumental (56 spill days), 0.70 for Little Goose (56 days of spill), and 0.76 for Lower Granite (14 spill days). The adult passage time measured during spill periods in 1993 at Ice Harbor Dam, a dam without flow deflectors, was similar to those measured at three dams on the lower Snake River with deflectors (i.e., Lower Monumental, Little Goose, and Lower Granite) (USACE 1994). Recognizing that significant effort was likely expended during design of each of these dams to minimize the effects of spill patterns on adult migration, this observation may suggest that flow deflectors do not significantly delay upstream migration of adult fish in this system.

Results of radio-tracking studies of adult fish conducted at Bonneville Dam in 1974 indicated that adult salmon and steelhead will swim into areas immediately below a spillway discharge with a flow deflector installed in 4 of 18 spillway bays (Monan and Liscom 1975). Spring chinook salmon were tracked between 3 and 9 April during which discharge in the Columbia River at Bonneville Dam averaged 334.9 kcfs and spill averaged 187.2 kcfs. Spillbays 13-15 were operated as one unit with average discharge through each bay set at approximately 10.4 kcfs. Spillbay 18 was also fitted with a flow deflector, but not monitored because very little water spilled over it. Of the 42 adult chinook tagged and released downstream of Bonneville Dam, six fish (14.3%) swam into the area below spillbays 13, 14, and 15. Observation of the same six fish at the Bonneville counting station revealed one suffered a "slight scrape" on the left side of the caudal fin. Fish exposed to spill deflectors at Bonneville Dam did not appear to suffer debilitating injuries from exposure to the hydraulic conditions (i.e., turbulence and high surface velocities) found immediately below spillways with deflectors.

In a similar study, 27 of 30 tagged adult chinook salmon reached Lower Granite Dam at a time when discharge in the Snake River averaged 143 kcfs and spill averaged 105 kcfs (Liscom and Monan 1976). Nineteen out of the 27 chinook reaching the dam (70%) swam into areas below spillway deflectors that are installed in all eight spillbays at Lower Granite Dam. No visible injuries were observed as the fish progressed past the viewing window. This study should be viewed with some caution, as Lower Granite Dam was still under construction and flow conditions were not representative of present day operating conditions. By 20 May, no fish had entered the fishway located on the north side of Lower Granite Dam, while only six entries occurred in the south entrance. Between the hours of 1500 and 1700, discharge in spillbays 6, 7, and 8 (those adjacent to the north fishway) were reduced by 30 percent by increasing discharge in the middle bays. At precisely 1745 hrs, a fish entered the north fishway and from that point on, fish appeared to use the fishways in near equal proportions (47% of initial entries occurred in the north fishway and 53% in the south fishway). As a result, it appears that the adult salmon migration may be impacted more by general tailrace flow patterns than by the presence or absence of flow deflectors.

2.4 CONCLUSIONS

Results of studies evaluating the impacts of flow deflectors as a gas abatement on juvenile and adult fish survival have not been consistent, and sometimes have contradictory conclusions (Johnsen and Dawley 1974; Long et al. 1975; Muir et al. 1995). Differences in these results may be caused by a number of experimental factors. Included, but not limited to are: experimental design and sample size, fish species tested (e.g., steelhead versus chinook salmon), magnitude of discharge under which spills and subsequent survival are evaluated, and the differences in structural and hydraulic characteristics of the dams where the tests were conducted. The timing of the study (night versus day testing) may have also biased the survival data obtained during some of the cited studies. In some situations, benefits provided by gas abatement measures such as flow deflectors (lowered TDG levels) may be reduced or outweighed by injuries and mortalities attributed directly or indirectly to these mitigation measures.

Of the three injury types considered in this literature review, immediate mechanical injury is the most studied and best understood. Gas abatement structures can result in a number of hazards to juvenile and adult fish, such as hydraulic shear zones, which have been shown under laboratory conditions to injure and kill fish (Groves 1972). Short term delayed injury is believed to be a potential threat to fish given the turbulent conditions found in the stilling basin and tailrace environments downstream of spillways with gas abatement structures during certain periods of the year (e.g., spill events). However, this type of injury has only been investigated by two studies reviewed to date, which suggested that short term injuries are likely to be minor compared to injuries occurring during and immediately after passing over a spillway. Long term delayed injury to fish is the least understood of the three types of injury evaluated. Indirect mortality effects of juvenile salmon migrating downstream during spill conditions have not been addressed in any prior spillway passage injury and/or mortality studies (USACE 1994). Recently, Schreck et al. (1998) concluded that the portion of spill that fish pass through influences their risk of predation at the Dalles, demonstrating the complexity of separating impacts of gas abatement. Long-term delayed mortality has been addressed in a number of adult salmon radio tracking studies. Studies conducted to date indicate that manipulation of discharge through spillways fitted with flow deflectors can be achieved to allow for successful adult passage.

3. LITERATURE SYNTHESIS

A number of studies have been conducted on the mechanical injury and mortality of fish in spillways and stilling basins of dams. Many of these studies provide estimates of survival (or mortality) of salmonid fish passing through spillways and stilling basins based upon the results of field experiments and observations. In addition, some of these studies describe the types of injury which occur to fish while passing through spillways, including abrasion and descaling, head injuries including damage to gills, operculum and eyes, and internal injuries including hemorrhaging and damage to organs. Unfortunately, only a few studies have attempted to describe the causal relationships between the physical conditions occurring within the spillway and stilling basin environment (i.e., high velocities, rapid deceleration, shear zones, and turbulence) and injury and mortality rates in fish. All of these were laboratory experiments, including high velocity jet studies conducted by Johnsen (1970a, 1970b, 1970c, 1972) and Groves (1972a, 1972b) for the USACE, aerial drop experiments in which fish were released from a tower (Richie 1956; Sweeney and Richie 1961) or helicopter (Regenthal 1956), and to rapid changes in pressure (see literature review by Cada et al. 1997). No studies could be found which described the relationships between injury and mortality rates of fish and the physical conditions measured within spillways and stilling basins.

There is presently a need for developing a mechanistic (i.e., cause-and-effect) understanding of how the physical conditions present in spillways and stilling basins injure and kill fish. The development of a mechanistic understanding or model of fish injury and mortality would be very useful for both identifying and minimizing the potential impacts of structural and operational modifications to spillways and stilling basins on fish survival. This is especially pertinent to the structural modifications that have been proposed for the purpose of reducing TDG concentrations below Columbia and Snake river dams. The most commonly used structural modification intended to reduce TDG levels are spillway deflectors, which serve to reduce the plunge depth of water released from the spillway into the stilling basin and thus minimize gas supersaturation. Spillway deflectors have been installed at Lower Granite, Little Goose, Lower Monumental, McNary, and Bonneville dams to reduce TDG levels (USACE 1996). Other structural modifications that have been proposed for gas abatement for the Columbia and Snake rivers include raising the elevation of the stilling basin or tailrace. Under certain operating ranges, spillway deflectors can substantially reduce total dissolved gas levels in the tailrace of hydroelectric projects, but overall improvements in injury and mortality rates of fish passing these facilities have not been clearly demonstrated. Thus, it will be important to show that the benefits derived from the proposed gas abatement measures (i.e., potential increased survival resulting from reduced TDG levels) outweigh their costs (i.e., potential increased spillway injury and mortality rates).

A fish injury model would require several types of information, including:

- Describing the responses of fish in terms of injury and mortality to increasing levels of velocity, shear, turbulence, and strike;

- Defining critical thresholds in these response curves below which injuries and mortality are minimal, and beyond which injury and mortality rates increase rapidly;

- Delineating those areas within a spillway and stilling basin which exceed the critical velocity, shear, and turbulence values found to injure and kill fish (this can be accomplished either by direct measurement or hydraulic modeling); and

- Determining the probability of fish entering these high injury zones while passing downstream through the spillway and stilling basin.

With the exception of the laboratory studies mentioned previously (e.g., high velocity jet experiments of Groves and Johnsen), we could not find any studies which described the responses of fish to increasing levels of velocity, shear, and turbulence within spillways and stilling basins. Moreover, the data presented in these laboratory studies were generally insufficient on an individual basis for defining injury responses over a wide range of velocity, shear, and turbulence values. Also, these data were usually presented in tabular form, which is not as useful as graphical or statistical methods for describing response relationships between physical variables and fish injury, and for delineating the critical threshold values of these variables beyond which injury and mortality rates become severe.

The purpose of this section of the report is to synthesize the literature where possible to better describe potential relationships or response between physical variables and mortality rates in spillways. This will be accomplished by: 1) providing a brief review of conclusions of prior literatures reviews on the subject of mechanical injury in spillways; 2) combining and integrating the results of laboratory studies to better describe response curves between mechanical injury and variables including as velocity and shear; and 3) combining and integrating the results of field studies of fish survival through spillways and stilling basins to determine if mortality rates can be predicted from spillway characteristics such as total hydraulic head and spilling basin depth. Studies which evaluated injury and mortality of fish passing through hydroelectric turbines were not included in this analysis (see literature review by Cada et al. 1997 for more information on this topic). Injuries sustained by fish passing through turbines are generally caused by many factors not present in dam spillways, including those caused by mechanical grinding, blade strike, and by low pressures and cavitation around the turbine blades.

3.1 CONCLUSIONS OF PRIOR LITERATURE REVIEWS ON MECHANICAL INJURY

Two literature reviews have been previously completed on the mechanical injury of fish in spillways and stilling basins: 1) a compendium on the survival of fish passing through spillways prepared by Bell and DeLancy (1972) for the USACE; and 2) a review of fish responses to spillways prepared by Ruggles and Murray (1983) for the Department of Fisheries and Oceans of Nova Scotia. Both of these reviews summarized available data on mechanical injury and mortality of fish in spillway and stilling basin environments.

The earlier of these literature reviews was completed by Bell and DeLancy (1972), and provided a number of important observations and conclusions regarding the mechanical injury of fish in spillways. These include:

- A number of experiments have been conducted and observations obtained regarding the effects of mechanical injury associated with dam spillways and stilling basins on fish. These experiments include measurements of injury and mortality for free falls through the air from various heights (e.g., tower drop experiments), falls within a column of water, and survival estimates for fish passing through a variety of different spillways types (e.g., ogee, chute, ski jump). Fish were subjected to velocities ranging from 10 to 100 fps in the spillway and high velocity experiments, and to drops from heights ranging from 2 to 300 ft in the freefall experiments.

- Injuries sustained to fish included abrasions, eye damage, embolisms, hemorrhaging, and internal damage to organs. Many of the injuries were found to be typical of those expected due to scraping and exposure to shear zones.

- Injury and mortality in fish passing through spillways was thought to be related to a number of factors, including volume of discharge, spillway type, pressure changes, impacts from objects (e.g., baffle blocks), abrasion, high velocities, and shearing effects.

- None of the experiments reviewed measured velocity deceleration or the magnitude of the shear zones to which the fish were exposed. This information would be very useful to compare the results of the various studies. Further, none of the studies measured the amount of time that fish were exposed to high shear zones and turbulence in energy dissipating areas of spillways.

- Survival rates of fish were found to vary between 98 and 100 percent for fish entering pools from free falls less than 50 fps, were approximately 80 percent at velocities of 60 fps, and probably approach zero for velocities exceeding 80 fps. Survival rates of fish entering a plunge pool in a column of water may approximate the highest survival rates observed under free fall conditions. The authors make these conclusions by combining tests of terminal velocity of free falling fish with injury studies from free fall tests.

- Survival rates of fish passing through a large hydraulic jump or stilling pool should range between 93 and 98 percent. The survival rate of fish directly striking a fixed object such as a baffle in a spillway should be near zero percent.

- Survival rates in spillway and stilling basin environments can be increased by minimizing turbulence, back-roll, and the amount of energy dissipated per unit area.

The literature review completed by Ruggles and Murray (1983) also provided a number of important observations and conclusions regarding physical injury and mortality of fish in spillways and stilling basins. These are summarized as follows:

- Injury and mortality of fish in the spillway environment can be caused by a number of conditions, including: 1) rapid pressure change; 2) rapid deceleration; 3) shearing effects; 4) turbulence; 5) striking forces; and 6) scraping and abrasion. Unfortunately, the relative importance of these factors in contributing to spillway injury and mortality cannot be determined from existing literature.

- Both small and large fish sustain some free-fall injuries if velocities exceed 52 fps. However, smaller fish are less likely to accelerate to velocities of this magnitude under free-fall conditions, than large fish.

- Fish traveling in water jets discharging into still water are injured for jet velocities greater than 66 fps, while mortality rates rise sharply beyond velocities of 78 fps.

- Delays to downstream migration caused by spillways may result in increased mortality to predation, though this has not been quantified. Fish may become trapped in back-roll areas below spillways, increasing susceptibility to fish and avian predation.

- Mortality rates from spillway and stilling basin passage may be higher than the immediate mortality observed in the literature. However, the differences between immediate and delayed mortality have not been quantified.

- No studies could be found which directly investigated sublethal effects of spillways on fish.

- Survival of fish at ski-jump and free-fall spillways can be improved by designs which minimize striking of fish against dam face, and which allow fish to fall free of the water column. Dissolved gas levels can be reduced through the installation of flow deflectors which may reduced gas bubble trauma (GBT) and improve the survival of fish passing dams.

- Fish mortality in spillways and stilling basins is related to the form and concentration of energy dissipation. For tunnel type spillways, fish mortality is related to the length of the conduit, concentration of flow, and type of energy dissipation facility utilized. For spillways terminating in a flip-bucket, fish mortality is related to the height of fall, concentration of flow, jet velocity, and depth of the tailwater. For spillways terminating in hydraulic-jump stilling basins or submerged-bucket dissipaters, mortality is related to the concentration of flow and the depth of the tailwater. Finally, mortality of spillways, which drop vertically into plunge pools, is related to the height of fall, the concentration of flow, and the depth of the plunge pool.

- The conditions believed responsible for causing fish mortality in spillways will generally increase in proportion to the height of the spillway

- Spillways that dissipate energy at a slower rate may improve the chances of fish survival; this can be achieved by increasing the volume of water in the stilling basin. Increased energy dissipation rates in stilling basins provides more potential for immediate injury to fish as well increases dissolved gas production further endangering downstream migrants.

Both of these literature reviews identified the need for developing a consistent method for comparing the results of different studies regarding spillway and stilling basin injury and mortality. Injury and mortality rates of fish in spillways are influenced by a number of factors, including the type spillway, discharge, hydraulic head, method of energy dissipation, the amount of energy dissipated, and the area or volume within which energy is dissipated. Of these factors, hydraulic head and energy dissipation were identified as the most important factors ultimately determining the survival rate of fish passing through spillways and stilling basins. However, no literature reviewed to date has attempted to quantify the relationships between hydraulic head, energy dissipation, and fish injury.

3.2 ANALYSIS OF LITERATURE

A number of factors have been identified in the literature reviews of Bell and DeLancy (1972) and Ruggles and Murray (1983) which can cause physical or mechanical injuries to fish in spillways and stilling basins. These factors are:

- *Rapid pressure change*
- *Rapid deceleration*
- *Shearing effects*
- *Turbulence*
- *Striking impacts*
- *Scraping and abrasion*

The extent of the injuries sustained by a fish while passing through a spillway and stilling basin is related to several factors, including: 1) the magnitude of the physical forces to which the fish are exposed; 2) the length of time during which the fish is exposed to these forces; and 3) the susceptibility and resiliency of the fish to injury.

The magnitude of the physical forces occurring within a spillway and stilling basin is directly related the velocity of water passing over the spillway. The maximum velocity at the terminal end of a spillway is a function of the total head of the dam, and can be approximated by the following equation:

$$v_t = \sqrt{2gh}$$

where:
v_t = velocity of flow at tailwater level (ft/sec);
h = head difference between headwater and tailwater levels (ft);
g = acceleration of gravity (ft/sec^2).

This equation is most applicable to ogee (overflow), chute, conduit, and siphon spillways, but can also be used to estimate the maximum velocity of free overflow (straight drop) spillways in which most water remains in a coherent stream.

Most of the forces that are great enough to injure and kill fish occur within the stilling basin, which is the area where energy in water released from a spillway is dissipated. Rapid and efficient energy dissipation is desirable in stilling basins to reduce the velocity of water released from a spillway (Ruggles and Murray 1983), an objective which unfortunately increases the likelihood of injury and mortality of fish passing through the stilling basin. Reducing the velocity of water is important for minimizing scour to the streambed in the tailwater region, and erosion around the foundation of a dam. This is accomplished by concentrating the release of energy to hardened areas (e.g., concrete lined apron) within the stilling basin. The rapid dissipation of energy within a stilling basin is accompanied by the rapid deceleration of water, localized shear zones, and high turbulence. Striking injuries occur when fish carried within high velocity waters impact solid objects such as baffle blocks located within the spillway and stilling basin, or the streambed because of the action of hydraulic rollers and high turbulence. Striking injuries can also occur when fish impact the water surface after falling through the air from a free overfall spillway, or after being projected into the air after passing through a deflector bucket.

The severity of mechanical injury to a fish not only depends upon the magnitude of the physical forces to which the fish is exposed, but also upon the length of time during which the fish is exposed to these forces. A fish will typically move downstream through the spillway and stilling basin of a dam very rapidly. However, in some instances a fish can become caught within the backroll areas within a hydraulic jump basin, or within strong eddy regions located in the tailwater of a dam. This can substantially increase the amount of time in which fish may be exposed to violent forces such as shear and high turbulence. Injury and mortality rates can be lowered by spillway designs that reduce the retention time of fish within energy dissipation areas (Bell and DeLancy 1972).

3.2.1 Rapid Pressure Change

Rapid changes in pressure generally can occur in several areas within a spillway and stilling basin. Negative (subatmospheric) pressures can form along the surface of uncontrolled ogee crest spillways (BOR 1974). The presence of any unevenness, depressions, or projections along the crest of uncontrolled spillways can amplify these negative pressures to the level where cavitation can develop. The shape of the crest of ogee type spillways are typically designed to minimize the formation of large negative pressures. Negative pressures can also form immediately below the gate of controlled ogee spillways. Regions of both high pressure and low pressure can also form within conduit or tunnel type spillways, shaft spillways, and siphon spillways (BOR 1974). Zones of high positive and negative pressure also occur within submerged passageways or sluiceways (USACE 1996), which is a type of conduit spillway. Finally, positive pressures can form within stilling basins below overflow (ogee) and free-fall (e.g., ski jump) type spillways; rapid changes of pressure result when water released from the spillway plunges into deep stilling basins or pools.

Pressure is typically measured in pounds per square-inch (psi), or in Newtons per square meter (n/m^2). Injuries to fish caused by sudden changes in pressure include embolisms, eye injuries (popped eyes), and hemorrhaging (Bell and DeLancy 1972). Injury and mortality rates are probably highest for fish passing through conduit or tunnel type spillways (including submerged passageways), since the magnitude of pressure changes which have been predicted to occur within these spillways is high relative to that predicted for other overflow and free-fall type spillways. There has been concern over the proposed use of submerged passageways as a gas abatement measure for Columbia and Snake River dams, because mortality rates of fish passing through these spillways may be high; fish passing through these spillways are likely to experience rapid and large changes in pressure (USACE 1996). A study conducted by the Oregon Department of Fish and Wildlife (ODFW 1992, cited in USACE 1996) suggested that the mortality of juvenile chinook salmon passing through submerged passageways could be as high as 70 percent under conditions of high head and discharge, and approximately 30 percent under conditions of low head and discharge.

However, a recent review of literature of mechanical injury to fish passing through hydroelectric turbines suggests that fish are unlikely to be injured by rapid changes in pressure (Cada et al. 1997). Laboratory studies conducted by Harvey (1963) found that sockeye salmon fry and juveniles exposed to pressures as high as 300 psi did not incur significant levels of mortality (i.e., less than 1%). Moreover, mortality rates were low when these fish were subjected to sudden changes in pressure (decompression rates as high as 7,500 psi/sec). The greatest cause of mortality was found to be exposure of these fish to vacuum conditions. The threshold value for mortality of fish exposed to subatmospheric pressures was determined to be 12.1 psia based upon comparisons of test and control fish (Harvey 1963). Mortalities of sockeye salmon increased to about 2 percent when these fish were exposed to pressures of 2.5 psia.

Other studies have also suggested that salmonids are generally tolerant to rapid changes in pressure (Turnpenny et al. 1992, cited in Cada et al. 1997). Salmonids exposed to pressures (P_e) less than 10% of the acclamation pressure (P_a) typically have the highest mortality rates, which have ranged from 0 to 10 percent in experiments conducted by a number of investigators (Cada et al. 1997). Mortality rates of fish exposed to pressure changes in which P_e/P_a values exceed 0.10 (i.e., lower net changes in pressure) have found to range between 0 and 2 percent. These low mortality rates have been attributed to the capability of salmonids to rapidly vent excess gas from their swim bladders under rapid decompression. Damage (e.g., rupturing) of swim bladders is probably the greatest cause of mortality of fish exposed to rapid pressure changes (Cada et al. 1997). Cada et al. (1997) concluded that most surface-acclimated fish would be protected from injuries if pressures of 8.8 psia or greater were maintained.

Exposure of fish to cavitation zones within a conduit or siphon spillway is more likely to cause injury and mortality of fish than rapid pressure changes. Experiments conducted by Muir (1963) indicated that juvenile coho salmon rapidly exposed to low vapor pressures and then instantaneously returned to normal atmospheric pressure incurred high mortality rates (i.e., 60%). This study concluded that high pressure shock waves resulting from the collapse of cavitation bubbles was the primary cause of the observed mortalities.

Pressure injuries are likely minimal in most spillways and stilling basin environments. This is especially the case in ogee type spillways, which are designed to minimize the formation of negative pressure along the spillway surface. Pressure injuries would be expected to be greatest in tunnel or conduit spillways, including submerged passageways. Unfortunately, no studies have been found which have directly measured the rates of pressure induced injuries in spillways.

3.2.2 Rapid Deceleration

Fish carried in high velocity waters released from a spillway or passing through a submerged passageway can undergo rapid changes in velocity (i.e., acceleration and deceleration). Stilling basins and closed conduit systems are designed to rapidly reduce the velocity of water in order to minimize bed scour in the tailwater regions of a dam. Deceleration is greatest when the high velocity jet produced by a spillway suddenly expands within a stilling basin (see Appendix A for a hydraulic analysis of submerged jets) or within a conduit sluiceway.

Acceleration and deceleration is typically measured in terms of gravitational acceleration (g's). Unfortunately, no studies could be found which measured the direct relationships between acceleration or deceleration (g) and injury and mortality of fish. The only studies which were found to be applicable for defining and predicting deceleration-related injuries were a number of high velocity jet experiments conducted by Johnson (1970a, 1970b, 1972). In these experiments, juvenile coho salmon, chinook salmon, and steelhead trout were ejected from a high velocity jet (4 inch nozzle) into a stilling tank. As noted in Appendix A, the rate of energy dissipation and deceleration experienced by fish traveling in a submerged jet can vary significantly depending on the size and location of the fish within the jet, the diameter of the jet, and the jet velocity. Some of the fish in these experiments were exposed to high shear zones located along the margin of the jet. Consequently, the mortality rates recorded in these experiments likely resulted from injuries caused by both rapid deceleration and shear. Never-the-less, these experiments provided valuable information regarding the relationships between the velocity of the jet (fps) and fish mortality.

Data obtained from Johnson's experiments were graphed according to two size classes of fish: less than 10 cm in total length, and greater than 20 cm in total length (Figure 1). Mortality rates for the larger size class of fish were zero (i.e., 100% survival) for velocities less than 58 fps, while mortality rates for the smaller size class of fish were zero for velocities below 66 fps. Mortality rates increased exponentially above these threshold values for both size classes of fish.

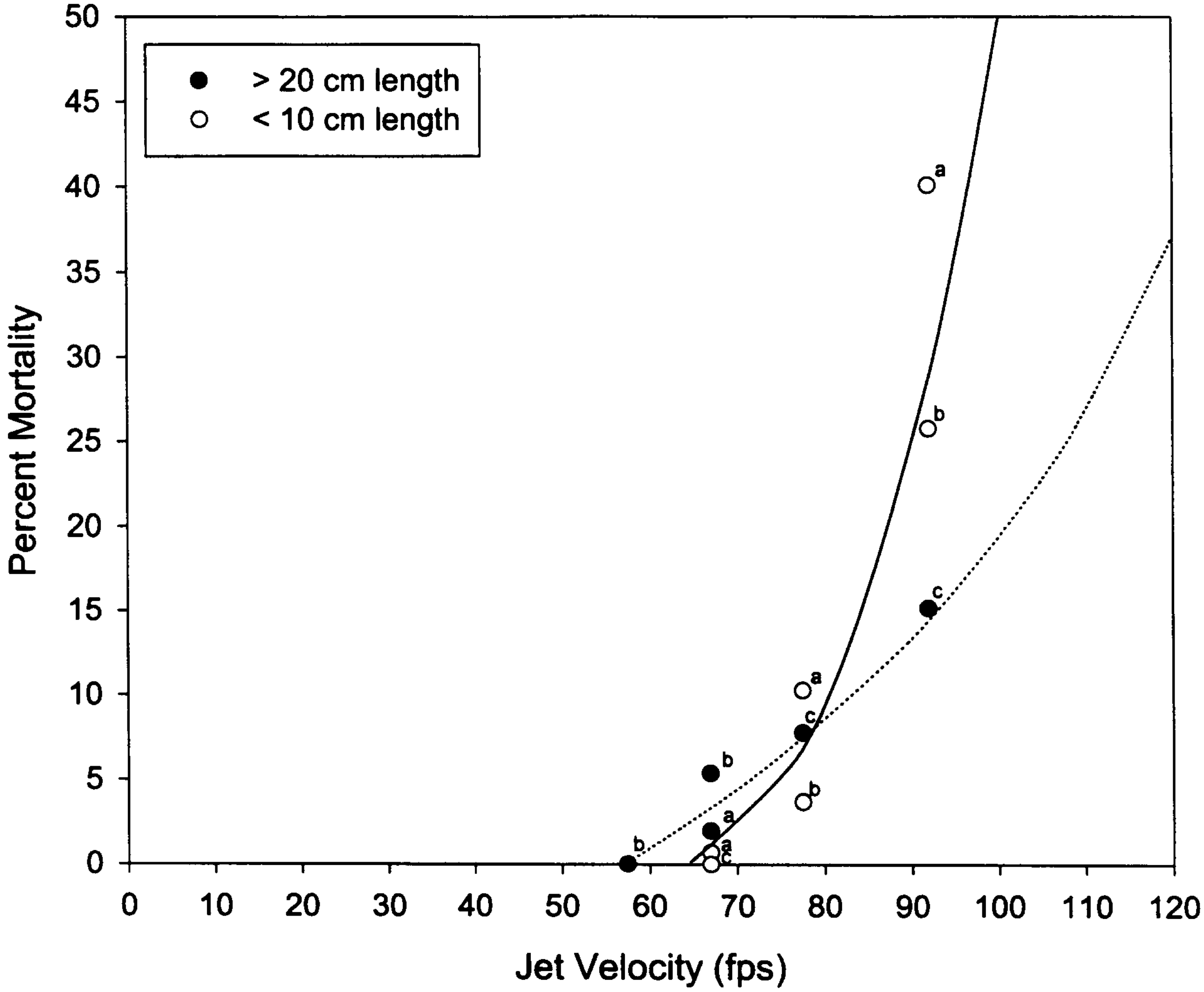

Figure 1. Relationship between jet velocity and mortality of fish ejected from high velocity jet into stilling tank. Sample sizes range from 150 to 600 fish per experiment using juvenile (a) coho salmon, (b) chinook salmon, and (c) steelhead trout (source: Johnson 1972).

For the smaller size class of fish, mortality rates increased very rapidly for jet velocities between 70 and 90 fps. The same relationship was observed for the larger size class of fish, though mortality rates increased at a lower rate (i.e., smaller slope of curve) than that of the smallest size class. Both curves suggest that mortality rates would be high (greater than 25% for smallest age class, and greater than 15% for largest age class) for jet velocities greater than 90 fps.

The differences in the mortality curves between the two size classes of fish may be associated with two aspects of the jet experiments. The larger fish were at least twice as long as the diameter of the jet, essentially guaranteeing that each fish is exposed to the highest shear zones at the jet periphery. Some of the smaller fish may not encounter the highest shear zones or decelerations due to their location with the jet. This could help explain the lower threshold value for mortality observed in the larger size class of fish (Figure 1). However, as jet velocities rise, levels of shear and deceleration increase rapidly, exposing all regions of the jet to harmful levels. Large fish may be more resilient to both deceleration and shear forces due to greater tissue strength when compared to smaller fish, possibly explaining the higher mortality rates of smaller fish at the highest test velocities. There are likely other potential explanations for the experimental results, but the hydraulics of the jet experiments provide some likely reasons for the outcome.

One important consideration in interpreting these laboratory experiments is that the diameter of the jet as well as the velocity of the jet influence the fluid deceleration and the rate of energy dissipation (see Appendix A). For the 92 ft/sec jet experiments conducted by Johnson (1972) with a 4-inch diameter nozzle, a fish traveling along the centerline of the jet would experience a maximum deceleration of approximately 123 g. In contrast, a fish traveling at the centerline of a 10-foot diameter jet with the same initial velocity would experience a deceleration of only about 4g. Thus, the apparent association of jet velocity with fish mortality that is implied by these experiments cannot be directly applied to large scale hydroelectric facilities. Spillways of dams with heads of 100 feet produce jet velocities in the tailrace of approximately 80 ft/sec. The Johnson data (Figure 1) would suggest that the mortality could exceed 10 percent at these velocities. However, tests at dam spillway have found considerably lower mortality. This scale factor may partially explain these differences between laboratory studies and field tests.

3.2.3 Exposure to Shear Zones

Hydraulic shear occurs when water having a high velocity passes in close proximity to water having a much lower velocity. The spatial difference in velocity produces a shear force that acts within the fluid and can apply forces to objects within the flow field. No studies were found which directly measured the types of shear likely to occur within spillways and stilling basins and injure fish.

Laboratory experiments by Grove (1972) were conducted to investigate the effects of hydraulic shear on juvenile salmon. In these experiments, juvenile salmonids were subjected to abrupt contacts with the margins of jets of moving water at various speeds. Fish were injected into a jet of water having mean velocities ranging from 30 and 120 ft per second. Tests were conducted on juvenile coho, chinook, and sockeye salmon. Between 5 to 25 fish were consecutively flushed through a submerged tube into the water jet within three inches of the nozzle. The first series of tests suggested that fish were unaffected by when injected into velocity jets of 30 fps or less, but were injured by higher jet velocities (Figure 2). Injuries ranged in severity from impaired behavior and orientation to physical injury and death. Fish with visible injuries usually regained normal behavior within 5 to 30 minutes. It is likely that while fish are recovering from this type of trauma, they would be more vulnerable to predation. Visible injuries were mostly in the head region (i.e., that first exposed to the high velocity jet), and included the rupturing and dislodgment of eyes, and damage to gills and operculum. Torn and bleeding gills were also common. Mortally injured fish generally died within 48 hours of the test.

In a second set of experiments, smaller fish were found to be more susceptible to injury than larger fish. The severity of the injury was related to the part of the fish contacted by the jet. Injury was greatest when the head of the fish was oriented away from the origin of the jet. Smaller fish were more susceptible to injury because a larger portion of their body was exposed to the margin of the jet compared to that of larger fish. High speed photography indicated that the zone of greatest injury was located within 2 to 3 inches of the jet nozzle in the region of the highest velocity differences. Injury in larger fish was greatest when the head region (including eyes and gills) came in contact with the zone of highest shear. Injuries were first observed to occur at jet velocities ranging from 16 to 40 fps. However, the probability of injury was found to be more related to the orientation of the fish to the jet rather than the velocity. Contacts without injury were observed at velocities of up to 60 fps. Immediately after contact, fish were rapidly accelerated to speeds up to 45 fps for the upper range of jet velocities measured in the experiments (i.e., 60 fps nozzle velocities). The author did not provide estimates of actual acceleration rates.

A third set of experiments was conducted by Groves (1972) to evaluate the susceptibility of fish to injury as a function of fish size. These data were graphed to describe the relationships between jet velocity and injury rates among three age classes of fish (Figure 3). Smaller fish (i.e., 35 to 80 mm total length) were more susceptible to injury and mortality than larger fish (i.e., > 95 mm total length). This increased susceptibility of smaller fish to injury is probably related to reduced tissue strength, and the exposure of proportionately more of their body surface to the sharply defined margins along the jet. Injury versus velocity curves were fitted for all

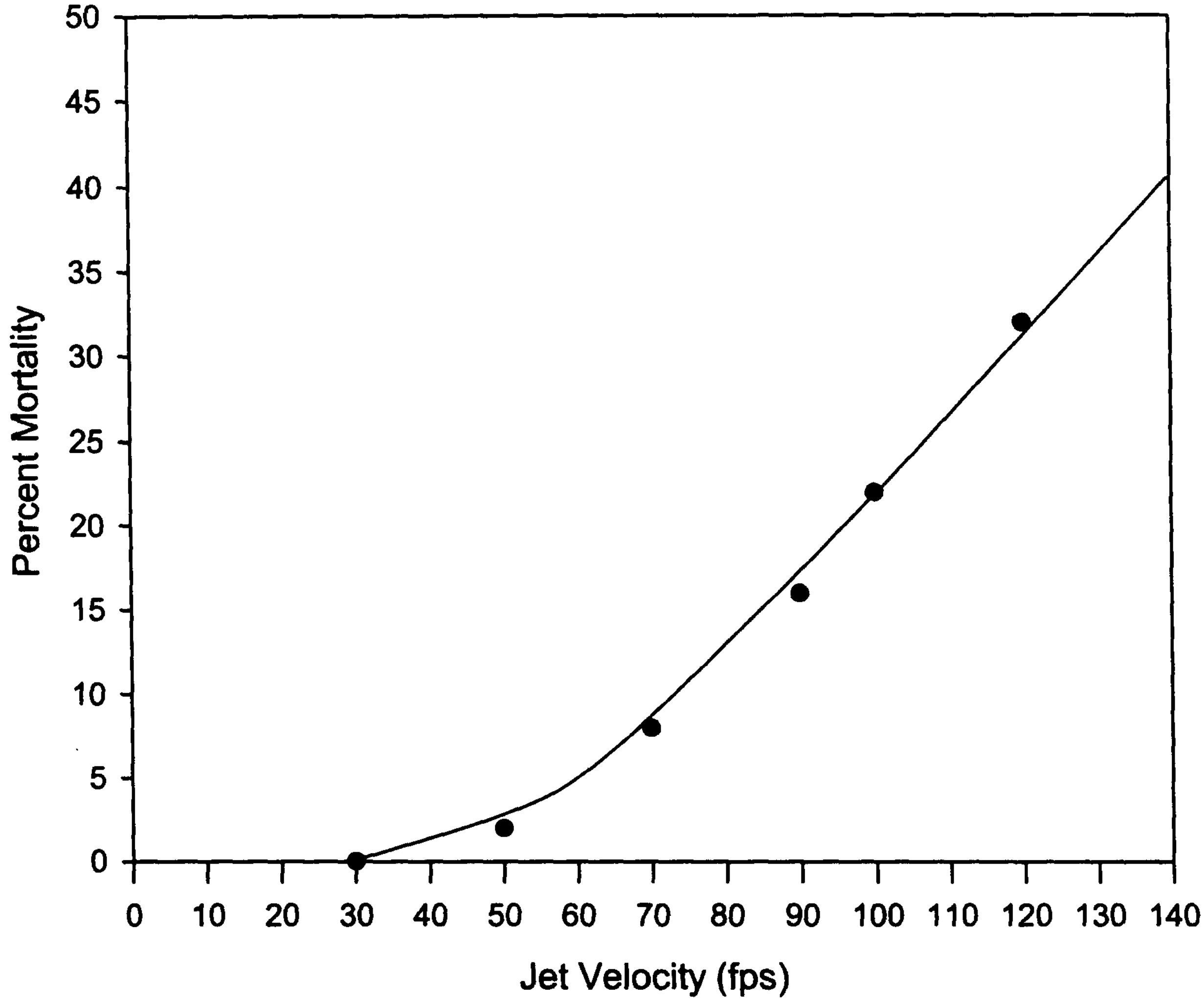

Figure 2. Relationship between jet velocity and mortality of fish injected from a slow velocity tube into a high velocity jet. Sample size is 50 fish per experiment using juvenile coho salmon (average length = 10 cm; source: Groves 1972).

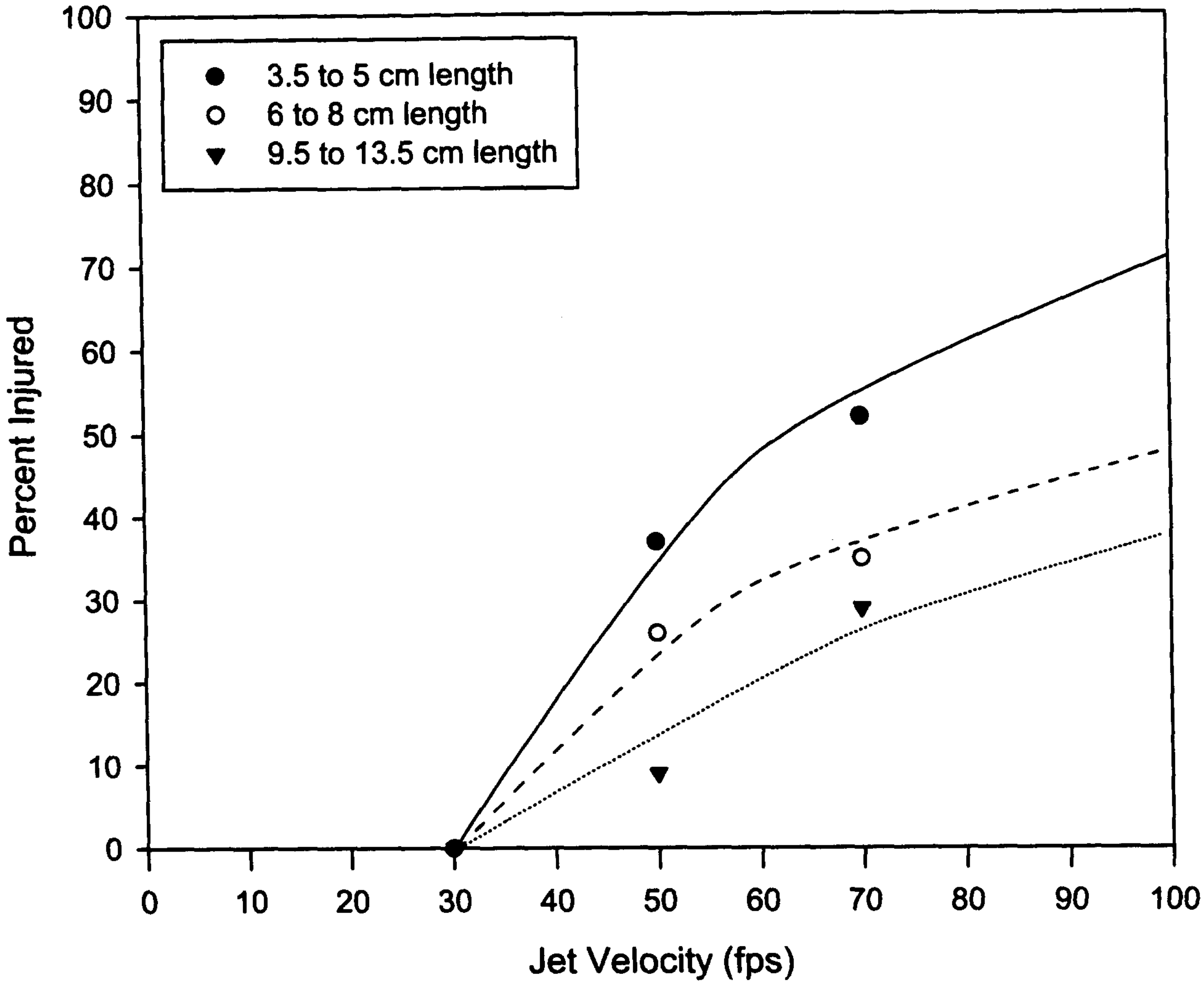

Figure 3. Relationship between jet velocity and injury of fish injected from a slow velocity tube into a high velocity jet. Sample size ranges from 50 to 201 fish per experiment using juvenile coho and chinook salmon (source: Groves 1972).

three age classes (Figure 3), though the ranges of observations were insufficient for properly defining relationships.

Although there are highly turbulent shear zones associated with submerged jets, the experiments performed by Groves (1972) may not replicate conditions actually experienced by fish in the vicinity of jets. Grove's experimental apparatus injected fish directly into the fringes of a jet. A submerged jet entrains fluid as it expands away from the discharge point. It is quite possible for fish to be entrained into a jet through this process. The hydraulic shear encounter by a fish entrained into the jet would generally not be as high as the shear zone associated with the laboratory experiments. As previously discussed, laboratory jet experiments were performed by Johnson (1970a) at 67 ft/sec. Fish surviving the experiment were anesthetized in the jet tank. During subsequent observations, 30 percent (60 fish) of the fish in the tank were re-entrained into the jet and none of them were injured in the process. From the Groves experiments, an injury rate of nearly 50% and a mortality rate of 8% might be expected at this jet speed.

3.2.4 Turbulence

Turbulent flow occurs when fluid particles move in a highly irregular manner, which can exist over a wide range of spatial scales (molecular level too large eddies; Cada et al. 1997). Turbulence is sometimes defined using a statistical approach, and is measured as the variance in multidirectional velocity vectors compared to mean current (i.e., unidirectional) velocity. High turbulence is widely cited as a major factor contributing to the injury of fish passing through spillways and stilling basins (e.g., Bell and DeLancy 1972; Ruggles and Murray 1983). However, no studies were found which described or measured relationships between turbulence levels and fish injury. Turbulent is accompanied by hydraulic shear within the fluid. Both turbulence and hydraulic shear operate at varying temporal and spatial scales. No studies were found that address the temporal or spatial scales important to fish injury within a turbulent fluid.

3.2.5 Strike

Striking injuries occur when a fish rapidly impacts a solid object in the water, or when a fish impacts the surface of the water following free-fall through the air. Injuries resulting from object strike include loss of mucous and scales on the surface of the body, damage to and loss of eyes, damage to gills and operculum (gill covers), and internal hemorrhaging. Striking injuries are most likely to occur when fish carried in high velocity water impact submerged objects in the spillway (e.g., flow deflectors) or stilling basin (e.g., baffle blocks). Striking injuries are also frequently observed when fish are released into the air from water spilling over free-fall spillways of high head dams, or are ejected into the air from spillways possessing bucket-type deflectors (e.g., ski jump spillways); (Bell and DeLancy 1972; Ruggles and Murray 1983).

Striking injuries are typically quantified according to the velocity of the fish prior to striking an object, or the height of the freefall through the air to which a fish is subjected.

Most studies examining strike injuries in fish have involved freefall experiments in which mortality rates were measured after fish were dropped at various heights from a helicopter (Regenthal 1956) or tower (Sweeny and Ritchie 1981). Data from these studies were graphed to describe the relationships between mortality rates among four size classes of fish and height of freefall (Figure 4). Mortality rates for all size classes of fish, were zero after being dropped heights of 35 ft or less. Percent mortality values were highest for the largest sized class of fish, and progressively decreased as fish became smaller in size (Figure 4). Mortality rates were high (approximately 80%) for the largest size class of fish when dropped from heights of 300 ft. However, mortality rates for the smallest size class of fish were very low (less than 1%) over the entire range in heights from which fish were dropped. The increasing susceptibility to injury and mortality of fish with increasing size is a function of the terminal velocity of fish falling through the air (Bell and DeLancy 1972; Ruggles and Murray1983). The terminal velocity of large fish is much higher than that of small fish due to decreased wind resistance. The mortality values of all age classes "flatten out" with increasing height, as the terminal velocity for each size-class is approached.

3.2.6 Synthesis of Field Data

As mentioned earlier, the literature reviews completed by Bell and Delancy (1972), and Ruggles and Murray (1983) both suggested that hydraulic head may be a useful predictor of injury rates of fish passing through spillways and stilling basins. However, the relationship between mortality rates and hydraulic head has not been delineated among the various dams where morality data have been collected. For this reason, we compiled the data for the majority of field studies conducted to date, in which the mortality rates of fish passing over spillways has been estimated (Table 1). Estimates of mortality rates were obtained for a number of different spillway types, including siphon spillways (Seton Creek, B.C.), ogee spillways without and with deflectors (e.g., Bonneville Dam, Lower Monumental Dam), chute spillways (e.g., Condit and Yale dams), and freefall spillways (e.g., Glines Dam, Baker Dam). The hydraulic head (i.e., normal pool elevation minus normal tailwater elevation) for these dams ranged from 25 to 323 ft. The maximum velocities estimated from the hydraulic head of these spillways ranged from 40 to 144 fps (Table 1). All of the field studies found in the literature involved salmonid fish, and most focused on injury and mortality of juvenile fish at dams in the Pacific Northwest. Mortality rates observed at these dams ranged from 0 to 51.9 percent (Table 1).

The mortality rates of fish passing through spillways increased with increasing spillway velocity (Figure 5). Mortality rates were generally less than 5 percent for spillways having maximum

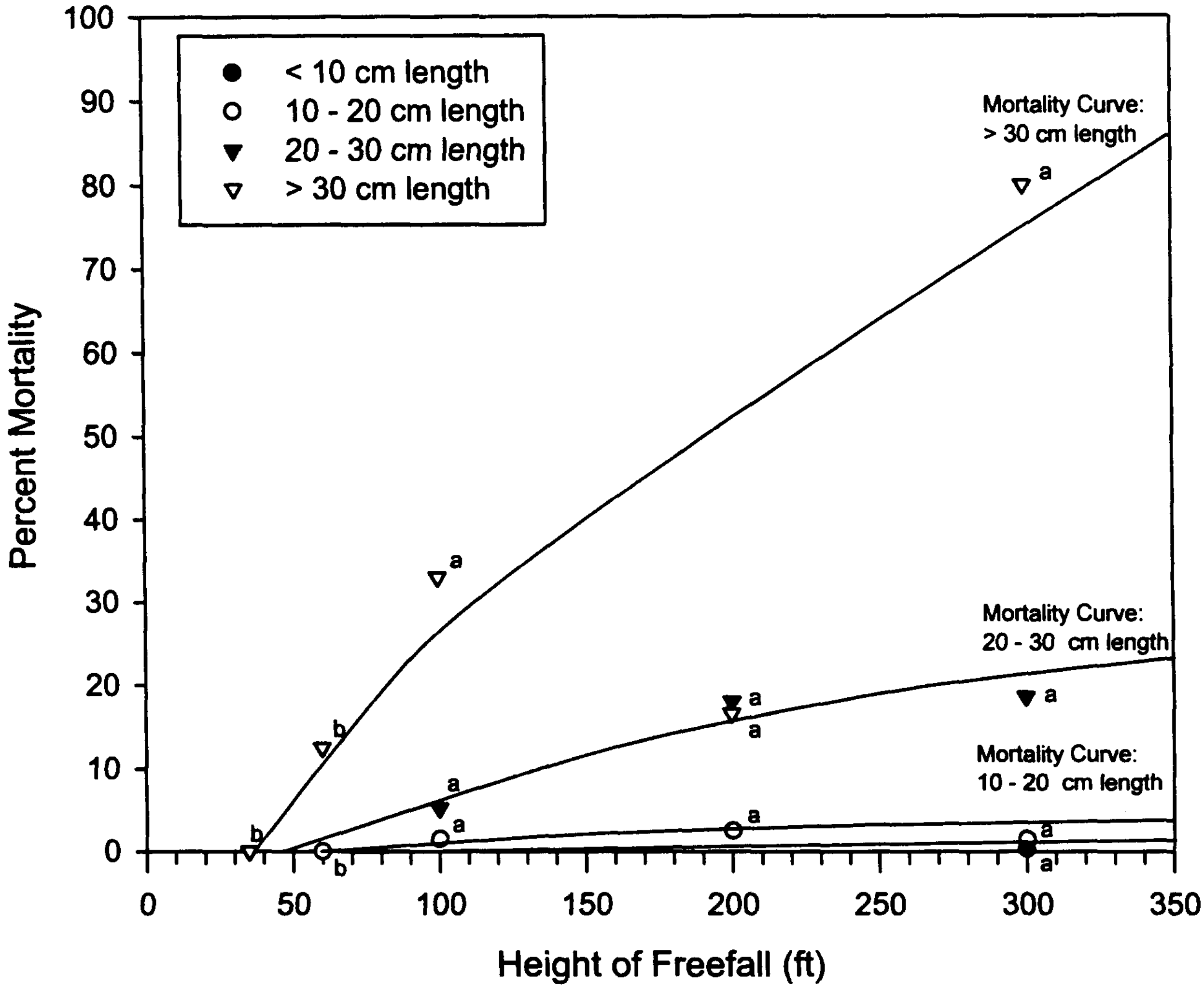

Figure 4. Relationship between freefall height and mortality of salmonid fish. Mortality curve is near zero for fish less than 10 cm in length. Mortality estimates obtained from: (a) aerial drop of coho salmon and rainbow trout from helicopter, Regenthal 1956; and (b) aerial drop of atlantic salmon from tower, Sweeny and Ritchie 1981.

Table 1. Summary of spillway mortality estimates for juvenile salmonids obtained at dams in the Pacific Northwest. Estimates are for fingerling and yearling fish (generally between 5 and 15 cm length). Maximum velocity values calculated from hydraulic head of each dam.

Literature Source	Location	Spillway Type	Stilling Basin	Hydraulic Head (ft)	Maximum Velocity (fps)	Fish Species Investigated	Estimated Mortality (%)
Andrew and Geen 1958	Seton Creek, BC	siphon	submerged jump	25	40	sockeye	1.2
Holmes 1952	Bonneville Dam	ogee without deflectors	baffled horizontal apron	52	58	chinook	3.0
Johnsen and Dawley 1974	Bonneville Dam	ogee with deflectors	baffled horizontal apron	52	58	chinook	6.0
Johnsen and Dawley 1974	Bonneville Dam	ogee without deflectors	baffled horizontal apron	52	58	chinook	1.9
Normandeau 1996	The Dalles	ogee	baffled horizontal apron	78	71	chinook	2.1
Schoeneman et. al 1961	McNary Dam	ogee	baffled horizontal apron	85	74	chinook	0.5
Schoeneman et. al 1961	Big Cliff Dam, WA	ogee	horizontal apron	90	76	chinook	6.0
Iwamoto et al. 1994	Little Goose Dam	ogee	roller bucket	98	79	chinook	0.0
Schoeneman and Junge 1954	Elwha Dam, WA	chute	exposed rocks	100	80	chinook	37.0
Park and Achord 1987	Lower Granite Dam	ogee	horizontal apron	100	80	chinook	1.0
Long et al. 1975	Lower Monumental Dam	ogee	horizontal apron	100	80	steelhead	2.2
Muir et al. 1995	Lower Monumental Dam	ogee with deflectors	horizontal apron	100	80	chinook	7.3
Muir et al. 1995	Lower Monumental Dam	ogee without deflectors	horizontal apron	100	80	chinook	1.6
Raymond and Simms 1980	John Day Dam	ogee	baffled horizontal apron	105	82	chinook	0.0
Seiler and Neuhauser 1985	Condit Dam, WA	chute	pool with exposed rocks	125	90	coho	29.8
Schoeneman 1959	Alder Dam, WA	chute and freefall	plunge pool	140	95	chinook	3.0
Schoeneman and Junge 1954	Glines Dam, WA	freefall	plunge pool	180	108	chinook, coho	6.8
Hamilton 1955	Baker Dam, WA	ski jump to chute	plunge pool	240	124	coho	63.5
Hamilton 1955	Baker Dam, WA	ski jump to chute	plunge pool	240	124	sockeye	54.0
Regenthal 1955	Baker Dam, WA	ski jump to chute	plunge pool	240	124	coho	51.9
Vernon and Hourston 1957	Cleveland Dam, BC	ski jump / horizontal jet	plunge pool	240	124	steelhead, coho	50.0
Schoeneman et. al 1955b	Yale Dam, WA	chute	plunge pool	323	144	coho	50.0

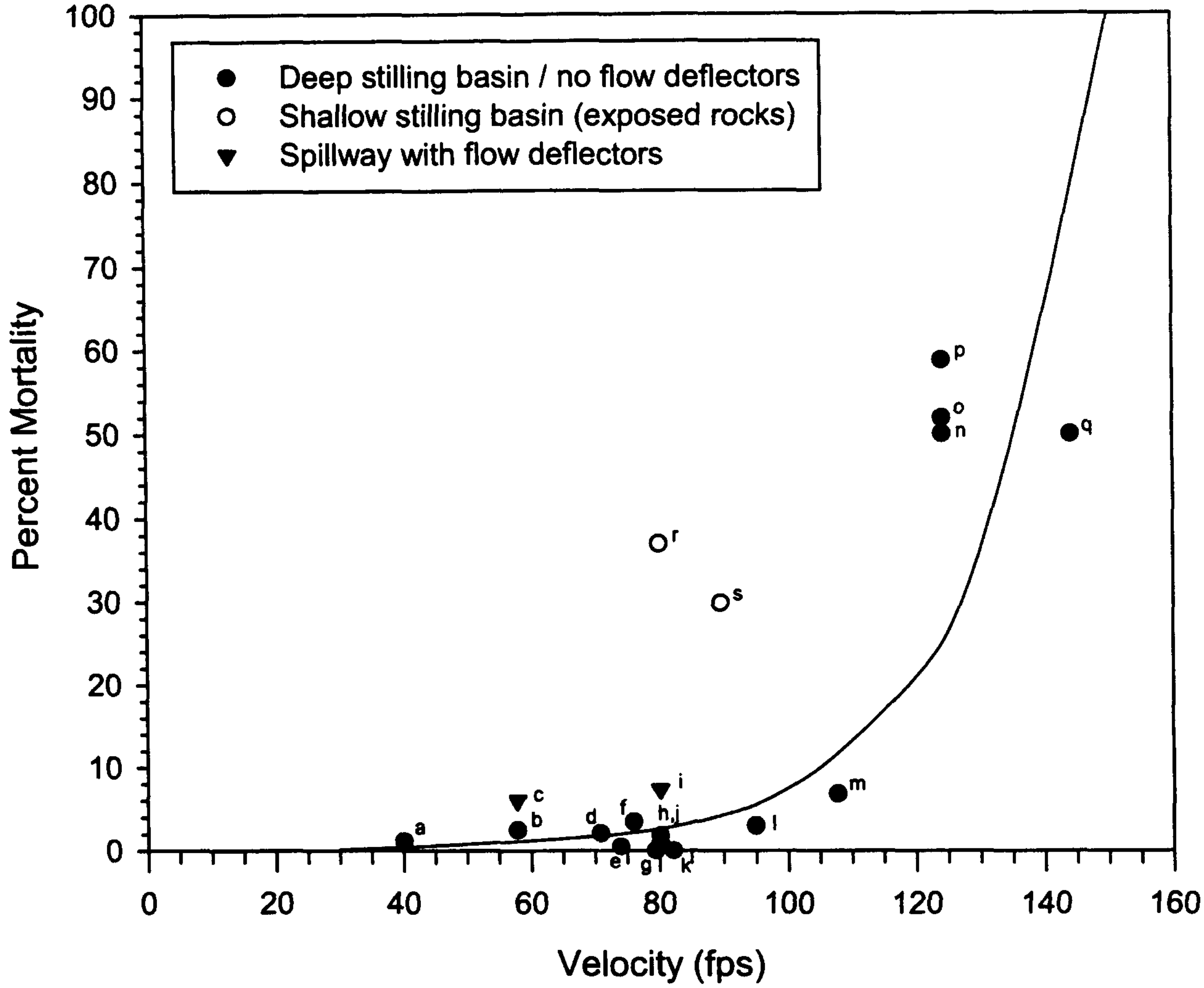

Figure 5. Relationship between maximum velocity (calculated from hydraulic head) and mortality of juvenile salmonids measured at dams in the Pacific Northwest. Plotted curve for dams with deep spilling basins and without flow deflectors.

List of Dams (including type of spillway and literature source)

a - Seton Creek Hydroelectric Project, BC; siphon and submerged jet (Andrew and Geen 1958)
b - Bonneville Dam; ogee with no flow deflectors (Holmes 1952; Johnsen and Dawley 1974)
c - Bonneville Dam; ogee with flow deflectors (Johnsen and Dawley 1974)
d - The Dalles; ogee (Normandeau Associates 1996)
e - McNary Dam; ogee and bucket (Schoeneman et al. 1961)
f - Big Cliff Dam; ogee and bucket (Schoeneman et al. 1961)
g- Little Goose Dam; ogee (Iwamoto et al. 1994)
h - Lower Monumental Dam; ogee with no flow deflectors (Long et al. 1975; Muir et al. 1995)
i - Lower Monumental Dam; ogee with flow deflectors (Muir et al. 1995)
j - Lower Granite Dam; ogee (Park and Achord 1987)
k - John Day Dam; ogee (Raymond and Sims 1980)
l - Alder Dam, WA; flume and freefall (Schoeneman 1959)
m - Glines Dam, WA; freefall (Shoeneman and Junge 1954)
n - Cleveland Dam, BC; ski jump and horizontal jet (Vernon and Hourston 1957)
o - Baker Dam, WA; ski jump to chute (Hamilton 1955)
p - Baker Dam, WA; ski jump to chute (Regenthal 1955)
q- Yale Dam, WA; chute (Schoeneman et al. 1955)
r- Elwha Dam, WA; chute (Shoeneman and Junge 1954)
s - Condit Dam, WA; chute (Seiler and Neuhauser 1985)

velocities less than 100 fps. The exception to this rule was spillways that discharge into shallow stilling basins or directly onto bedrock outcroppings. Mortality rates were relatively high for these spillway conditions (i.e., Elwha and Condit dams). The Dalles Dam has a shallower stilling basin and tailrace than other dams or the Columbia River. Recent tests (Dawley et al. 1998) indicate a 13 percent mortality of juvenile coho and 8 percent mortality of subyearling chinook. The 95 percent confidence intervals for the coho and chinook tests were 6 percent to 20 percent and 1 percent to 14 percent, respectively.

Mortality for spillways with deeper stilling basins and without deflectors increased according to an exponential curve (Figure 5). A critical threshold of mortality of 100 fps is suggested by this curve. Mortality rates increase rapidly at dams having maximum spillway velocities greater than this value. This threshold velocity value corresponds to a head height of 130 ft. This values is somewhat greater than the 100 ft head value which Ruggles and Murray (1983) suggested as the threshold value for high mortality rates for fish passing through spillways and stilling basins. The curve fitted to the mortality data from the literature increases approximately as the cube of velocity.

3.3 SUMMARY OF FINDINGS

The rate of injury and mortality to fish passing through a spillway and stilling basin should be related to: 1) the velocity of the column of water (i.e., jet) within which the fish is contained; 2) the level of deceleration through the stilling basin; 3) the magnitude and range of pressures to which the fish is exposed; and 4) the probability of the fish being exposed to high shear zones located along the margins of the jet, or impacting objects located within the spillway and stilling basin. All of these factors are related to the amount of energy, which is contained in the water passing through a spillway, and the rate at which this energy is dissipated within the spillway and stilling basin.

Stilling basins have traditionally been designed to maximize energy dissipation and to confine the physical area in which this dissipation occurs. Attainment of these objectives results in an efficient and cost effective spillway design. Unfortunately, achievement of these objectives also tends to maximize injury to fish. All of the sources of mechanical injury to fish become more pronounce with increasing energy dissipation. Turbulence, hydraulic shear, fluid deceleration, and rapid pressure changes are all necessary components to achieve the energy dissipation. As discussed in Appendix A, a free discharging submerged jet dissipates this energy at a certain rate. Although not identical, free surface hydraulic jump stilling basins have similar energy dissipation characteristics. Increased energy dissipation rates are achieved through the addition of baffle blocks or sometimes incorporation of natural rock features for a specific site. Besides increasing energy dissipation rates which introduces more potential for fish injury, these features of stilling basins also provide increased striking potential risk.

Energy dissipation rate may be the best single indicator of injury risk to fish passing dams. Since energy dissipation rate generally scales with the cube of jet velocity (Appendix A), it is understandable that there is a strong correlation between velocity in dam spillways and injury to fish. Some of the scatter in the data is likely associated with variations in rates of energy dissipation associated with specific stilling basin designs. The more efficient energy dissipators pose greater risk to fish. Consequently, within the range of conventional spillway design, water velocity itself may provide a first order approximation of anticipated mortality of fish passing dams. Further resolution may be achieved through quantification of energy dissipation rates for specific spillway designs.

The following conclusions can be made from our review of the literature:

- Most experiments recorded either immediate mortality (e.g., measured immediately after fish had passed through spillway and stilling basin) or delayed (e.g., 7-day) mortality.

- Mortality rates observed in spillways are generally less than those measured in experiments for the same range of velocities. Due to scale effects, energy dissipation rates are very different at laboratory scale compared to field scale. This could be one of the potential causes for the differences that have been observed.

- Fish size is probably an important factor in determining rates of injury. Smaller fish are less likely to be exposed to shear zones and impact objects due to their physical size. However, small fish are more likely to be injured if they are entrained within shear zones or impact an object, because their tissue is weaker than that of larger fish.

- Mortality rates generally rise with increasing dam height and associated spillway velocities. Although studies provide point estimates of survival through spillways, the broad confidence bands about these estimates make it difficult to discern the range between 0% mortality and 8% mortality. Due these confidence bands, comparative studies of different spillway configurations often conclude that there are no statistical differences in survival. As dam heights exceed 150 feet, spillway mortality begins to increase significantly.

- Very little variation was observed for the mortality versus velocity (i.e., hydraulic head) curve developed from the literature, even though mortality (or survival) rates were obtained at a wide variety of dams and experimental conditions. The most important exception to the curve are spillways which dissipate energy over very shallow stilling pools (e.g., those with exposed rock or bedrock ledges).

- Point estimates of mortality of spillways with and without flow deflectors have suggested mixed results. However, no statistical differences in direct mortality have been established for spillways with flow deflectors compared to those without deflectors. Likewise, no tests have confirmed any overall effect of flow deflectors with consideration for the potential benefits related to gas bubble trauma (GBT).

- High mortality rates are observed at high head dams that have shallow stilling basins. High turbulence and abrasion may result in increased mortality under these conditions (Vernon and Hourston 1957). High mortality rates are also observed at free-fall and chute spillways that discharge over rocks or bedrock ledges (e.g., Elwha Dam). Depending on the orientation of high velocity flow as it enters a still basin and other characteristics of the flow, a shallow basin could result in either enhanced or reduced energy dissipation rates. The conclusions regarding high mortality rates in shallow basins probably pertain only to basins where energy dissipation is increased by this feature.

3.4 FUTURE STUDIES

Developing a mechanistic understanding of mechanical injury will be challenging because fish passing through spillways and dams can be injured or killed by a number of factors, including rapid deceleration, exposure to shear zones, high turbulence, and striking solid objects. The injury and mortality rates observed in spillways and stilling basins are likely caused by a combination of these factors. The following concerns and issues need to be addressed in future studies to better understand the physical mechanisms leading to injury and mortality of fish within spillways and stilling basins:

1) The direct effects of rapid deceleration, shear zones, turbulence, and object striking on injury and mortality rates of fish needs to be better defined from laboratory and field studies. There is a real need to better define the relationships between each of these factors and injury rates for different types of spillways.

2) There is a need to obtain measurements of localized velocities, accelerations and the magnitude of shear zones in stilling basins.

3) Future experiments should examine interrelations between the velocity of the jet within which a fish is contained, the width of the jet, and fish size.

4) There is a need to be able to predict injury and mortality rates from: 1) the amount of energy which is dissipated through a stilling basin; 2) the ways in which energy is dissipated in the stilling basin; and 3) the total area or volume within which energy is dissipated.

5) Traditional spillway design generally results in spatially efficient energy dissipation. This characteristic probably increases injury to fish passing through spillways. Theoretically, it seems preferable to have lower energy dissipation rates downstream of spillways. This would require longer and less efficient stilling basins. Current error bounds around mortality estimates at spillways make it difficult to discern differences in mortality that may be associated with varying levels of energy dissipation in stilling basins. Increasing sample sizes to reduce these error bounds along with detailed evaluations of energy dissipation within the structures may guide stilling basin design to reduce injury to fish.

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APPENDIX A

Hydraulics of Submerged Jets

A. Hydraulics of Submerged Jets

Flow emanating from a submerged jet is highly turbulent. Hydraulic shear and turbulence within the flow are mechanisms that have been identified as significant potential sources of injury to juvenile fish passing hydroelectric facilities. A brief review of some of the properties of the flow in submerged jets provides a potential framework to investigate the relationships between fluid shear, turbulence, and fish injury. Some basic properties of a submerged round jet discharging into still water are discussed below.

Figure A-1 is a diagram of the flow characteristics of a jet discharging into a still body of water. Flow emerging from the jet entrains ambient fluid as the jet expands. There is a "zone of establishment" in which there is a potential core with a constant centerline velocity. Beyond this zone, the jet is fully developed and continues to entrain and mix surrounding ambient fluid while maintaining a distinctive gaussian shape as the jet expands.

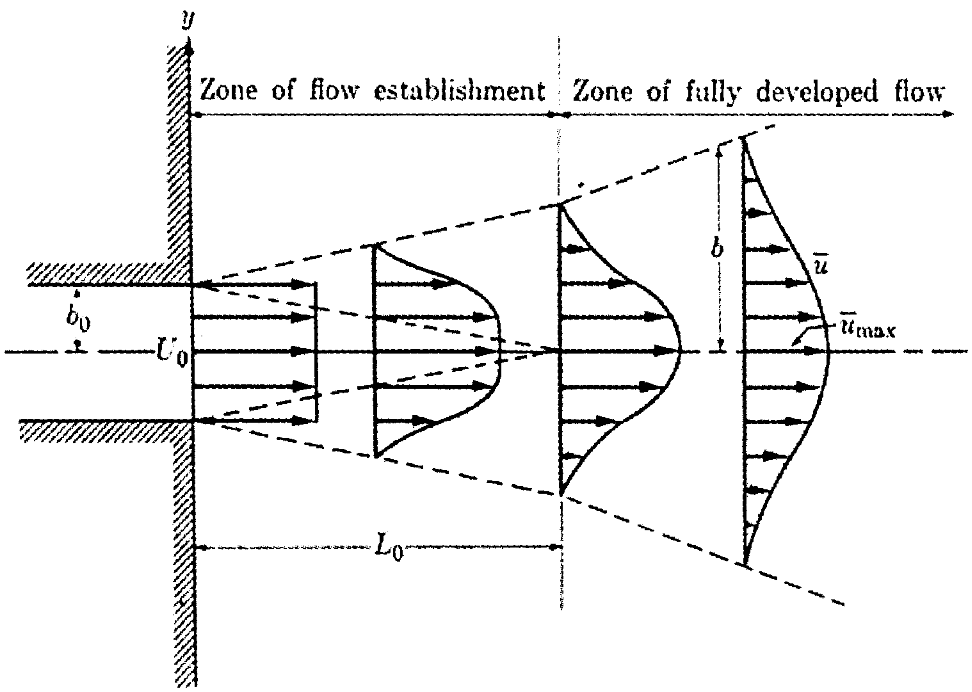

Figure A-1. Illustration of flow characteristics of a submerged jet (Daily & Harleman)

A.1. Velocity Field

Numerous researchers have investigated the velocity field associated with a submerged jet. The velocity distribution in the fully developed zone can be theoretically derived (e.g. Daily and Harleman, 1966) and can be expressed in the form:

$$V(r,z) = \frac{6.4V_0D_0}{z(1+\frac{r^2}{0.016z^2})^2}$$

where V_0 is the velocity at nozzle exit, D_0 (=$2r_0$) is the diameter of the nozzle, r is the radial distance from centerline of the jet and z is the downstream distance from the nozzle exit.

A.2. Energy

With the velocity field V(r,z) defined, the energy contained in the jet can be determined. Energy per unit weight of water (E), defined as the ratio of energy flux to mass flux through the cross-section, is written as:

$$E = \frac{\pi\rho\int_0^\infty V^3(r,z)rdr}{2\pi\rho g\int_0^\infty V(r,z)rdr}$$

where ρ is the fluid density and g is the acceleration of gravity.

Carrying out the integration, we obtain:

$$E = E_0\frac{1.019(1-\Omega^5)}{1-\Omega}(\frac{D_0}{2z})^2$$

where $E_0 = \frac{V_0^2}{2g}$ is the energy per unit weight at the nozzle exit, and:

$$\Omega = (62.5(\frac{D_0}{2z}+0.1464)^2+1)^{-1}$$

Figure A-2 is a dimensionless plot depicting the energy contained in a round jet as it disperses into still water. Energy content derived from laboratory velocity field data along with the theoretical solution presented by Daily and Harleman are shown in the plot. The laboratory velocity measurements were taken close to the nozzle exit within the flow establishment zone while the analytical solution of Daily and Harleman is suitable in the fully developed zone, which is about 7 diameters downstream of the nozzle exit.

As is shown in Figure A-2, the energy in the fluid dissipates exponentially from its initial energy level to less than 10 percent within 12 diameters away from the discharge point. This energy is dissipated within the fluid in the form of turbulence induced by hydraulic shear. The highest energy dissipation rates are also near the discharge point, decreasing with distance away from the exit.

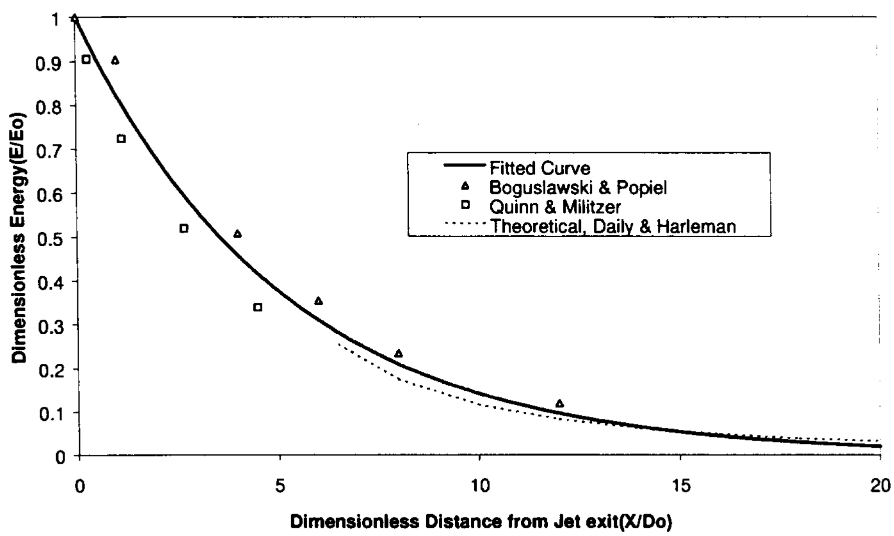

Figure A-2. Dimensionless Energy as a function of dimensionless distance from jet exit

The curve fitted through the experimental and analytical data in Figure A-2 can be expressed as:

$$E = E_0 e^{-0.195z/D_0}$$

Energy dissipation rate per unit volume of fluid is defined as:

$$F = \frac{\partial(\rho g Q E)}{A \partial z}$$

where Q is the volumetric flow rate passing through the cross-section. At the nozzle exit, the dissipation rate is the highest (which is apparent from the slope of the energy graph shown above). From the previous equation, the energy dissipation rate at the nozzle exit can be derived as:

$$F(z=0) = -\frac{0.195}{D_0} \rho g \frac{V_0^3}{2g}$$

Thus the energy dissipation is inversely proportional to the nozzle diameter and directly proportional to the cube of the exit velocity. Figure A-3 shows the energy dissipation at the nozzle exit for different pipe diameters and velocities.

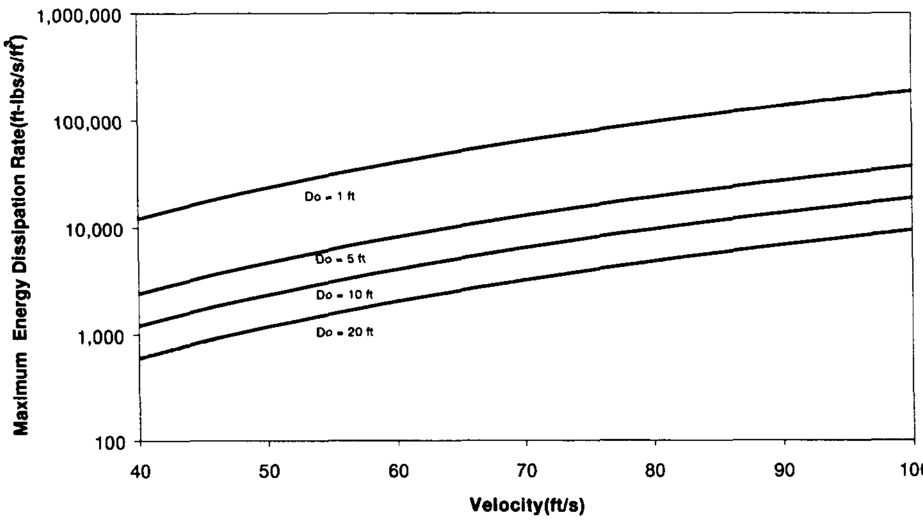

Figure A-3. Energy dissipation rate at jet discharge for various jet diameters

Energy dissipation is concentrated on the periphery of the jet. The calculation of energy dissipation per unit volume of fluid was made over the entire jet area, while in fact the dissipation rate varies from low in the center of the jet to high in the highly turbulent region closer to the jet periphery. Thus, there can be a large variation in the turbulence and energy dissipation depending on the location within the jet. For juvenile salmonids approximately 100 mm in length, significantly different injury rates might be expected in a small jet where the size of the fish guarantees that it will encounter very high energy dissipation zones compared to a large jet where the position of the fish may play a role in determining the level of energy dissipation encountered.

A.3. Fluid Deceleration

Another aspect of the properties of flow emerging from a submerged jet is the rapid deceleration as the turbulent jet enters still water. Along the centerline of a jet, the fluid velocity begins decreasing approximately 7 diameters from the exit point at the end of the flow establishment zone. The deceleration at the centerline can be defined as:

$$a = V\,\partial V/\partial z\,.$$

With V as defined previously, and at r=0 (at centerline), we obtain:

$$a = -6.4^2 V_0{}^2 \frac{D_0^2}{z^3}$$

The maximum deceleration of the fluid along the centerline occurs at the end of the flow establishment where $z = 6.4D_0$. Therefore:

$$a_{c\max} = -0.156\frac{V_0^2}{D_0}$$

Figure A-4 presents the variation in centerline deceleration for submerged jets with velocities ranging from 40 to 100 ft/s and jet diameters ranging from 1 to 20 ft.

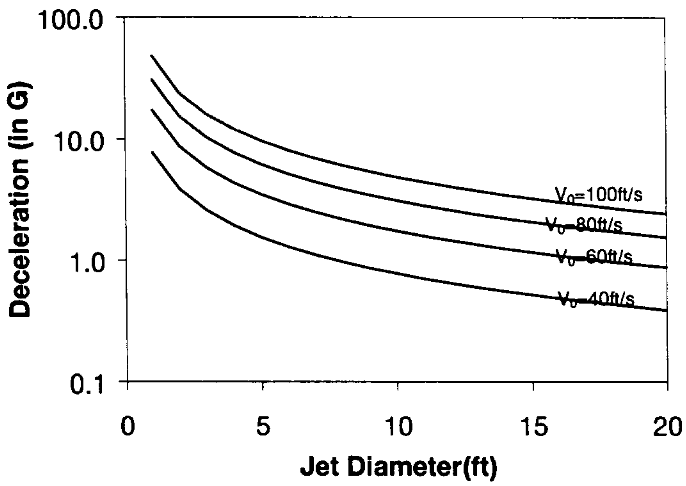

Figure A-4. Maximum deceleration along centerline of jet

Maximum deceleration rates increase with increasing velocity and decrease with increasing jet diameter. As the figure shows, an 80 ft/s jet emerging from a 1 foot diameter opening experiences a deceleration of about 31 g (acceleration of gravity), whereas the same velocity water emerging from a 10 foot diameter jet experiences only about 3.1 g of deceleration.

The above analysis of deceleration was made along the centerline of the jet. Different flow paths have significantly higher deceleration rates depending on the location within the jet. Through analysis of the velocity field measurements of Boguslawski and Popiel (1979), the radial distribution of maximum decelerations was estimated. This distribution is shown in Figure A-5. As depicted in the graph, maximum decelerations along the periphery of the jet are about three times as high as at the center of the jet. This suggests that a fish traveling in the periphery of a jet will experience significantly higher deceleration forces than a fish traveling near the jet centerline.

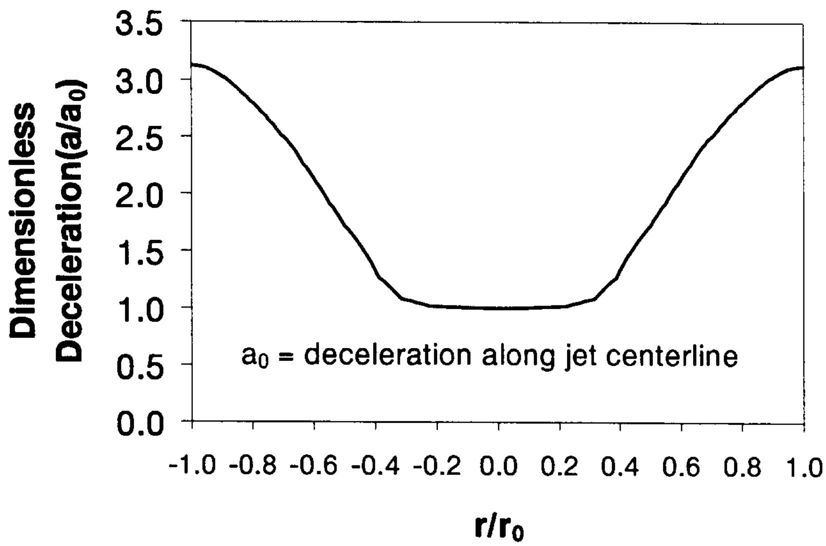

Figure A-5. Radial distribution of maximum deceleration in a submerged jet

With this radial distribution of deceleration, the probability that a fish might encounter a certain deceleration rate can be determined if the radial distribution of fish within the jet is known. Assuming an equal distribution of fish at all locations in a jet with an initial velocity of 80 ft/s, Figure A-6 was prepared showing the probability of a fish encountering different levels of deceleration for several jet diameters. The plot shows that a percentage of the fish exiting a 10-ft diameter jet with a velocity of 80 ft/s will experience decelerations as high as 10 g, while others near the center of the jet experience decelerations of 3 g.

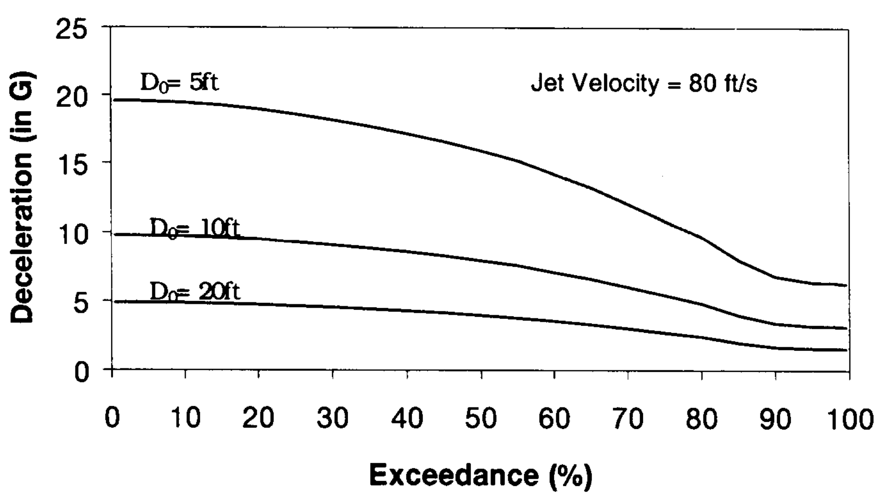

Figure A-6. Probability of entering a zone with a deceleration rate greater than or equal to given value.

A.4. Summary

A review of some of the characteristics of submerged jets was performed to aid in the understanding of the causes of injury to juvenile fish passing hydroelectric dams. The analysis was made for a single round jet discharging into still, ambient water. Two hydraulic characteristics of the jet were investigated: energy dissipation and fluid deceleration.

Based on evaluations of both energy dissipation and water deceleration, the jet velocity, size, and location within the jet may play important roles in understanding injury to fish associated with high velocity flow entering relatively slow moving water. This scale effect should also be considered when evaluating laboratory data with respect to field applications. As an example, a 4-inch fish passing from an 80 ft/s, 6-inch diameter jet into still water will likely experience decelerations greater than 100 times the acceleration of gravity. In contrast, at the same velocity in a 10-ft diameter jet, the same fish would be subjected to 3 to 10 times gravity depending on the position of the fish within the jet. There are similar differences in energy dissipation rates for the two conditions.

The purpose of this evaluation was to point out the importance of carefully examining the hydraulic conditions in attempting to understand potential sources of injury to fish at hydroelectric facilities. Additional theoretical analyses, laboratory studies, and field investigations are warranted given our current knowledge of the hydraulic mechanisms that cause these injuries.

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APPENDIX B

Annotated Bibliography of Literature Regarding the Mechanical Injury of Fish with Emphasis on Spillways and Stilling Basins

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Reference Type: Technical Report
Record Number: 1
Author: Bell, M.C., and A.C. DeLacy
Year: 1972
Title: A compendium on the survival of fish passing through spillways and conduits
Agency: U.S. Army Corps of Engineers
Division: Fisheries Engineering Research Program
City: Portland, Oregon
Date: January 1972
Report Number: Contract Number DACW 57-67-C-0105
Pages: 121
Injury Type: immediate, short term delayed
Relevance: Primary
Keywords: Spillway, stilling basin, pressure, abrasion, velocity, shearing
Abstract: The data reviewed cover information, both observed and recorded, on fish passage through spillways, natural falls, conduits and pipe systems. Experiments and observations were conducted under prototype and laboratory conditions. Factors that were considered are: species of fish, size of fish, condition of fish, numbers of predators, effects of diseases, food availability, feeding habits, behavior patterns, type of bucket or stilling basin, distance of fall (total head), velocity through gate, discharge (cfs), temperature, turbidity, type of recovery gear, methods of release.

The apparent assumptions made by the investigators were: (1) fin excision and other methods of identification did not cause unknown differential survival between groups of marked fish; (2) natural river mortality occurring between the test site and the point of recapture was the same for all lots of fish used in a particular series of tests or season; (3) natural and fishing mortalities in the ocean and rivers were the same for the lots of fish in a particular test. Depending upon the nature and objective of the individual investigation, the variables and assumptions will be involved in unique combinations and in each case they must be given appropriate consideration.

Data sheets numbered 70 to 114 and a table on page 121 were prepared and cover the information pertinent to many of the individual experiments, giving reference to the parallel items for each experiment. A graph on page 121 is taken from the report of the Corps of Engineers and sums up the results of a number of experiments conducted at the Bonneville project. The data covering the Cougar Dam experiments are on pages 27 to 30. This series of experiments did not lend itself to the compilation as prepared for the other experiments. The literature reviewed is listed in the bibliography, pages 46 to 50. A cross-index of selected excerpts from the reports has been prepared and is included on pages 51 to 59. Comments of the experimenters are cross-indexed under major headings, making it possible to compare results from the various tests. To assist further in interpreting the data, a series of sketches depicting physical conditions through which the fish passed are shown on pages 116 to 120. By the use of the sketches, it is possible to visualize the physical conditions under which the tests were conducted and the changing conditions by which energy is dissipated as flowing water passes, or falls from a height, into a stilling pool. Also shown on the sheets are conditions under which the fish would be in free fall.

Notes: The objectives of the study were to prepare a compendium containing and interrelating available research information pertinent to the passage and survival of fish through spillways.

Release site	spillway type	head	species/ age	estimated survival
McNary Dam	ogee & bucket	85 -	chinook/fingerling	98%
Big Cliff Dam	bucket	90	chinook/fingerling	98%
Bonneville	ogee & bucket	85	chinook/fingerling	54.2%
McNary Dam	ogee & bucket	85	chinook/fingerling	to
Elwha Dam	chute	100	chinook/fingerling	98.5%
Elwha Dam	chute	100	chinook/fingerling	63%
Glines Dam	freefall	180	chinook/fingerling	94%
			coho/yearling	92%
Baker Dam	freefall to chute	240	coho/yearling	68%, 79%, 83%
Baker Dam	freefall to chute	250	coho/sockeye	36%, 46%
Capilano River	ski jump	240	coho & steelhead/ smolts	50%
Baker Dam	flume & freefall	260	coho	97% - 100%
Mud Mtn.	Tunnel	80– 20	chinook/yearling	8.6%
			coho/yearling	97.5%
Seton Creek	siphon	25	sockeye/smolt	98.8%
Ariel	still pool	185	coho/rainbow	100%
Puyallup & Dungeness	helicopter	300	coho/rainbow	99.7% 98.5%
Ontario	air drop	300-400	brook	3.0%-3.8%

Status: Copy in house

Reference Type: Technical Report
Record Number: 55
Author: Bjornn, T.C., and C.A. Peery
Year: 1992
Title: A review of literature related to movements of adult salmon and steelhead past dams and through reservoirs in the lower Snake River
Agency: U.S. Army Corps of Engineers
Division: Walla Walla District
City: Walla Walla, Washington
Date: October 1992
Report Number: Technical Report Number 92-1
Pages: 80
Relevance: Secondary
Keywords: Upstream, migration, dams
Abstract: A synthesis of published and unpublished literature on the upstream migration of adult salmon and steelhead *Oncorhynchus mykiss*, with particular reference to passage through reservoirs and over dams, was prepared as part of an evaluation of fish passage through the lower Snake River. Most of the information on adult migrations in the Snake and Columbia rivers was collected on chinook salmon *O. tshawytscha* and steelhead. The amount of flow, temperature and turbidity of the water, and partial barriers are natural factors that affect the rate of migration and survival of upstream migrants. Human-caused alterations in flow, temperatures, and turbidities through the construction of dams and creation of reservoirs may be beneficial or detrimental to migrants, depending on the amount of change from natural and the fishs' ability to adapt. Dams and reservoirs placed in the migration path of adult salmon and steelhead usually create unique passage problems because the structures and discharges differ and the stocks of fish involved change from one section of the river to the next.

Survival rates of adult salmon and steelhead in the Snake and Columbia rivers were not assessed before the construction of the dams, but some information on migration rates was obtained. In free-flowing rivers, salmon have been observed migrating at rates up to 24 km/d (15 mi/d). Lesser rates of migration have been observed when rivers were turbid and in winter when steelhead suspend their migration till spring. Migration rates in reservoirs ranged from 16 km/d for fall chinook salmon in Brownlee Reservoir, a large storage pool, to 56 km/d for spring chinook salmon in Ice Harbor and Little Goose reservoirs, run-of-the-river pools.

The time required for adult salmon and steelhead to migrate past dams varies with the structure, flow, spill, powerhouse discharge, turbidities, and the positioning of fishway entrances. Some fish approach and pass over a dam in less than a day, but the average reported time to pass a dam has ranged from 1 to 5 d in several studies. Passage rates are slower when there are high flows and spills that make it difficult for fish to find fishway entrances.

The fishways used by adult fish and the rate of passage is influenced by the distribution of discharge from a dam and the effectiveness of the attraction flows at the fishway entrances. When there is little or no spill, few fish use the fishway entrances near the spillway. Small amounts of spill have been shown to increase use of entrances near spillways, but large amounts of spill can completely block some fishway entrances to fish use.

Discharges from the powerhouse can vary widely depending on the flow in the river and power demand. During high flows all turbines may be running at capacity, but at lower flows only 1 or 2 turbines may be used at the Snake River dams. The preferred turbines to operate for optimum fish passage has been studied at some dams, but not well defined in a way that can be universally applied. If passage problems occur at a dam, then site specific studies will probably be required.

Hydroelectric power peaking can affect adult fish migrating past dams through daily changes in discharge and by the volume of discharge during periods of peak power production. Rates of discharge change did not seem to affect fish entry into the fishways, but passage rates were lower during peak discharge periods than at lower discharge rates, presumably because the high discharges made the fishway entrance attraction flows less efficient. The effect on fish of reducing discharges from selected dams to zero at night to conserve water for daytime power production has not been settled. Although fish are believed to move less at night, and would, therefore, be minimally affected by no flow through the reservoirs at night, the results of two studies are in conflict. A more extensive study of zero flow at night in the lower Snake River is underway.

Considerable study has gone into the location and structure of fishway entrances. Fishway entrances on either bank of the river, flanking the spillway, and along the powerhouse appear to give fish sufficient opportunities to enter fishways, except perhaps, when high flows create currents that obscure some entrances from the fish. Entrance size and depth, and discharges from the entrances appear adequate if attraction flows are good enough to lead the fish to the entrances. Fish can exit, as well as enter, the fishways at the entrances, and enough fish do so at some entrances to have a net entrance rate of zero or less. The extent of the problem is under study at the lower Snake River dams and a fishway fence designed to discourage fish from exiting certain entrances is being tested.

Once fish enter the fishways, passage is relatively rapid, usually a matter of a few hours, except that most fish move through the fishways during the daytime. Fishways with 1:10 slopes, vertical baffles, overflow weirs with submerged orifices, and velocities less than about 1 m/s allow the fish to ascend with minimal delays. A few fish have been observed to partially ascend and then move down and even exit fishways, before eventually reascending. Instances of fish taking a long time to pass through a fishway often involve up and down movements, and may be related to other factors such as turbidity and gas supersaturation.

The rate of fallback over dam by adult salmon and steelhead varies with flow and spill, by dam, and species. Spring and summer chinook salmon have the highest fallback rates (up to 30+%), particularly at dams with limited powerhouse capacity, because they migrate upstream during the spring runoff. The location of fishway exits in relation to the spillway is an important factor at some dams. Fallback rates can also be high for steelhead (up to 20+%) at some dams that are in the overwintering areas of the mid Columbia and lower Snake rivers. Mortality rates of fallback fish have not been well documented, but a high percentage of tagged fish have been observed reascending dams.

Water temperatures influence the rates of migration of steelhead and salmon. High water temperatures have slowed the migrations of fall chinook salmon and steelhead into the Snake

River during August and September, and perhaps affected the migration rates in the lower Columbia River. Steelhead also slow their migration in late fall as water temperatures decline and they do not resume their migration to the spawning grounds until the following spring when temperatures increase from winter flows.

High concentrations of dissolved nitrogen were a persistent problem in the lower Snake River before all six turbines were installed at each dam and "flip-lips" to prevent deep plunging of spilled water were installed in the spillways. Nitrogen supersaturation at problem concentrations can occur when river flows exceed the capacity of the powerhouses and the volume of spill (more than 60 kcfs) makes the flip-lips ineffective.

A portion of the adult salmon and steelhead migrating to spawning grounds and hatcheries die enroute, and those losses can be both natural and human-caused. Discrepancies between counts of fish at dams have been relatively large in some instances, which has raised the concern about extraordinary losses at some dams. Some of the discrepancies have been caused by high fallback rates with subsequent reascension at specific dams, and some can be accounted for as fish caught by fishermen, fish spawning in the main stem rivers or entering tributaries. However, significant portions of the discrepancy cannot be accounted for in some areas and they may in fact be losses of fish to a variety of causes. Discrepancies between counts of steelhead at McNary, Priest Rapids, and Ice Harbor dams have been large in some years and have not been accounted for fully, an indication, that significant losses may occur in some years, mostly among fish destined to enter the Snake River. Discrepancies in counts of salmon and steelhead between four Snake River dams and losses in radio tracking studies have been relatively low.
Notes: The objective of the study was to provide a synthesis of literature on the upstream migration of adult salmon and steelhead.

This paper mentions that differences in gate openings of four feet or more in adjacent spillways creates a slack water area adjacent to a high velocity jet. Fish moving between the two areas will be killed by shear force.
Status: Copy in house

Reference Type: Journal Article
Record Number: 51
Author: Bouck, G.R., and S.D. Smith
Year: 1979
Title: Mortality of experimentally descaled coho salmon (*Oncorhynchus kisutch*) in fresh and salt water
Journal: Transactions of the American Fisheries Society
Volume: 108
Pages: 67-69
Injury Type: Long-term
Relevance: Tertiary
Keywords: Slime, handling, stress
Abstract: Removal of slime from 25% of the body caused no deaths among smolts of coho salmon in fresh water or in seawater (28ppt). Removal of slime and scales from the same percentage of body area caused no deaths in fresh water, but 75% mortality within 10 days in seawater. The 10-day median tolerance limit was 10% scale removal immediately before the smolts entered seawater. Mortality was highest when the scales were removed from the area of the rib cage. Recovery of smolts in freshwater from a loss of scales that would be lethal in seawater occurred rapidly; 90% of the fish regained tolerance to seawater within 1 day.
Notes: The objective of the study was to describe the potential long-term mortality that might occur as a result from descaling of smolts striking flow deflectors while passing through spillways. Mortality was highest if the injury occurred in the rib cage area. Salt-water tests indicated that a relatively small amount of descaling can cause significant mortality to smolts entering the marine environment.
Status: Copy in house

Reference Type: Technical Report
Record Number: 56
Author: Copp, H.D.
Year: 1968
Title: Stilling basin hydraulics and downstream fish migration
Agency: Washington State University
Division: Research Division
City: Pullman, Washington
Date: November 1968
Report Number: Research Report Number 66/9-47
Pages: 23
Relevance: Secondary
Keywords: Spillway, bucket, "roller"
Abstract: This report is the result of cursory investigation into the hydraulic characteristics of spillways. It is not intended to show all of the variables within the various types of buckets, nor is it intended to be a precise design study. To some degree, experienced judgment has been used in its preparation; therefore, direct comparisons of energy relationships should not be made. It is intended to indicate possible varying conditions to which fish are subjected when passing through a spillway and to illustrate one approach for determining the length of time that fish may spend in a given type of bucket.

The reader is warned not to use these data as criteria for design of a particular spillway, or to extrapolate directly the variable, as only limited spillway criteria were considered. The methods suggested here, however, are applicable criteria for further study, if desired. The study does not indicate the recirculation pattern or the possible number of repeats that fish or other floating objects could encounter in passing through such energy dissipators.

This study does not indicate the recirculation pattern or the possible number of repeats that fish or other floating objects could encounter in passing through such energy dissipators.
Notes: The objective of this report was to indicate the possible conditions to which fish are subjected when passing through a spillway.

If entrained in a "roller," downstream migrating fish may witness: an insignificant abrupt drop in flow and pressure as they move under the spillway gates unless that drop is instantaneous; or as most cases, a relatively short period of overall pressure reduction at the spillway gate. Both circumstances can have profound outcomes on fish physiology.
Status: Copy in house

Reference Type: Conference Proceedings
Record Number: 100
Author: Coutant, C.C., and R.R. Whitney
Year: 1997
Title: Fish behavior in relation to modeling fish passage through hydropower turbines: a review
Conference Name: Fish Passage Workshop
Editor: Alden Research Labs
Conference Location: Milwaukee, WI
Pages: 9
Relevance: Secondary
Abstract: We evaluated the literature on fish behavior as it relates to passage of fish near or through hydropower turbines. The goal was to foster compatibility of engineered systems with the normal behavior patterns of fish species and life stages such that entrainment into turbines and injury in passage are minimized. We focused on aspects of fish behavior that could be used for computational fluid dynamics (CFD) modeling of fish trajectories through turbine systems. Downstream-migrating salmon smolts are generally surface oriented and follow flow. Smolts orient to the ceilings of turbine intakes but are horizontally distributed more evenly, except as affected by intake-specific turbulence and vortices. Smolts often enter intakes oriented head-upstream. Non-salmonids are entrained episodically, suggesting accidental capture of schools (often of juveniles or in cold water) and little behavioral control during turbine passage. Models of fish trajectories should not assume neutral buoyancy throughout the time a fish passes through a turbine, largely because of pressure effects on swim bladders. Fish use their lateral line system to sense obstacles and change their orientation, but this sensory-response system may not be effective in the rapid passage times of turbine systems. Effects of pre-existing stress levels on fish performance in turbine passage are not well known but may be important. There are practical limits of observation and measurement of fish and flows in the proximity of turbine runners that may inhibit development of information germane to developing a more fish-friendly turbine. We provide recommendations for CFD modelers of fish passage and for additional research.
Notes: This paper summarizes available literature on fish behavior in relation to fish passage through hydropower turbines.

No data is presented on injury to downstream migrating salmonids passing through spillways and/or stilling basins.
Status: Copy in house

Reference Type: Technical Report
Record Number: 64
Author: Davidson, F.A.
Year: 1961
Title: The effect of tailwater elevation and spillway discharge on the passage of salmon and steelhead through the fish ladders at Rock Island Dam
Agency: Public Utility Number 2 of Grant County
Date: October 1961
Pages: 55
Relevance: Tertiary
Keywords: Spillway, tailwater, fish
Notes: This objective of this report is to identify the effects of tailwater and spillway discharge on salmon and steelhead passage at Rock Island Dam.

No mention of injury to downstream migrating salmonids passing through spillways and/or stilling basins.
Status: Copy in house

Reference Type: Technical Report
Record Number: 41
Author: Dawley, E.M., L.G. Gilbreath, and R.D. Ledgerwood
Year: 1988
Title: Evaluation of juvenile salmonid survival through the second powerhouse turbines and downstream migrant bypass system at Bonneville Dam, 1987
Agency: U.S. Army Corps of Engineers and National Marine Fisheries Service
Division: Coastal Zone and Estuarine Studies
City: Seattle, Washington
Date: January 1988
Report Number: Contract Number DACW57-87-F-0323
Pages: 45
Relevance: Tertiary
Keywords: Turbine, bypass, survival
Notes: The objectives of the study were: (1) to determine the short-term survival of juvenile salmon in the turbine intake, bypass system, and downstream of the dam; and (2) determine the long-term survival of subyearling chinook released from the above sites.

No mention of spillway or stilling basin mortality or injury.

Low recovery rates hampered efforts to draw conclusions from the tests.
Status: Copy in house

Reference Type: Technical Report
Record Number: 62
Author: Dawley, E.M., L.G. Gilbreath, R.G. Ledgerwood, P.J. Bentley, B.P. Sandford, and M.H. Schiewe
Year: 1992
Title: Relative survival of subyearling chinook salmon passing through turbines, bypass, or tailrace of the second powerhouse or the spillway at Bonneville Dam, 1987-90
Agency: National Marine Fisheries Service for the U.S. Army Corps of Engineers
Division: Coastal Zone and Estuarine Studies Division
City: Seattle, Washington
Date: May 1992
Report Number: Report Number DACW57-87-F-0323
Pages: 7
Relevance: Secondary
Keywords: Spillway, survival, turbine, bypass, tailrace
Notes: In seventh progress report fish passage development and evaluation program 1984-1990.

The objectives of this four-year study were to evaluate the survival of subyearling fall chinook salmon after passage through the spillway, the second powerhouse turbines, juvenile bypass system, and the tailrace at Bonneville Dam.

Juvenile fish were released at various points and recaptured via purse and beach seining activities to get relative survival estimates among treatment groups.

The only mention of injury to downstream migrating salmonids was that few descaled fish (<3%) were captured at Jones Beach.
Status: Copy in house

Reference Type: Technical Report
Record Number: 101
Author: Dawley, E.M., L.G. Gilbreath, E.P. Nunnallee, and B.P. Sandford
Year: 1998
Title: Relative survival of juvenile salmon passing through the spillway of the Dalles Dam, 1997
Agency: National Marine Fisheries Service for the U.S. Army Corps of Engineers
Division: Fish Ecology Division
City: Seattle, Washington
Date: March 1998
Report Number: Contract MIPR E96970020
Pages: 46
Relevance: Primary
Keywords: spillway, survival
Abstract: In 1997, the National Marine Fisheries Service initiated a study at The Dalles Dam to evaluate survival of juvenile Pacific salmon *(Oncorhynchus* spp.) when 64% of the river flow was passed through the spillway. The high spill is presumed to provide increased protection for the migrants. Research has generally found that survival of fish passed through spillways at dams on the Columbia and Snake Rivers is higher than for fish passed through turbines. However, at The Dalles Dam, two conditions associated with the spillway under high spill levels are unlike other dams: 1) the stilling basin is shorter and the tailrace is shallower, resulting in severe turbulence that may cause physical injury to migrant salmon; and 2) the large proportion of water that passes through the shallow area may substantially increase predation on salmonids by gulls, *(Larus* spp.) and northern squawfish *(Ptychocheilus oregonensis).*

Approximately 43,000 yearling coho salmon (*0. kisutch)* (April and May) and 53,000 subyearling fall chinook salmon (*0. tshawyacha)* (June and July) were collected from the juvenile bypass system at Bonneville Dam Second Powerhouse and tagged with passive integrated transponder (PIT) tags. Half were released upstream from the spillway at The Dalles Dam and half-downstream at a site away from turbulence and predation. After migrating through 74 km of reservoir, a portion of the test fish passed through the Bonneville Darn PIT-tag interrogation equipment located in the juvenile fish bypass system. An average of 12.0% of the coho salmon and 14. 1% of the subyearling chinook salmon released into the tailrace of The Dalles Dam were interrogated at Bonneville Dam. Relative survival estimates for spillway passage were 87.1% (95% confidence interval [Cl]: 80.4 - 93.9%) for coho salmon and 92.1% (CI: 85.5 - 98.7%) for subyearling chinook salmon. There were no apparent survival trends related to the date of release, the spill bay through which passage occurred, or the volume of water flow through the spillway or individual spillbays. Survival appeared higher for fish that passed the spillway at night compared with those that passed during the day. However, recoveries of fish were insufficient for this difference to be statistically significant ($P > 0.05$).

Results of this study suggest that when 64% of the river flow is passed through The Dalles Dam spillway at high river volumes (spring flows ranged from 379,400 to 526,500 ft^3/second and summer flows ranged from 242,200 to 529, 100 ft^3/second), survival of juvenile salmon passed through the spillway is lower than at other dams. The efficiency of spill for passing fish appears to decrease above 30% spill and the limited hydroacoustics data at The Dalles Dam suggests that 80% fish passage efficiency may be achievable at spill volumes lower than 64% of the river

flow. Thus, passage survival of juvenile salmonids at spill rates lower than 64% warrants further investigation at The Dalles Dam.
Notes: The objective of the study was to estimate the relative survival of juvenile coho and subyeatling chinook salmon passing through The Dalles Dam at a time when 64% of the Columbia River passed through the spillway.

The Dalles Dam: tainter gate-controlled concrete ogee type spillway

Release site/% river spilled	species/age	estimated relative survival
Dalles/65%	coho/juveniles	87.1%
Dalles/63%	chinook/subyearling	92.1%

Status: Copy in house

Reference Type: Technical Report
Record Number: 90
Author: Dunn, C.A.
Year: 1975
Title: 1974 Wynoochee Dam study: observations of 1974 juvenile out-migration, and evaluation of 1973 fish passage success from adult returns
Agency: State of Washington Department of Fisheries for the U.S. Army Corps of Engineers
Division: Management and Research Division
City: Seattle, Washington
Date: April 1975
Report Number: Contract Number DACW 67-73-C-0057
Pages: 49
Relevance: Primary
Keywords: Dam, mortality
Abstract: Wynoochee Reservoir was monitored during the spring and summer of 1974 to observe the downstream migration of the anadromous fish species and determine the success of their passage through the egression from the reservoir. Large-scale test groups composed of coho salmon and steelhead trout smolts were liberated in the upper Wynoochee River, above the reservoir. These fish moved down the river and through the reservoir satisfactorily. Egression of both hatchery and native fish species from the reservoir appeared to be almost 100% successful. No smolted fish were observed by late July, except a few native "1+" coho. Comparison of these observations with those of a previous study in 1973 suggested the success of fish egression from Wynoochee Reservoir was associated with the volume of outflow from Wynoochee Dam.

The overall success of juvenile coho salmon passage through Wynoochee Reservoir and Dam in 1973 was determined by sampling the returns of these fish as jacks in 1973 and adults in 1974. The returns of an experimental group released in April 1973 showed a survival rate of 85.3%: the returns of an experimental group released in June 1973 showed a survival rate of only 50.9%. Not only was there a loss in the numbers of fish in 1973, but in size as well. The April-liberated fish showed a loss of 1.8 cm in length and 0.7 lb in weight. The June-liberated fish showed a loss of 0.2 cm in length and 0.1 lb. in weight. The downstream fish passage system at Wynoochee Dam, as operated in 1973, was clearly unsatisfactory.
Notes: The objectives of the study were to: (1) evaluate the overall fish passage success, and (2) evaluate specific fish passage components and operating procedures.

Wynoochee Dam: 175 feet high, chute-type spillway, six outlet pipes.

1973 out-migration of juveniles based on adult returns.

Release site	species/age	estimated survival
Wynoochee Dam	coho/juvenile	85.3%
Wynoochee Dam	coho/juvenile	50.9%

Status: Copy in house

Reference Type: Technical Report
Record Number: 10
Author: Groves, A.B.
Year: 1972
Title: Effects of hydraulic shearing action on juvenile salmonids
Agency: U.S. Army Corps of Engineers
Division: North Pacific Division
City: Portland, Oregon
Date: November 1972
Report Number: Report Number 40 in Fourth Progress Report on Fisheries Engineering Research Program 1966-1972
Pages: 3
Relevance: Secondary
Keywords: Velocity, jet, mortality
Notes: Summary in fourth progress report on fisheries engineering program 1966-1972.
The objective of the study was to test the hypothesis that hydraulic shearing action can kill and injure fish.

Injury occurs when one part of the fish contacts a different velocity than the rest of its body. See the full report for data
Status: Copy in house

Reference Type: Technical Report
Record Number: 65
Author: Groves, A.B.
Year: 1972
Title: Effects of hydraulic shearing actions on juvenile salmonids
Agency: National Marine Fisheries Service
Division: Northwest Pacific Fisheries Service
City: Seattle, Washington
Date: 1972
Pages: 7
Injury Type: Immediate, short term, possible long term
Relevance: Primary
Keywords: Velocity, mortality, jet
Notes: The objective of the report was to expose fish to jet velocities to test the hypothesis that hydraulic shearing action could injure fish.

This is the full report referred to in the above reference.

Fps	% disabled	% visibly injured	percent survival at 48 hrs
30	0	0	100
50	18	8	98
70	42	28	92
90	56	24	84
100	62	20	78
120	74	14	68

Films showed that the injuries took place within milliseconds of time. Fish did really contact the same velocities as those calculated for each test, as they were in contact only with the outer margins of the jet.

Size of fish affected the degree of injury. When larger fish contacted the jet, other than headfirst contact, no damage was seen. Smaller fish suffered injury regardless of flow direction and/or velocity.

	35-50 mm	60-80 mm	95-135 mm
Fps	% injured	% injured	% injured
30	0	0	0
50	37	26	9
70	52	35	29

Status: Copy in house

Reference Type: Thesis
Record Number: 9
Author: Hamilton, J.A.R.
Year: 1955
Title: An investigation of the effect of Baker Dam on downstream migrant salmon
University: University of Washington
City: Seattle, Washington
Pages: 138
Thesis Type: Doctoral dissertation
Injury Type: immediate, short term, long term
Relevance: Primary
Keywords: Dam, mortality
Abstract: The effects of a hydroelectric plant and dam 250 feet high on seaward-migrant sockeye salmon (*Oncorhynchus nerka*) and coho salmon (*O. kisutch*) were investigated in 1951 and 1952 at Baker Dam in Western Washington. The objectives of the investigation were: one, to determine the character of the downstream migration from the reservoir; two, effect of the spillway and turbines on the survival of the seaward migrants; three, to evaluate the cause or causes of any existing mortality. The principal method consisted of sampling the native sockeye and coho seaward migrants with fyke nets located in the tailrace below the powerhouse and in the river below the spillway. The fyke-net catches revealed that over 95 per cent of the sockeye and coho migrants leaving the reservoir used the surface spillway exit and that less than 5 per cent left through the tunnel, the intake of which was submerged 85 feet at full reservoir. It was concluded from the fyke-net studies that 64 per cent of the native sockeye and 54 per cent of the native coho died as a result of injuries sustained while passing down the spillway when one spillway gate was open. The turbines killed 34 per cent of the native sockeye and 28 per cent of the native coho under full load conditions. Two supplementary methods applied to sockeye provided confirming results. The adult return of marked seaward-migrating sockeye released over the spillway, into the tunnel and into the river below the dam established a spillway mortality of 63 per cent and a turbine mortality of 37 per cent. Further confirmation of the effects of the hydroelectric structure and dam was provided by the decline of 55 per cent in the sockeye run since the dam was constructed. Most of the injury and mortality to the seaward-migrating salmon was caused by abrasion on the spillway and pressure changes and cavitation in the turbines and on the spillway. It was concluded that a dam of this type has a very detrimental effect on the downstream migrants and that the spillway is responsible for the major part of the mortality.
Notes: Baker Dam is 285 feet tall with 250 feet of head.

The objective of the report was to study the effects of a hydroelectric plant and dam 250 feet high on seaward-migrant sockeye salmon and coho salmon. Most of the spill is confined to the central gates that discharge onto the spillway face and then into the spillway pool. The spillway pool is 170 feet wide, 270 feet long, and 41 feet at its deepest point. The total fall is approximately 240 feet.

Spillway mortalities:

Year	species	spill conditions	estimated mortality
1951			
	sockeye	one gate open	64.9%
	coho	one gate open	49.9%
1952			
	sockeye	one gate open	62.1%
	coho	one gate open	59.9%
	sockeye	two gates open	82.2%
	coho	two gates open	65.2%
total corrected for delayed injury and capture probabilities			
	sockeye		63.5%
	coho		54.0%

Pressure change (cavitation) and abrasion are two hypothesized causes of injuries. The most frequent injuries were due to abrasion, some of which caused immediate death. It was concluded that abrasion from the spillway was the major cause of injury, when compared to spillway pool.
Status: Copy in house

Reference Type: Technical Report
Record Number: 66
Author: Iwamoto, N., and J.G. Williams
Year: 1993
Title: Juvenile salmonid passage and survival through turbines
Agency: National Marine Fisheries Service for the U.S. Army Corps of Engineers
Division: Coastal Zone and Estuarine Studies Division
City: Seattle, Washington
Date: August 1993
Report Number: Project Number E86920049
Pages: 27
Relevance: Tertiary
Keywords: Pressure, mechanical injury
Notes: The objective of this paper is to address some of the issues concerning juvenile salmonid passage and survival through hydroelectric turbines in the Columbia and Snake rivers and present some of the estimates of survival along with their applicability to existing river conditions.

Most injury is the result of pressure changes and mechanical damage.

This paper reviews numerous papers (9) concerning turbine mortality on the Columbia and Snake rivers, all of which average 90%.
Status: Copy in house

Reference Type: Technical Report
Record Number: 91
Author: Iwamoto, R.N., W.D. Muir, B.P. Sandford, K.W. McIntyre, D.A. Frost, J.G. Williams, S.G. Smith, and J.R. Skalski
Year: 1994
Title: Survival estimates for the passage of juvenile chinook salmon through Snake River dams and reservoirs
Agency: National Marine Fisheries Service for the U.S. Department of Energy Bonneville Power Administration
Division: Coastal Zone & Estuarine Studies Division
City: Seattle, Washington
Date: April 1994
Type of Work: Annual Report 1993
Report Number: Project Number 93-29; Contract Number DE-AI79-93BP10891
Pages: 140
Relevance: Primary
Keywords: Spillway, survival
Abstract: A pilot study was conducted to estimate the survival of hatchery-reared yearling chinook salmon through dams and reservoirs on the Snake River. The goals of the study were to: 1) field test and evaluate the Single-Release, Modified-Single-Release, and Paired-Release Models for the estimation of survival probabilities through sections of a river and hydroelectric projects; 2) identify operational and logistic constraints to the execution of these models; and 3) determine the usefulness of the models in providing estimates of survival probabilities.

Field testing indicated that the number of hatchery-reared yearling chinook salmon needed for accurate survival estimates could be collected at different areas with available gear and methods. For the primary evaluation, seven replicates of 830 to 1,442 hatchery-reared yearling chinook salmon were purse-seined from lower Granite Reservoir, PIT-tagged, and released near Nisqually John boat landing (River Kilometer 726).

Secondary releases of PIT-tagged smolts were made at Lower Granite Dam to estimate survival of fish passing through turbines and after detection in the bypass system. Similar secondary releases were made at Little Goose Dam, but with additional releases through the spillway. Hatchery-reared yearling chinook salmon for the secondary releases came from juvenile collection and bypass facilities at each dam. For the secondary evaluations, replicates of 750 to 1,500 PIT-tagged fish were released on three dates for each release site at each dam while primary release groups were passing.

PIT-tag slide gates at Lower Granite and Little Gooses dams returned PIT-tagged smolts back to the Snake River. This allowed multiple detections at downstream dams of fish from the primary and secondary release groups and from PIT-tagged yearling chinook salmon released from hatcheries upstream from Lower Granite Dam. Although the majority of PIT-tagged fish were diverted, variability in diversion efficiency at the two dams influenced the precision of survival estimates.

Nevertheless, first year results indicated that detecting a fish at an upstream site did not influence the probability of its subsequent detection at downstream sites, that detection did not influence subsequent survival, that the chosen models accurately predicted sampling variability, and that treatment and reference fish were mixed at subsequent detection sites.

Thus, all Single-Release Model assumptions were satisfied, and precise survival estimates for a limited period of the hatchery-reared yearling chinook salmon migration were obtained. Results indicated that survival from the primary release site (31 km upstream of Lower Granite Dam) to the tailrace of Lower Granite Dam in river flows of approximately 60-70 kcfs was approximately 90%. Survival from the tailrace of Lower Granite Dam to the tailrace of Little Goose Dam was approximately 86%.

Based on the success of the 1993 pilot study, we believe that the Single-Release and Paired-Release Models will provide accurate estimates of juvenile salmonid passage survival for individual river sections, reservoirs, and hydroelectric projects in the Columbia and Snake rivers.
Notes: The goals of the study were to: 1) field test and evaluate the Single-Release, Modified-Single-Release, and Paired-Release Models for the estimation of survival probabilities through sections of a river and hydroelectric projects; 2) identify operational and logistic constraints to the execution of these models; and 3) determine the usefulness of the models in providing estimates of survival probabilities.

Little Goose Dam: spillway deflectors located in bays 2 through 7 (8 total spillway bays)

Release site	species/age	spillway passage survival
Little Goose Dam spillway gate 3	chinook/yearling	1.011
Little Goose Dam spillway gate 3	chinook/yearling	1.053
Little Goose Dam spillway gate 3	chinook/yearling	0.963

Status: Copy in house

Reference Type: Technical Report
Record Number: 89
Author: Johnsen, R.C., and E.M. Dawley
Year: 1974
Title: The effect of spillway flow deflectors at Bonneville Dam on total gas supersaturation and survival of juvenile salmon
Agency: National Marine Fisheries Service for the U.S. Army Corps of Engineers
Division: Coastal Zone and Estuary Studies
City: Seattle, Washington
Date: December 1974
Type of Work: Final Report
Report Number: Contract Number DACW-57-74-F-0122
Pages: 23
Injury Type: Immediate, short term
Relevance: Primary
Keywords: Spillway, tailrace, deflector, survival, fall chinook
Notes: The objectives of this study were to: (1) evaluate the level of dissolved gases at various flows through standard and modified (deflector) spillways; and (2) determine the success of passage of juvenile chinook salmon through a standard and modified spillway.

Bonneville Dam: 80 feet head, ogee and bucket spillway with (bays 4 through 15) and without (bays 1 through 3 & bays 16 through 18) flow deflectors.

Release site	species/age	estimated survival
with deflectors	chinook/juveniles	39.6
without deflectors	chinook/juveniles	43.7
control (tailrace)	chinook/juveniles	45.6

The researchers believed that there was little difference (not significantly different) in survival between groups released at the dam.
Status: Copy in house

Reference Type: Technical Report
Record Number: 61
Author: Johnson, R.L.
Year: 1970
Title: Tests of fingerling fish passage at Bonneville Dam
Agency: U.S Army Corps of Engineers
Division: Fisheries Engineering Research Program
City: Portland, Oregon
Date: April, 1970
Report Number: Report Number 18 in Fourth Progress Report on Fisheries Engineering Research Program 1966-1972
Pages: 4
Relevance: Tertiary
Keywords: Tailrace, ice rack, trash racks, fish passage
Notes: In fourth progress report on fisheries engineering research program 1966-1972,

The objective of the study was to compare the effectiveness of the ice and trash sluice with the power units for passing fingerling fish downstream to the tailrace.

The tests describe simulated downstream passage of fingerling fish through Bonneville Dam powerhouse.

Grapefruit were used as test objects in the test.

Results indicate the number of grapefruit that were observed, but no mention of injury.
Status: Copy in house

Reference Type: Technical Report
Record Number: 60
Author: Johnson, R.L.
Year: 1970
Title: Fingerling fish mortalities at 57.5 fps
Agency: U.S Army Corps of Engineers
Division: Fisheries Engineering Research Program
City: Portland, Oregon
Date: April, 1970
Report Number: Report Number 22 in Fourth Progress Report on Fisheries Engineering Research Program 1966-1972
Pages: 14
Relevance: Primary
Keywords: Velocity, mortality
Notes: In fourth progress report on fisheries engineering research program 1966-1972,

The objective of the study was to if shear forces cause mortality in fingerling fish as they are subjected into calm water via a high velocity jet.

Initial study of a series that were intended to study the mortality of fingerling fish passing from a submerged high velocity jet (57.5 fps) into relatively calm water.

No test fish showed injury or died after a one week holding period post test.
Status: Copy in house

Reference Type: Technical Report
Record Number: 26
Author: Johnson, R.L.
Year: 1970
Title: Fingerling fish research effect of mortality of 67-fps velocity
Agency: U.S. Army Corps of Engineers
Division: North Pacific Division
Date: December 1970
Report Number: Report Number 23 in Fourth Progress Report on Fisheries Engineering Research Program 1966-1972
Pages: 6
Relevance: Primary
Keywords: Velocity, mortality
Notes: In fourth progress report on fisheries engineering research program 1966-1972,

The objective of the study was to determine whether shear force causes mortality in fingerling fish as they are subjected to a high velocity jet.

The conclusion was that 67 fps was near the threshold or critical velocity that should cause mortality.
Status: Copy in house

Reference Type: Technical Report
Record Number: 13
Author: Johnson, R.L.
Year: 1972
Title: Fingerling fish research, high velocity flow through four-inch nozzle
Agency: U.S Army Corps of Engineers
Division: Fisheries Engineering Research Program
City: Portland, Oregon
Date: April, 1972
Report Number: Report Number 24 in Fourth Progress Report on Fisheries Engineering Research Program 1966-1972
Pages: 5
Relevance: Primary
Keywords: Mortality, velocity
Notes: In fourth progress report on fisheries engineering research program 1966-1972,

The objective of the study was to determine if shear force causes mortality in fingerling fish as they are subjected to calm water after passing through a high velocity jet.

This is the last of a series of reports that were intended to test the mortality of fingerling salmonids as they are carried into relatively still water by a submerged jet of water.

A relationship between mortality and velocity is developed on page 3.

Fps	estimated survival
57.5	100%
67	97.6%
77.5	92.8%
92	69%

Mortality increases dramatically above 60 fps.
Status: Copy in house

Reference Type: Technical Report
Record Number: 53
Author: Junge, C.O., and D.E. Schoeneman
Year: 1958
Title: An evaluation of the mortalities to downstream migrant salmon at McNary Dam
Agency: State of Washington Department of Fisheries for the U.S. Army Corps of Engineers
City: Seattle, Washington
Report Number: Contract Number DA35026-Eng-20893
Pages: 56
Relevance: Primary
Keywords: Spillway, mortality
Abstract: A three year study (1955-1957) was conducted to determine the mortality rate for downstream migrant salmonids passing over the spillway or through the turbines at McNary Dam, a typical Columbia River low head, river-run dam. Mortalities were determined by releasing a group of marked fish in the particular exit under study (spillway or turbine) and by releasing a control group, differently marked, immediately below the dam. Samples of the released fish were recovered at various stations below the dam and survival rates were computed from the ratio of the number of experimental to control recoveries. Tests were devised to determine whether or not the assumptions involved in the estimating procedure were adequately satisfied.

During the first two years (1955-1956) estimates were obtained for fingerling chinook salmon (fish in their first year) at McNary Dam. In 1957, yearling chinook were tested at Big Cliff Dam, a structure on the Santiam River with a turbine and spillway similar to those at McNary Dam. As a control measure, fingerling chinook were also tested at Big Cliff Dam.

In all experiments it was indicated that the turbine and not the spillway was the major source of mortality. For each exit, no significant difference was found between the mortalities at McNary Dam and Big Cliff Dam on fingerling chinook, and no significant difference was found between the mortality rates for the fingerling chinook and yearling chinook studied at Big Cliff Dam. The estimated mortality to salmon passing over the spillway was 2 percent with a 95 percent confidence interval from zero to 4 percent. The estimated mortality rate to salmon passing through the turbines was 11 percent with a 95 percent confidence interval from 9 to 13 percent. The consistency of the results of the various phases studied indicated that the assumptions were well satisfied and that the estimates obtained were valid representations of the mortalities experienced under the tested conditions.
Notes: The objective of the study was to evaluate the possible cumulative effects of a series of dams on downstream migrating salmon.

McNary Dam and Big Cliff Dam are low-head dams with 85-90 feet of head with a gate-controlled concrete ogee type spillway.

Spillway mortality

Site (year)	species	age	estimated survival
McNary (1955)	chinook	0	98%
McNary (1956)	chinook	0	100%

Big Cliff (1957)	chinook	0	94%
Big Cliff (1957)	chinook	1+	99%

No significant difference in mortality was seen between spillways.

This report also cites mortality studies conducted on the Glines Dam (Elwha River) and Baker Dam.

Status: Copy in house

Reference Type: Technical Report
Record Number: 58
Author: Ledgerwood, R.D., E.M. Dawley, L.G. Gilbreath, P.J. Bentley, B.P. Sandford, and M.H. Schiewe
Year: 1990
Title: Relative survival of subyearling chinook salmon which have passed Bonneville Dam via the spillway or the second powerhouse turbines or bypass system in 1989, with comparisons to 1987 and 1988
Agency: National Marine Fisheries Service for the U.S. Army Corps of Engineers
Division: Coastal Zone and Estuarine Studies Division
City: Seattle, Washington
Date: July 1990
Report Number: Contract Number E85890024 and Contract Number E86890097
Pages: 136
Injury Type: long term
Relevance: Primary
Keywords: Bonneville Dam, survival, spillway
Notes: The study objectives were to evaluate the relative survival of subyearling fall chinook salmon passing Bonneville Dam Second Powerhouse by way of turbines, spillway, and bypass.

Spillway height (above lowest bedrock) is 197 feet.

Date	species/age	descaled/injured	not injured
22-24 June	chinook/0+	0.00%	100%
6-8 July	chinook/0+	0.52%	99.42%
13-15 July	chinook/0+	1.46%	98.54%
20-22 July	chinook/0+	2.45%	97.55%

Status: Copy in house

Reference Type: Technical Report
Record Number: 42
Author: Ledgerwood, R.D., E.M. Dawley, L.G. Gilbreath, L.T. Parker, B.P. Sandford, and S.J. Grabowski
Year: 1994
Title: Relative survival of subyearling chinook salmon at Bonneville Dam, 1992
Agency: National Marine Fisheries Service for the U.S. Army Corps of Engineers
Division: Northwest Fisheries Science Center
City: Seattle, Washington
Date: December 1994
Report Number: Contract Number DACW57-85-H-0001
Pages: 83
Injury Type: Short-term, long-term
Relevance: Tertiary
Keywords: Bypass, survival, fish
Abstract: The objective of this study was to compare relative survival among marked groups of subyearling chinook salmon released into the bypass system of Bonneville Dam First Powerhouse, the turbines at the First and Second Powerhouses, and at a site in swift water about 2.5 km downstream from the dam.

Mechanisms affecting survival difference were thought to be water velocity in the bypass conduit and shear forces at the outlet of the bypass pipe. The following conclusions were based on one year of study, with special operating conditions of equal flow through both powerhouses implemented at Bonneville Dam in order to 1) attract predators equally to the two tailrace areas, 2) provide an unbiased comparison of survival among the various routes of juvenile fish passage as well as to minimize tailrace eddies, 3) provide high flows past the juvenile bypass outlet, and 4) allow adequate attraction flows to the various fishway entrances for upstream migrant adult salmonids. The regional drought that severely reduced river flow during 1992 may have created a worst scenario for salmonid survival due to heavy predation of test fish in the tailrace areas. It is important to consider a wide range of test conditions before formulating conclusions regarding the safest routes for juvenile salmon passing Bonneville Dam during the summer. Conclusions include:

1) Under the drought conditions of 1992, recoveries of marked subyearling chinook in the estuary indicated significantly reduced survival of fish released into the bypass system at the First Powerhouse compared to fish released into the First Powerhouse turbines or fish released downstream from the tailrace.

2) Fish passing through the Second Powerhouse turbines and tailrace had significantly reduced survival compared to fish passing through the First Powerhouse turbines and tailrace.

3) The downstream-released fish had significantly higher survival than all other release groups.

4) Tule stock subyearling chinook salmon used in this study were subjected to cold-water rearing and reduced rations to maintain a size range at release similar to normal summer migrants (upriver bright stock). However, test fish, particularly those from the final week of test releases, may have suffered extreme stress due to elevated Columbia River water temperatures resulting from the regional drought. While the immediate impacts of dam passage are thought to be fully expressed in mark-recovery differences among juvenile fish recovered at Jones Beach,

the overall survival of test fish may have been reduced by temperature stress. This potential overall lower survival of test fish may affect comparisons among treatment groups using CWT data from adult contributions to the various ocean and river fisheries and returns to the lower river hatcheries.

5) Because 75 to 90% of the summer migrating juvenile salmon encountering the powerhouses at Bonneville Dam pass through turbines instead of bypass systems, and because of the significant difference between turbine plus tailrace passage survivals at the First and Second Powerhouses, it is extremely important to identify the safest passage route over a wide range of river flows.

Recommendations:

1) Tag recovery of adults should be compiled through 1997 to assess passage survival differences adequately.

2) The study should be repeated for 3 additional years to bracket a wide range of river flow and other physical conditions before making conclusions regarding the relative survival of summer migrating subyearling chinook salmon through the various passage routes at Bonneville Dam.

Notes: The objective of this study was to determine the relative survival of juvenile salmonids through the bypass of the first powerhouse, the turbines of the first and second powerhouses, and a site located downstream.

No evaluation of spillway and/or stilling basin survival was conducted.

Status: Copy in house

Reference Type: Technical Report
Record Number: 25
Author: Liscom, K.L., and G.E. Monan
Year: 1976
Title: Radio tracking studies to evaluate the effect of the spillway deflectors at Lower Granite Dam on adult fish passage, 1975
Agency: National Marine Fisheries Service for the U.S. Army Corps of Engineers
Division: Northwest Fisheries Center
City: Seattle, Washington
Date: January 1976
Report Number: Delivery Order Number DACW68-75-C-0112
Pages: 18
Relevance: Tertiary
Keywords: Adult passage, fallback, deflector, spillway
Abstract: During the study period, 27 of the 30 radio-tagged chinook salmon were tracked in the study area at Lower Granite Dam. The remaining three were found below Little Goose Dam. One was recovered dead, and the other two were still swimming below Little Goose Dam when the study ended. Of the 27 tagged fish reaching the study area, 17 eventually passed over the dam during the 4 weeks of tracking. Two fish were tracked in the study area below the dam for several days and then the signals abruptly stopped. The remaining 8 fish were near the dam or in the vicinity at the time the study was terminated. Behavior below the dam was variable. When approaching the dam, the north shore was favored by 56% of the fish 33% entered along the south shore and 11% approached from mid-channel. Milling about below the dam was extensive, but certain preferred routes were apparent. All routes experienced back and forth movement with none used exclusively for any one direction. Holding areas were well defined with the "quiet" water area north of the locks and its extending wingwall the most frequently used. Of the total hours spent by tagged fish in the immediate area below Lower Granite Dam, 44% were spent in this area. All but two tagged fish reaching the dam spent some time in the "quiet" water. The mid-channel area just below the spill and powerhouse was used 12% of the time. At this point, the current from a large eddy in front of the powerhouse turned downstream and merged with the spill flows. Tagged fish determined as having been within the potentially dangerous spill area made 49%, of their entries into this area when spill was between 50,000 and 65,000 cfs. These conditions existed 24% of the total tracking time. Spill of 126,000 to 159,000 cfs was present 35% of the time and 161, of the entries were made then. The fact that some radio-tagged chinook were plotted close to the spill and maintained themselves in that location for some time, indicates that subsurface hydraulic conditions are present that fish can negotiate unharmed. Relatively little time was spent adjacent to, but downstream from the fishway entrances. Only 1.5% of the total time tagged fish spent in the area was spent in front of either fishway entrance. There were 88 entries made into the fishway entrances, 42 into the north entrance and 46 into the south entrance. Of the total entries, 19% resulted in fish passage over the dam. Most fish made more than one entry to the fishway before passage; 35% made one entry only. Both entrances were entered by 53%, of the tagged fish. Only 12%, of the fish entered a single entrance more than once before crossing the dam. On their final entrance before crossing the dam, 4 fish used the north entrance and 13 used the south. Once they made their final entrance, the fish spent an average of 4 hours negotiating the fishway and crossing the dam. Tagged fish did not show any interest in the north entrance until May 20. Up to that time, fish

had made six entries into the south entrance resulting in two passages. On May 20, between 1500 and 1700 hours, the spill gates were regulated to change the spill pattern. To reduce flow by the north entrance, flow from bays 6-8 was reduced by 3% with like increases in the center area. Soon after, a tagged fish approached the north entrance and entered at 1745 hours. Tagged fish made use of the entrance from then on, resulting in 47% of the fish making their initial entry into the north entrance. However, while fish entered the fishway and moved up the channel initially, they were reluctant to continue through the tunnel under the spill section. During the early part of the study the lights in the tunnel were off. When the lights were turned on, the fish moved through more readily. During the remainder of the study, 30 trips were made from the north entrance through the tunnel into the powerhouse collection system. However, 87% ended with the fish exiting into the tailrace. The tunnel was also entered by four fish via the powerhouse collection system.
Notes: The objectives of the study were to: (1) determine what degree adult salmon frequent the area below spillway deflectors; (2) if salmon are severely injured or killed by conditions created by spillways; and (3) effects of hydraulic patterns from spillway deflectors on entry of adult salmon into fish collection facilities at Lower Granite Dam.

No mention of injury to downstream migrating salmonids passing through spillways and/or stilling basins.
Status: Copy in house

Reference Type: Technical Report
Record Number: 67
Author: Liscom, K.L., and G.E. Monan
Year: 1977
Title: Radio tracking studies of spring chinook salmon in relation to evaluating potential solutions to the fallback problem and increasing the effectiveness of the powerhouse collection system at Bonneville Dam, 1976
Agency: National Marine Fisheries Service for the U.S. Army Corps of Engineers
Division: Coastal Zone and Estuarine Studies
City: Seattle, Washington
Date: January 1977
Type of Work: Final Report
Report Number: Delivery Order Number DACW57-76-F-0720
Pages: 32
Relevance: Tertiary
Keywords: Fallback, spill, radio tag
Notes: The objectives of the study were to: (1) evaluate the effectiveness of the deflector net in reducing fallback; (2) determine if fish released into the forebay fall back at different rates from those exiting the Bradford Island fishway; (3) which specific spill gates are used during fall-back, (4) determine the swimming depths of fish as they swam around the net; and (5) monitor the radio-tagged fish as they approach the powerhouse.

No mention of injury to downstream migrating salmonids passing through spillways and/or stilling basins.
Status: Copy in house

Reference Type: Technical Report
Record Number: 28
Author: Long, C.W., W.M. Marquette, and F.J. Ossiander
Year: 1972
Title: Survival of fingerlings passing through a perforated bulkhead and modified spillway at Lower Monumental Dam April-May 1972
Agency: National Marine Fisheries Service for the U.S. Army Corps of Engineers
Division: North Pacific Division
City: Portland, Oregon
Date: December 1972
Report Number: Contract Number DACW68-72-C-0101
Pages: 2
Relevance: Secondary
Keywords: Bulkhead, flow deflector, fish survival
Notes: In fourth progress report on fisheries engineering research program 1966-72.

The objective of the study was to investigate the effects of a perforated bulkhead and a flow deflector on juvenile salmon.

This report summarizes the results of the first year of the study.

The ratio of recovery of the test:control fish indicates a mortality of 15%, but the power of the test was not great enough to detect significance due to low numbers of recaptured fish.

Survival through the flow deflector was much higher (30% or higher) than the bulkhead.
Status: Copy in house

Reference Type: Technical Report
Record Number: 68
Author: Long, C.W., and F.J. Ossiander
Year: 1974
Title: Survival of coho salmon fingerlings passing through a perforated bulkhead in an empty turbine bay and through flow deflectors (with and without dentates) on spillway at lower Monumental Dam, Snake River April-May 1973
Agency: National Marine Fisheries Service for the U.S. Army Corps of Engineers
Division: Coastal Zone and Estuarine Division
City: Seattle, Washington
Date: March 1974
Report Number: Contract Number DACW-68-72-C-0101
Pages: 20
Relevance: Primary
Keywords: Flow deflectors, mortality
Notes: The objectives of the study were to evaluate fingerling passage and survival through the bulkhead and flow deflectors (with and without dentates) installed at Lower Monumental Dam.

Test structure	replicate	species/age	estimated survival
Deflector with dentates	1	coho smolts	100%
Deflector with dentates	2	coho smolts	81%
Deflector with dentates	3	coho smolts	98%
Deflector without dentates	1	coho smolts	100%
Deflector without dentates	2	coho smolts	100%
Deflector without dentates	3	coho smolts	100%

No losses are expected from passage through a spillway bay equipped with plain flow deflectors.
Status: Copy in house

Reference Type: Technical Report
Record Number: 15
Author: Long, C.W., F.J. Ossiander, T.E. Ruehle, and G.M. Matthews
Year: 1975
Title: Survival of coho salmon fingerlings passing through operating turbines with and without perforated bulkheads and of steelhead trout fingerlings passing through spillways with and without a flow deflector
Agency: National Marine Fisheries Service for the U.S. Army Corps of Engineers
Division: Coastal Zone and Estuarine Studies Division
City: Seattle, Washington
Date: February 1975
Report Number: Contract Number DACW68-74-C-0113
Pages: 16
Injury Type: Long-term
Relevance: Primary
Keywords: Flow deflector, spillway, fish survival
Abstract: Perforated bulkheads and spillway flow deflectors were designed by the Corps of Engineers to reduce the high levels of dissolved nitrogen and other gasses in the Snake and Columbia rivers caused by passage of water through standard spillways and low-head dams. The National Marine Fisheries Service, in cooperation with the Corps began studies at Lower Monumental Dam during the spring outmigration of salmon fingerlings in 1972. Results showed that perforated bulkheads installed in skeleton units caused high mortality (50%) to young fall chinook salmon, but flow deflectors with dentates were less harmful (less than 15% mortality). Studies in 1973, conducted with fingerling coho salmon, confirmed that skeleton units equipped with perforated bulkheads caused high mortalities and showed that coho had a higher survival in passing through a spillway equipped with a plain flow deflector than one having a flow deflector with dentates. Studies reported here measured survival of fingerling coho salmon through operating turbines with and without perforated bulkheads and survival of fingerling steelhead trout through spillways with and without flow deflectors.
Notes: Fish were released at Lower Monumental Dam and recovered at Ice Harbor and McNary Dams. Results indicated that survival of steelhead fingerlings was greater through spillways equipped with flow deflectors (2.2% mortality) versus standard spillways (27.5% mortality). Results imply that either the larger steelhead are significantly more susceptible to injury in a standard spillway, or the spillways at Lower Monumental Dam are more harmful than those at McNary Dam. In any event, the addition of flow deflectors to the ogee of existing spillways should result in significantly higher survival of steelhead that pass through spillways.

Release site	species/age	estimated survival
with deflectors	steelhead/fingerlings	97.8%
without deflectors	steelhead/fingerlings	72.5%

Status: Copy in house

Reference Type: Technical Report
Record Number: 69
Author: Mathews, S.B.
Year: 1980
Title: Effects of Wynoochee Dam on anadromous fish
Agency: U.S. Army Corps of Engineers
Division: Seattle District
City: Seattle, Washington
Date: October 1980
Report Number: Contract Number DACW67-80-M-1761
Pages: 21
Relevance: Primary
Keywords: Wynoochee Dam, fish mortality
Abstract: An assessment of the studies of the Washington Departments of Fisheries and game on the effects of the Wynoochee River Dam and analysis of pertinent data relating to the decline of fish runs in that river.
Notes: A maximum drop of 166 feet between pool elevation and the tailwater.

The objective of this study was to review the information relating to actual or potential declines in fish runs and clarify certain aspects so that a rapid understanding of the extent of fish loss can be agreed upon.

This report summarizes some of the information pertaining to Wynoochee Dam mortality.

Species/age	dam passage survival rate
coho/1+	86%
steelhead/ 1+	76%
chinook/0+	60%
chinook/1+	72%

Mortality appears to occur in the tailrace, not through the low-level dam outlets.
Status: Copy in house

Reference Type: Technical Report
Record Number: 32
Author: Monan, G.E., and K.L. Liscom
Year: 1975
Title: Radio tracking studies to determine the effects of spillway deflectors and fallback on adults chinook salmon and steelhead trout at Bonneville Dam, 1974
Agency: National Marine Fisheries Service for the U.S. Army Corps of Engineers
Division: Coastal Zone and Estuarine Studies Division
City: Seattle, Washington
Date: February 1975
Report Number: Contract Number DACW57-74-F-0122
Pages: 38
Relevance: Tertiary
Keywords: Spillway, deflector, adult, fallback,
Abstract: Major modifications of spillways at dams in the Columbia and Snake Rivers have been proposed and initiated as part of an overall program for control of dissolved gas levels. Deflectors are being added to the spillways to prevent water passing over from plunging to depths. Prior to installation of spillway deflectors at all dams, fisheries agencies and the Corps desire to make certain that hydraulic conditions created by the modifications do not adversely affect survival and passage of fish at the projects. Initial studies at Lower Monumental Dam, where two of the eight spillbays had deflectors installed, revealed that while adult chinook salmon frequented to a limited degree the potentially dangerous area immediately below the modified spillbays, there was no evidence that fish were injured or their passage was impaired. Based on this finding with adults and on similar findings with juveniles, fishery agencies have recommended that additional spillbays be modified at major dams in the Columbia River Basin. Bonneville Dam is one of the dams scheduled for modification. Radiotracking was chosen to study the effects the modifications had on adult salmon and steelhead trout. The primary objectives of the study were to determine: (1) whether adult salmon and steelhead trout frequent the potentially dangerous areas below the modified spillbays, and if so, (2) whether the fish are injured or killed by hydraulic conditions immediately below the deflectors. A secondary objective was to determine fish behavior in relation to fallback.
Notes: The study objectives were: (1) identify whether or not adult salmon and steelhead trout frequent areas below spillways with deflectors, (2) determine the extent of mortality (if any) below the spillways with deflectors.

No mention of injury to downstream migrating salmonids passing through spillways and/or stilling basins.
Status: Copy in house

Reference Type: Technical Report
Record Number: 70
Author: Monan, G.E., K.L. Liscom, and L.C. Stuehrenberg
Year: 1979
Title: Radio tracking studies to determine the effects of spillway deflectors on adult salmonids
Agency: National Marine Fisheries Service for the U.S. Army Corps of Engineers
Division: Coastal Zone and Estuarine Studies Division
City: Seattle, Washington
Date: July 1979
Pages: 7
Relevance: Tertiary
Keywords: Spillway deflector, fish, radio tag
Abstract: To alleviate nitrogen pollution problems in the Snake and Columbia rivers, the addition of spillway deflectors was being considered for the spillways of key dams. Because model studies indicated the hydraulic conditions that would be created in the spill basins of modified dams were potentially hazardous to adult salmonids, radio-tracking studies were designed to investigate the problem before deflectors were installed at key dams. A pilot installation of deflectors was completed at Lower Monumental Dam in 1973, and fish behavior in the spill basin was monitored during a radio-tracking program. Another radio-tracking study of fish behavior in relation to a partial installation of deflectors was carried out at Bonneville and Lower Granite dams. No negative information was developed in these two studies; consequently, full complements of deflectors were installed at Bonneville and Lower Granite dams. Radio-tracking studies of fish behavior in relation to these installations were carried out in 1975. Of the total chinook salmon released carrying radio tags, 38 percent (55 fish) swam into potentially hazardous hydraulic conditions (as did one of the four steelhead tagged and released). No evidence was found that indicated any of the exposed fish suffered debilitating injuries or manifested behavioral changes. Hydraulic conditions affected the entry of adult salmonids to fish collection facilities, but the spill patterns can be manipulated to enhance passage.
Notes: In Fifth progress report on fisheries engineering research program 1973-1978.

The objectives of the study were to: (1) determine to what degree adult salmonids frequent the area below a spillway with deflectors installed; (2) are salmonids injured or killed by hydraulic conditions immediately below the deflectors; and (3) what effect do the hydraulic pattern from spillway deflectors have on entry of adult salmonids to fish collection facilities?

No mention of injury to downstream migrating salmonids passing through spillways and/or stilling basins.
Status: Copy in house

Reference Type: Technical Report
Record Number: 71
Author: Monk, B.H., W.D. Muir, and R.F. Krcma
Year: 1986
Title: Studies to evaluate alternative methods of bypassing juvenile fish at the Dalles Dam - 1985
Agency: National Marine Fisheries Service for the U.S. Army Corps of Engineers
Division: Coastal Zone and Estuarine Studies
City: Seattle, Washington
Date: June 1986
Type of Work: Final Report
Report Number: Contract Number DACW57-85-H-0001
Pages: 50
Relevance: Tertiary
Keywords: Submersible travelling screens, juvenile passage efficiency
Abstract: At the present time, juvenile salmonids passing The Dalles Dam on their downstream migration must pass through the turbines or be bypassed by means of the ice and trash sluiceway or spillway. During periods of no spill, Nichols (1979) estimated that passage through the sluiceway was about 40 to 60%. To increase the overall percent passage, a fingerling bypass system similar to that being used at other U.S. Army Corps of Engineers (CofE) projects has been proposed. These systems consist of submersible traveling screens (STS) in the turbine intakes, vertical barrier screens and orifices in the gatewells, and a bypass channel (Fig. 1). In 1985, tests were conducted at The Dalles Dam to determine the benefits of this type of system. Data from previous studies conducted by the Oregon Department of Fish and Wildlife (ODFW) indicated fewer yearling fish were usually found in the gatewells at the upstream end of the powerhouse at The Dalles Dam than at the downstream end (Fig. 2) (Nichols 1979). The data on subyearling chinook salmon, however, were insufficient to ascertain their distribution across the powerhouse. If the data for yearling fish could be verified and the same distribution was true for subyearlings, it might be possible to provide adequate protection for downstream migrants by installing screen systems in only a portion of the 22 turbine units.

In 1985, the National Marine Fisheries Service conducted a series of fish distribution and fish guiding efficiency tests to determine: (1) the benefits of an STS-type fingerling bypass system for The Dalles Dam and (2) if the system would need to be installed in all 22 turbine units or if installation in selected units would provide adequate protection. Vertical distribution and FGE studies were conducted to determine actual and potential fish guiding efficiencies (FGE) of an STS system. The vertical distribution studies would also help determine if there were actually less fish passing through parts of the powerhouse as other studies have indicated or if the fish were simply deeper in the water column which could give that impression. Horizontal distribution tests were conducted on subyearling chinook salmon to supplement the limited data obtained by Nichols (1979).

Notes: The objectives of the study were: (1) determine the benefits of an STS-type fingerling bypass system for the Dalles Dam, (2) determine if this system would need to be installed in all 22 turbine #1 units or in just a select few turbines. Vertical distribution and fish guiding efficiency tests were conducted in order to meet the objectives.

No mention of injury to downstream migrating salmonids passing through spillways and/or stilling basins.
Status: Copy in house

Reference Type: Technical Report
Record Number: 21
Author: Monk, B.H., W.D. Muir, and M.H. Gessel
Year: 1987
Title: Studies to evaluate alternative methods of bypassing juvenile fish at the Dalles Dam - 1986
Agency: National Marine Fisheries Service for the U.S. Army Corps of Engineers
Division: Coastal Zone and Estuarine Studies
City: Seattle, Washington
Date: May 1987
Report Number: Contract Number DACW57-85-F-0295
Pages: 16
Relevance: Tertiary
Keywords: Guiding efficiency, bypass, fish
Abstract: Juvenile salmonids passing the Dalles Dam on their downstream migration must pass through the turbines or be bypassed by means of the ice and trash sluiceway or spillway. During periods of no spill, Willis (1982) estimated that passage through the sluiceway was about 40%. To increase the overall percent passage, a fingerling bypass system similar to that being used at other U.S. Army Corps of Engineers (COE) projects was proposed. These systems consist of submersible traveling screens (STS) in the turbine intakes, vertical barrier screens and orifices in the gatewells, and a bypass channel. In 1986, the National Marine Fisheries Service, under contract to the COE, continued studies begun in 1985, to evaluate the potential benefits of this type of system. Fish guiding efficiency (FGE) test results obtained during 1985 indicated the use of a standard length STS would result in unacceptably low FGEs (<70%) for all salmonid species except steelhead. Vertical distribution (VD) tests conducted at the same time in Units 2, 12, and 18 showed that all salmonid species except steelhead were distributed too deeply in the turbine intakes to be intercepted by a standard length STS. Therefore, the STS would probably have to be either lengthened and/or lowered in the intake to increase FGE. Tests conducted with subyearling chinook salmon in 1985 compared the FGEs of a standard STS and an STS modified to operate 30 inches lower in the intake. During these tests, the lowered screen significantly increased the FGE for subyearling chinook salmon from 8.4 to 13.9% A similar proportionate increase would be more than sufficient to provide for acceptable FGEs for yearling salmonids. Therefore, in 1986, all testing was done with a 30-inch lowered STS to determine if similar benefits could be realized for spring chinook and sockeye salmon.

Tests in 1985 were conducted from 16 to 21 April with the ice and trash sluiceway closed and from 30 April to 3 May with the sluiceway operating under normal conditions (0600 to 2200 h). In the later tests, the FGE for yearling chinook salmon increased by 12%. The FGE test schedule in 1986 was designed to determine if this increase was actually due to sluiceway operation or due to a change in vertical distribution of the later arriving migrants. In 1986, FGE studies were conducted in Unit 2 at The Dalles Dam to evaluate an STS modified to extend 30 inches lower in the gatewell in an effort to increase FGE for yearling chinook salmon to an acceptable target level of 70%.

Recommendations: To reach a minimum target level of 70% FGE for yearling chinook salmon at The Dalles Dam, it appears that either an extended STS will be required to intercept more flow

or the vertical distribution of the salmonids in the turbine intake will have to be altered by secondary mechanical devices similar to those being tested at other COE projects.
Notes: The objective of the study was to determine if a 30-inch lowered STS was sufficient to increase the fish guiding efficiency for yearling spring chinook and sockeye salmon to a target level of 70%.

No mention of injury to downstream migrating salmonids passing through spillways and/or stilling basins.
Status: Copy in house

Reference Type: Technical Report
Record Number: 23
Author: Muir, W.D., R.N. Iwamoto, C.R. Pasley, B.P. Sandford, P.A. Ocker, and T.E. Ruehle
Year: 1995
Title: Relative survival of juvenile chinook salmon after passage through spillbays and the tailrace at Lower Monumental Dam, 1994
Agency: National Marine Fisheries Service for the U.S. Army Corps of Engineers
Division: Coastal Zone and Estuarine Studies Division
City: Seattle, Washington
Date: August 1995
Report Number: Contract Number E86940101
Pages: 27
Relevance: Primary
Keywords: Spillway, deflector, survival
Abstract: Juvenile salmonids pass Lower Monumental Dam through spillbays, the bypass system, or turbines. Previous studies have indicated that among the different passage routes, survival was highest for fish passing via spillbays and bypasses, with lower survivals through turbines. The juvenile salmonid passage facilities at Lower Monumental Dam have been recently upgraded to include submersible traveling screens, vertical barrier screens, raised operating gates, a new collection channel, and a new juvenile bypass facility. The effects of these upgrades on passage survival has not been previously evaluated, and the most recent passage survival data was based on research conducted during the 1960s and 1970s. In 1994, the National Marine Fisheries Service initiated research to determine juvenile fish passage survival through the facility bypass, spillbay, and tailrace of Lower Monumental Dam. Specific objectives were to: 1) obtain statistically sound survival estimates on the passage of juvenile salmonids through spillbays, with and without flow deflectors, and the facility bypass; and, 2) compare the survival of dam-passage groups with fish released downstream from the dam.

Relative survivals averaged 0.984 for fish released into Spillbay 8 (without a flow deflector) and 0.927 for fish released into Spillbay 7 (with flow deflector). However, the difference was not statistically significant ($P = 0.1190$). The differences observed between the two conditions warrant further testing with increased replication to better define whether the addition of flow deflectors would benefit juvenile salmon passage. Spillbay evaluation should be repeated in future years to determine if there are differences in survival between the two types of spillbays by increasing the number of replicates. Bypass releases should be made during future years if conditions warrant to evaluate this route of passage.
Notes: Objectives of the project were: (1) to obtain survival estimates on the passage of juvenile salmonids through spillways (with and without deflectors); (2) compare the survival of fish that have passed Lower Monumental Dam with fish that are released downstream from the dam.

This document was incorrectly cited as Iwamoto et al. (1994) in USCAOE (1994).

Release site	type	relative survival
spillbay 8	w/o flow deflector	1.033
spillbay 8	w/o flow deflector	0.924
spillbay 8	w/o flow deflector	0.996
spillbay 7	w/ flow deflector	0.973
spillbay 7	w/ flow deflector	0.912
spillbay 7	w/ flow deflector	0.896

Differences were not significant between spillbays ($p<0.05$), but the differences were great enough to warrant further testing.
Status: Copy in house

Reference Type: Technical Report
Record Number: 99
Author: Normandeau Associates, Inc. (Normandeau), J.R. Skalski, and Mid Columbia, Inc.
Year: 1996
Title: Potential effects of modified spillbay configurations on fish condition and survival at The Dalles Dam, Columbia River.
Agency: Prepared for the U.S. Army Corps of Engineers
City: Portland, Oregon
Date: April 1996
Report Number: Contract Number DACW57-95-C-0086
Pages: 29
Injury Type: Immediate, short term
Relevance: Primary
Keywords: Spillbay, mortality, injury
Notes: The objectives of the study were to estimate the immediate (1 h) and 48 h survival of juvenile salmon introduced into a spillbay modified with a bulkhead forming an I-slot (spill #3), an unmodified spillway (spillbay #4), and a spillway modified with in an overflow configuration (spillbay #6). Secondly, they wanted to identify the nature and the magnitude of injury/mortality of juvenile chinook passing through the spillbays at The Dalles Dam.

The Dalles Dam: tainter gate-controlled concrete ogee type spillway

Release site	species/age	estimated survival
Dalles #3 (I-slot)	chinook/juveniles	99.3%
Dalles #4 (unmodified)	chinook/juveniles	95.5%
Dalles #6 (overflow)	chinook/juveniles	99%

Status: Copy in house

Reference Type: Technical Report
Record Number: 22
Author: Park, D.L., J.R. Smith, E. Slatick, G.A. Swan, E.M. Dawley, and G.M. Matthews
Year: 1977
Title: Evaluation of fish protective facilities at Little Goose and Lower Granite Dams and nitrogen studies relating to protection of juvenile salmonids in the Columbia and Snake rivers, 1976
Agency: National Marine Fisheries Service for the U.S. Army Corps of Engineers
Division: Coastal Zone and Estuarine Studies
City: Seattle, Washington
Date: March 1977
Report Number: Contract Number DACW68-75-C-0111
Pages: 82
Relevance: Tertiary
Keywords: Gas abatement, deflectors, supersaturation
Abstract: During 1976, the National Marine Fisheries Service (NMFS), under contract to the U.S. Army Corps of Engineers, continued to evaluate the following: (1) fish protective facilities for juvenile salmonids at Lower Granite and Little Goose Dams, (2) a mass transportation system for increasing survival of downstream migrant salmonids, and (3) dissolved gas abatement procedures in the Columbia and Snake Rivers. At Lower Granite Dam, emphasis was placed on traveling screen research and collection of smolts and their transportation by truck and aircraft. It is important to determine if transportation, found to be successful at Little Goose Dam, can be successfully employed further upstream nearer the smolt rearing areas. Experiments were also designed to determine if salt water is beneficial in alleviating stresses during transport, thereby increasing survival to the sea. Traveling screen research involved tests with the standard traveling screen and an adjustable angle traveling screen designed by the Corps of Engineers. Tests were made with the standard screen located in the bulkhead slot, and the adjustable angle screen located in the bulkhead slot and the fish screen slot. At Little Goose Dam, emphasis was placed on evaluating the mass transportation of juvenile salmonids. A portion of the smolts transported to Bonneville Dam were marked and some groups were hauled in salt water. We also continued to recover adults returning upriver from juvenile migrations marked and transported from Little Goose Dam in 1973 and from Lower Granite Dam in 1975. Throughout the study area, we also conducted research relating to the following: (1) the effects of stress on chinook salmon--includes data on descaling, gas bubble disease, and contagious diseases and (2) the levels of dissolved gasses in the Columbia and Snake Rivers especially as related to spillway flow deflectors at Little Goose and McNary Dams.
Notes: The study objectives were to: (1) evaluate the fish protective facilities for juvenile salmonids at Lower Granite and Little Goose dams, (2) evaluate the mass transportation system for increasing survival of downstream migrant salmonids, (3) evaluate the gas abatement procedures in the Columbia and Snake rivers, (4) identify the effects of stress on chinook salmon, and (5) evaluate the levels of dissolved gas in the Columbia and Snake rivers, especially as related to spillway deflectors at Little Goose and McNary dams.

No mention of injury to downstream migrating salmonids passing through spillways and/or stilling basins.
Status: Copy in house

Reference Type: Technical Report
Record Number: 72
Author: Park, D.L.
Year: 1979
Title: Transportation of smolts and related studies in the Snake and Columbia rivers 1973-78
Agency: National Marine Fisheries Service for the U.S. Army Corps of Engineers
Division: Coastal Zone and Estuarine Studies
City: Seattle, Washington
Date: July 1979
Report Number: Research summary in Fifth Progress Report on Fisheries Engineering Research Program 1973-1978
Pages: 15
Relevance: Tertiary
Keywords: Barge, smolt transport, submersible travelling screen
Abstract: Research by the National Marine Fisheries Service under contract to the U.S. Army Corps of Engineers indicates that survival of juvenile salmonids (smolts) can be enhanced by capturing them at upriver dams in the Snake River and transporting them by truck or barge to safe release sites in the Columbia River below Bonneville Dam.

Starting in 1973, emphasis was placed on developing optimum methods for transporting smolts around dams, enhancing guiding efficiencies of submersible traveling screens in turbine intakes, and reducing injury or stresses to juveniles passing through the bypass system.

Progress can be summarized as follows:
1.) Barges and trucks in combination appear to be a promising mode for mass transport of fingerlings.
2.) Adults returning from smolt transport tests indicate that in every year 1973 to 1976, both chinook salmon and steelhead benefited from transportation (exception, 1976 (incomplete returns only) when chinook salmon tested received no benefit)
3.) A submersible traveling screen for turbine intakes has been developed that, when set at a 65 degree angle to flow, produces guiding efficiencies as high as 87% with near-zero descaling of fish.

Tests have defined the size, placement, and conditions necessary for maximum fish passage through orifices leading from turbine gate wells to bypass systems at specific dams on the Snake River.
Notes: In fifth progress report on fisheries engineering research program 1973-1978.

The main objectives of this study were to: 1) evaluate benefits of transporting smolts by truck, barge, and airplane around dams; 2) optimize the efficiency of submerged travelling screens into bypass collection systems; and 3) define orifice passage efficiencies.

No mention of injury to downstream migrating salmonids passing through spillways and/or stilling basins.
Status: Copy in house

Reference Type: Technical Report
Record Number: 20
Author: Park, D.L., and S. Achord
Year: 1987
Title: Evaluation of juvenile salmonid passage through the bypass system, turbine, and spillway at Lower Granite Dam -1986
Agency: National Marine Fisheries Service for the U.S. Army Corps of Engineers
Division: Coastal Zone and Estuarine Studies
City: Seattle, Washington
Date: May 1987
Report Number: Contract Number DACW68-84-H-0034
Pages: 11
Injury Type: Longer term
Relevance: Primary
Keywords: Mortality, fish, spillway
Notes: The objectives of the study were to measure the mortality of juvenile fish passing downstream of Lower Granite Dam via the spillway, through the turbine, or through the bypass system. The primary objective was to estimate the comparative short-term survival and condition of juvenile spring chinook salmon passing through the above routes.

Release site	non-descaled	partially descaled	severely descaled
spillway 2	93.2%	5.8%	1.0%

The number of recoveries of marked fish were insufficient for analyses of mortality rates.
Status: Copy in house

Reference Type: Technical Report
Record Number: 92
Author: Raymond, H.L., and C.W. Sims
Year: 1980
Title: Assessment of smolt migration and passage enhancement studies for 1979
Agency: National Marine Fisheries Service for the U.S. Army Corps of Engineers
Division: Coastal Zone and Estuarine Studies Division
City: Seattle, Washington
Date: May 1980
Report Number: Contract Number DACW68-78-C-0051 and Contract Number DACW57-79-F-0411
Pages: 87
Relevance: Primary
Keywords: Spillway, mortality, survival
Notes: The objectives of this study were to: (1) determine the current status (timing) of the smolt migration for use by the coordinator responsible for scheduling daily spill and augment river flows; (2) ensure that spill allocated for fish passage was judiciously used; (3) determine the percentage of the total smolt migration being transported from dams; (4) assess the success of the 1979 smolt migration; (5) determine if smolts are using the spill; (6) determine if fish using the spill survive at a higher rate than those passing through the turbines; (7) find a method of spilling water near the surface that would be as effective at passing smolts yet require far less water than the conventional deep spill; and (8) determine if significant numbers of juveniles could be moved across the powerhouse to an area where a more effective fingerling bypass could be installed.

John Day Dam: 20 spillway gates with no spillway deflectors in surface spill mode

Release Site	species/age	spillway passage survival
John Day Dam spillbay 16	chinook/smolts	118.7%
John Day Dam spillbay 16	chinook/smolts	96.5%

Mortality was not significantly different than zero on both occasions.
Status: Copy in house

Reference Type: Technical Report
Record Number: 74
Author: Regenthal, A.F.
Year: 1954
Title: Downstream migrant studies in the Snohomish River system
Agency: State of Washington Department of Fisheries
Report Number: Progress report for Puget Sound Stream Studies February-August, 1954
Pages: 9
Relevance: Tertiary
Keywords: Migration timing, residence timing
Notes: The objectives of the study were to: (1) determine when various species of salmon arrive at the Snohomish River mouth; (2) estimate the residence time in the mouth of the river; and (3) determine their migration routes.

No mention of injury to downstream migrating salmonids passing through spillways and/or stilling basins.
Status: Copy in house

Reference Type: Technical Report
Record Number: 75
Author: Regenthal, A.F.
Year: 1955
Title: Report on the test of a ski-jump spillway, Baker Dan, 1955
Agency: Washington Department of Fisheries
Pages: 11
Relevance: Primary
Keywords: Spillway, mortality, salmon
Notes: The objective of the study was to determine the mortality of downstream migrant salmon passing from forebay to tailwater via a timber spillway section. The reservoir surface is approximately 240 feet above the spillway pool.

Results of the study are not conclusive due to a storm that washed out part of the collecting gear.

Release site	species/age	estimated survival
sky jump	coho/yearling	68%, 79%, 83%
simulated spillway	coho/yearling	60%

No estimate of delayed mortality was undertaken. Hamilton (1955) had 18% delayed mortality, leaving this study with questionable results.
Status: Copy in house

Reference Type: Technical Report
Record Number: 73
Author: Regenthal, A.F., and W.H. Rees
Year: 1957
Title: The passage of fish through Mud Mountain Dam, 1957
Agency: Washington Department of Fisheries
Pages: 13
Relevance: Tertiary
Keywords: Passage, dam, salmon
Notes: The objective of the study was to determine the passage rate of coho and chinook salmon through a submerged orifice at high forebay levels on Mud Mountain Dam (approximately 200 feet of head) near the bottom of the forebay.

No mention of injury to downstream migrating salmonids passing through spillways and/or stilling basins.
Status: Copy in house

Reference Type: Journal Article
Record Number: 57
Author: Ruggles, C.P., and D.G. Murray
Year: 1983
Title: A review of fish response to spillways
Journal: Canadian Technical Report of Fisheries and Aquatic Sciences
Volume: 1172
Pages: 1-31
Injury Type: Immediate, short term delayed
Relevance: Primary
Keywords: Downstream fish passage through dams, spillways, hydraulic characteristics, dams, migration, mortality, gas-bubble disease, gas supersaturation of water
Abstract: Juveniles from most fish taxa will pass downstream over or through spillways, if flow is sufficient. Fish passing over relatively high spillways may be injured by rapid pressure changes, rapid deceleration, shearing forces, turbulence, abrasion and the striking force on the water in free fall. Injuries begin to occur when impact velocity of a fish striking a water surface exceeds 16 meters per second. Water below some spillways may become supersaturated with atmospheric gas to an extent that gas-bubble disease in fish may occur. Flow deflectors placed near the base of the spillways have been successful in reducing the deep plunging action, which is responsible for air entrainment and subsequent nitrogen supersaturation. Spillways are not currently perceived to be a serious source of fish mortality in Canada, although nitrogen supersaturation below spillways was identified as a potential fish-conservation problem in three rivers in British Columbia. Guidelines are presented which provide design and operating suggestions for spillways to eliminate or reduce their impact on fish.
Notes: This objective of this paper was to address the impact on fish of spillways at dams.

Site	head (ft)	max. velocity (fps)	species/age	estimated survival
McNary	80	83	chinook/juv	98%
Big Cliff	90	83	chin./juv	98%
Bonneville	85	64	chin./fingerling	54.2%
McNary	85	83	chin./fingerling	to
Elwha	85	>40	chin./fingerling	98.5%
Elwha	100	>40	chinook/fingerling	63%
Glines	180	terminal	chinook/fingerling	94%
			coho/yearling	92%
Baker	240	>80	coho/yearling	68%, 79%, 83%
Baker	250	>80	sockeye/coho	36%, 46%
Capilana R.	240	terminal	coho/steelhead	50%
Alder Dam	26	29-49	coho	97-100%
Mud Mtn.	80-120		coho/chinook	8.6-97.5%

Seton Creek	25	29 avg.	sockeye/smolt	98.8%
	142	29 avg.	sockeye/smolt	92.6%
Ariel	185	terminal	coho	100%
Puyallup	300	terminal	coho	97.7%
Dungeness	300	terminal	rainbow	98.5%

Status: Copy in house

Reference Type: Technical Report
Record Number: 35
Author: Schoeneman, D.E., and C.O. Junge, Jr.
Year: 1954
Title: Investigations of mortalities to downstream migrant salmon at two dams on the Elwha River
Agency: Washington Department of Fisheries
Date: April 1954
Report Number: Research Bulletin No. 3
Pages: 51
Injury Type: immediate, short-term delayed
Relevance: Primary
Keywords: Spillway, stilling basin, survival
Abstract: At the Glines spillway, which has a free fall of 180 feet, no significant mortalities were noted for either of the two species studied. During the special study period with spill varying from 0 to 8 feet of gate opening the same results were obtained using chinook fingerling. At the Elwha spillway, which is the contained flow type with 100 feet of head, a pronounced chinook mortality was noted. It may seem unusual that the largest chinook mortalities occurred at the dam with the lowest head. It is pertinent to note that for a constant head the energy to be dissipated in the spillway varies directly with the amount of spilled water. The manner in which this energy is dissipated determines the mortality rates. Under small spill conditions with a free-fall type of spill, a part of the energy is dissipated by aerating action. Under sufficiently heavy spills, much of the energy must be dissipated in the pool below the spillway thus creating turbulence, which may kill fish. In the free-fall spillway at Glines dam, the present study indicates that for spills of 8 feet or less, the manner in which the energy is dissipated causes no significant kill. It might be expected that in a contained type of spillway a formalized energy dissipater would kill fish. It was not possible to test this hypothesis at the Elwha dam because the spill strikes directly onto rocks. (See Table 22 for 63% survival.)

The natural migrational pattern of the unmarked chinook fingerlings and silver yearlings planted in lake Mills showed that chinook fingerlings will sound to a depth of 65 feet for egress when other exits are not available, but will choose a surface exit with a greater degree of frequency as the surface attraction increases. Yearling silvers, on the other hand, rarely sound to obtain egress from the forebay, but will remain in the lake until such time as a favorable exit is presented. This trend has also been noted in connection with research experiments at White river.
Notes: The objectives of the study were to examine the effects of power dam turbines and spillways on downstream anadromous fish. Specifically to: (1) develop a valid technique to estimate the survival rates of migrants passing through the various exits of a dam; (2) study the number of fish using the various exits; and (3) study the injuries occurring to fish using the various exits.

Release site	species/age	estimated survival
Glines Dam	coho/yearlings	92.25%
Glines Dam	chinook/fingerlings	94.13%
Elwha Dam	chinook/fingerlings	62.9%

Status: Copy in house

Reference Type: Technical Report
Record Number: 18
Author: Schoeneman, D.E., C.O. Junge Jr., W.E. Bostick, and T.K. Meekin.
Year: 1955
Title: Research relating to mortality of downstream migrant salmon passing McNary Dam
Agency: Washington Department of Fisheries for the U.S. Army Corps of Engineers
Report Number: Contract Number DA 35026-Eng-20893
Pages: 59
Relevance: Primary
Keywords: Spillway, mortality, fish
Abstract: In the spring of 1955 experiments were conducted at McNary dam to study the mortality rates of chinook fingerling passing through Turbine No. 2 under normal operating conditions, and over Spillway No. 21 with a five foot spill on the ogee section. Estimates were determined by planting differently marked fish in the upstream end of the exit to be studied and at the outlet of the exit, then recovering samples at various stations below the dam, and noting the ratio of the marked recoveries. These fish were marked by tattooing, and a device for tattooing large numbers of fish was developed for this study, since effects of fin-clipping could influence mortality estimates.

Most of these fish were recovered by floating scoop-nets the first group of which was located 20 miles downstream at Boardman, Oregon. The second group was located 68 miles below Boardman. For the third fishing area at Bonneville dam, 150 miles below McNary dam, the permanent inclined plane traps were used. Fishing stations were located along both shores of the Columbia River in order to test assumptions required for a representative sample. This was done by comparing the ratio of experimental to control fish recaptured at the various shore stations and fishing areas along the river and also comparing duplicated experiments.

The estimated survival rate for fish passing through No. 2 Turbine is 87%. This figure is based upon a recapture of 1639 control fish and 1425 experimental fish out of 360,000 fish released. Reproducibility at the various fishing stations and for duplicate experiments was very good. The confidence interval at the 95% level is 81% to 93%.

The estimated survival rate for fish passing over the spillway is 98%. This figure is based upon a recapture of 850 control fish and 833 experimental fish out of 180,000 fish released. The confidence interval at the 95% level is 89% to 108%. Reproducibility for the various stations where scoop-nets were fished was very good, but a great variation between the fishing stations at Bonneville dam was observed. Also, in attempts to duplicate the original experiment, a representative sample could not be obtained. For these reasons more experimentation is indicated before a final survival rate should be quoted for the spillway.

It should also be noted that only one set of conditions was tested at each exit studied. Other operating conditions could conceivably change the survival rate and should be tested for a more adequate survey.

Other relevant observations were made on the survival of salmon migrants between McNary dam and Bonneville dam. Examination of the recovery data at Boardman indicates that the average

percentage of water strained by the scooping-nets is approximately equal to the percentage of marked fish recaptured, or 0.65% of the water strained and 0.61% of the fish were recaptured. At the Arlington area an average of 0.49% of the total flow of the Columbia River was strained while recapturing only 0.26% of the marked fish. At Bonneville dam approximately 1.7% of the total flow of the Columbia River was strained, while recapturing only 0.12% of the fish. Other studies of the recovery data also give indication of a natural mortality (possibly due to predation) occurring to juvenile salmon as they migrate downstream in the Columbia River.
Notes: The objectives of the study were to: determine the survival of salmonid fishes passing downstream through the spillway # 21 and draft tubes of McNary Dam.

Release site	species/age	estimated survival
McNary Dam	chinook/0+	98%

Status: Copy in house

Reference Type: Technical Report
Record Number: 77
Author: Schoeneman, D.E., T.K. Meekin, and C.O. Junge, Jr.
Year: 1955
Title: Dam mortality studies conducted on the Lewis, Big White Salmon, and Chelan rivers 1954
Agency: Washington Department of Fisheries
Pages: 13
Relevance: Primary
Keywords: Spillways, mortality, salmon
Notes: The objectives of the study were to: (1) study the effects of two spillways on downstream migrating salmon on the Lewis River; (2) determine the effects of turbines on the Northwestern Dam on the Big White Salmon River; and (3) test the mortalities from turbines in the Chelan Dam.

Release site	species/age	estimated survival
Yale Dam	coho/yearlings	46%
Ariel Dam	coho/yearlings	54%
Ariel Dam	chinook/fingerling	36%

Several tests failed to meet their assumptions, leading to questionable results.
Status: Copy in house

Reference Type: Technical Report
Record Number: 76
Author: Schoeneman, D.E., and C.O. Junge, Jr.
Year: 1956
Title: Research relating to mortality of downstream migrant salmon passing McNary Dam (1956)
Agency: Washington Department of Fisheries for the U.S. Army Corps of Engineers
Type of Work: Final Report
Report Number: Contract Number DA 35026 - Eng - 20893
Pages: 31
Relevance: Primary
Keywords: Survival rate, spillway, turbine, dam
Abstract: In 1956 experiments on the mortality rates of chinook fingerling passing through the spillway gates and turbines of McNary Dam were continued in order to augment the results of the 1955 study. Again the recovery ratios of experimental to control releases were used to estimate survival rates. Revised methods for releasing the control groups were used in 1956 to improve initial mixing with the experimental groups. Fishing stations were located at Boardman, The Dalles, and at Bonneville Dam.

In 1956, turbine #4, with a setting of 0.75, had an estimated survival rate of 92 percent. This value is not significantly different from the 1955 survival estimate of 87 percent for turbine 2 with a setting of 0.80. Also, since reproducibility at the various fishing stations and for duplicate experiments was good for each year, all of these data may be combined for a final survival estimate of 89 percent. The 95 percent confidence interval is from 84 to 94 percent. The reproducibility of the survival estimates at different turbines and for different years indicates the reliability of the method used, and rules out a suggested possibility that the estimated mortality is due to the route of migration of the experimental group through an area of increased predation. Further, a predation study conducted by the U.S.F.W.S. in conjunction with the mortality experiments gave no indication that predation was a significant factor during this period.

The recovery ratio in 1956 for spillway gate #21 with a five foot gate opening was 1.01. This compares very well with the 1955 survival estimate of 98 percent for the same spillway gate with the same gate opening. Combining the data for both years an estimate of 100 percent survival is obtained with a 95 percent confidence interval from 94 to 106 percent. In both years recoveries classified as "shore recoveries" were omitted in estimating the survival rates for the spillway. In 1955 the necessity for this omission was indicated by a very low recovery ratio for the Washington shore station at Bonneville. In 1956 the recovery ratios for the "shore" rafts at The Dalles were consistently low for both shores and for both experiments (red and yellow tattoo). It is evident that these "shore" fish are small in numbers and that they probably are not a fixed population, but merely represent fish that have temporarily separated from the main migration population for some reason. In every instance, where "shore" groups were noted, a slack water or eddy area was noted immediately above the fishing station.

There is no indication that the turbine recoveries required division into two groups (shore and non-shore) as was necessary for the spillway recoveries.

Notes: The objectives of the study were to study the mortality occurring to downstream migrant salmon passing through the spillway gates and turbines of McNary Dam.

Release site	species/size	estimated survival
McNary Dam	chinook/0+	101%

Status: Copy in house

Reference Type: Technical Report
Record Number: 79
Author: Schoeneman, D.E., and C.O. Junge, Jr.
Year: 1957
Title: Research relating to mortality of downstream migrant salmon passing Big Cliff Dam 1957
Agency: Washington Department of Fisheries for the U.S. Army Corps of Engineers
Type of Work: Final Report
Report Number: Contract Number DA 35026-Eng-20893
Pages: 23
Relevance: Primary
Keywords: Spillway, mortality, dam, salmon
Abstract: In 1955 and 1956 experiments were conducted to determine the mortality rates of fall chinook fingerling salmon passing through the spillway gates and turbines of McNary Dam. Since mortalities to yearling fish had not been tested, the 1957 studies at Big Cliff Dam on the Santiam River in Oregon were conducted on spring chinook yearling salmon as well as fall chinook fingerling. The turbine and spillway conditions at Big Cliff Dam were very similar to those at McNary dam; in fact, the mortality rate for fall chinook fingerling found at Big Cliff Dam were not significantly different from those which had been determined at McNary Dam. Further, the mortalities to yearling chinook were not significantly different from the mortalities to fall chinook fingerling. For these reasons it is possible to combine all data for the three year study for each exit studied. As a result, the turbine mortality rate under 0.75 or 0.80 turbine rating is estimated to be 11 percent, with a 95 percent confidence interval from 9 to 13 percent. Similarly, the spillway mortality rate estimate is two percent with a 95 percent confidence interval from 0 to 4 percent. A study of the turbine, using chinook fingerling with a greatly reduced wicket gate opening (0.40 rating) indicated a mortality of 21 percent which was very significantly greater than with normal operating conditions (0.80 rating). Under the ideal experimental conditions found on the Santiam River, a high and very constant recovery rate was obtained. As a result, the 1957 studies not only determine precise and accurate mortality estimates for yearling fish, but also give added confidence to the estimates of the earlier studies at McNary Dam.
Notes: The objective of the study was to determine the mortality occurring to downstream migrant salmon passing through the spillway gates and turbines of McNary Dam, using a structure similar to McNary Dam, but located on a smaller river which is more conducive to experimentation.

Big Cliff Dam: 90 feet head, concrete ogee type spillway.

Release site	species/age	estimated survival
Big Cliff Dam	chinook/yearlings	99%
Big Cliff Dam	chinook/0+	94%

Status: Copy in house

Reference Type: Technical Report
Record Number: 80
Author: Schoeneman, D.E., and C.O. Junge, Jr.
Year: 1960
Title: Research relating to mortality of downstream migrant salmon passing Big Cliff Dam 1957 - Summary Report
Agency: Washington Department of Fisheries for the U.S. Army Corps of Engineers
Type of Work: Summary Report
Report Number: Contract Number DA 35026-Eng-20893
Pages: 9
Relevance: Primary
Keywords: Spillway, mortality, salmon, dam
Abstract: Following is a summary report submitted by the State of Washington, Department of Fisheries to the U.S. Army Corps of Engineers. Data were collected and analyzed by the Washington State Department of Fisheries in conformity with a contract between the Department of Fisheries and the U.S. Army Corps of Engineers. This report summarized pertinent data that were obtained from these conducted at Big Cliff dam on the Santiam River in Oregon, and combines these data with those obtained from the years 1955 and 1956 at McNary dam.
Notes: The objective of the study was to determine mortality to downstream migrating salmonids passing through McNary Dam turbines and spillways.

Big Cliff Dam: 90 feet head, concrete ogee type spillway.

Release site	species/age	estimated survival
McNary Dam	chinook/0+	98%
McNary Dam	chinook/0+	101%
Big Cliff Dam	chinook/0+	94%
Big Cliff Dam	chinook/yearlings	99%

Status: Copy in house

Reference Type: Journal Article
Record Number: 34
Author: Schoeneman, D.E., R.T. Pressey, and C.O. Junge, Jr.
Year: 1961
Title: Mortalities of downstream migrant salmon at McNary Dam
Journal: Transactions of the American Fisheries Society
Volume: 90
Pages: 58-72
Injury Type: Immediate and short-term
Relevance: Primary
Keywords: Turbine, mortality, salmon, dam
Abstract: Studies conducted with live fingerling salmon in full-scale test apparatus indicated that few fish will be killed or injured as a result of rapid pressure changes as they pass underneath the spillway gates release of pressure occurring in approximately 5 milliseconds. Since the release of pressure vas considerably faster under the experimental conditions than would occur in a Kaplan turbine under similar head, it is concluded that this factor was not a cause of mortalities at McNary Dam. Another possible cause of mortality is the spilling process, which generally takes place at Columbia River dams during the spring months when most fingerling salmon are migrating. When a spillway gate is raised, water from the forebay spurts under the gate and drops onto the concrete ogee section which carries it to the base of the dam where the tremendous force of the water is spent against the concrete energy dissipators. The cavitation which occurs at pitted areas in the concrete ogee section and the abrasive action of the rough concrete can cause injuries and possible mortalities. Tests on the effects of baffles eliminate the probability of any significant mortality due to fish striking the energy dissipators. If large quantities of water are being discharged, a back-roll may be created between the energy dissipators and the base of the spillway, with the possibility that fish caught in this back-roll could not escape and would be killed. Areas of danger mentioned above apply to almost every type of hydroelectric structure. The degree of severity, however, may be influenced by height and design of the structure, and the species and age of fish passing through it.
Notes: This paper is similar to the Schoeneman and Junge (1960) paper. The objective of the study was to determine mortality to downstream migrating salmonids passing through McNary Dam turbines and spillways.

McNary Dam: 85-90 feet head, gate-controlled concrete ogee type spillway
Big Cliff Dam: 90 feet head, gate-controlled concrete ogee type spillway

Release site	species/age	estimated survival
McNary Dam	chinook/0+	98%
McNary Dam	chinook/0+	101%
Big Cliff Dam	chinook/0+	94%
Big Cliff Dam	chinook/yearlings	99%

Status: Copy in house

Reference Type: Technical Report
Record Number: 102
Author: Schreck, C.B., L.E. Davis, and C. Seals
Year: 1998
Title: Evaluation of procedures for collection, bypass, and transportation of outmigrating salmonids. Objective 1: Migratory behavior and survival of yearling spring chinook salmon in the lower Columbia River and estuary.
Agency: Oregon State University
Division: Oregon Cooperative Fishery Research Unit
City: Corvallis, Oregon
Date: 1998
Report Number: Contract No. MPE-96-10
Pages: 31
underneath the spillway gates release of pressure occurring in approximately 5 milliseconds. Since the release of pressure vas considerably faster under the experimental conditions than would occur in a Kaplan turbine under similar head, it is concluded that this factor was not a cause of mortalities at McNary Dam. Another possible cause of mortality is the spilling process, which generally takes place at Columbia River dams during the spring months when most fingerling salmon are migrating. When a spillway gate is raised, water from the forebay spurts under the gate and drops onto the concrete ogee section which carries it to the base of the dam where the tremendous force of the water is spent against the concrete energy dissipators. The cavitation which occurs at pitted areas in the concrete ogee section and the abrasive action of the rough concrete can cause injuries and possible mortalities. Tests on the effects of baffles eliminate the probability of any significant mortality due to fish striking the energy dissipators. If large quantities of water are being discharged, a back-roll may be created between the energy dissipators and the base of the spillway, with the possibility that fish caught in this back-roll could not escape and would be killed. Areas of danger mentioned above apply to almost every type of hydroelectric structure. The degree of severity, however, may be influenced by height and design of the structure, and the species and age of fish passing through it.
Notes: This paper is similar to the Schoeneman and Junge (1960) paper. The objective of the study was to determine mortality to downstream migrating salmonids passing through McNary Dam turbines and spillways.

McNary Dam: 85-90 feet head, gate-controlled concrete ogee type spillway
Big Cliff Dam: 90 feet head, gate-controlled concrete ogee type spillway

Release site	species/age	estimated survival
McNary Dam	chinook/0+	98%
McNary Dam	chinook/0+	101%
Big Cliff Dam	chinook/0+	94%
Big Cliff Dam	chinook/yearlings	99%

Status: Copy in house

Reference Type: Technical Report
Record Number: 81
Author: Seiler, D., and S. Neuhauser
Year: 1985
Title: Evaluation of downstream migrant passage at two dams: Condit Dam, Big White Salmon River, 1983 & 1984; Howard Hanson Dam, Green River, 1984
Agency: State of Washington Department of Fisheries
Date: October 1985
Injury Type: Immediate, short term, long term
Report Number: Progress Report Number 235
Pages: 94
Relevance: Primary
Keywords: Spillway, mortality, stilling basin
Notes: The objectives of the study were to: (1) evaluate downstream migrant passage survival through Condit Dam's spillways and turbines; and (2) measure smolt production by planting coho fry into the White Salmon upstream of Condit Dam.

Condit Dam

Release site	water volume	species/age	estimated survival
Spillway#1,2	350 cfs	coho/smolt	89.0%
Spillway#1,2	700 cfs	coho/smolt	75.3%
Spillway#1,2	700 cfs	coho/smolt	77.0%
Spillway#1,2	350 cfs	coho/smolt	89.0%
Spillway#1,2	350 cfs	coho/smolt	77.0%
Spillway#1,2	700 cfs	coho/smolt	89.0%
Spillway#3,4	150 cfs	coho/smolt	62.9%
Spillway#5	350 cfs	coho/smolt	61.0%
Spillway#3,4	150 cfs	coho/smolt	67.2%
Spillway#5	350 cfs	coho/smolt	66.1%

The objectives of the study were to evaluate passage survival through Howard Hanson Dam and measure smolt production from the fry and fingerling plants.

Howard Hanson Dam: 235 feet high

Results of this study were not conclusive although it was hypothesized that the bypass system may inhibit migration and inflict some injury.
Status: Copy in house

Reference Type: Technical Report
Record Number: 63
Author: Sims, C.W., and R.C. Johnsen
Year: 1979
Title: Evaluation of the fingerling bypass system outfalls at McNary and John Day Dams
Agency: National Marine Fisheries Service for the U.S. Army Corps of Engineers
Division: Coastal Zone and Estuarine Studies
Date: September 1979
Report Number: Contract Number DACW57-76-F-0630 and Contract Number DACW57-77-F-0148
Pages: 15
Relevance: Tertiary
Keywords: Orifice, “crowder,” dam
Notes: In fifth progress report on fisheries engineering research program 1973-1978.

The objectives of the study were: (1) determine the success of a simulated corner orifice (SCO) and a "crowder"; and (2) determine the extent of mortality at the existing bypass outfalls below John Day and McNary dams.

No mention of injury to downstream migrating salmonids passing through spillways and/or stilling basins.
Status: Copy in house

Reference Type: Technical Report
Record Number: 82
Author: Swan, G.A., R.F. Krcma, and F.J. Ossiander
Year: 1984
Title: Research to develop an improved fingerling protection system for Lower Granite Dam
Agency: National Marine Fisheries Service for the U.S. Army Corps of Engineers
Division: Coastal Zone and Estuarine Studies
City: Seattle, Washington
Date: April 1984
Report Number: Contract Number DACW68-78-C-0051
Pages: 28
Relevance: Tertiary
Keywords: Dam, turbine, fish guiding efficiency
Abstract: To reduce the losses of juvenile salmonids from passage through turbines at hydroelectric dams, fish must be diverted from the turbine intakes and bypassed around the dams. The objectives of the research conducted at Lower Granite Dam on the Snake River in 1983 were as follows: (1) field test means of increasing water flow into the bulkhead slot of the turbine intake and thus reduce the amount of water and fish deflected under the submersible traveling screen and improve fish guiding efficiency and (2) evaluating the fish passage benefits of using 12-inch diameter orifices from the turbine bulkhead slot to the fish bypass conduit instead of 8-inch diameter orifices.

The research indicated that raising the operating gate in the operating gate slot improved fish guiding efficiency (FGE). An acceptable FGE was achieved for spring chinook salmon and steelhead when the operating gate was raised 20 feet.

A single 12-inch diameter orifice was found to be about as effective as two 8-inch diameter orifices for passing juvenile chinook salmon and steelhead out of the bulkhead slot. However, because passage was still unsatisfactory for steelhead, two 12-inch diameter orifices were recommended for adequate fish passage.
Notes: The objectives of the study were: (1) to field test the revised submersible traveling screen conditions; and (2) evaluate the benefits of using 12-inch diameter bypass orifices for improving orifice passage efficiencies and determine if closure of the fish screen slot would adversely impact fish guiding efficiency at Lower Granite Dam.

No mention of injury to downstream migrating salmonids passing through spillways and/or stilling basins.
Status: Copy in house

Reference Type: Technical Report
Record Number: 83
Author: Swan, G.A., R.F. Krcma, and F.J. Ossiander
Year: 1985
Title: Development of an improved fingerling protection system for Lower Granite Dam 1984
Agency: National Marine Fisheries Service for the U.S. Army Corps of Engineers
Division: Coastal Zone and Estuarine Studies
City: Seattle, Washington
Date: May 1985
Report Number: Contract Number DACW68-84-C-0034
Pages: 33
Relevance: Tertiary
Keywords: Dam, fish passage efficiency, screen, gate
Notes: The objectives of the study were: (1) to evaluate the use of two 12-inch diameter orifices to measure orifice passage efficiencies with a fully raised operating gate; (2) to compare standard vertical barrier screen to balanced flow vertical barrier screen; (3) compare north versus south orifice locations; and (4) test various placements of solid plate barrier screen modifications for improving orifice passage efficiency at Lower Granite Dam.

No mention of injury to downstream migrating salmonids passing through spillways and/or stilling basins.
Status: Copy in house

Reference Type: Technical Report
Record Number: 97
Author: U.S. Army Corps of Engineers Portland District
Year: 1956
Title: Effect of structures at main Columbia River dams on downstream migration of fingerlings
Agency: U.S. Army Corps of Engineers Portland District
Division: North Pacific Division
City: Portland, Oregon
Date: November 1956
Report Number: In Progress Report on Fisheries Engineering Research Program North Pacific Division Corps of Engineers, U.S. Army, November 1956
Pages: 4
Relevance: Secondary
Keywords: Spillway, mortality, survival
Notes: In Progress Report on Fisheries Engineering Research Program North Pacific Division Corps of Engineers, U.S. Army, November 1956.

The objective of the study was to determine the immediate effect of turbines and spillways on survival of fingerling salmon by releasing fish directly into these structures and retrieving released fish as soon as possible below the dam using gossamer bags and attached balloons.

In addition, laboratory experiments were used to determine the effect of pressure changes and if the gossamer bags would protect or injure fish when compared to free-swimming fish.

Results of the spillway tests were inconclusive due to poor physical condition of the test fish and problems with the gossamer bags.
Status: Copy in house

Reference Type: Technical Report
Record Number: 96
Author: U.S. Army Corps of Engineers Portland District
Year: 1960
Title: Effect of structures at main Columbia River dams on downstream migration of fingerlings
Agency: U.S. Army Corps of Engineers Portland District
Division: North Pacific Division
City: Portland, Oregon
Date: July 1960
Report Number: In Progress Report on Fisheries Engineering Research Program North Pacific Division Corps of Engineers, U.S. Army, July 1960
Pages: 19
Relevance: Secondary
Keywords: Spillway, mortality, survival
Notes: In Progress Report on Fisheries Engineering Research Program North Pacific Division Corps of Engineers, U.S. Army, July 1960.

The objective of the study was to determine under prototype conditions the rate of survival or mortality of fingerling salmon in passing through turbines, spillway gates and stilling basins of main stem Columbia River dams. The study utilized young fish released in gossamer bags attached to self-inflating balloons to aid recovery efforts.

In addition, the study included tests of fish enclosed in gossamer bags simulating the conditions found below Bonneville Dam spillway in an attempt to determine if gossamer bags impaired and injured or protected the fish during the spillway survival tests. Laboratory tests were also conducted to determine the effects of pressure change, agitation, Venturi, and impact.

The results of the Bonneville Dam and McNary Dam spillway tests were essentially the same as those recorded in 1956, inconclusive due to: poor condition of test fish; high water temperature in the river; and high mortality of test fish stemming from difficulties with the gossamer bags.

Laboratory tests indicated that: (1) sudden drops in pressure (occurring in a fraction of a second) is harmful to fish; (2) water shot at fish in a barrel at 100 psi killed fingerling salmon; (3) pressure as low as 0.5 absolute psi did not cause significant mortality to fingerling salmon; and (4) impact of fingerling salmon against a steel plate set at 45- and 90-degree angles to flow (45.6 cfs) did not cause significant mortality.
Status: Copy in house

Reference Type: Technical Report
Record Number: 85
Author: U.S. Army Corps of Engineers
Year: 1979
Title: Effect of spillway bucket roughness on fingerling
Agency: U.S. Army Corps of Engineers
Division: North Pacific Division
Date: September 1979
Report Number: Research summary in Fifth Progress Report on Fisheries Engineering Research Program 1973-1978
Pages: 4
Injury Type: Immediate, short term, longer term
Relevance: Primary
Keywords: Spillway, bucket, injury, mortality
Abstract: Effect of surface roughness on fingerling fish passing through a 50-foot-radius spillway bucket was investigated in a 6-inch-wide section of bucket. Coho and chinook fingerling 3.5 to 6.0 inches long were tested. Less than 3 percent were injured in a smooth bucket. None was killed or stunned. Injuries were principally torn opercles. In a moderately rough bucket opercle injury was 6.3 percent, head injury 2.8 percent, scaling 6.0 percent, stunned fingerling 0.7 percent, and first day mortality 0.2 percent. With heavy roughness opercle injury dropped to 1.0 percent; head injury was 22.0 percent, scaling 34.0 percent, stunned fingerling 13.0 percent, and first day mortality 9.8 percent. Seven day mortality was 12.3 percent. Smaller fingerling had the most opercle injury; larger fingerling had the most head damage.
Notes: In fifth progress report on fisheries engineering research program 1973-1978.

The objectives of the study were investigate in a laboratory the effects of surface roughness on fingerling fish passing through a 50 foot spillway bucket.

80 fps velocity.

Bucket type	1 day mortality	7 day mortality	7 day survival
smooth surface	0.0%	1.3%	98.7%
moderate roughness	0.2%	1.0%	99%
heavy roughness	9.8%	12.3%	87.7%

Status: Copy in house

Reference Type: Technical Report
Record Number: 86
Author: U.S. Army Corps of Engineers
Year: 1979
Title: Fingerling passage through John Day spillway
Agency: U.S. Army Corps of Engineers
Division: North Pacific Division
Date: September 1979
Report Number: Research summary in Fifth Progress Report on Fisheries Engineering Research Program 1973-1978
Pages: 2
Relevance: Tertiary
Keywords: Spillway, fingerling salmon, flow condition
Abstract: Spillway operation to create flow conditions for fingerling passage through a single bay of the John Day spillway was studied in a hydraulic model. Water from the pool surface was withdrawn over stoplogs and discharged under the spillway gate at small openings with the John Day Pool at El 265 and 258. Similar conditions for Foster spillway were observed to show flow conditions that would occur during field tests.
Notes: In fifth progress report on fisheries engineering research program 1973-1978.

The objectives of the study were to develop favorable flow conditions for fingerling passage through a single bay of the John Day spillway using a 1:50 scale physical hydraulic model of the dam.

No mention of injury to downstream migrating salmonids passing through spillways and/or stilling basins.
Status: Copy in house

Reference Type: Technical Report
Record Number: 87
Author: U.S. Army Corps of Engineers
Year: 1979
Title: Ejection of fingerling in high-velocity jet
Agency: U.S. Army Corps of Engineers
Division: North Pacific Division
Date: September 1979
Report Number: Research summary in Fifth Progress Report on Fisheries Engineering Research Program 1973-1978
Pages: 3
Relevance: Primary
Keywords: Fingerling salmon, injury, jet
Notes: In fifth progress report on fisheries engineering research program 1973-1978.

The objective of the study was to expose fingerling coho salmon, chinook salmon, and steelhead trout to a high velocity jet in shallow water to determine extent of injury, if any.

Jet velocity (fps)	mortality	survival
57.5	0.0%	100%
67.0	2.4%	97.6%
77.5	7.2%	92.8%
92.0	31.0%	69%

Status: Copy in house

Reference Type: Technical Report
Record Number: 88
Author: U.S. Army Corps of Engineers
Year: 1979
Title: Adult fish exposed to high velocity jet
Agency: U.S. Army Corps of Engineers
Division: North Pacific Division
Date: September 1979
Report Number: Research summary in Fifth Progress Report on Fisheries Engineering Research Program 1973-1978
Pages: 3
Relevance: Tertiary
Keywords: Fish, swim, behavior
Abstract: The behavior of adult salmonids swimming in shallow, low velocity flow in the vicinity of high velocity flow was observed in a tank with an 80-fps jet injected at one side at mid-depth. Flow was similar to that from a spillway nappe deflector. Three tests were made. Results were inconclusive but indicated that adult fish were not attracted to the high velocity jet, would avoid it, and could ride out at least one contact with it.
Notes: In fifth progress report on fisheries engineering research program 1973-1978.

The objective of the study was to determine the behavior of adult fish swimming in low velocity flow in the vicinity of high velocity flow.

No mention of injury to downstream migrating salmonids passing through spillways and/or stilling basins.

Test results were inconclusive because of high chlorine content of the test water.
Status: Copy in house

Reference Type: Technical Report
Record Number: 84
Author: U.S. Army Corps of Engineers
Year: 1979
Title: Spillway deflectors to reduce buildup of nitrogen saturation
Agency: U.S. Army Corps of Engineers
Division: North Pacific Division
Date: September 1979
Report Number: Research summary in Fifth Progress Report on Fisheries Engineering Research Program 1973-1978
Pages: 11
Relevance: Tertiary
Keywords: Spillway, deflector, dam
Abstract: Flow conditions causing gas supersaturation (nitrogen supersaturation) in water passed through spillways were improved with hydraulic model studies. Deflectors to direct aerated spillway flow along the tailwater surface rather than to the bottom of the stilling basin with flows less than the 10-year flood were developed. The lower pressure of the shallower depth of skimming flow would force less gas into solution. Deflectors were short so larger flows would override and plunge into the stilling basin for energy dissipation. Effect of deflectors on downstream flow, especially fish passage conditions, was studied to determine which spillway bays should not have deflectors and develop the best spill pattern. Deflectors were developed for Bonneville, John Day, McNary, Ice Harbor, Lower Monumental, Little Goose, and Lower Granite Dams and installed at all but John Day and Ice Harbor Dams.
Notes: In fifth progress report on fisheries engineering research program 1973-1978.

The objectives of the study were to develop and test flow deflectors to direct aerated spillway flow along the tailwater surface rather to the bottom of the stilling basin using flows less than the 10-year flood for: Bonneville, John Day, McNary, Ice Harbor, Lower Monumental, Little Goose, and Lower Granite dams.

No mention of injury to downstream migrating salmonids passing through spillways and/or stilling basins.
Status: Copy in house

Reference Type: Technical Report
Record Number: 30
Author: U.S. Army Corps of Engineers Walla Walla District
Year: 1994
Title: Ice Harbor spillway deflectors preliminary letter report
Agency: U.S. Army Corps of Engineers Walla Walla District
City: Walla Walla, Washington
Date: October 1994
Pages: 145
Relevance: Primary
Keywords: Deflectors, spillway, mortality
Abstract: The immediate installation of spillway deflectors on all ten bays at Ice Harbor is not needed because of the potential for adult passage problems observed and described by and Carnegie. It is not prudent to overrule these strong recommendations with the current, able information. Although this option would not cause problems with erosion within the basin, the risk to adult passage is too great without further investigations.

The installation of deflectors on either the center six or eight bays is not recommended out conducting hydraulic model testing to define the impacts of pier extensions on the nation of the stilling basin and on adult passage conditions. The dam safety concerns would also need to be addressed prior to allowing installation of deflectors on less than the full spillway.

However, spillway deflectors at Ice Harbor could provide a 5 to 10 percent reduction in dissolved gas supersaturation. For the most likely future operating scenarios, this could result in improvements for both juvenile and adult migrating fish. Therefore, it is recommended that a plan combining features from three of the options identified in this report be pursued. The recommended plan is to prepare a design memorandum (DM) for installing spillway deflectors at Ice Harbor and concurrent with the completion of the DM and its review and approval period, prepare the plans and specifications. The DM preparation would include conducting necessary hydraulic model studies (using both a general and a spillway sectional model) to optimize various design aspects as well as to evaluate and minimize any adverse impacts on adult fish passage conditions. Possible field investigations to evaluate impacts to adult fish passage have also been included as part of the DM preparation. Concurrent work on the plans and specifications while completing and approving the DM is estimated to reduce the time to advertising the contract by about 4 months.

At this point, the most likely alternative to be recommended by the DM is to construct deflectors on the center eight spillway bays and to extend the two existing pier extensions to the end of the stilling basin. However, the existing pier extensions may already be sufficiently long to prevent stilling basin erosion similar to what has occurred at Lower Monumental Dam. The hydraulic model testing conducted as part of the DM preparation will be used to verify whether the existing pier extensions are adequate and to evaluate impacts of the various designs on adult fish passage.

Part of the recommended plan is to monitor the progress of the current regional study looking for more effective methods of obtaining reduced supersaturation levels downstream of each of the lower Columbia and lower Snake River dams (Gas Supersaturation Abatement Study). Besides

generally monitoring the progress of the study team throughout the abatement study, the progress will be checked prior to completing the DM. Based on the current schedules this would occur shortly after the study team has completed the report for Phase 1. The results of Phase I would then be factored into the recommendation of the DM.

It should also be noted that if no stilling basin modifications are found that can provide acceptable adult fish passage conditions, then efforts toward constructing spillway deflectors would be terminated. Testing is also planned for next year to determine whether there are negative impacts on juvenile fish because of spillway deflectors.

The fully funded cost of preparing the DM and P&S is estimated at $1.3 million and will take approximately 24 months. A large portion of the 24 months is attributable to the construction and testing of necessary hydraulic models to address adult fish passage concerns and to optimize design features (see Chart 1 on the next page). If the DM recommends installing eight deflectors on the center spillway bays and the two associated pier extensions, the total, fully funded cost is $7.0 million (including the costs of DM and P&S preparations). The time required for full implementation will depend on what modifications are finally selected, what length of work window is allowed, and when in the annual hydrologic cycle, approval and funding is received.
Notes: The objective of this letter report is to provide a summary of studies pertaining to juvenile fish survival over spillways and juvenile fish survival over spillways with and without flow deflectors.

This report incorrectly identifies Iwamoto et al. (1994) as the source of the Lower Monumental study comparing spillway survival between bays with a flow deflector and bays without a flow deflector. The correct citation is Muir et al. (1994).

Studies reviewed are:

Study cited	summary
Schoeneman et al. (1956; 1961)	survival was 98% in bays without flow deflectors
Raymond and Sims (1980)	survival estimates ranged from 96.5-119%
Holmes (1952)	survival estimates ranged from 96-97%
Ledgerwood et al. (1990; 1991) Dawley et al. (1988; 1989)	survival was 106% compare to downstream control recoveries
Iwamoto et al. (1994)	survival was 98.2% in spillway bays without flow deflectors compared to 92.8% spillway bays with flow deflectors
Johnsen and Dawley (1974)	survival was 4% greater in spillway bays without flow deflectors compared to spillway bays with flow deflectors

Long et al. (1975)

survival was 73% in spillway bays with flow deflectors compared to 98% in spillway bays without flow deflectors

Status: Copy in house

Reference Type: Technical Report
Record Number: 37
Author: U.S. Army Corps of Engineers Portland District and Walla Walla District
Year: 1996
Title: Dissolved gas abatement study, Phase I
Agency: U.S. Army Corps of Engineers Portland District and Walla Walla District
Division: Portland District and Walla Walla District
City: Portland, Oregon and Walla Walla, Washington
Date: April 1996
Type of Work: Technical Report
Pages: 111
Relevance: Primary
Keywords: Spillway, mortality, deflector, fish
Abstract: The Dissolved Gas Abatement Study (DGAS) was initiated in response to the Gas Bubble Expert Panel's recommendation that the National Marine Fisheries Service (NMFS) that structural and operational changes would be needed to reduce total dissolved gas (TDG) supersaturation in the river system based on the current spill program. Subsequently, NMFS Biological Opinion (1995) for Operation of the Columbia River Hydro System detailed that the Corps of Engineers will develop and implement a gas abatement program at all projects. This report provides a comprehensive analysis and summary of the actions taken to date and provides recommendations to move forward with a program to effectively manage TDG in the Lower Snake and Columbia River System.

The Dissolved Gas Abatement Study is part of the Columbia River Salmon Migration Analysis (CRSMA) which consists of several programs aimed at improving the survival of endangered salmon species. Other programs within the CRSMA are examining drawdown, surface attraction, bypass systems, transportation, turbine rehabilitation, spill patterns, and light and sound applications as a means of improving fish passage through the Lower Snake and Columbia River projects. In an effort to improve downstream migration and survival of juvenile salmon, the Corps of Engineers has been spilling at the eight Lower Columbia and Lower Snake River projects as requested by the National Fisheries Service. The special spillway releases consist of up to 80 percent of the instantaneous total river discharge and occur throughout the salmon migration season from March through August. The spillway discharge tends to entrain large quantities of air and plunge deeply into the tailwater. This tendency forces the air into solution and results in high concentrations of TDG supersaturation. High exposure to TDG supersaturation causes mortality in juvenile and adult migratory fish, resident fish, and other organisms. The Phase 1 Dissolved Gas Abatement Study was established in order to define, evaluate, and recommend methods to reduce TDG created during spillway operations of the eight existing Corps of Engineers Projects on the Lower Snake and Columbia Rivers. The original goal of the study was to determine how the projects' could be modified to comply with the federal and state TDG water quality standard. The water quality standard states that TDG concentrations should not exceed 110 percent saturation for discharges up to the ten-year seven-day peak flood event. In addition, the DGAS will provide the justification for implementation of gas abating measure in the form of estimated TDG reductions and associated biological benefits.

Historical Information. An effort was made to collect all relevant historic information including information specific to the study projects' spillways such as operation, design, and function; information pertaining to the river system such as available storage and hydropower development; information about the migratory fish such as natural behavior and gas tolerance; and TDG data. Most of this information was readily available, but TDG data and related biological information is relatively sparse. The Columbia and Snake River fixed monitoring system (FMS) for water quality and TDG is the primary source of TDG data for the river system. The FMS expanded from a few stations in 1984 to 37 stations throughout a major portion of the basin in 1995. The FMS, originally experimental, has become instrumental in regulating TDG concentrations throughout the river system. The present FMS design objectives are: 1) to provide the water quality data needed to schedule spill at Corps' eight Lower Snake and Columbia River dams, and 2) to monitor TDG for compliance with existing State water quality standards. The FMS data is virtually all of the TDG data that existed prior to the DGAS field data collection efforts.

Alternative Analysis. Operational as well as structural modifications were considered as potential alternatives for reducing dissolved gas concentrations in the rivers in an effort to improve the survival of migratory fish and to comply with TDG water quality standards. Operational changes were evaluated at some projects based on field data studies. Revisions to spill patterns were found to provide minimal gas reductions. Never the less, reductions of 1 to 2 percent TDG supersaturation can be attained for the four Snake River projects by spilling evenly across the deflectored bays. The even spill distribution should only be implemented at night due to concerns for interfering with adult attraction flows during the daytime. The other projects need to be evaluated after additional field data has been collected. A team of hydraulic, structural, biological, and gas transfer experts examined the structural alternatives for potential gas reductions, discharge capacity, fish passage, fish survivability, constructability, operation and maintenance concerns, and impact to total project discharge capacity. Based on field studies of the existing projects, a shallow stilling basin and tailrace were found to be the key attributes for lower TDG production. Deflectors also provide significant gas reductions within a specific range of discharge and tailwater conditions. The recommended structural alternatives include deflectors, a raised stilling basin, and a raised tailrace. These alternatives should provide significant reduction in TDG production at the eight study projects. However, further analysis is required in order to estimate TDG reductions, associated fish exposure, and survival rates of fish passing through the structures. These benefits need to be analyzed at each project and on a system-wide basis.

Numerical Model Development. The Columbia River Salmon Passage (CRiSP) model was found to be the most suitable of the existing numerical models of the river system for analyzing system-wide effects of gas abatement alternatives. The model can be used to analyze system-wide gas reductions and fish survival. Recalibration of the model is necessary in order to accurately represent TDG concentrations and fish in the river system. The recalibration will depend on new research and data. The model will be used in Phase II to assess the system-wide gas reductions and biological benefits that can be accomplished with structural and operational changes at specific projects. Development of the model began during Phase I but is not yet complete. The current status of the model is presented in this report.

Field Studies. In order to develop a model that represents the river system, TDG production and the spatial and temporal distribution as it is transported downstream must be understood. This requires specific data beyond what currently exists. There was essentially no existing data regarding the spatial distribution of TDG in the river system prior to the field studies performed under the DGAS. Only FMS single-location measurements of TDG were available from which to infer the temporal characteristics of TDG concentrations that are linked to the highly dynamic operation of the river. To remedy the shortcomings of available data, extensive field studies were performed during Phase I and will continue into Phase II. Spillway performance tests were performed in order to determine the TDG concentration produced during spill at each project for a range of spillway gate openings. Transect data was collected throughout the river system to help understand the spatial and temporal distribution of TDG. Biological studies are being performed to better delineate the direct biological effects of GBT on fish survival. Two areas that need additional refinement include a better understanding of the range of complex exposure histories and the relationship of the exposure histories to mortalities. All of the field data is in support of the numerical modeling efforts, predicting TDG characteristics of the structural alternatives, and determining the biological effects of reducing TDG in the system based on implementing gas abatement alternatives.

Fixed Monitoring System (FMS). An analysis was performed to assess the Corps FMS's ability to represent TDG in the river system. The analysis was based on transect data collected near the fixed monitor sites. In general, the analysis found that forebay fixed monitors are highly representative of forebay TDG concentrations. However, the system is inconsistent in representing tailrace TDG concentrations. The analysis found that most of the tailrace fixed monitors on the Snake River projects' represent the highest TDG concentrations from the spillway discharge. However, the tailwater monitors on the Lower Columbia are inconsistent in what they represent. The concentrations these tailwater monitors represent are highly dependent on project operations. The operation of these projects are highly variable with significant changes in spillway discharge and spill patterns on a twelve-hour cycle. Matters are complicated even more because the monitors are inconsistently located with respect to the projects' spillway. The McNary tailrace monitor typically represents peak TDG concentrations from spillway discharge; the Bonneville monitors represent variable degrees of mixed TDG concentrations from powerhouse and spillway discharge; The Dalles monitor represents varied degrees of mixed TDG concentrations or sometimes only low TDG concentrations from the powerhouse releases; and the John Day monitor represents peak spill or varied degrees of mixed powerhouse and spillway TDG concentrations. For the DGAS model development, average TDG concentrations across the river are needed and maximum TDG concentrations resulting from spill are needed. The average data is needed for calibration of the mixing and transport portion of the numerical model, and the peak data is needed to calibrate the spillway TDG production portion of the model. This data cannot be collected with sparse longitudinal fixed monitors.

The overall quality of the FMS data set is also of great concern. A thorough evaluation of the CROHMS data base found that a substantial number of data points were completely missing, and a substantial portion of the existing data were highly suspect. To be useful, the data base should only include data that have been reviewed for errors. Specific recommendations for improvement to the FMS and CROHMS data base are included in this report.

Recommendations. This report presents the knowledge gained throughout the Phase I of this study and the current status of major components of the study. The recommendations include minor changes in spillway operations, continuation of the current plan to install deflectors at John Day and Ice Harbor, and continuation of the Phase II Dissolved Gas Abatement Study.

The goal of Phase II is to recommend structural modifications to reduce TDG supersaturation generated during spillway operation at the eight Lower Snake and Columbia River dams as much as possible. Based on the results of Phase I, the original goal of meeting the 110 percent TDG water quality standard for up to a ten-year event appears to be unattainable. However, the alternatives recommended in Phase I will provide significant reductions. Specific estimates of reductions attainable for each alternative will be reported as soon as they are available. The recommendations of Phase II will be supported with estimates of TDG reductions and biological benefits on a system-wide basis. The Phase II Plan of Study includes detailed alternative analyses to estimate the gas reductions attainable through implementation of the structural alternatives and to estimate the fish survival associated with each alternative. A prototype test will be essential to confirm estimated gas production and biological benefits. The alternatives will then be analyzed using a numerical model to estimate to estimate gas reductions and increased fish survival on a system-wide basis. The numerical model required for this analysis does not exist yet. Development of the model began during Phase I and will be completed in Phase II. A substantial amount of research is required and will be performed during Phase II in support of the numerical model development. The field research includes water quality data collection to identify TDG production, transport, and dispersion; biological studies to understand affects of TDG exposure on fish; and physical model studies to understand the hydraulic action at each project and of each gas abatement alternative. Regional coordination will continue throughout the study to report progress and new findings. Based on the current schedule, the study will be completed in the year 2000.

Notes: The objective of this report is to provide a comprehensive analysis and summary of structural and operational changes made by the Corps to reduce total gas supersaturation in the Lower Snake and Columbia River; essentially a program to manage total dissolved gases. The report is a response to spilling at eight Lower Columbia and Lower Snake River Dams to improve survival of downstream migrating smolts. The report contains explanation of structural alternatives considered for dissolved gas reduction in spillways, stilling basins, and tailraces below dams. Provides background information on Gas Bubble Disease in the Columbia River. Includes a stilling basin modification study at John Day and Ice Harbor Dams, and a summary of dissolved gas abatement studies in 1995.

Like the U.S. Army Corps of Engineers Walla Walla District (1994), this report incorrectly identifies the Iwamoto et al. (1994) document as a source of comparing spillway survival between bays with deflectors and bays without deflectors at Lower Monumental Dam The correct source of that information is Muir et al. (1995). Like U.S. Army Corps of Engineers Walla Walla District (1994), this review contains a section on the effects of spillway deflectors or "flip lips":

Study cited	summary
Johnsen and Dawley (1974)	survival was 4-5% less in spillway bays with flow deflectors compared to spillway bays without flow deflectors
Iwamoto et al. (1994)	survival was 4-5% less in spillway bays with flow deflectors compared to spillway bays without flow deflectors
Long et al. (1975)	survival was 73% in spillway bays without flow deflectors compared to 98% in spillway bays with flow deflectors
Ruggles and Murray (1983)	critical factor may not be the deflector, instead it depends on the type of energy dissipation structure
Bell and DeLacy (1972)	injuries occur where sharp differences in flow are present, such may be the case with flow deflectors and the survival rates may depend on the amount of flow moving through a spillbay.

Status: Copy in house

Reference Type: Technical Report
Record Number: 94
Author: Washington Department of Fisheries
Year: 1956
Title: Research relating to mortality of downstream migrant salmon passing McNary Dam
Agency: Washington Department of Fisheries for the U.S. Army Corps of Engineers
Division: North Pacific Division
Date: November 1956
Report Number: In Progress Report on Fisheries Engineering Research Program North Pacific Division Corps of Engineers, U.S. Army, November 1956
Pages: 5
Relevance: Primary
Keywords: Spillway, mortality, survival
Notes: In Progress Report on Fisheries Engineering Research Program North Pacific Division Corps of Engineers, U.S. Army, November 1956.

The objective of the study was to determine whether or not a significant mortality occurs to downstream migrant salmon passing over the spillway or through the turbines at McNary Dam.

Site	head (ft)	species/age	estimated survival
McNary (1955)	80	chinook/0+	98%
McNary (1956)	80	chinook/0+	101%
combined	80	chinook/0+	100%

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Reference Type: Technical Report
Record Number: 98
Author: Washington Department of Fisheries
Year: 1960
Title: Research relating to mortality of downstream migrant salmon passing McNary and Big Cliff Dams
Agency: Washington Department of Fisheries for the U.S. Army Corps of Engineers
Division: North Pacific Division
Date: July 1960
Pages: 5
Relevance: Primary
Keywords: Spillway, mortality, survival
Notes: In Progress Report on Fisheries Engineering Research Program North Pacific Division Corps of Engineers, U.S. Army, July 1960.

The objective of the study was to conduct an over-all evaluation of McNary Dam using a structure similar to, but smaller than, McNary Dam in hopes that greater recovery rates would reduce the total number of fish needed for precise estimation of mortality.

Site	head (ft)	species/age	estimated survival
McNary (1955)	80	chinook/0+	98%
McNary (1956)	80	chinook/0+	101%
Big Cliff (1957)	90	chinook/0+	94%
Big Cliff (1957)	90	chinook/1+	99%
Combined			98%

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Reference Type: Technical Report
Record Number: 93
Author: Wright, S.G., and C.A. Dunn
Year: 1974
Title: 1973 assessment of downstream fish passage through multi-level outlet pipes at Wynoochee Dam
Agency: Washington Department of Fisheries Management and Research Division for the U.S. Army Corps of Engineers
City: Seattle, Washington
Date: January 1974
Report Number: Contract Number DACW 67-73-C-0057
Pages: 50
Keywords: Dam, mortality, outlet, fish
Abstract: During 1973, Wynoochee Dam (located approximately 40 miles north of Montesano, Washington) was studied to evaluate the unique multi-level outlet pipe system incorporated into the dam as the only means for passing downstream migrating fish species. Large scale test groups, composed of coho salmon and steelhead trout smolts, were released in the upper Wynoochee River, above Wynoochee Dam. These fish moved down the upper river and through the reservoir satisfactorily, but attraction in the immediate vicinity of the outlet pipes appeared quite poor. More than 25% of the entire coho population did not attempt to negotiate actual passage through the outlet pipes. In addition, these experimental fish exhibited and average migration delay of 1.5 months.

Small scale tests, utilizing coho and chinook salmon smolts, (released at various sites to test specific components of the facility) indicated that all experimental fish experienced significant mortalities in at least one valid test. The actual fish loss in negotiating the downstream fish passage facilities was, for coho, 14 percent. The source of fatal injury to these migrating fish was probably in the tailrace of the dam, and not in the outlet pipes themselves. In any case, the downstream fish passage system is clearly unsatisfactory and needs improvements. The full effect Wynoochee Dam has upon the fish resource will not be evident until marked adult fish returns are sampled in 1974.
Notes: The objectives of the study were to: (1) evaluate overall fish passage success; and (2) evaluate specific fish passage components and operating procedures.

Wynoochee Dam: 175 feet high, chute-type spillway, six outlet pipes.

1973 survival estimate studies based on recapture facilities

Release site	species/age	estimated survival
Wynoochee Dam outlet pipes 1-4	coho/1+	70.1%
Wynoochee Dam d/s of pool (control)	coho/1+	81.5%

A point estimate for survival of 86% was calculated, noting that most of the mortality occurs in the tailrace from a series of obstructions to discharged flow.
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