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CHAPTER 6. HYDROELECTRIC SYSTEM DEVELOPMENT: EFFECTS ON JUVENILE AND ADULT MIGRATION

> *"Dam construction presents a serious threat to the continued expansion - and indeed the very existence - of the commercial and recreational value of the Fraser River fisheries resource.... Although the fish-dam problem has existed for centuries in many countries, no practical solutions have yet been found that afford complete protection for anadromous fish in rivers obstructed and altered by large dams."*
>
> Andrew, F.J. and G.H. Geen, 1960. Sockeye and pink salmon production in relation to proposed dams in the Fraser River system. International Pacific Salmon Fisheries Commission Bull. XI. 259pp.

Development of the Hydroelectric System

Development of the hydropower system in the Columbia River basin began in the late nineteenth century on the tributaries. The first dam on the mainstem Columbia River was Rock Island Dam, completed in 1933. From 1933 to 1975, full development proceeded (Figure 1.2), to the point that Grand Coulee Dam blocked the Columbia River mainstem first in 1941, and Hells Canyon Dam blocked the Snake River in 1967. Later (1955), Chief Joseph Dam was constructed downstream of Grand Coulee Dam. There are now thirteen hydroelectric dams on the Columbia River and Snake River mainstem that are passable by salmon, five in the mid-Columbia reach (i.e., the mainstem from Chief Joseph Dam to the confluence of the Snake River), four in the Snake River, and four in the lower Columbia River mainstem. Two Canadian mainstem dams, as well as three on tributaries there, two projects in Montana, and one in Idaho realized as a result of a 1964 treaty, provide the primary capability for storage of water within the Columbia Basin (Bonneville Power Administration 1980). Hydroelectric power generation, flood control, and irrigation were the benefits expected to be derived from the full development of the potential of the Columbia Basin (Logie 1993). The Hanford Reach, the one remaining undammed portion of the river, was debatable as a potential dam site, due to the potential for flooding of underground storage facilities for atomic wastes at the Hanford Reservation.

Seventy dams located on tributaries in the basin are also part of the coordinated hydroelectric system. Some of these dams, such as those on the Cowlitz River, are not passable by salmon, and others, such as those above Hells Canyon Dam, lie above impassable dams. Another 128 dams on tributaries, while not part of the coordinated hydroelectric system, present passage and water quality problems for anadromous and resident fish species.

Total storage capacity of the reservoirs in the system amounts to 55.3 million acre feet (68.2 billion m^3), which is about 25 percent of the basin's average total annual runoff (Logie 1993). This capacity is used to store a portion of the spring freshet for the benefit of later power production, and drawdown in late winter and early spring for the benefit of downstream flood control and other purposes (Logie 1993). As a comparison, storage capacity in the Colorado River is about four times the average annual runoff in that system. In addition to the seasonal shifts in flow made possible by the storage capacity provided by dams in the basin, the storage capacity has made possible production of power on demand, a practice known as load following. Load following can lead to rapid and large changes in river flow as power plants are managed to take advantage of short-term markets for power. For example, many plants routinely reduce flows at night to the minimum necessary to keep turbines running that are required for plant operations. As a result, river flow can change by a magnitude of four times or more in a matter of an hour (Independent Scientific Advisory Board 1998a).

Effects of Dams on Anadromous Fishes

As the nearest large river to the north, the Fraser River stands as an example where experience with salmon is useful for comparison with experience in the Columbia. In 1960 at the behest of the International Pacific Salmon Fisheries Commission, Andrew and Geen (1960) undertook an analysis of the probable effects of hydroelectric development in the Fraser River, British Columbia on salmon production in the Fraser system. The proposed development would have involved construction of 18 dams on the mainstem and 44 dams on tributaries. They concluded that dam construction presented a serious threat to the continued existence of the Fraser River fishery and noted that no practical solutions had yet been found that provide protection for anadromous fish in rivers obstructed and altered by large dams (*see quote at beginning of chapter*). Largely on the basis of their conclusions, the Fraser River mainstem remains undammed to this day. Although their study was completed 37 years ago, their conclusion that no practical solution to the fish-dam problem has yet been found still applies, as borne out by experience in the Columbia River, which is summarized below.

Dams and Other Obstacles to Migrations of Salmon

High flows that result from natural events can present problems in passage for adult salmon. For example, it is well established that sockeye adults are unable to pass upstream through the Tumwater canyon on the Wenatchee River until spring flows decline to below about 4,000 cfs (French and Wahle 1968; Allen and Meekin 1980; Mullan et al. 1986; Chapman et al. 1995). Burgner (1991) reported that sockeye adults tend to move upstream in slower water and eddies along the stream banks. Such habitat is not available in Tumwater Canyon at flows above 4,000 cfs.

In addition to providing storage of the spring freshet for later use in long-term operations, and making possible short-term fluctuations as daily electric loads are followed, construction and operation of dams for hydroelectric power production has produced a change in flow conditions encountered by adult salmon migrating upstream. Formerly, flow was spread over the entire cross section of the river, with the volume being concentrated in a channel cut by scouring action of the river. At present, flow is usually concentrated through the powerhouse and into the tailrace. During times when flow exceeds powerhouse capacity, spillways are operated that, in most cases, but not all, split the flow away from the powerhouse. At some point downstream, water from the two sources meets to continue downstream. Passage facilities (fish ladders) for adult salmon are normally located at each end of the powerhouse and at the bank opposite the powerhouse. Usually, access to the passage is available at openings across the powerhouse. While this arrangement attempts to simulate natural conditions, it is necessary to adjust operations of individual turbines and spill bays at times to compensate for adverse flow conditions that may be produced at passage entrances under some flows (Bjornn and Peery 1992; Dauble and Mueller 1993; Mendel et al. 1994). The Fish Passage Center annually produces a plan for adult passage for each project on the mainstem Columbia and Snake rivers. It includes measures specific to each project, that are designed to optimize conditions for passage of adults (Fish Passage Center 1994).

In some tributaries, irrigation removals have created problems for passage of adults. For example, low flows at the mouth of the Yakima River below Rosa Dam during the summer months lead to high water temperatures that are a barrier to passage of adult salmon. The same occurs for sockeye (and perhaps chinook) in the Okanogan River, and elsewhere. This is discussed further in the section on habitat. Another example among many, is the Umatilla River, where flow in the lower river is insufficient to provide passage for salmon.

The typical mainstem dam on the Columbia River presents challenges to the migrations of both adult and juvenile anadromous fishes. The mainstem dams are for the most part around 100 feet high, although Rock Island Dam is about 50 feet high. In contrast, Grand Coulee and Hells Canyon dams are over 700 feet high and are impassable to fish. Adult salmon and steelhead moving upstream from right to left in Figure 6.1 may pass the project by way of fish ladders or by way of the navigation channel in those dams equipped with one (the mid-Columbia dams are not so equipped). Careful adjustments of flow and other characteristics of the ladders are required to keep them functioning properly. For example, changes in elevation of the forebay or tailrace require corresponding adjustments in the ladder. Levels of spill at some projects may produce conditions in the tailrace that create irregular patterns of flow that can confuse adults attempting to find ladder entrances. Many of these adjustments are now computerized.

Juvenile emigrants, moving downstream in the direction from left to right in Figure 6.1, may pass the project by one of four basic routes: the powerhouse, the spillway, the navigation channel, or the fish ladders. The four lower Columbia River and four Snake River dams are equipped with turbine intake screens that divert juvenile salmon away from the turbines into bypass systems. Juvenile salmon migrating downstream past those projects with fish passage facilities for juveniles may use several routes. They either pass through the turbines, spillways, turbine intake bypass systems, navigation locks, or ice and trash sluiceways, which have been modified for fish passage. A few juvenile salmon may pass by way of fish ladders designed for adult passage, but these are not designed, located, or operated in ways that will attract juveniles.

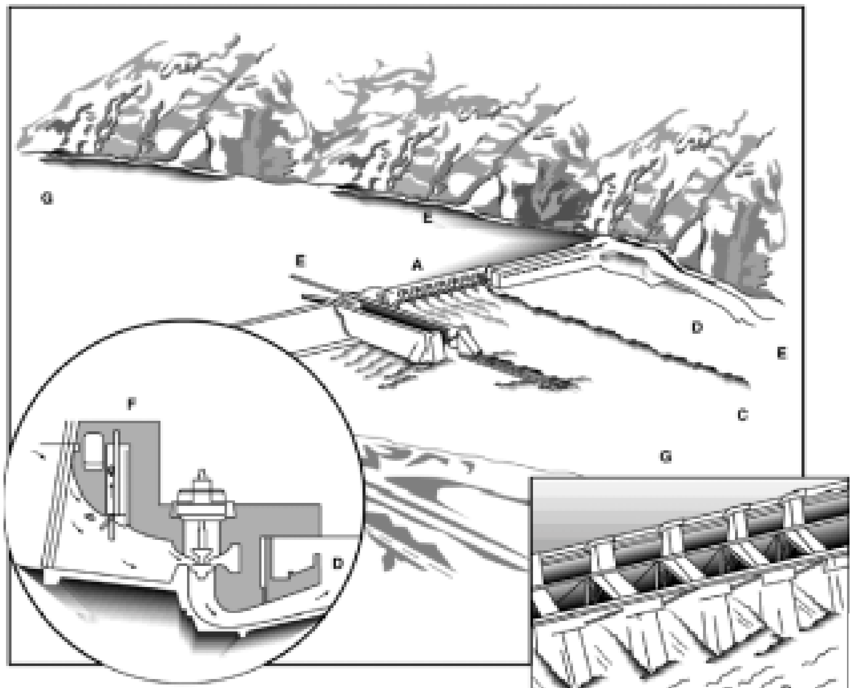

Figure 6.1. Diagram of a typical hydroelectric dam in the Columbia River Basin.

> The figure shows the spillway (A and inset B), the powerhouse to the right of the spillway, powerhouse cross-section (area F in the circular inset), and the navigation lock (E) to the left of the spillway (not present in mid-Columbia dams). In the powerhouse cross section, fish are shown moving up into a bypass inside the powerhouse, while the water continues on through the turbine. The diagram also shows the powerhouse tailrace (D), the adult fish ladder exit and entrance (E on the right), and navigability (G).

Other Effects of Dams on Spawning of Anadromous Fishes

Maturing salmon typically ascend freshwater streams where they deposit their eggs in gravel of suitable size. In the case of sockeye, some populations also may spawn in near-shore areas of lakes, where spring water provides the interstitial water movement in the gravel required for successful incubation of eggs. Survival of eggs and alevins depends upon movement of clean water of suitable temperature and oxygen content through the permeable gravels in which the redds are constructed. Specific requirements for flow, permeability of gravel, and effects of temperature on development may be found in Salo (1987), Groot and Margolis (1991), Meehan (1991), and Rhodes et al., (1994).

Some stocks of chinook are adapted to spawn in the mainstem of the Snake and Columbia rivers. Other stocks of chinook and the principal stocks of other species of salmon have life histories adapted to spawning and rearing in the tributaries. Observations of chinook spawning in the mainstem indicate that velocity of flow may be more important than water depth in determining location of their spawning (Chambers 1955). Chinook have been observed spawning in water as deep as 30 or 35 feet (Chapman 1943; Chambers 1955; Meekin 1967; Chapman et al. 1983; Garcia et al. 1994). While the areas in the reservoirs are no longer suitable due to low water velocities, chinook have been observed spawning in the tailraces immediately below most Columbia and Snake river mainstem dams (Horner and Bjornn 1979; Dauble and Watson 1990; Garcia et al. 1994).

Chambers observed chinook that spawned in water velocities ranging from 2.75 - 3.75 ft./second, with very few above 3 ft./second. Bovee (1978) developed probability-of-use curves for chinook spawning in various water velocities. His curves indicate spawning is most likely to occur at velocities between 0.67 ft./second and 4 ft./second. At Vernita Bar, velocities on the spawning grounds varied with flow, but were probably chosen by the fish at low flows when velocities were in the range of 1-2 ft./second (Chapman et al. 1983). (Connor et al. 1995b) cite Groves (*in press*) as determining that suitable velocities for spawning of fall chinook are 1.3 - 6.6 ft./second. Suitable substrate is also necessary. In the normal Columbia Basin stream, substrate size will be affected by velocity.

The Hanford site, where the fall chinook salmon population is presently most successful, has the most intact habitat and ecological processes of any mainstem site in the Columbia basin. It is characterized by broad gravel spawning bars primarily about 5-12 km (3.1-7.5 miles) and 40 km (25 miles) downstream of Priest Rapids Dam that are occupied in October-March by thousands of salmon constructing their redds (Dauble and Watson 1990). Annual spawning surveys were conducted by D. Watson beginning in the 1940s. Bauersfeld (1978) and Chapman et al. (1983) have characterized the effects of gravel size and flow regimes for the most densely occupied spawning area at Vernita Bar. These redds generally lie upriver of a 48-km (30-mile) zone of islands, side channels, backwaters, and sloughs that extends to the city of Richland (especially the White Bluffs, F-Area, and Hanford townsite areas). These diverse habitats provide a mixture of critical rearing, resting, and feeding areas for juvenile chinook salmon and are without a doubt, a key component in the success of the Hanford Reach fall chinook.

Dams in the mainstem inundated areas formerly used for spawning by chinook and perhaps other salmonids. The reservoirs created by the dams reduced the area where suitable water velocities and substrate are to be found. At present, the main salmon spawning in the mainstem Snake and Columbia rivers above Bonneville Dam is the ocean-type fall chinook salmon (Healey 1991), although there were other stocks that spawned on mainstem gravel bars in the past (Fulton 1968; Lichatowich and Mobrand 1995). The basin's healthiest population is in the mid-Columbia in the undammed Hanford Reach (Dauble and Watson 1990). The remaining mainstem-spawning populations are now confined to small numbers of fall chinook salmon that spawn in the tailraces of each of the dams on the mainstem Columbia and Snake rivers and the main channels of some lower Columbia River tributaries. (Horner and Bjornn 1979; Dauble et al. 1989; Garcia et al. 1994, M. Erho, personal communication). Other, troubled populations spawn in what remains of the undammed Snake and Clearwater rivers (Garcia et al. 1994) between Lower Granite Reservoir and migration-blocking storage dams (Hells Canyon Dam on the Snake River and Dworshak Dam on the Clearwater River). Before Brownlee and Hells Canyon dams were constructed beginning in the late 1950s, fall chinook salmon spawned in the mainstem Snake River well above the dam sites (Krcma and Raleigh 1970). By the time Brownlee Dam was built, salmon had already been blocked from the upper reaches of the Snake River by hydroelectric and irrigation dams that date back to as early as 1901 (Swan Falls).

In the unimpounded Snake River above Lewiston, Idaho, chinook salmon spawn in scattered redds at rapids between river kilometer 238.6 (head of Lower Granite Reservoir) and 396.6 (Hells Canyon Dam). They also spawn in the lower Clearwater River. There is more suitable spawning area than spawning activity (Connor et al. 1994).

In the Snake River, there are several tributaries with productive spring chinook salmon populations, although populations are in decline and the stock is listed as endangered. One of the most far-removed tributaries from the ocean is the upper Salmon River in Idaho, which is still a major natural salmon production area (Kiefer and Lockhart 1995). Before construction of Brownlee and Hells Canyon dams beginning in the late 1950s, spring chinook salmon spawned in Eagle Creek and the Weiser River, both upstream tributaries to the Snake River (Krcma and Raleigh 1970). In the mid-Columbia River, there are naturally reproducing populations of spring chinook and summer chinook that are not abundant. A large number of yearling chinook juveniles come from upper Columbia River hatcheries (Dauble et al. 1989). Spring chinook salmon also occur in the Willamette and Yakima rivers.

In the 1970s, the importance of load following during chinook spawning that led to exposure of redds and incubating eggs in the Hanford Reach became appreciated (Watson et al. 1969; Bauersfeld 1978; Chapman et al. 1983). Because of the great importance of this spawning area, studies were conducted which led to identification of flow control measures that could improve spawning success. The result was a long-term (years 1988-2005) Vernita Bar Settlement Agreement among the fishery agencies and the power, flood control, and irrigation interests to stabilize flows. The agreement was approved by the Federal Energy Regulatory Commission (FERC) in December 1988. Recently (1999), following a recommendation of the ISAB for further study to identify measures that would protect emerged juveniles from stranding as a result of load variations, an agreement was reached to further stabilize hourly fluctuations in flow during the time when emerged fry are still in the area, preparing to migrate downstream. This has led to a reduction in juvenile mortalities caused by strandings (Douglas Ancona, Grant County P.U.D., personal communication.)

In the mainstem Columbia and Snake rivers other than in the Hanford Reach, the basin is fully developed for hydropower production to the extent that, other than in the Hanford Reach, the reservoir of each downstream project impinges upon the tailrace of the one upstream. However, even so, extreme reductions of flow have led to dewatering of redds, such as at Chief Joseph Dam in 1967 (Meekin 1967), and elsewhere in unusual circumstances, such as in reaction to load rejection[1] at a project (personal communications mid-Columbia P.U.D. biologists).

In the tributaries, rapid, large fluctuations in flow that are associated with load following have been shown to produce adverse effects on resident fishes downstream. For example, in the Kootenai River, the Proposed Recovery Plan for Endangered Kootenai River Sturgeon notes that there has been no successful spawning of this fish since Libby Dam was put into operation as part of the hydropower system. The indication is that fluctuations in flow have adversely affected reproductive success of the sturgeon. The plan calls for stable flows during the spawning and incubation period of this fish (U.S. Fish and Wildlife Service 1995). Adverse effects on other resident fishes in the Kootenai River have been documented (Perry and Perry 1991; Independent Scientific Advisory Board 1997). In the Hungry Horse/Flathead Lake basin, adverse effects on biota in the Flathead River system and downstream have been documented, as a result of which the FERC has issued an order calling for stable flows out of Kerr Dam (Stanford and Hauer 1992; Independent Scientific Advisory Board 1997).

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[1] "Load rejection" is the term used for powerhouse shutdown resulting from an unforseen problem in transmission. The lack of generation leads to containment of river flow above the dam until spill gates can be opened. As a result, water elevation in the tailrace will be lowered. FERC requires that each project have an emergency plan prepared to deal with such situations.

Rearing of Juvenile Salmon

Rearing of sockeye juveniles takes place in lakes, of which three remain in the Columbia Basin, representing about 5 percent of the lake area formerly available to them (Mullan 1986). Rearing of chum salmon is short-term, as the juveniles move downstream immediately after emergence from the gravel. Coho and steelhead typically spawn and rear in the tributaries. Chinook rear both in the tributaries and mainstem. There are two major life-history types of chinook in the basin, generally distinguished by the relative lengths of freshwater rearing (Gilbert 1912; Groot and Margolis 1991). Ocean-type chinook are usually mainstem or coastal river spawners with short migration distances to the sea, whereas stream-type stocks spawn in the tributaries, and thus have longer migration routes (Taylor 1990). Ocean type chinook exhibit a short freshwater residence for rearing (feeding and growing), usually leaving the river ecosystem within six months of emergence from the spawning gravel. Stream-type chinook, on the other hand, reside in the stream for one year or longer before emigrating rapidly to the ocean. Steelhead and coho may be thought of as exhibiting the “stream type” life history, as they typically spend a year to several years in the stream.

The amount of space available for rearing of juveniles has an effect on the rate of survival of fry, and this, of course is a function of flow. Silliman (1950), examining counts of adult chinook at Bonneville Dam, during a time prior to full development of the hydropower system (1935-45), found that volume of flow during April-May of the year of their outmigration as juveniles explained 27 percent of the variability in numbers of adults returning. Considering the large number of factors that can affect the number of returning adults, he concluded that flow was a significant factor in production of chinook. Since there was little storage capacity in the basin at that time, April-May flows must have been strongly correlated with flows during the rearing phase of chinook juveniles as well as during their outmigration during the time period considered by Silliman. We have discussed the necessary features of desirable salmon habitat already. The point to be made here is that volume of flow affects the amount of available habitat and its quality. The historical record generally shows better salmon production in wet years (Anderson et al. 1996). Droughts have been particularly devastating for survival of juvenile salmonids and returns of adults in subsequent years in this and other river basins (e.g. California). A number of studies have demonstrated that production of coho smolts, and in some cases of chinook smolts, is related to average flow in the nursery stream, and varies from year to year with flow in the particular tributary (Jager et al. 1997). The effects of flow in the nursery areas are in any case difficult to separate from effects of temperature because flow and water temperature are themselves correlated. A more complete discussion of temperature effects is provided in another section of this report.

The mainstem of the Columbia and Snake rivers have both ocean and stream type chinook (Figure 6.2). Presently, ocean-type fish are represented by fall chinook salmon (and less abundant summer chinook in the mid-Columbia) that spawn in the mainstem and lower reaches of tributaries and rear (feed and grow) in the mainstem as they move slowly in spring and summer toward the sea. Stream-type chinook undergo a year or more of rearing in tributary headwaters and move rapidly through the mainstem in spring. Stream type chinook include spring chinook salmon (and summer chinook in the Snake River drainage). Coho salmon, which often rear for 2 years in tributaries, and steelhead/rainbow trout, which most often rear for 1 to 2 years, but can rear up to 7 years before leaving tributaries to migrate to sea move out rapidly in the spring along with the spring chinook (Peven et al. 1994).

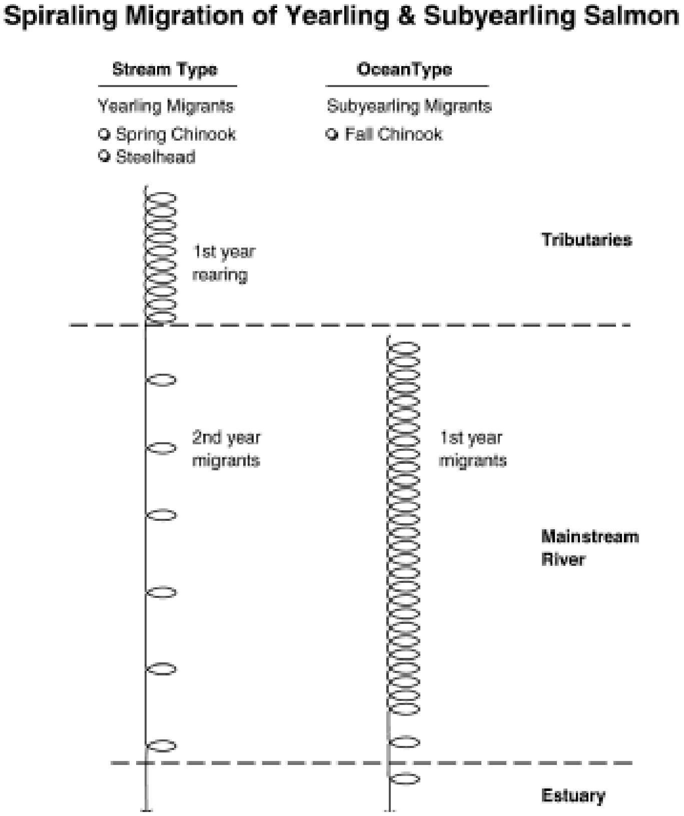


Figure 6.2. Spiraling migrations of stream-type and ocean-type salmonids showing occupancy of tributaries and mainstem, and relative amount of time spent holding and moving (spiraling lengths) in these habitats. Each spiral loop indicates a period of holding and feeding.

All of the anadromous salmonids have in common the need to migrate downstream through the mainstem. Thus the mainstem typically hosts the stream type (yearling) chinook, steelhead, and coho during the spring when river flows are normally highest of the year. Some subyearling (ocean-type) chinook may be seen at that time as well, but their peak in abundance comes later in the summer, in July or August in the mid-Columbia reach and later in the lower river.

Downstream Migration of Juvenile Salmon and Steelhead

Central to evaluation of the Council's flow-survival hypothesis for juvenile salmonids is an understanding of how juveniles migrate downstream. As we seek ways to modify the hydrosystem toward a more normative condition discussed earlier, we must have a sound scientific basis for what is normal in the lives of the fish we wish to preserve. What is their normal behavior? What habitats in the migratory corridor do they normally use and need? How has this normal behavior been altered by the hydropower system and related water uses? With much of the original landscape now missing, can we deduce fish needs by comparing environments in which stocks are doing fairly well with those where they are doing poorly?

Because so much of the debate over survival of downstream migrants has revolved around issues of travel time, the ways fish interact with water flow to accomplish their downstream movement is important. Are they simply passive particles being flushed downstream? If so, then water travel time may be preeminent. Or is there, as seems likely, a more complex behavior? Are fish selecting particular portions of the migratory corridor (large-scale spatial complexity)? Are they orienting to particular hydraulic features of the moving water (fine-scale spatial complexity)? Are they moving at different times of day (temporal complexity)? What are the differences in these behaviors that constitute inter- and intra-specific diversity? How do our existing and proposed hydropower mitigation schemes such as intake screening, flow augmentation, reservoir drawdown, dam breaching, surface bypasses (among others) fit with the normal fish uses of their environment? This section briefly discusses our rather primitive understanding of fish migration behavior during downstream migration for the purpose of evaluating mitigation alternatives.

Surface Orientation

Most studies of juvenile salmon migration in rivers and reservoirs have shown a surface orientation during movement. Smoltification is accompanied by a transition to more pelagic behavior and surface orientation (Schreck 1984). Netting of fish in the unimpounded mainstem Snake and Columbia rivers showed a predominantly surface orientation (Mains and Smith 1963; Dauble et al. 1989), as did studies in Snake River reservoirs (Smith 1982).

Early studies of passage at dams showed accumulation of fish at the surface in dam forebays and a preference for surface outlets (Andrew and Geen 1960; Smith et al. 1968; Coutant and Whitney 2000). The development of fish bypasses at Columbia basin dams was influenced greatly by observations that fish drawn into deep turbine entrances sought to return to the surface through gatewells (Long 1968b; Marquett et al. 1970; Bentley and Raymond 1976). The natural surface orientation of juvenile salmonids, especially at dam forebays, is presumed to be a principal reason why a surface flow bypass at Wells Dam on the mid-Columbia River has been so successful at passing fish (Johnson et al. 1992).

Numerous studies have shown that juvenile salmon do not readily find their way downstream past dams with deep outlets (Whitney et al. 1997; Coutant and Whitney 2000). This was the primary factor in failure of fish passage facilities at Brownlee Dam on the Snake River, as well as at a number of other dams in the Basin (see the additional discussion in Chapter 7 of juvenile fish passage facilities and mitigation activities at the dams).

Daily Migration Cycles

There is an abundant literature demonstrating alternating movement and holding periods by migrating juveniles within a daily cycle. Northcote (1984), in summarizing research on the mechanisms of fish migration in rivers, noted that most downstream movement is not constant, but nocturnal except during periods of high turbidity. Jonsson (1991) reviewed the effects of water flow, temperature, and light on fish migration in rivers and noted that many authors have found downstream migrations to occur mainly during darkness. When migration is not completed in a single night, as it might be in coastal rivers, the migrants occupy holding areas during daylight (McDonald 1960; Hartman et al. 1967; Solomon 1978; Hansen and Jonsson 1985). These observations have often been confirmed experimentally; see references in Jonsson (1991).

Daily cycles are evident in the Columbia River Basin. Mains and Smith (1963) identified diel periodicity in studies of the undammed Snake and Columbia rivers in the 1950s (Figure 6.3). There was a notable diurnal periodicity when juvenile salmonid passage was examined at John Day Dam in 1986 (Jonsson et al. 1991). Most juveniles (chinook yearlings, chinook subyearlings, steelhead, coho, and sockeye) were caught between sunset and sunrise (Johnsen et al. 1987, Figure 6.4 a-e). Although perhaps an artifact of dam passage, the similarity to movement in the undammed reaches studied by Mains and Smith (1982) suggests this is an innate behavior. Laboratory flume studies with fall chinook subyearlings show day-night differences in tendency to be displaced downstream in changing water velocities (Nelson et al. 1994). This was also seen in New Zealand subyearling chinook salmon (Irvine 1986), indicating an innate basis for nighttime movement.

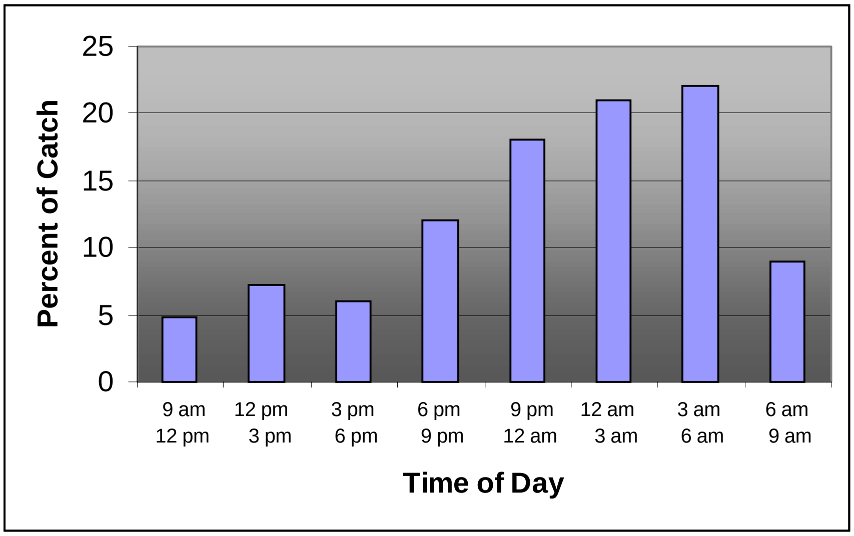


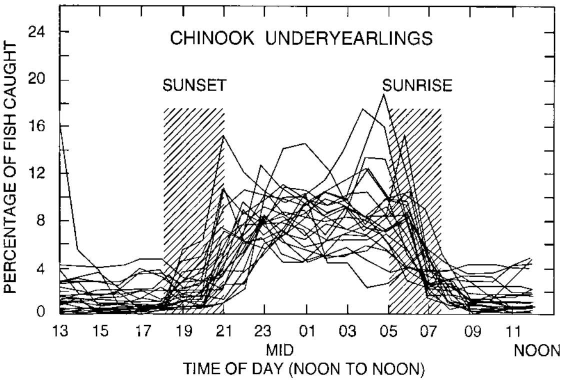
Figure 6.3. Diel patterns of seasonal chinook salmon catch per unit volume in experimental fyke nets placed in the unimpounded Columbia River at Byer's Landing (near Richland, Washington) in 1955 by 3-hr periods (Mains and Smith 1963).

Use of Flow Dynamics in Migration

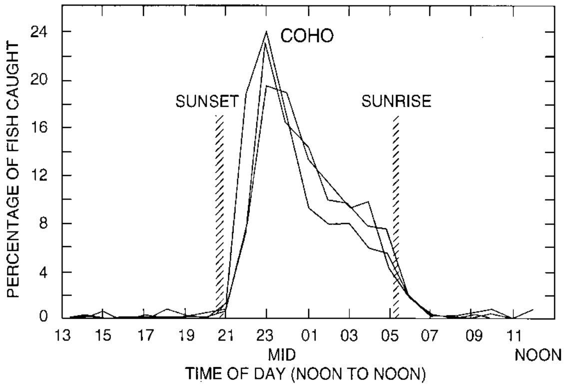
There is increasing evidence that juvenile salmon make use of certain features of flow hydrodynamics in their migration (Coutant 1998). For example, accelerating flows appear to foster fish movement. Wild and hatchery yearling chinook salmon and steelhead at the Salmon River and Snake River traps and steelhead at the Clearwater trap show increases in sample counts during and shortly after flow increases (visual inspection of graphs) (Fish Passage Center 1994; Buettner and Brimmer 1995).

The fluid dynamics literature for rivers suggests many features that may be used by migrating salmonids to assist their migration. These features include surges or stage waves, turbulent bursts, and vortices. Presently though, the advanced development of hydrodynamic theories and practices has not been matched by parallel studies in fish behavior.

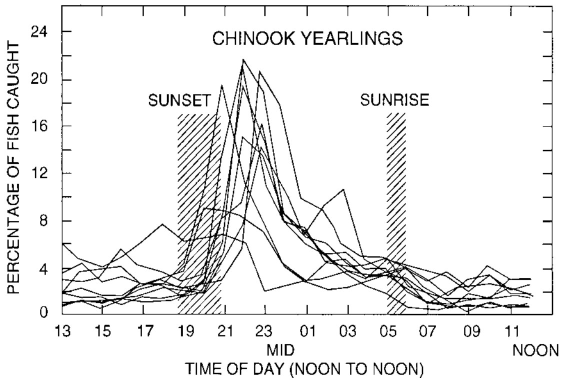
A) Underyearling chinook, May 18 - October 26, 1986.



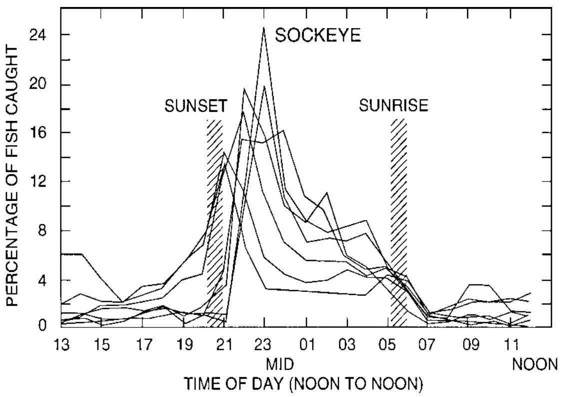
D) Coho, May 18 - June 8, 1986.



B) Yearling chinook, April 6 - June 15, 1986.



E) Sockeye, April 27 - June 15, 1986.



C) Steelhead, April 6 - June 15, 1986.

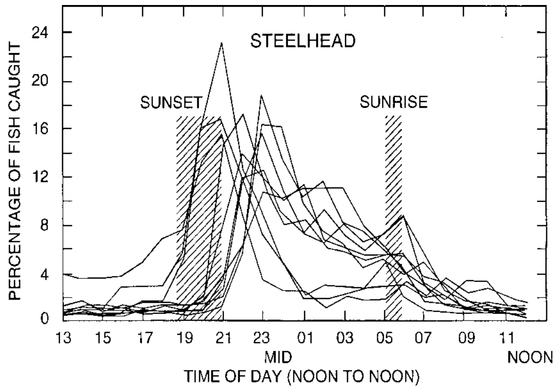


Figure 6.4. Composites of weekly diel patterns of the passage of juvenile salmonids through John Day Dam in 1986, as measured by gatewell counts (Johnson and Wright 1987): A) subyearling chinook salmon; B) yearling chinook salmon; C) steelhead trout; D) coho salmon; and E) sockeye salmon.

The somewhat confusing literature on juvenile salmonid responses to flow (rheotaxis) might be clarified if the focus of attention were to be directed to the fluid dynamic structure of flows as orienting mechanisms. The effectiveness of flow baffles for guiding fish at certain spill sites (e.g., Wells Dam) are likely the result of inducing features of fluid flow that are naturally important for fish migration. Future studies of these factors might suggest ways that flow structures in bypass structures and dams forebays might be modified in ways that assist guidance of migrants.

Downstream Migration: Active versus Passive

Downstream migration of juvenile salmonids is more complex than their simply being washed downstream by river flows. Once migration is initiated, downstream migration is more aptly characterized as a discontinuous movement rather than as the continual linear progression characteristic of a water particle (Figure 6.5).

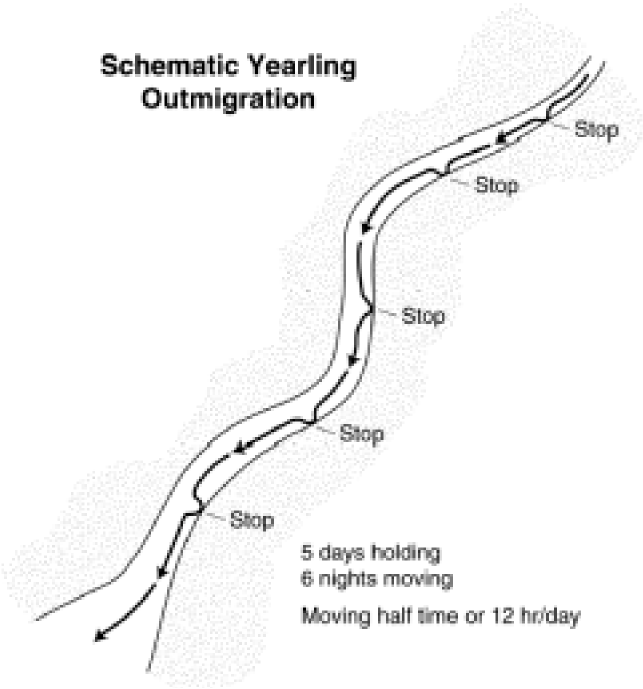


Figure 6.5. A conceptual view of juvenile salmonid downstream migration, which involves periods of movement in the mid-channel followed by stops, which are periods of resting and feeding along shorelines and in backeddies.

Physiological and behavioral changes in most anadromous juvenile salmonids cue their increased tendency to move downstream. Larger juveniles approach a time when they are ready to move from the system. There is a large but rather inconclusive literature concerning the environmental and biological cues that stimulate migration (Groot and Margolis 1991). Several studies have shown a general relationship between increased size of juvenile salmonids and selection of greater water depth and/or current velocity (Dauble et al. 1989), although these studies have generally been made in small streams rather than mainstems of large rivers. Fish in deeper, swifter water of tributary streams would thus be more readily transported downstream passively.

When young salmon reach a certain size (or receive other cues, such as length of day), they also transform physically (silvery color, deciduous scales, and change in body shape), physiologically, and behaviorally from the parr stage to the smolt stage that is better adapted to make the transition to saline water, a process referred to as "smoltification" (Hoar 1976). On the other hand, there is evidence that the process of moving downstream can itself lead to development of the characteristics associated with smoltification (Beeman et al. 1990).

Along with the characteristics mentioned above, these transformations include changed swimming behavior and proficiency, lower swimming stamina, and increased buoyancy that also make the fish more likely to be passively transported by currents (Saunders 1965; Folmar and Dickhoff 1980; Smith 1982). In general, the smoltification process is timed to be completed as fish are near the fresh water-salt water transition. Too long a migration delay after the process begins is believed to cause the fish to miss the "biological window" of optimal physiological condition for the transition (Walters et al. 1978). Nonetheless, the smoltification process is usually identifiable among yearlings after the time they leave their tributary rearing areas.

The concept of migration as mostly passive, taking advantage of downstream displacements by water currents, is initially attractive for fish in the Columbia River Basin. Hoar (1954) favored the idea of passive migration of sockeye and coho salmon, which he reasoned were carried by currents when their heightened activity at migration time brought them to zones of water movement. Smith (1982), using experimental observations of coho salmon, supported the idea of fish orienting mostly head-upstream during emigration while drifting seaward. Recent laboratory flume experiments by Nelson et al. (1994) confirmed swimming behavior by chinook salmon subyearlings at about one body length per second (bl/s) heading into the current during downstream displacement. This behavior, in experimental fish taken from migrating populations in McNary pool and McNary and John Day dams throughout the main 4-month migration period, would allow fairly passive displacement. Passive migration has been the predominant view for Atlantic salmon that migrate from Scotland (Thorpe and Morgan 1978; Thorpe et al. 1981) and Maine (McCleave 1978). Thorpe (1982) reasoned that there should be little biological advantage in a migrant expending scarce energy resources by actively swimming. High water discharge in rivers correlates with downstream movement of juveniles in a variety of fish species (Jonsson 1991).

Passive displacement may account for downstream movement, but this seems insufficient for explaining the full migratory behavior of juvenile salmonids. Active downstream movement of sockeye salmon fry after hatching was observed and even attributed to a compass orientation mechanism rather than to simply following currents (Groot 1965; Brannon et al. 1981). Complex behavioral changes both stimulate and maintain behavior (Hoar 1976). Many migration studies have involved Atlantic salmon, in which response to currents is complex, and includes a mix of passive and oriented movement (Arnold 1974). Atlantic salmon studies showed that active swimming is used for a considerable portion of the distance traveled even though it may be a small proportion of the time (Fangstam et al. 1993). Most studies just cited identified at most 6 to 9 hours of the 24 during which juveniles moved with the current at a speed more or less consistent with current velocity, often at night. There is an active process of transition between daytime feeding and nighttime movement. Smith (1982) acknowledged active swimming for only about a third of the time as a possibility in Columbia River salmon smolts. Adams (1995) found that yearling steelhead moved about 50% faster than yearling chinook salmon through Lower Granite Reservoir under the same flow rates, indicating migration mechanisms different from passive drift.

Behavior of Subyearling Chinook Migrants

The actual or probable historical distribution of fall chinook subyearlings in space and time during migration can be reconstructed from several sources. Early accounts (Rich 1920) including quantitative observations at unimpounded Hanford and Snake River sites (Mains and Smith 1963; Dauble et al. 1989), shoreline seining surveys in unimpounded reaches (Becker 1973a; Dauble et al. 1980; Key et al. 1994; Key et al. 1995), and from the estuary below Bonneville Dam (Dawley 1986), provide useful information on unimpounded conditions. Spatial and temporal distribution in the impounded Snake River is available from Smith (1974a), Curet (1993,) and Key et al., (1994; 1995) and in the impounded Columbia River at McNary Reservoir (Key et al. 1994; 1995) and John Day Reservoir (Giorgi et al. 1990).

Subyearling Migration in Rivers

Before dams, subyearling chinook salmon used the lower river throughout the summer (Figure 6.6) for a combination of rearing and seaward migration (Rich 1920). Even after dams were built, subyearling chinook salmon migrated through the reservoirs at relatively slow migration rates through the summer and into autumn (Raymond et al. 1975; Miller and Sims 1984; Johnsen et al. 1987; Giorgi et al. 1994).

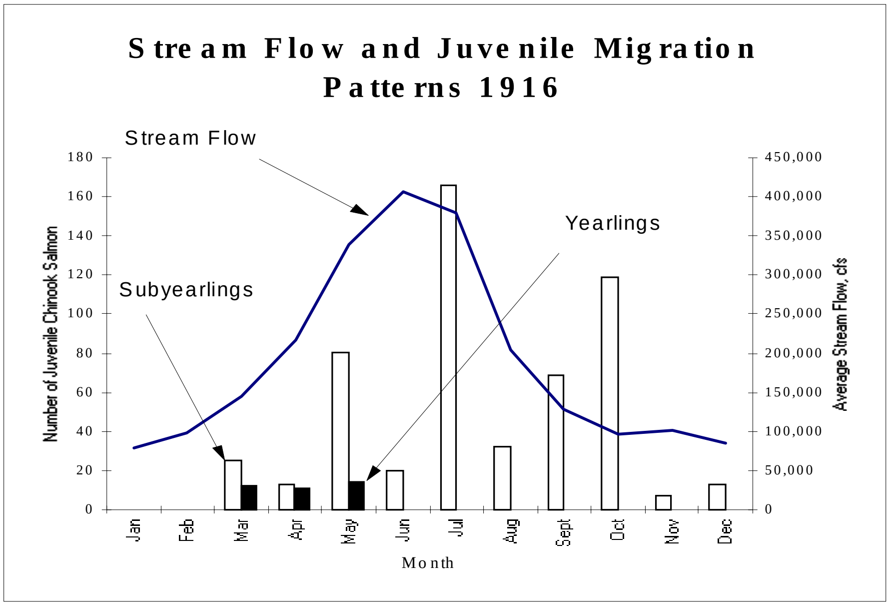


Figure 6.6. Stream flow and juvenile migration patterns from 1916 near the Dalles, Oregon. Note the relationship of the yearling and subyearling emigrations to the natural hydrograph and the ten month duration of the subyearling emigration period (Rich 1920).

There has been concern over the demonstration that the time of seaward migration has been lengthened by the effects of lower water velocities in reservoirs than found in unimpounded river conditions (Raymond 1968; Park 1969; Raymond 1979). The lengthened migration times coincide with general population declines of Snake River fish. Temporal patterns of counts of fish passing dams has provided most of this information; there has been little investigation of what behavioral changes may have occurred to the fish in the reservoirs during the delay. The importance of this delay for survival is unclear. Giorgi et al. (1990) have attempted to consolidate some of this information for John Day Reservoir.

The use of shoreline habitats by juveniles is well demonstrated at Hanford and is probably a key component in the success of that stock (see Figure 6.7 and discussion of shoreline habitats in Chapter 5). Subyearling chinook salmon fry drift downstream throughout the river cross section in March-May after they emerge from redds (Dauble et al. 1989; Key et al. 1994; 1995) and move to shoreline areas where they begin to rear.

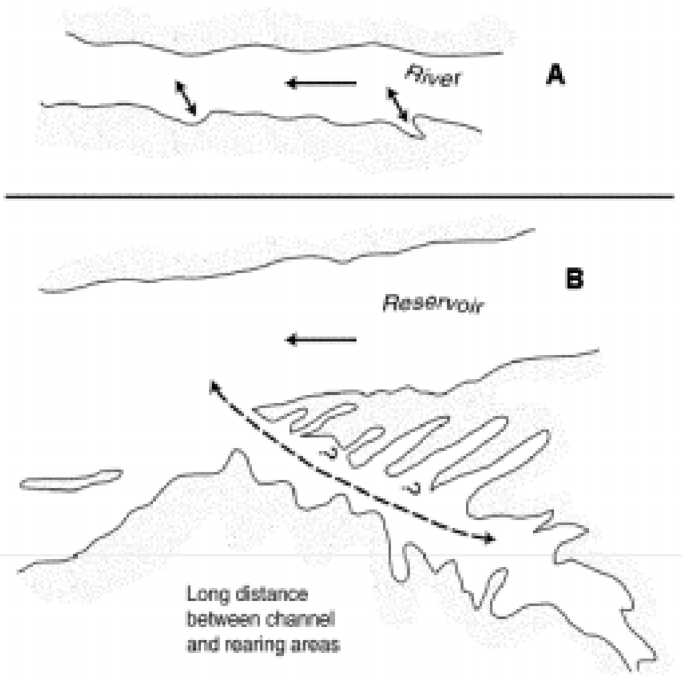


Figure 6.7. Proximity of holding and moving habitats for juvenile salmonids in (A) the natural river, where coves and backeddies are near the main channel, and (B) a reservoir, where flooded tributaries or old river channels create long distances between shoreline feeding locations and the main channel.

Young chinook parr occupy large expanses of shoreline areas of reduced current velocity (Dauble et al. 1989; Key et al. 1995) where they feed primarily on emerging chironomids and terrestrial insects (Becker and Coutant 1970; Becker 1973a; Dauble et al. 1980). Shoreline or bank aggregations of early chinook salmon juveniles have been observed in other systems, with deeper water used as fish grow, e.g., Big Qualicum River, BC (Lister and Genoe 1970). Production of aquatic chironomids and terrestrial insects dropping into the water is probably facilitated in the Columbia River Basin by rising waters of the freshet which inundate large areas of gently sloping cobble bars, sandy shores, and vegetated riparian zones of sloughs and high-water channels (see Figure 6.7 and discussion in Chapter 5). Because laboratory studies have shown that chinook salmon feeding rates were highest in moderate turbidities and low in clear water (Gregory and Northcote 1993), the turbidity of freshets was probably also important for rearing.

There is a daily cycle of movement. The chronology of subyearling chinook movement through the nearly 90-km Hanford reach can be deduced from catches in fyke nets suspended at different depths across the river cross section and shoreline seining and electrofishing (Dauble et al. 1989). Fish move downstream gradually in a diurnal cycle, feeding in shallows in the daytime and moving downstream in deeper, swifter water at night. Peak fyke-net catches in the channel occur at 2200 to 2400 h with fish distributed throughout the water column, particularly during the later phases of rearing and migration (Dauble et al. 1989). Fish collections identified an activity pattern that included migration, feeding, and resting periods. Much of the pattern seems to be daily, although an individual fish could spend more than one day in a shoreline area. This rearing-migration pattern both moves the fish downstream (at night) and to the shoreline during the day, where ample food exists for sustained growth. Because the Hanford reach is undammed, and flows are regulated for their benefit, the present pattern of juvenile fall chinook salmon distribution may approximate the historical condition. Chapman et al. (Chapman et al. 1994a) referred to the phenomenon as “zigzagging.” The behavior pattern was described in detail by Hillman and Chapman (1989). We referred to the pattern as ”spiraling” in the prepublication draft of *Return to the River* (see Figures 6.2 and 6.5).

Hatchery-released fall chinook salmon smolts may be less oriented to shorelines than are wild fish. They were less abundant in nearshore areas than were wild fish in studies at Hanford (Dauble et al. 1989). These artificially-reared fish may be less inclined to alternate between feeding and migrating, at least in the initial weeks following release from Priest Rapids hatchery just upstream of the Hanford reach. This behavioral difference may be significant in determining relative survival during emigration.

Subyearlings in the Snake River

Snake River fall chinook salmon emerge from the gravel later than at Hanford, with peaks occurring in late April to late May (Connor et al. 1995a; Connor et al. 1995b). They rear in nearshore areas from mid -March through mid-July both here and in the Clearwater River, depending on emergence dates, with a mid-May to mid-June peak. Fish appear to concentrate in particular shoreline areas and stay there for some time, based on high percentages of recaptures of tagged fish (Connor et al. 1995a). As water warms and flows begin to decline, rearing fish move downstream. Since 1991, flow augmentation from Hells Canyon Dam has been used to assist these fish in moving past Lower Granite Dam during the summer. Migration past Lower Granite Dam of PIT-tagged fish has sometimes been protracted (into early September) but sometimes truncated by late July. These studies, which are continuing, have not yet sought daily patterns in movement.

A daily pattern of downstream migration of subyearlings was documented in the Snake River before it was impounded. Mains and Smith (1963) observed a pattern that was similar to that at the Hanford Reach. During their study, most migration occurred at night, although there seemed to be some subyearlings moving downstream in the main channel at all times of day. They did not examine diurnal patterns of horizontal distribution, but noted high overall catches near shore, where shoreline proximity, not velocity, was stated as the main factor. Daily patterns were also evident in catches of fall chinook subyearlings emigrating downstream in the Snake River as it entered Brownlee Reservoir in the 1960s, before this population was extirpated (Krcma and Raleigh 1970). This stock migrated mostly from sunrise to 10 am and from 3-7 pm. Because this timing contrasts with mostly nightime migration elsewhere, there once might have been stock differences in diurnal timing.

Subyearling Migrations in Reservoirs

Early studies at dams showed that more subyearling chinook salmon moved through the dams themselves at night than in the day. In research using special bypasses at Bonneville Dam, Gauley et al. (1958) found significantly more subyearling chinook moving from 6 pm to 6 am in four out of five seasons – 1946, 1949, 1950, and 1953. Diel movement of migrating subyearling chinook salmon in the turbine intakes at The Dalles Dam in 1960 was shown by Long (1968a), where the passage at night was 60-70 percent of the daily total. The clear diurnal pattern for subyearlings was evident at John Day Dam in 1986 in all weeks from mid-May to the end of October, although there were always some fish moving during the day (Johnson and Wright 1987).

Studies in Snake River impoundments show similar behavioral patterns for subyearlings under reservoir conditions. Snake River fall chinook were captured in impounded waters upstream from Lower Monumental Dam during emigration. Migrating fish were sampled by gill nets set in relatively shallow (48 feet deep) and deep (96 feet) areas of the reservoir (but there was no sampling along shore). Most chinook (92%) were taken at night in the upper 12 feet of the central, deep portion of the reservoir (80% of these in the upper 6 feet). Few were collected in the reservoir during the day in either the deep or shallow reservoir station, suggesting that the chinook salmon were elsewhere, most likely near the unsampled shoreline. These data seem to indicate migration with a daily pattern of high abundance in upper pelagic waters of the reservoir at night (for active migration) and resting or feeding in the shoreline area not sampled in the daytime. This pattern would be consistent with observations at Hanford.

A shoreline distribution of subyearling juvenile chinook in the impounded Snake River in daytime was confirmed over several years of shoreline seining (agency reports 1986-1993 by D. H. Bennett, Idaho State University) and through three years of shoreline seining and open water trawling of Lower Granite and Little Goose reservoirs by Curet (1993). Slow-velocity, sandy shores were preferred and artificial shorelines of rock rip-rap were strongly avoided. Curet observed that fish became more pelagically oriented during the day once shoreline temperatures exceeded 18-20°C. Thus, diurnal warming of nearshore shallows could cause some change in inshore-offshore movements in reservoirs during the later spring and summer migration times. Curet (1993) linked these high shoreline temperatures to reduced feeding and higher than normal metabolic demands. He concluded that subyearling chinook appear to not just pass quickly through, but to use the shoreline and open water areas of the reservoirs for rearing before migrating farther downriver.

The Snake River and Hanford fish both share the same emigration path in reservoirs of the Columbia River below the confluence of the Snake River. Beeman et al. (1990) concluded from a study of juvenile feeding in the McNary pool (including a riverine section below Hanford, an intermediate section below the Snake River confluence, and the dam forebay) that the river and reservoirs are not used as a conduit for rapid migration; but that there is summer rearing and gradual downstream movement in the reservoir system in much the same way as these juveniles historically used the free-flowing Columbia River. Subyearling chinook salmon did not exhibit consistent downstream movement indicative of continual, directed seaward migration in studies of John Day Reservoir in the early 1980s (Giorgi et al. 1986). A majority of fish captured by purse seine, marked, and released at transects throughout the reservoir were recaptured at or upstream from the site of release. They were not consistently displaced passively downstream via the current. Although Giorgi et al. (1986) felt that their observed upstream movement was not consistent with the tail-first drift model of migration, there could be more consistency than was appreciated. A scenario can be visualized in which nighttime "drift" in the pelagic zone, alternated with shoreline feeding in the day, actually moves the fish upstream as it weakly swims against a non-existent (or very slow) current. With no orientation other than suspended objects nearby, the fish may be behaving quite normally. Flume experiments by Nelson et al. (1994) showed daytime swimming behavior could exceed the test water velocity (especially in August), thus displacing fish upstream.

Key et al. (1994; 1995) found the shoreline orientation of subyearling juvenile chinook salmon in the daytime and low numbers there at night to occur also in a slough of McNary Reservoir, just downstream of the Snake-Columbia confluence. At this point in time and space, the fish had transformed to the smolt stage. They concluded that the shoreline orientation was more related to fish behavior than to either fish size or environmental conditions (temperatures were not sufficiently high to force fish away from shallows). Their analysis of fish distribution led them to hypothesize that subyearlings in the reservoir situation now move to the bottom in intermediate depths (rather than to the channel), where they become torpid during the night. This hypothesis has not been tested by field sampling at night.

Subyearling Migrations in the Freshwater Estuary

A pattern of spatial distribution of fall chinook salmon subyearlings somewhat similar to that at Hanford was seen in the tidal freshwater Columbia River estuary below the most downstream dam, where conditions more nearly approximate the pre-dam condition (Dawley 1986; Ledgerwood et al. 1990b). Here, the subyearlings from both upriver sources and lower river tributaries were most abundant during May through September, when beach seines were the most effective gear for capturing juveniles (indicating shoreline orientation). Dawley et al. (1986) caught most fish (90%) during daylight hours with peaks during early morning and at dusk. Subyearlings caught in pelagic (open-water) habitats were larger than those collected in intertidal areas. They were in the top 3 m of the water column, and had fewer food items in their stomachs, suggesting active emigration (Dawley 1986). These larger fish tended to be from upriver sources, which suggested they had completed their rearing. Generally, feeding was most intense in the shallow, intertidal areas (McCabe et al. 1986). Subyearlings in shore areas tended to move gradually downstream as they fed in the daytime (Dawley 1986). Ledgerwood et al. (1990b) also found a clear daily pattern of abundance of subyearlings in beach seine catches, with a peak about 1.5 hr after sunrise followed by steady catches during daylight and a minor peak 1.5 hr before sunset. Night catches along the shoreline were low. Purse seine catches in the river channel peaked just before sunrise and decreased throughout the day. Generally low night catches in the channel suggested that there was no pronounced nightime movement.

Migration timing in the upper estuary and the sizes of migrants indicates a migration pattern that is not characterized by constant flushing by high flows. The annual pattern of movement of subyearlings seen by Dawley et al. (1986), in which few fish moved through the area as early as June and many moved in August, showed that these fish were not migrating with high early-summer flows.

Marked hatchery releases in the upper estuary summarized by Dawley et al. (1986) showed no relationship between rate of downstream migration and river flows, despite an earlier migration of upriver subyearlings in high water years than in low water years. There was, however, an increased rate of movement with increasing fish size. The evidence supports fish remaining in the river until reaching 7-8 cm length before entering the estuary. The trend toward later timing of migrants in the estuary (Dawley 1986) might be partially explained by a slower growth rate in the river (because of less abundant preferred food and higher than optimum temperatures), rather than changes in river velocity.

For each of these estuary studies, daytime shoreline feeding and night (or twilight) migration would seem to fit the distribution most accurately (perhaps with less night-time movement in the estuary than in upriver sites, as consistent with longer estuarine residence shown by Reimers (1973) and slower estuarine than riverine movement shown by Dawley et al. (1986). River flow and velocity seem to be little involved.

Experimental Research on Subyearlings

Experimental results on subyearling swimming behavior by Nelson et al. (1994) were more complex than could be explained by continual, passive or directed movement. Orientation into the current (positive rheotaxis) was the most common observation. As water velocities increased, the number of fish exhibiting positive rheotaxis increased. At slower velocities in the 5 to 50 cm/s range studied, fish swam upstream at rates comparable to the experimental water velocity thus maintaining their position in the flume. As velocities were increased, a threshold velocity of 25 to 40 cm/s was passed at which fish reduced their swimming to speeds of 0.5-1.5 bl/s and they were displaced downstream. This displacement was not "passive", as even during times of displacement experimental fish were never displaced downstream as far as they would have been by drifting with the current. During all trials, fish rarely drifted without locomotor control. These experimental results are consistent with a holding behavior in low flows (typical of the shoreline feeding part of a spiral) and controlled downstream displacement at high flows (consistent with the downstream movement part of a spiral). The experiments also showed that fish tended to swim slower at night, which is the normal time of downstream displacement. This change in threshold for displacement could provide the necessary twice-daily transitions for a spiral migration. The authors cite convincing literature to support a behavioral explanation for these observations rather than one based on fatigue (fish would not have become physiologically fatigued by the velocities and length of time exposed in their tests, based on published studies of salmon fatigue).

There were also hints of other relevant behaviors not yet fully explored in the tests by Nelson et al. (1994). There was one day of directed downstream swimming in late May during the normal peak emigration and a selection of highest velocities in the flume for downstream displacement during dates of most active emigration. The authors propose an increased "disposition to emigrate" during this time that would coincide with a change to lower threshold water velocities for a fish to reduce its swimming speed to the minimum orientation velocity of about 1 bl/s. Perhaps the migratory spiral for subyearlings has a seasonal change in periodicity, with a behavioral basis for a longer spiraling length at the times (related to day lengths?) of normal peak river flows.

Management Implications for Subyearling Chinook: Hanford and Snake River Stocks

The difference in success of fall chinook salmon in the Snake River and the Columbia River at Hanford provide useful contrasts that may be related to rearing and migration habitats.

The Hanford stock flourishes (Dauble and Watson 1990), whereas the Snake River stock is listed as endangered and continues to decline (National Marine Fisheries Service 1995a). Understanding differences in the habitats and behaviors that promote survivorship of these two stocks may be useful for stemming the decline of Snake River salmon. These stocks share habitat from the confluence of the Columbia and Snake rivers to the ocean, but differ in their upstream habitats. They may also differ in locations of their ocean residence, which could affect overall population success (A. Giorgi, personal communication).

Beyond differences in the amount and quality of spawning habitat available to the returning adults, the relative success of the two stocks of fall chinook may be related to the quality and diversity of mainstem habitats available to their juveniles. Hanford Reach fall chinook have access to shorelines with abundant insect food in the riparian vegetation and flooded cobble beaches, and benefit from stabilization of lows at critical periods. Snake River fall chinook, soon after entering Lower Granite Reservoir however, move to reservoir shorelines characterized by eroding soil banks or rock rip-rap, both of which are poor habitats for producing abundant insect prey (Janecek and Moog 1994). By late May or early June, shoreline waters in the Snake River reservoirs are often too warm for young salmonids and juvenile feeding must occur in pelagic waters where their preferred food is scarce. In these reaches, pelagic Cladocera, not shoreline chironomids, were the dominant food item for subyearlings, even though chironomids provided the greatest caloric value (Rondorf et al. 1990). Subyearlings shifted their diet to smaller, less preferred Daphnia species in embayments of Lake Wallula (behind McNary dam) due to the prey's higher densities and ease of capture in the pelagic environment. Curet (1993) demonstrated that juvenile fall chinook in Lower Granite and Little Goose reservoirs were not obtaining sufficient food to account for much more than basal metabolism (7% greater than estimated maintenance ration), which could be one of the factors contributing to their lack of population success.

The shoreline-feeding portion of the migration behavior may be most critical for long-term survival in the early stages of rearing and migration of subyearling chinook salmon. It is at this time when the Snake River and Hanford stocks differ most. It could be argued that superior growth and energetic reserves of Hanford fish acquired in the high quality riverine habitat of the free-flowing reach just below the spawning areas are enough to carry them through the poorer food resources of downstream reservoirs, whereas the Snake River subyearlings are impoverished nearly from the start by barren shorelines of Lower Granite and Little Goose reservoirs. Even though subyearlings are well fed and have grown rapidly in the reach below Hells Canyon Dam (Rondorf, personal communication), they may not endure the poor migration habitats of the Snake River reservoirs. This hypothesis is controversial and is presently under investigation. Studies by Muir et al. (1996) suggest that the condition of smolts emigrating out of the Lower Snake River is good, whereas recent work by James Congleton and students of the University of Idaho show physiological stress and poor condition factors for Snake River smolts, particularly for those migrating in the summer months (presentation at the US Army Corps of Engineers' Anadromous Fish Evaluation Program, 1999 Annual Research Review, Walla Walla, November 17, 1999).

As the migration behavior of subyearling chinook is better understood in relation to smoltification, parts of McNary Reservoir may be found to be critically important to survival of the Snake River stocks. From the mouth of the Snake River to nearly the Walla Walla River (a distance of about 14.5 km) the Snake River side of the Columbia River (i.e., south shore) is a series of sloughs and wetlands unlike the opposite shore (Asherin and Claar 1976). These wetlands are probably the combined result of an ancient Snake River channel (Burbank Slough) and sediments from the present Snake River confluence that have been distributed in two major sets of bars down the Columbia River. Key et al. (1995) conducted diurnal sampling of subyearling chinook salmon in Villard Slough in this complex and much of the remainder of sampling appears to have been carried out in this reach. Smolts from the Snake River appear to be drawn into these long slough areas to feed during the day, but are apparently unable to return to the channel at night to resume downstream drift. One can speculate that this trapping on the Snake River side (but not on the side occupied by flows from the upper Columbia River), in combination with the advanced state of smolt development of Snake River emigrants, could be responsible for a disproportionate loss of Snake River fall chinook at this point compared to the Hanford stock coming down the Columbia channel (along the north shore) at the same time.

The Snake River Canyon reach, which is physically dominated by the canyon itself, may never have had the ecological complexity, habitat diversity, and food web productivity that existed in the downstream lower-gradient alluvial reaches, such as the Hanford Reach. Consequently, Snake River fall chinook may have evolved mechanisms to partially compensate for naturally poor feeding habitat during emigration through the lower Snake River mainstem. Taylor (1990), in his review of 160 chinook salmon populations ranging from California to Alaska, Kamchatka, and New Zealand, indicated that increased migration distance selects for larger size at seaward migration, due to increased metabolic demands of migration. Recent research has, indeed, found the Snake River subyearlings in the unimpounded reach between Lower Granite Reservoir and Hells Canyon Dam to be larger than Hanford fish at comparable dates despite emerging later from the gravel and having more distance yet to travel (Key et al. 1994).

How much of the dissimilarity between stocks in their emergence timing and early size could be due to temperature differences has not been determined (Hells Canyon Dam discharges are warmer in winter and cooler in spring and summer than temperatures at Hanford). But despite this apparent growth rate and size advantage, the Snake River stock now does poorly.

Management Risks for Subyearlings: Passive versus Active Migration Modes

There may be risks for subyearling salmon associated with management actions based on a constant flushing model. Because subyearlings spend a large amount of time in shoreline habitats for feeding, management alternatives for the mainstem that focus on increasing water velocities in the main channel through reservoir drawdowns or flow augmentation need careful evaluation. In the early 1990s, lowering of reservoir elevations in the spring freshet season was one of the principal methods proposed for attaining high water velocities thought to be conducive to constant flushing in the mainstem Snake and Columbia rivers (NPPC 1994a; NPPC 1994b; National Marine Fisheries Service 1995a). The logic behind the seasonal drawdown proposal is that a smaller volume of water in a reservoir would translate to a more rapid movement of a unit volume of water through it, including contained fish. However, seasonal reservoir drawdowns to attain the presumed benefits of spring flows for constant flushing behavior in yearling emigrant salmon are likely to negatively impact habitat needed by subyearling salmon. Because the critical habitat for subyearling survival most likely is flooded shorelines, complex backchannels, and other vegetated habitats that are productive of invertebrate food, temporary seasonal drawdowns could be counterproductive and actively decrease food availability for emigrating juveniles. As an experimental drawdown of Lower Granite Reservoir in 1992 showed, drawdowns created long expanses of muddy shorelines that would have little or no food available for subyearling salmon during the shoreward portion of their daily migratory spiral. Moderate flooding of a stable, vegetated riparian shoreline is more compatible with the fall chinook salmon's migration behavior and ecology. In contrast to seasonal drawdowns, permanent drawdown would allow riparian vegetation to develop. Seasonal flooding of this habitat would enhance the river’s productivity during emigrations, presuming flows were stabilized to some degree.

High levels of flow, when not coupled with flooding productive shoreline areas, would appear to reduce food availability for juvenile fall chinook in the present reservoir system. Rondorf et al. (1990) observed a reduction of the present main food item, pelagic cladocerans, in midreservoir and dam forebay stations during June that coincided with peak seasonal flows. High flows apparently flushed away these planktonic food items, which were the main replacements for the insects (midges and caddisflies) eaten in the riverine section below Hanford.

Information Needs for Subyearling Chinook Salmon

1) The secondary effects of flow differences on nearshore habitat conditions of present-day reservoirs (temperature, flow, and food production) need to be measured and evaluated. These factors may be more important to fish survival than the flow (velocity) itself, and may be amenable to other solutions.

2) The effects of shoreline modifications along reservoirs (rip-rap, erosion, and permanent sloughs) compared to the riverine condition need to be evaluated. Because rip-rap is a poor producer of food for salmonids, its predominance along the reservoir system may have a major negative effect on subyearling survival. Shoreline erosion in other reaches may limit productivity. Permanent sloughs at the margins of reservoirs may warm the water, harbor predators, and restrict the natural onshore-offshore spiraling migration pattern of subyearlings.

3) There is considerable uncertainty about the effects on subyearlings of changes in river flows designed to aid yearling migrants, principally spring chinook salmon and steelhead. Effects of augmented flows and/or reservoir drawdowns on nearshore habitats also need to be analyzed, because actions that aid yearlings are probably detrimental to subyearlings.

4) The effects of augmented flows on rearing fall chinook in unnaturally cold reaches of the Snake and Clearwater rivers in spring needs study. This should include not only rearing (probably delayed) and dispersion (premature emigration) into the reservoir tailwater areas, but also the reaches of lower river into which the fish are dispersed and where they encounter overly warm water in summer.

Yearling Chinook Migrants

Most spring and summer chinook salmon from the Snake River drainage are of the stream type, migrating to sea rapidly after one year in freshwater. However, Curet (1993) notes personal observations by Idaho Department of Fish and Game personnel that some subyearlings in the Snake River are of spring chinook origin. Mattson (1962) observed three distinct migrations in Willamette River spring chinook in the 1940s – in their first spring and summer as subyearlings, in fall as a migration of subyearlings at time of heavy rains, and in spring as a movement of yearlings. Spring chinook from the mid-Columbia tributaries migrate as yearlings, as do the spring chinook reared in mid-Columbia hatcheries. There are suggestions that some stocks of spring chinook now extirpated had primarily subyearling emigrations (J. Lichatowich, personal communication). Summer chinook salmon in the mid-Columbia above Hanford are allied with the fall runs rather than with the spring runs, as in the Snake River system. Whereas subyearling chinook salmon exhibit a slow downstream migration that we have seen is composed of downstream movement interspersed with shoreline feeding on a daily cycle, the yearlings are commonly thought to have a very different migratory pattern, consisting of a rapid emigration of fish from the river during the spring freshet which is consistent with flushing behavior.

Evidence for Flushing for Yearlings

Yearlings are normally in the process of smoltification as they migrate downstream. This process of physiological change begins 20-30 days after river migration begins (Beeman et al. 1990). Decreased swimming performance (and greater ease of passive movement by currents) during smoltification seems to be a part of their emigration strategy (Smith 1982).

Wild/natural spring chinook from Idaho move rapidly downstream with spring flow in the unimpounded tributaries. In all years studied (1988-1992) by Kiefer and Lockhart (1995), wild spring chinook salmon smolts from the upper Salmon River were stimulated to migrate in spring by increases in discharge (often storm events) and their peak of arrival at Lower Granite Dam coincided with peaks in flow there. Such results suggest a flushing mechanism. Similar results were obtained for spring salmon smolts tagged in the Middle Fork Salmon River (Matthews et al. 1992). There was also a downstream movement of parr in autumn stimulated by rapid declines in temperature (Kiefer and Lockhart 1995). Higher percentages of parr emigrated from higher elevations (harsher climate). Natural migration in Snake River tributaries must be somewhat slower than water flow, otherwise smolts stimulated to emigrate at the first increase in discharge would not arrive at the first mainstem dam on the Snake River at peak flow (Kiefer and Lockhart 1995).

Similarly, rapid emigration of wild yearling smolts was observed between an outmigrant trap on the Salmon river and either a Snake River trap at Lewiston or Lower Granite Dam in 1993 (Buettner and Brimmer 1995). A two-fold increase in discharge increased migration rate to Lower Granite Dam by 5.2 times. Hatchery and wild chinook were shown to be capable of traveling between the Salmon River and Snake River traps (164 km) in 24 to 30 hours.

Telemetry studies by Schreck et al. (1995) showed clear periods of flushing and directed downstream swimming. A majority of fish at these times moved at rates faster than measured water velocities, particularly in two years when the radiotelemetry was conducted during prominent high-water freshets. When flows were low or declining, fish usually moved more slowly than the water. Many fish moved uniformly as a group, although the lead fish and the order of the others changed numerous times, suggesting differing lengths of time spent in resting and feeding. Some fish migrated considerably more slowly than the majority, remaining in the upper river for considerable lengths of time following tagging and release.

Migration rates varied with water velocities (Schreck et al. 1995). This occurred along the Willamette River as fish generally moved more rapidly in the upstream zones of more rapid water flow. They also moved more rapidly during times of high flow than during times of lower flow in any one year. During non-freshet spring periods (3 of 5 years studied), fish moved more slowly than the water over 24-hour periods. High and rising flows, however, appeared to stimulate an emigration of fish from the river in a manner consistent with flushing behavior. At freshet times, fish appear to have long spiraling lengths, and thus exit from the system quickly.

Flow Structure as an Aid to Migration for Yearling Chinook

Accelerating flows and hydrodynamic features such as waves or surges appear to assist the migration rate of yearling migrants (Figure 6.8). Yearling chinook salmon on the unimpounded Snake River (Mains and Smith 1963) and the Willamette River (Schreck et al. 1995) have been observed to move on the increasing arm of the freshet. Similarly, Hesthagen and Garnas (1986) showed that significantly more Norwegian Atlantic salmon migrated when the discharge was increasing (with a drop in temperature) than under the opposite conditions.

Our analysis of data from the Fish Passage Center (1994) and Buettner and Brimmer (1995) suggest that fish movement increases in the Snake River system with accelerating flow (Figure 6.8). Wild and hatchery yearling chinook salmon and steelhead at the Salmon River and Snake River traps and steelhead at the Clearwater trap show increases in sample counts during and shortly after flow increases. The effect seems to be present still at Lower Granite Dam, but not downstream at Snake River dams (the wild yearling chinook index was not included in the 1993 report for Columbia River dams). Wild steelhead seem to show the effect in FPC data from McNary, John Day, and Bonneville dams.

Achord et al. (1995b) noted a historical pattern of migration on rising water flow in Snake River chinook yearlings, with the pattern still evident in PIT-tag detections at Lower Granite Dam of spring chinook tagged the previous summer as parr. Lower dams did not show the historical pattern; migration coincided with peak flows. For summer chinook yearlings, the main passage of tagged fish was during rising flows at all three dams. The evidence for a flushing mechanism of migration (discussed above) generally includes observations of migration on rising flows, especially freshets.

With increasing evidence that yearling chinook salmon move downstream on rising flows (see references to migration with freshets cited above and by (Northcote 1984), and similar observations for steelhead), it is tempting to suggest that they may be adapted to catching the stage wave (flood surge) as well as the water mass. Rapid increases in flow or other disturbances in a channel generate a moving surge or stage wave downstream that is recognized in the field of fluid dynamics (Albertson and Simons 1964). Such surges or waves move ahead of the main water mass and at rates faster than water particle movement (which also accelerates as stage increases). Koski (1974) found that the velocity of the wave in the Snake River in Hells Canyon was 12.9 fps at 7,700 cfs and 11.4 fps at 5,000 cfs, whereas the average velocity of the watermass was 2.3 fps at 7,700 cfs and 1.7 fps at 5,000 cfs.

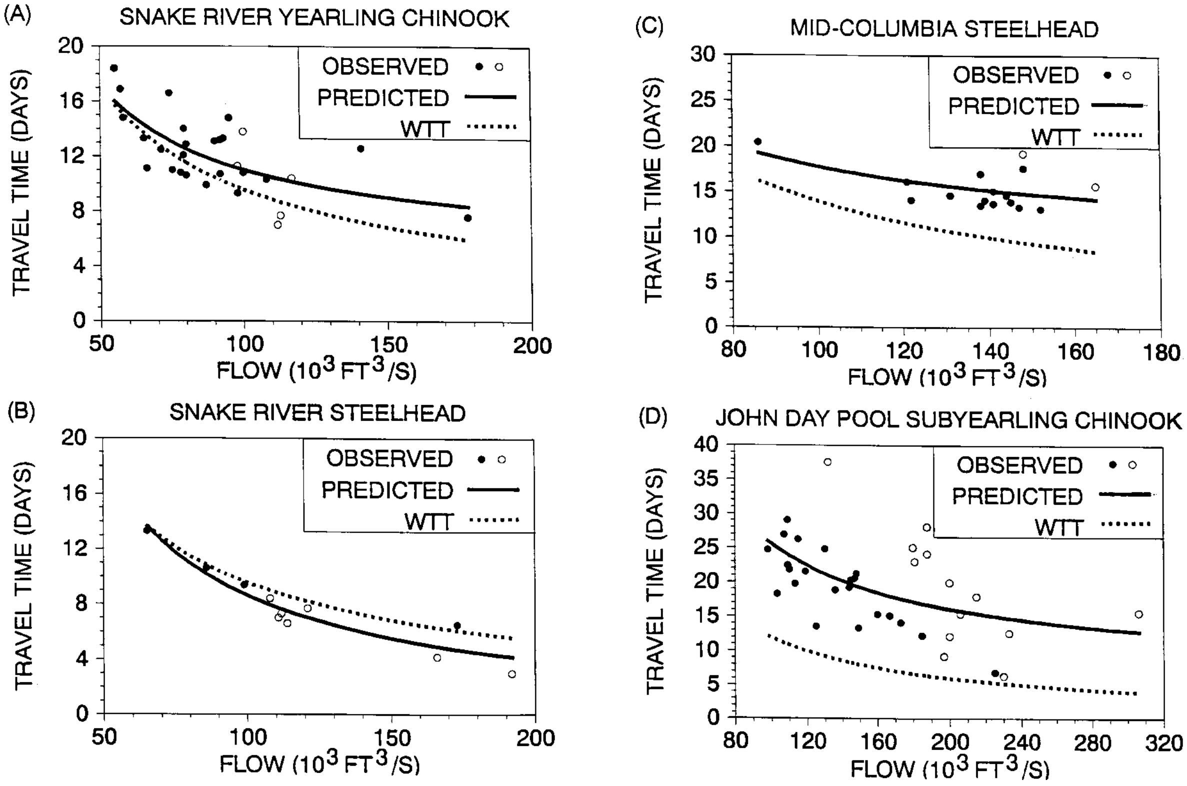


Figure 6.8. Observed fish travel times with summary regression lines and an estimate of water travel time (WTT) over a range of river flow rates for (a) Snake River yearling chinook salmon, (b) Snake River steelhead trout, (c) middle Columbia River steelhead trout, and (d) lower Columbia River (John Day pool) subyearling chinook salmon. Open circles 1981 – 1983; solid circles 1984 – 1991 (Berggren and Filardo 1993).

Smolts adapted to migrating on moving surges would get both a directional cue and an assist that could move them, too, at rates faster than water particle movement. Telemetry studies in the Willamette River (Schreck et al. 1995) showed spring chinook yearlings accelerating to faster than water velocities in swift, shallow reaches (where small waves would be expected to merge into larger surges). Conversely, as depth increases, the wave height decreases and waves have less tendency to pile up as surges or bores. Reservoirs would thus inhibit the formation of surges and continuation of surges begun in riverine sections. Waves in slowly moving reservoir waters could easily propagate upstream as well as downstream. A fish could lose both directional cue and assistance in moving downstream.

The role of hydrodynamic features other than thalweg velocity in fish emigration needs to be further explored, for a proven link to such features as stage waves and turbulent bursts. A greater understanding of hydrodynamic features may offer opportunities for water management that could be more effective in moving fish with less water than would current applications, such as the water budget.

Yearling Chinook in the Estuary

Studies of migration in the upper estuary are generally consistent with the riverine studies. A diel pattern of movement in the upper estuary seems to be prevalent, although somewhat different from that in the mainstem river. In the upper Columbia River estuary at Jones Beach (Rm 46), Dawley et al. (1986) and Ledgerwood et al. (1990b) found that the majority of yearling chinook salmon migrated midriver (few were caught in beach seines; more were caught in pelagic purse seines). Their migration rates were about the same in the estuary as in the river. Peak catch was mid- to late-morning. After a period of low catches between dusk and midnight, there were larger catches (but still fairly low) during the rest of the night. The authors conclude that because mid-river-oriented yearling fish do not appear in shoreline areas during darkness, when migration rates are low, they probably hold near the bottom in deep areas of low current velocity. The yearlings were feeding, as evidenced by stomach contents. From release to recapture, groups of yearlings analyzed by Dawley et al. (1986) did not show movement rates that were well correlated with river flows (in data that spanned very high to very low flow years). Despite differences in timing between the river and estuary, there is evidence of a periodic, rather than a constant flushing, character to the migration.

Yearling Chinook in Reservoirs

Yearling chinook in reservoirs also emigrate rapidly and generally more rapidly at higher flows. Buettner and Brimmer (1995) chronicled travel time and migration rate of PIT-tagged wild chinook salmon through Lower Granite Reservoir. They calculated that a two-fold increase in discharge increased migration rate by 4.1 times. This change occurred while flows were accelerating from about 60 to 160 thousand cfs. However, as flows decelerated later in the season, travel rate slowed markedly in a pattern that did not conform to the flow-migration rate relationship seen during accelerating flows. Thus, a pattern of migrating largely on accelerating flows may persist in reservoirs as well as rivers. Because discharge is not easily related to water velocities experienced by the fish, it is difficult to infer swimming behavior. These data need to be integrated with those of Achord et al. (1995b) discussed above for the same reaches. The Fish

Passage Center summarized median travel times over six years for yearlings passing through Snake River and mid-Columbia River reservoirs that show fairly clearly that in the Snake River and lower Columbia mainstem, fish move faster at higher flows during the migration period, especially evident at lower flow ranges (Fish Passage Center 1994). Complicating these relationships is the tendency for later-migrating fish to move faster.

Early studies at dams identified a clear diurnal periodicity in passage of yearlings. Gauley et al. (1958) found significantly more yearlings migrating through a Bonneville Dam bypass in four out of five years in the 1940s and 1950s during nighttime hours than during daytime hours. Long (1968a) found about 94 percent of yearling chinook salmon passed The Dalles Dam in nighttime hours in 1960. Yearling chinook salmon passed John Day Dam mostly at night, with prominent peak movement between sunset and midnight in all weeks between early April and mid June 1986 (Johnsen et al. 1987). Radiotelemetry of individual chinook salmon smolts has shown a diel periodicity of movement. For fish tagged and released upstream of John Day Dam, both arrival at the dam and passage through it occurred on a diel cycle, with peaks near dusk (Giorgi et al. 1986). A pattern of alternating movement and rest appears to be well established for reservoirs close to these dams.

The otherwise consistent diel pattern was not borne out in studies of PIT-tagged spring and summer chinook yearlings at two Snake River dams and McNary Dam in 1992 or 1993. Achord et al. (1995b) found diel patterns in the fish bypass systems to be weak, inconsistent between dams, and often the reverse of the normal pattern – peaks often occurred in the daytime. The anomaly, although not well understood, could signal a breakdown or a variation of the usual diel migration in these reservoirs.

Radiotagged smolts released at John Day Dam traversed the The Dalles pool at speeds of about 2.0 m/h and usually did not stop in the reservoir before arriving at The Dalles Dam forebay (Snelling and Schreck 1994). After passing the dam volitionally (through the ice-and-trash sluiceway or through spillways), nearly one-third held in downstream areas.

Smith's (1982) postulation that smolts swim weakly upstream and thereby move downstream tail-first at a velocity less than that of water movement, has been used to explain the difference between water particle travel time and smolt travel time (Berggren and Filardo 1993). Although perhaps partially true, this explanation fails to acknowledge the observed diurnal periodicity of migration with hours of little or no migration. A general relationship of travel time and flow velocity would still hold, based on just the hours of nighttime migration.

The progressive increase in smoltification of chinook salmon yearlings with time in the migration season appears to correlate with depth of travel and thus, changes in fish guidance efficiency at dams (Giorgi et al. 1988b). More thoroughly smolted fish were caught in the tops of fyke net screens over turbine intakes, whereas less thoroughly smolted ones were caught nearer the bottom in three of four test dates. Decreases in swimming performance observed during smoltification of coho salmon (Glova and McInerney 1977; Flagg and Smith 1982), also are consistent with the results of these collections. These tests suggest an increased tendency of more developed fish to flush, at least during the movement period. The results also are consistent with studies of Atlantic salmon, which increase their buoyancy by filling the swim bladder in an apparent effort to aid the transition from bottom dwelling to pelagic existence during migration (Giorgi et al. 1988b).

Degree of smoltification clearly affected travel times of yearling chinook through Lower Granite pool and the correlation of travel times to changes in flow (Beeman et al. 1990; Giorgi 1993). Whereas fish with low levels of ATPase (beginning of smoltification) traveled the reservoir length slowly and showed a marked increase in travel times at lower flows, the more smolted fish with high ATPase levels had a nearly uniformly rapid rate of movement over all flows. Slowing was seen only at the lowest flows. Cramer and Martin (1978), as reported in Giorgi (Giorgi 1993) observed that larger Rogue River chinook salmon migrated fastest. Viewing migration as a spiraling event suggests that the less smolted fish could stop to rest more often or for longer durations than the more smolted fish, which may move more continuously (rather than just at a faster speed). These alternatives could be tested with radiotelemetry.

Population Contrasts for Yearling Chinook: Snake and Willamette Rivers Compared

As with subyearling chinook, it is useful to look for well-studied populations that differ in their success and compare their migratory behavior and habitats. A contrast as clear as between Hanford and upper Snake River subyearling fall chinook salmon populations is not available for yearlings. It seems reasonable, though, to compare the successful Willamette River spring chinook salmon (a population that does not pass mainstem dams) with the endangered Snake River spring/summer chinook that pass eight dams on the Snake and Columbia rivers. Some comparable study techniques (telemetry) have been used, although data are sparse.

Alternating periods of downstream movement and resting, followed by periods of resting and feeding was an evident behavior in the Willamette River spring chinook tracked in their downstream migration through most of the undammed river from Dexter Dam upstream of Eugene to Willamette Falls near Portland (Schreck et al. 1995). Fish fed well, predominantly on immature insects characteristic of drift. In contrast, yearlings from the Snake or upper Columbia swam the length of The Dalles pool without stopping (Schreck et al. 1995). Migration was interrupted at the dam forebay, but fish maintained an active searching behavior, rather than a holding (resting/feeding) one. Only one route of passage at the dam allowed fish to find and use holding areas near islands. Examination of the Snake River reservoirs shows few, if any, habitats that would qualify as normal holding areas, based on the limited data on habitat suitability from the Willamette River and The Dalles tailwater. Although lack of a flow appropriate to support constant flushing behavior in the Snake River has been viewed as the critical missing habitat factor for its unsuccessful salmon populations, it may be that the lack of both high, accelerating velocities and suitable habitats for resting and feeding are equally important. Further data collection and analysis of the situation with these two populations may lead to results useful for management in the Snake River.

Information Needs for Yearling Chinook Salmon

1) Yearling chinook salmon are more oriented to center channel movement with current during high river flows than are the subyearlings, although a diel periodicity of migration with holding and feeding episodes is apparent.

The following critical points need additional study and evaluation:

2) Durations and intervals of movement and holding, presumably for resting and feeding, need to be better defined for yearlings in both riverine and reservoir reaches. The common view of these fish as being flushed nearly continuously to the ocean from tributary rearing areas may be insufficient for effective management.

3) The role of hydrodynamic features other than thalweg velocity in fish emigration needs to be explored. A proven link to such features as stage waves and turbulent bursts, or pulsing flows may offer opportunities for water management that might be more effective in moving fish with less water than would current procedures.

Sockeye Salmon

Juvenile sockeye salmon emigrate as one-year-olds from the upper Columbia River, principally from lakes Osoyoos and Wenatchee in the Okanagan and Wenatchee rivers respectively (Fryer 1995). One other stock, the Snake River stock from lakes in the Stanley Basin of Idaho, now restricted to Redfish Lake, are on the endangered species list. Their abundance is extremely low, so the juveniles are rarely seen at downstream sampling locations. Historically, sockeye salmon existed in all moraine lakes in the Stanley Basin of Idaho (Salmon River drainage) (Evermann 1895), in lakes in the Yakima River basin, and in the numerous large lakes in the upper Columbia River Basin, as well as the three named above. The lake area in the Columbia Basin now open to sockeye in the Columbia Basin is approximately 5 percent of the area formerly available to them (Mullan 1986).

Netting in the Hanford Reach found most emigrating juvenile mid-Columbia sockeye salmon at night (2200 to 0400 hours) in the deepest part of the channel, along with yearling chinook (Dauble et al. 1989). Where these fish were located in daylight hours was unexplained.

Sockeye smolts at John Day Dam migrated with a distinct diurnal cycle in studies in 1986 by Johnson et al. (1987). There were daily peaks shortly after sunrise. Passage rates during much of the night were similar to daytime rates early in the migration (late April-early May) but much higher in all weeks thereafter until mid June. Earlier dam passage studies (Gauley et al. 1958; Long 1968b) did not tally sockeye. Giorgi (1993) observed that the current low level of the Snake River stock, despite some PIT-tagging of Redfish Lake juveniles, meant that it is unlikely that there would be sufficient data to investigate effects of flow on migration times and survival for many years.

Much of what we know about sockeye salmon migration has come from extensive research on the species in British Columbia. Sockeye smolt migration in British Columbia has been shown to peak at dusk and dawn (Groot 1965; Hartman et al. 1967). Speed of migration in British Columbia sockeye smolts changed with time of day and the net displacement of fish increased as the season progressed (Johnson and Groot 1963). Downstream migrating fish tend to rise to the surface (Groot 1965; McCart 1967). Smolts entering a river from a lake swim actively with the currents (Groot 1982). Groot (1982) considered sockeye salmon migration to be a number of "hops" during which fish rise to the surface during peak times of activity and return to greater depths during periods of lower activity.

Steelhead

Steelhead populations have been crossbred and transferred extensively throughout the streams of both Oregon and Washington (Royal 1972; Reisenbichler and Phelps 1989; Reisenbichler et al. 1992). They spawn widely throughout the Columbia River Basin tributaries. Thus, the ability to distinguish stock-specific migratory behaviors has been compromised. Therefore, generalized species' responses are the most germane. The steelhead has the reputation of being a fast migrator and a species that would be aided by flows appropriate to support constant flushing behavior.

Yearling or age 2 steelhead migrate downstream in the mid-Columbia River from spawning tributaries and upstream plantings from hatcheries (Dauble et al. 1989). As in the case of spring chinook and sockeye salmon, steelhead were found at night (2400 to 0400 hours) in the deep part of the Hanford main channel (Dauble et al. 1989). Some were electroshocked in shoreline areas, but not enough to establish a diurnal pattern. Diurnal variation in appearance in the deep main channel suggests that there may be a cyclic pattern of migration.

Massey (1967) observed diurnal periodicity in steelhead emigration at Willamette Falls, Oregon, based on sampling of industrial shoreline water intakes. Peak movement was noon to 3 pm, with a minimum from midnight to 3 am. The majority of these fish moved downstream near the center of the river. Andrews (1958) noted that wild steelhead smolts in the Alsea River, Oregon moved both day and night, but the most rapid movement was just after sunset and just before sunrise.

Northcote (1962) observed the downstream movement of rainbow trout in streams with infra red light, and concluded that the majority were heading downstream, many were at or near the water surface, and that they swam at a speed greater than the surrounding water. This agrees with travel time data for Snake River steelhead presented by Berggren and Filardo (1993) that showed movement faster than water travel time. Rainbow/steelhead thus appear to be adapted to the flush, and to improve upon it by active swimming, at least for part of the day. As suggested above for yearling chinook salmon, the downstream migrants may be adapted to catching the stage wave as well as the moving water mass (Pacific Northwest River Basins Commission 1974).

In the upper Salmon River, which is a major production area for natural summer steelhead, smolts behaved similarly to spring chinook (Kiefer and Lockhart 1995). They began to emigrate in spring with the first rising flows and arrived at Lower Granite Dam with the peak flows. There was also an autumn downstream displacement of age 2 fish from higher elevations that seemed stimulated by falling temperatures.

Wild steelhead moved rapidly downstream in the upper Snake River system and increased their migration rate about proportionately to changes in flow, in PIT-tag studies by Buettner and Brimmer (1995). A two-fold increase in discharge increased migration rate by two times between the Clearwater trap and Lower Granite Dam and 2.1 times between the Salmon River trap and the dam. Both river and reservoir passage were included in these estimates.

Migrating steelhead smolts feed on their way to the ocean. Royal (1972), found most migrating steelhead in the Alsea River, Oregon, both wild and hatchery, had food in their stomachs. Aquatic insects were the main food items.

As with chinook salmon smolts, radiotelemetry of steelhead smolts has identified "holding" behavior as well as rapid downstream migration. Ward et al. (1994) observed holding behavior in some steelhead smolts even though most migrated through the 15.3-km Portland harbor in 1-2 d. Snelling and Schreck (1994) found that smolts released upstream and downstream of The Dalles Dam searched out a place to hold in the riverine sections just downstream. The holding areas were eddies near islands, the same places used by yearling chinook. These sites contrasted with the migration corridor in the deep channel. The authors related holding to stress, but it may reflect a normal pattern of migration.

In the estuary, Dawley et al. (1986) observed that steelhead traveled 50 percent faster than they did in the river. This observation is especially interesting in light of riverine migrations by steelhead being more rapid than water travel (Berggren and Filardo 1993). These fish may use tidal flows to their advantage, as has been seen in other species.

In Lower Granite Reservoir, Buettner and Brimmer (1995) found the rate of migration of wild steelhead also to be flow dependent. Statistical analysis of five years of data showed that a two-fold increase in flow increased migration rate by 2.5 times. Such data have been interpreted as support for a constant flushing mode of migration. As with chinook salmon yearlings, however, detailed analysis of the data for 1993 shows a slowing of migration on deceleration of flows that does not conform to the flow-rate relationship during accelerating flows.

In the impounded Snake River, Smith found most steelhead migrating in the upper 36 feet (1974a). About three-quarters of those caught were taken at night (between dusk and dawn). There was no indication of where these fish were in the daytime.

Yearling steelhead were identified in early studies at dams as having a diurnal pattern of migration with most passing at night. Studies at a Bonneville Dam bypass by Gauley et al. (1958) showed this pattern in four out of five seasons in the 1940s and 1950s. Long's studies of turbine passage at The Dalles Dam showed 80 to 90 percent of yearling steelhead passed in the night. The steelhead pattern of passage at John Day Dam from early April to mid June 1986 showed most fish traveling at night with prominent peak migration times shortly before midnight (Johnsen et al. 1987). These consistent patterns strongly suggest a spiraling migration behavior in which habitat other than main channel flow is also important.

Coho Salmon

Coho salmon migrations have been little studied in the Columbia and Snake rivers. Coho were declared extinct in the Snake basin in the late 1980s. They are also absent from the mid-Columbia reach. Most fish recently originated from hatchery stocks in the lower and mid-Columbia River (mid-Columbia hatchery rearing of coho was terminated in the early 1990s). They migrate as yearlings.

In the Columbia River estuary at Jones Beach, Dawley et al. (1986) and Ledgerwood et al. (1990b) found coho salmon in both beach seine and channel purse seine catches. There were erratic changes in numbers in beach seine catches through the day and generally low catches at night. Most fish were caught in beach seines between 0830 and 1430 h, with peak catches in mid-day. Channel samples showed little day-night differences except for a sharp peak just after sunrise. The data suggest schools of fish moving in both areas, but nearshore in the daytime. Marked releases of coho showed travel in the estuary at rates about 40 percent faster than in the river, suggesting some use of tidal currents to aid migration. Movement rate was not correlated with river flow.

As with other species of salmon, coho showed a diurnal passage pattern at dams. Studies at John Day Dam in 1986 revealed almost all coho moving at night with peak passage shortly before midnight (Johnsen et al. 1987). Considerable passage occurred through the night until shortly after sunrise. There is much uncertainty regarding this species, but its minor status in the Columbia River mainstem and complete hatchery dependence makes study and management less important than for other species.

Effects of Flow on Rate of Migration

Snake River

Chinook and Steelhead.

Within the Snake River and as far as McNary or John Day dams on the mainstem, the downstream migration for both steelhead (Figure 6.8b) and yearling chinook salmon (Figure 6.8a) is faster at high flows than at low flows (Raymond 1968; Sims and Ossiander 1981; Berggren and Filardo 1993; McConnaha 1993; Connor et al. 1994; Maule et al. 1994; Achord et al. 1995a; Achord et al. 1995b; Buettner and Brimmer 1995; Smith et al. 1997a; Smith et al. 1997b).

Buettner and Brimmer (1995) found that during the early part of the season when flows were increasing, travel time of radio tagged spring (yearling) chinook in Lower Granite Reservoir was reduced by high flows, but that later when flows were declining, travel time slowed. Achord et al. (Achord et al. 1995a; Achord et al. 1995b), also concluded that the principal portion of the outmigration of spring chinook smolts in Lower Granite Reservoir occurred during the early phase when flows were increasing. On the other hand, Smith et al. (1997a), using data from recovery of PIT tags and a larger body of data, measured travel time through a longer reach, from above Lower Granite Dam to McNary and John Day dams speculated that in their study faster travel time was associated with changes in fish physiology as smoltification progressed.

Connor et al. (1994) found travel time for hatchery origin sub-yearling chinook through Lower Granite Reservoir was reduced with larger size at release, with higher volume of flow, and higher water temperature. Giorgi et al. (1993) found no relationship of flow with travel time of subyearling chinook in any of the three years they conducted their study in John Day Reservoir, but found release date and/or temperature did affect travel time.

In tributaries, incremental increases in flow also have been found to stimulate movement of steelhead (Maule et al. 1994), and of spring chinook in the Salmon River, Idaho (Matthews et al. 1992; Kiefer and Lockhart 1995). Schreck et al. (1995) found that spring chinook in the Willamette River moved more rapidly during times of high flow than in times of low flow in a given year.

Analyses have been made more difficult by the fact that the level of smoltification of the fish can also affect their rate of migration and this often varies together with flow (Beeman et al. 1990; Giorgi et al. 1990; Berggren and Filardo 1993).

Mid-Columbia Reach

Yearling Chinook.

In the mid-Columbia reach there is no effect of flow on travel time, unlike the situation in the Snake River (Chapman et al. 1995). Chinook from the Winthrop, Entiat, and Leavenworth hatcheries and from the Rock Island sampler, showed no effect of flow on travel time to McNary Dam. The Fish Passage Center (1994) and Maule et el. (1994) found a weak effect of flow on travel time. However, in the latter two studies, the authors found that degree of smoltification of the fish was more important than flow in determining travel time. Giorgi et al. (1997a) using a large body of data from recoveries at McNary Dam of chinook, steelhead, and sockeye that were PIT tagged at Rock Island Dam, found that neither ocean type (sub-yearlings) nor stream type chinook (yearlings), showed any measurable response to flow in the mid-Columbia.

Subyearling Chinook.

Subyearling chinook (ocean type) from the mid-Columbia reach move downstream more slowly than yearling chinook (stream type) or steelhead (Figure 6.8a and 6.8d). For example, yearling hatchery chinook took an average of about 4.4 days to pass through John Day reservoir, compared to 14 days for subyearling chinook at the same flow, 250 kcfs (Chapman et al. 1994a). John Day, having the largest reservoir in the lower river, probably is the place where travel time is the longest. In the mid-Columbia reach, subyearling (summer/fall) chinook, on the average traveled an estimated 4.4 to10.0 mi./d in the years from 1984 through 1992 (Chapman et al. 1994a). While there was no relationship between travel time and flow, release date, or size at release, there was a significant effect of water temperature on rate of travel.

Steelhead and Sockeye.

Travel time of sockeye and steelhead was reduced as flow increased in the mid-Columbia Reach (Giorgi et al. 1997a). For steelhead (Figure 6.8c), travel time from the mouth of the Methow River to McNary Dam, a distance of 232 miles, was reduced 2.3 days (from 20 to 17.7 days in transit) by an increase in flow from a base of 80 kcfs to 100 kcfs (Chapman et al. 1994b). The reduction was estimated to be less at higher base flows (reduced 1 day by an increase in flow from 140 to160 kcfs) (Berggren and Filardo 1993; Chapman et al. 1994b).

At flows of 80 kcfs in the mid-Columbia reach, the predicted travel time of sockeye from the tailrace at Priest Rapids to McNary Dam was about 10 days, and an increase to 100 kcfs reduced predicted travel time by about three and a half days over the 161 mile reach (Chapman et al. 1990; Chapman et al. 1995). At higher flows there was less effect on travel time, according to the equation that was developed, amounting to only half a day reduction with an increase in flow from 160 to 180 kcfs. In the Snake River, Chapman et al. (1990) concluded that the flow augmentation which is aimed at hatchery chinook salmon is early for the sockeye outmigration.

Discussion of Travel Time Studies

Principles of Water/Fish Movement

There has been considerable effort devoted to the collection of data on migration rates of downstream-migrating salmonids and the statistical relationships to environmental variables (Buettner and Brimmer 1995). There has been less effort expended in conceptual thinking about migration speed, including consideration of the fundamental principles of animal and water movement, and relationships of these principles to the observed migratory timing. Even less attention has been given to whether and how different migration rates affect salmon survival (i.e., relationships between timing of movement and the innate behavioral patterns and ecological needs of the species and life stage). The exception to survival linkage has been attempted connections between initiation and rate of movement and the physiological processes of smoltification (Wedemeyer et al. 1980).

There is notable disagreement over what the empirical evidence about the rate of migration timing and river discharge tells us. McNeil (1992) found no positive relationship between flow and passage time. However, the preponderance of evidence clearly supports the links between flow and migration rate. Within the Snake River and as far as McNary or John Day dams on the mainstem, the downstream migration for both steelhead and yearling chinook salmon is faster at high flows than at low flows (Raymond 1968; Sims and Ossiander 1981; Berggren and Filardo 1993; McConnaha 1993; Connor et al. 1994; Maule et al. 1994; Achord et al. 1995a; Achord et al. 1995b; Buettner and Brimmer 1995; Smith et al. 1997a; Smith et al. 1997b). This view is reflected in proposed salmon restoration plans (NPPC 1994c; National Marine Fisheries Service 1995a). Some of the disagreement relates to the time periods selected for statistical analyses by McNeil, in which inclusion of dates outside the actual migration period can severely affect the results.

The level of smoltification of the fish affects the rate of outmigration making it difficult to separate the effect of this factor from the effect of flow (Berggren and Filardo 1993; Muir et al. 1995b; Giorgi et al. 1997a). Berggren and Filardo (1993) in a multivariate analysis, found only one variable, release date, explained the variation in measured travel time of yearling chinook in the mid-Columbia reach to McNary Dam. Obviously, degree of smoltification is a function of release date. Fish released later from hatcheries are more likely to be further along in development than earlier releases, resulting in lower travel times later in the season. Muir et al. (1995) demonstrated that the degree of smoltification affects the rate of migration of juvenile salmon. They found that smolt development responded to photoperiod and temperature so that as day length and temperature increased later in the season, the fish moved more rapidly.

That factors other than simply flow or rate of movement of water masses affect travel time of smolts (Figure 6.5) is shown by the fact that, with the exception of steelhead, their rate of movement is slower than the concurrent average water travel time (Beeman et al. 1990; Berggren and Filardo 1993; Buettner and Brimmer 1993). There is evidence that juvenile salmon make use of certain features of flow hydrodynamics in their migration. For example accelerating flow seems to foster fish movement. Wild and hatchery chinook salmon and steelhead captured at the Salmon River and Snake River traps and steelhead captured at the Clearwater trap show increases in sample counts during and shortly after flow increases (Fish Passage Center 1994; Buettner and Brimmer 1995).

Flow has attributes of volume (amount of discharge) and velocity (which is related to the shape of the channel). Average velocity in the Snake River between Lower Granite and Ice Harbor dams, calculated from the average cross section, increases linearly with flow from 0.25 fps at a flow of 20 kcfs to about 1 fps at 100 kcfs (Chapman et al. 1994a). In the mid-Columbia reach, average volumes of flow are usually much higher, but corresponding velocities between Wells Dam and Priest Rapids Dam are estimated to be similar to those in the Snake River at flows up to the level of normal highs in the Snake River. In the mid-Columbia reach, velocities are associated with flows in the upper reservoirs. On the other hand, in the reach from Wells to Rock Island dams which have relatively little storage capacity, velocities are higher (1 fps to 3.2 fps) over the range of flows from 80 to 240 kcfs, than in the Rock Island to Priest Rapids stretch of river (0.6 to 2.1 fps), where there is somewhat more storage capacity. While these average flow calculations can be misleading because velocity will not be uniform across the reservoir at any given flow, the point is that the more water impounded behind a dam, the larger the volume of flow required to reach velocities formerly reached in the unimpounded reaches.

Migration timing depends upon the fish's orientation and behavior in the water as well as whether downstream migrating salmonids flush or spiral. There has been much debate over whether downstream migrations, in general, are active or passive; see literature reviewed by (Jonsson 1991). Downstream swimming in the direction of water flow would generate quite rapid downstream movement, with travel times shorter than those for water during periods of active migration. This behavior, as observed in rainbow trout by Northcote (1962), especially when it might be coupled with accelerating flows as in a flood surge, could be very effective in moving fish rapidly. Orientation upstream at a stabilizing swimming velocity, as suggested by Smith (1982) and Williams et al. (1994), would generate a downstream drift at rates less than water movement. Totally passive migration is also possible, in which undirected (or no) fish movements result in net displacement at the rate of the water mass. Coupled with a possible spiraling migratory behavior having alternating times of displacement and resting or feeding, these orientation alternatives could give considerably different migration rates over distances of kilometers. Should these orientations differ temporally, such as in a daily cycle or between early and late migrants in a cohort or whether or not a stage wave is passing, the resulting travel times could be expected to differ in ways that would confound conventional statistical approaches.

Conclusions on Smolt Travel Time

1. In the Snake River, travel time of migrating yearling chinook and steelhead is faster at high flows. There is no affect of flow on travel time of juvenile salmonids in the mid-Columbia Reach.

2. In the Snake River, travel time for subyearling chinook is affected to a lesser degree by flow than yearling chinook and steelhead because of their naturally slower behavior in outmigration which takes them alternately into near-shore areas for feeding and out into the current for downstream migration.

3. Flow augmentation reduces travel time for yearling chinook and steelhead in the Snake River. During 1991-1995, travel time was reduced by 5-16% for yearling chinook and 6-17% for steelhead. The effects on subyearling chinook are not well established, but some reduction in travel time appears to occur at flows above 120 kcfs compared to flows below 60 kcfs.

Directions for Future Research

Our review in the preceding text shows that both passive and active migrations occur. As Jonsson (1991) noted, fish must actively initiate emigration. Clearly, fish that are holding during a diel cycle, either at the bottom or in shoreline backwaters, must actively swim to get themselves oriented into the main current for what might later be passive movement. Both avoiding obstacles during downstream movement (e.g., being swept into backeddies) and ending the movement phase of spiraling would require an active component. All of these complicate a simple interpretation of migration rates between widely separated points.

It may be useful in the future to compare the different implications for rivers and reservoirs with the results of field studies of fish passage to see which implications (and thus behaviors) are supported by the evidence. It has already led us to consideration of stage waves or surges in affecting migration. However, the effectiveness of surge pulsing remains to be demonstrated in impoundments. Another area of investigation might be to test different fish behaviors with river management alternatives in hydrodynamic models of river and reservoirs to develop computer simulations of fish passage timing. The simulations under different combinations of behaviors and water flow regimes can be compared to the field data. Additional scenarios can be examined, more than is possible with the actual historical record of flows, migration times, and other factors. For example, the effects on passage rates of different lengths of time spent in displacement and stationary resting/feeding can be examined for a range of flows even though there are few field studies of diurnal behavior. The objective of such analyses would be to indicate the possible habitat requirements of each species/stock and their projected gain (or loss) from velocity increases from managed reservoir drawdown or augmented flows.

Field evidence can be compared with migration behaviors using data compiled by Berggren and Filardo (1993). They provided both water and fish travel times over a range of river discharges for Snake River yearling chinook salmon, John Day Pool subyearling chinook salmon, mid-Columbia River steelhead, and Snake River steelhead (Figure 6.8). Their objective was to determine if there was a statistically significant relationship between travel times of water and fish. Subyearling chinook traveled much slower than water at all flows (by a factor of 3 at high flows and 2.5 at low flows). This migration pattern includes the observations of daytime residence in shoreline areas. Migration in May and June with about 16 hours of light and 8 hours of darkness is consistent with the model of nighttime movement with swimming against the current. Thus slow-water habitats are necessary to sustain these fish during 2/3 of the diurnal cycle.

Yearlings in the Snake River moved, on average, at a rate slightly slower than water at high flows (1.5 times as long to move the same distance) but essentially the same as water movement at low flows (Berggren and Filardo 1993). However, the data were widely scattered and some groups maintained the 1.5 ratio across the range of flows, whereas other groups (8 of 24) moved slightly faster than water (0.6 times as long to move the same distance). The inconsistency among groups suggests that the migration behavior of this class of salmon needs additional special study.

Snake River steelhead were unique in moving almost exclusively at a rate faster than water movement in the Snake River. The difference appeared to be greatest at high flows and nil at low flows. One interpretation of these travel times could be that the fish use directed downstream migration without spiraling. Steelhead would thus not need shoreline or other resting habitats and would be aided by a continuous faster water flow. Mid-Columbia steelhead, however, behaved quite differently. These fish took about 1.5 the time of water to cover a distance, which is more consistent with spiraling or at least swimming against the current. More work along these lines on all species and stocks may prove valuable.

Migration Summary

Selective drift, in which a fish selects only particular times and water currents (and rests or feeds during others) is important in determining downstream movement in river and tidal waters (Hillman and Chapman, 1989; Chapman et al., 1994; Weihs, 1978; Arnold and Cook, 1984; McCleave et al., 1984). Even the supposedly passive migrations of Atlantic salmon cited by Thorpe (1982) do not occur continually throughout 24 h, but show cyclic spurts of high activity (Solomon, 1978) and a predominantly nocturnal migration pattern with 87 percent caught between 2200 and 0200 h (Hesthagen and Garnas, 1986, and several references therein). What happens in the fish's life between times spent drifting or otherwise moving downstream is probably very important to survival.

From the previous discussion we can conclude that increased flow will speed the downstream migration of juvenile steelhead, coho, and chinook in the Snake River, but not in the mid-Columbia reach. The presumption has been that providing additional flow for fish during the juvenile outmigration will improve ecological conditions for them, which should result in improved rates of survival.

Effects of Hydrosystem Development on Life-History Diversity

The Columbia-Snake river basin, at the time Europeans arrived, was characterized by an assemblage of Pacific salmon species and stocks with highly divergent life-history strategies (see Chapters 3 and 4). This diversity developed as the Wisconsin glaciation retreated and the exposed landscape was recolonized by stream-type salmon from northern refugia and ocean-type fish from southern refugia (Lindsey and McPhail 1986; McPhail and Lindsey 1986). Differentiation probably occurred within stocks as they adapted to the peculiarities of specific tributary systems and the migration corridors to and from them. It is believed that migration distance and growth opportunity in the vicinity of spawning (a combination of water temperature and day length) were major factors in this differentiation (Taylor 1990).

Overall stock diversity was probably reflected in a diversity of migration behaviors related to constant flushing or spiraling, as well. It follows logically from the diversity of tributary habitats and flows that salmon as a group would diversify to make full use of different migratory corridors, as Rich (1920) observed. The differences in diurnal migratory behavior of the now extirpated Snake River stocks of spring chinook salmon studied by Krcma and Raleigh (1970) and other stocks is just one example. The primal river had spring freshets of varying magnitudes and durations that afforded quick passage, open channels for quick flush, backwaters for lingering, eddies and deep pools for resting, riparian habitats that afforded stragglers with abundant food and shelter, and so forth. Each habitat niche was probably occupied by a species or stock (often overlapping). Because each salmon species in the Columbia-Snake system has a multi-year life cycle and attainment of maturity can vary across several ages, each population was buffered from unfavorable conditions in any one or few years as the riverine environment varied from year to year. Good years for one species' or stock's migration strategy (habitat use) may have been bad for another one's strategy. Because the relative benefit could switch from year to year, the diversity of stocks would persist.

Any strategy that manages river flows consistently is likely to favor fish stocks with one migratory behavior or habitat use to the detriment of others. Some stocks might, therefore, be pushed to extinction or very low levels while others are protected and fostered. For example, consistently high flows in the Snake River in May coupled with reservoir drawdown may create a fast-flushing, bare channel highly suited for moving yearling spring chinook downstream rapidly (begging the question of any daytime resting requirements), but at the same time be inconsistent with the requirements of underyearling fall chinook salmon for slow-water areas with riparian vegetation for their characteristically slow downstream movement. It can be hypothesized that one factor contributing to the present sad state of the Snake River fall run fish might be because of the poor riparian habitat of the present Snake River (in contrast to the riparian vegetation-rich Hanford reach).

The most favorable flow strategy for a diverse assemblage of salmonids would be one that varies, favoring some stocks at one time and other stocks another time. In the normative river concept, this variability should mimic natural variability, although replacing a climate-driven variability with a planned one (assuming the reservoirs are not permanently drawn down to natural riverbed). Although not easy, one could envision flow management in which reservoirs are drawn down temporarily in different ways in successive years: for example, one year in three for maximal support of constant flushing behavior, and another in which floods are created to overtop riparian zones to create maximal shoreline habitat. The third year could be maintained stable. These flow strategies could be coupled with non-flow measures for salmon such as replacement of shoreline rock rip-rap with vegetation. The occasional exceptionally dry year (that restricts planned flooding) or wet year (that floods no matter what the plan) would add a certain primal variability.

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