Abstract.—A flow and survival relationship, based on 1970's research, for juvenile chinook salmon, *Oncorhynchus tshawytscha*, that migrate through the Snake and Columbia Rivers is the foundation of many fishery managers' recommendations for modifications to the hydropower system to stem the decline of populations recently listed under the Endangered Species Act. However, a review of the 1970's data found that estimated fish survivals through the hydropower system reflected conditions that no longer exist and that between 1977 and 1979 these estimated survivals were negatively biased. Debris entrained in front of, and throughout, the fish collection system of the uppermost dam on the Snake River resulted in fish descaling and most likely poor fish survival. Under the lowest flow conditions, decreased survival due to increased travel time was exacerbated by sporadic or less than optimal turbine operations, or both, which further delayed fish passage through the dams and, at the uppermost dam, subjected fish to debris for longer periods of time. Use of flow and survival relationships based on yearly estimates of juvenile migrant survival in the 1970's will probably not accurately predict survival of spring-migrating juvenile chinook salmon under present conditions. This is particularly true for survival predictions during low-flow conditions.

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A review of flow and survival relationships for spring and summer chinook salmon, *Oncorhynchus tshawytscha*, from the Snake River Basin

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The Columbia River watershed historically has produced more chinook salmon, *Oncorhynchus tshawytscha*, than any other river system in the world (Netboy, 1980). The majority of the spring chinook salmon originated in the Snake River Basin (Fulton, 1968). In the early 1880's, spring and summer chinook salmon provided commercial fisheries in the lower Columbia River with average annual catches of 17.7 million kilograms (Craig and Hacker, 1940). Heavy exploitation by these fisheries, however, caused a substantial depletion of the dominant summer stock; the fisheries, therefore, concentrated on the spring and fall stocks (Craig and Hacker, 1940; Gangmark, 1957). Summer chinook salmon populations from the mid- and upper Columbia River continued to decline such that by 1964 the commercial fishery for all summer fish was closed. By this time, Snake River Basin spring and summer chinook salmon accounted for approximately 78 percent of the remaining upper river populations (Fulton, 1968).

The primary causes of stock declines in the early years were overfishing, habitat destruction, and damming of tributaries for water withdrawal and small-scale hydropower (Craig and Hacker, 1940). Concern about the potential impacts on upstream salmonid migration and the loss of downstream migrant juveniles passing through turbines at mainstem hydropower projects was expressed even before construction of Bonneville Dam (Fig. 1)(Griffin, 1935). Because the river flow during the time of the juvenile migration generally far exceeded the capacity of the powerhouse turbines, most fisheries research related to migrant salmonid passage was directed toward adults and the development of adequate upstream passage facilities for them at dams. However, some research on juvenile salmonid survival through turbines was conducted in the early 1940's[1] after construction of Bonneville Dam and in 1954 after construction of McNary Dam (Schoeneman et al., 1961).

The first comprehensive program to study of juvenile salmonid migrants in the mainstem Columbia and Snake Rivers was initiated in 1961 by the Secretary of the U.S. Department of Interior. The program was instigated by construction of the high-head Brownlee Dam

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[1] Holmes, H. B. 1952. Loss of salmon fingerlings in passing Bonneville Dam as determined by marking experiments. U.S. Fish Wildl. Serv. Unpubl. manuscr., 62 p.

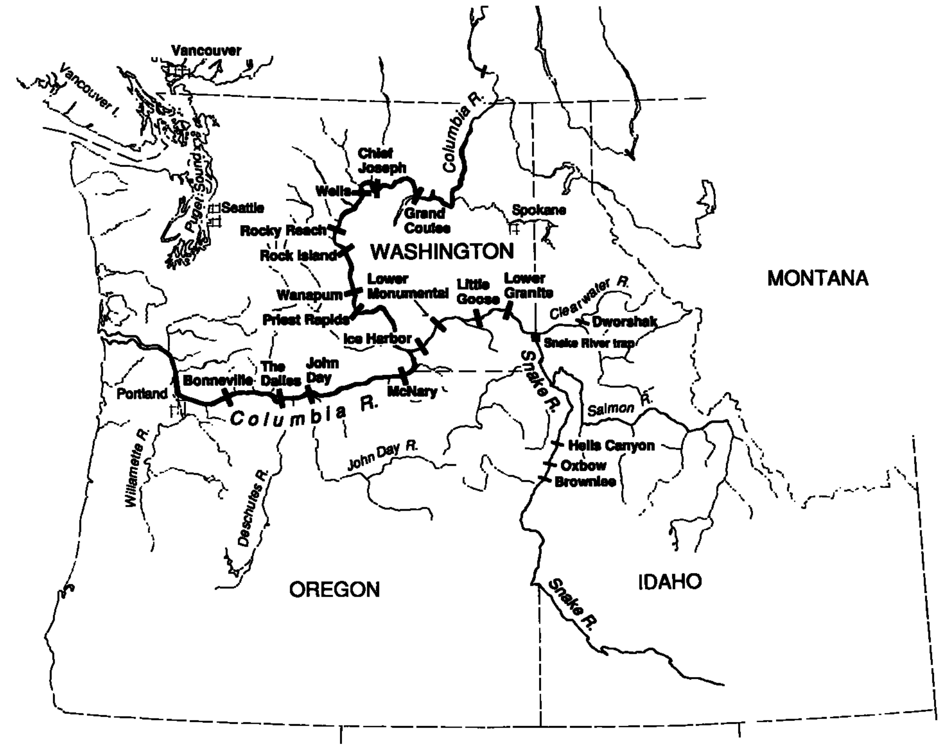

Figure 1

Map of the Columbia River Basin.

on the middle Snake River (Hells Canyon area) in 1958 and in anticipation of low-head dams authorized, but not yet constructed, for the lower Snake River (the stretch from its confluence with the Columbia River upstream to the confluence of the Clearwater River). As part of these efforts, one group of researchers from the Bureau of Commercial Fisheries (now the National Marine Fisheries Service [NMFS]) began studies with juvenile chinook salmon from the Snake River Basin to determine migration rates in relation to flow through areas of impounded and unimpounded stretches of the Snake and Columbia Rivers (Raymond, 1968). As the Lower Snake River dams and John Day Dam on the Lower Columbia River were completed, NMFS expanded these studies to estimate, in addition, the survival of fish passing through these impoundments. Raymond (1979) summarized the results of research from 1964 through 1975; results from 1976 through 1983 were detailed in a number of unpublished contract reports to the U.S. Army Corps of Engineers (COE).[2]

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[2] Sims, C. W., W. W. Bentley, and R. C. Johnsen. 1977. Effects of power peaking operations on juvenile salmon and steelhead trout migrations—progress 1976. Report to U.S. Army Corps of Engineering, Portland, OR, 44 p. Northwest Fish. Sci. Cent., NMFS.

Sims, C. W., W. W. Bentley, and R. C. Johnsen. 1978. Effects of power peaking operations on juvenile salmon and steelhead trout migrations—progress 1977. Report to U.S. Army Corps of Engineering, Portland, OR, 52 p. Northwest Fish. Sci. Cent., NMFS.

Raymond, H. L., and C. W. Sims. 1980. Assessment of smolt migration and passage enhancement studies for 1979. Report to U.S. Army Corps of Engineering, Portland, OR, 48 p. Northwest Fish. Sci. Cent., NMFS.

Sims, C. W., J. G. Williams, D. A. Faurot, R. C. Johnsen, and D. A. Brege. 1981. Migrational characteristics of juvenile salmon and steelhead in the Columbia River Basin and related passage research at John Day Dam. Report to U.S. Army Corps of Engineering, Portland, OR, 61 p. Northwest Fish. Sci. Cent., NMFS.

Sims, C. W., R. C. Johnsen, and D. A. Brege. 1982. Migrational characteristics of juvenile salmon and steelhead in the Columbia River System—1981. Report to U.S. Army Corps of Engineering, Portland, OR, 16 p. Northwest Fish. Sci. Cent., NMFS.

Sims, C. W., A. E. Giorgi, R. C. Johnsen, and D. A. Brege. 1983. Migrational characteristics of juvenile salmon and steelhead in the Columbia River Basin—1982. Report to U.S. Army Corps of Engineering, Portland, OR, 35 p. Northwest Fish. Sci. Cent., NMFS.

Sims, C. W., A. E. Giorgi, R. C. Johnsen, and D. A. Brege. 1984. Migrational characteristics of juvenile salmon and steelhead in the Columbia River Basin—1983. Report to U.S. Army Corps of Engineering, Portland, OR, 31 p. Northwest Fish. Sci. Cent., NMFS.

The methods used by NMFS researchers to estimate migration rates, timing, and survival were detailed by Raymond (1979). In brief, unique batch marks were applied by some combination of freeze brands and fin clips to yearling (stream-type migrants which were offspring of spring and summer stocks) wild or hatchery chinook salmon collected at hatcheries, from scoop traps and purse-seines, and/or at hydroelectric dams. The marked chinook salmon were then released from the collection sites and recaptured at downstream scoop-trap or purse-seine sites, or from gatewells or collection facilities at dams.

The estimated population of chinook salmon passing a capture site was derived from the formula $\hat{N} = n / \hat{CE}$, where $\hat{N}$ = the estimate of the total number of chinook salmon passing (either for the unmarked population as a whole or for specific mark groups); n = the number of chinook salmon collected (unmarked or marked); and $\hat{CE}$ = the collection efficiency. Collection efficiency was determined from separate groups of chinook salmon that were collected semiweekly at each capture site from the unmarked population of fish that was passing each capture site and subsequently marked uniquely for semiweekly upstream releases at each capture site. Estimates of collection efficiency for each site were derived from the formula $\hat{CE} = (r / (R - 10\%R) \times 100\%)$, where $\hat{CE}$ = the collection efficiency; R = the number of chinook salmon marked and released upstream specifically for collection efficiency estimates; and r = the number of chinook salmon recaptured from collection efficiency (R) releases. The number of chinook salmon released was decreased by 10% to account for suspected mortalities due to handling, marking, release procedures, and migration between the upstream release site back to the capture site. These methods also assumed that any adverse effects of handling, marking, and/or release procedures were equal for all release groups (Raymond, 1979).

Collection efficiency generally decreased as river flow increased. At Ice Harbor Dam, collection efficiency curves were fitted by regression techniques to paired data sets of individual collection efficiency estimates with the corresponding mean river flow during the period the estimates were made (Raymond, 1979). These curves were then used in future years to predict collection efficiency under various flows. At other capture sites, the data were considered too variable to develop reliable collection efficiency curves. In these cases, real-time estimates of collection efficiency were continually obtained during the period when fish were captured at the site.

The population estimate (N) was made in the following manner: if 15 marked chinook salmon of a particular group or 2,000 unmarked chinook salmon were captured at a collection site during a 24-hour period when the CE = 2%, then the estimated number of marked chinook salmon or the total number of unmarked chinook salmon which passed the collection site during the period would have been 750 (15/0.02) or 100,000 (2,000/0.02). Total population estimates were the sum of daily population estimates over the period of time when a specific, marked group of fish passed the site or over the period when the unmarked population passed.

Travel time of marked fish between two sites was determined by subtracting the date of release from a collection site (or the median passage date of fish at one capture site) from the median date of passage at a downstream capture site. Migration rates of fish were determined by dividing the distance between two sites by the travel-time estimate between the two sites. Survival estimates were made by dividing the population estimate at a downstream capture site by either the number of fish released at an upstream collection site or the population estimate at a capture site.

Nearly all fish used for marking in the first study years were products of natural spawning. The percentage of hatchery chinook salmon varied with hatchery output each year, but 100% of the Snake River stock was wild before 1966. Raymond (1988) estimated that from 1966 to 1969 hatchery fish represented about 15% of the chinook salmon migration that reached the upper dam (Ice Harbor Dam, 1966–68; Lower Monumental Dam, 1969) on the lower Snake River. According to his estimates, this percentage increased to 45–55% from 1970 to 1976 (the upper dam was Little Goose Dam, 1970–74; Lower Granite Dam, 1975–present) and averaged greater than 80% from 1981 to 1984.

The 1973–79 NMFS yearly point estimates of survival (Fig. 2) (1973–75 in Raymond [1979]; 1976–79 [see Footnote 2]) were used by NMFS researchers[3] to indicate the effects of the recently completed Snake River hydropower dams on juvenile fish survival. Particularly low juvenile fish survivals were observed under the low-flow conditions in 1973 and 1977, whereas survival estimates did not vary much under a broad range of higher flows. In the early 1990's, computer models were developed by the Northwest Power Planning Council, state fishery agencies, and tribes in the Pacific Northwest to predict survivals of juvenile fish migrating from Lower Granite Dam

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[3] Sims, C. W., and F. J. Ossiander. 1981. Migrations of juvenile chinook salmon and steelhead trout in the Snake River from 1973 to 1979, a research summary. Final Report to U.S. Army Corps of Engineering, Portland, OR, 31 p. Northwest Fish. Sci. Cent., NMFS.

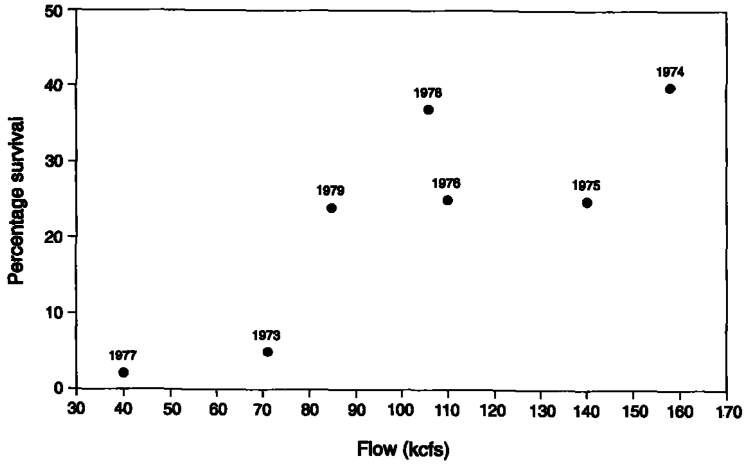

Figure 2

Survival estimates for juvenile spring and summer chinook salmon, *Oncorhynchus tshawytscha*, migrating through the upper dam (Little Goose Dam, 1973–74; Lower Granite Dam, 1975–79) on the lower Snake River to either John Day Dam (1976–79) or The Dalles Dam (1973–75) compared with the average river flow at Ice Harbor Dam during the period (±7 days) of peak migration for the years 1973 through 1979 (data from Sims and Ossiander [1981][see Footnote 3]).

to Bonneville Dam under present river conditions. To calibrate the models, they were fitted to the 1970's NMFS flow and survival data (after altering them to represent the turbine, bypass, and spill conditions that existed in the 1970's).

However, present river conditions and dam operations differ substantially compared with those in the 1970's. Further, detections in recent years of marked fish that migrated through the Snake River to McNary Dam under relatively low flows indicate that juvenile fish survive at a rate substantially higher than that which would be predicted from flow and survival relationships derived from the 1970's data. Because recent information is not in agreement with past data, but because the 1970's data are the foundation of some of the present computer models, we initiated a critical review of the NMFS data from the 1970's to determine whether these data were still relevant.

We initially reviewed all the NMFS data files from which estimates of survival were reported. These included original NMFS field notes, analyses of mark and recapture data, and yearly research summaries. We also reviewed field notes and data summaries from other concurrent NMFS research that documented the condition of fish collected at dams. On reviewing the original data, we determined that the lowest estimates of survival within the hydropower system (1973 and 1977) were mainly a result of low survival in the Snake River. Although the low flows increased travel time, more significantly, the entire migrant fish population was subjected to debris problems at the uppermost Snake River dam. Additionally, as a result of low flows, turbine operations were cut dramatically during nighttime hours (when fish normally pass dams) so that fish were delayed further and thus subjected to the effects of the debris for longer periods. We then compared the low 1970's survival estimates with some Snake River survival estimates of recent years.

Data review

Effects of dam operations and debris on fish condition

Juvenile salmon mortality for Snake River migrants was initially somewhat minimized because when the dams were first built, they were equipped with only three operating turbine units. This limited the amount of flow through the powerhouses to approximately 1,840–1,980 $m^3 \cdot s^{-1}$ (65–70 thousand cubic feet per second [kcfs]). From 35 to 75% of the total river flow (and a presumed equal percentage of the fish population) passed over the spillways during the spring seaward migration. Except under conditions where high atmospheric gas supersaturation decreased survival (Ebel and Raymond, 1976), survival of juvenile migrant fish through spillways was generally estimated at greater than 97% (Raymond, 1988). Three additional turbines were added to Ice Harbor Dam in 1975, to Little Goose and Lower Granite Dams in 1978, and to Lower Monumental Dam in 1979. This led to progressively less uncontrolled spill in the Snake River and a concomitant increase in fish passing through turbine intakes. To decrease fish mortality in the turbines, many of the fish that passed into turbine intakes at Little Goose and Lower Granite Dams were diverted to bypass and collection facilities (Smith and Farr, 1975; Matthews et al., 1977). However, the potential benefit of these bypass systems in decreasing the mortality of fish entering turbine intakes was compromised primarily because of debris that had collected at the dams.

With the exception of Ice Harbor Dam (which had a debris boom installed), huge amounts of woody debris began to accumulate at the upstream face, in the forebay, and on the trashracks of the dams as the Lower Snake River dams were constructed. Most of the debris accumulated at the uppermost dam in any given period. With periods of high spill, some debris passed downstream through spillways, but as the volume of spill decreased, the trash load at the upper dam increased. By 1979 at Lower Granite Dam, debris extended upstream from the dam approximately 1 km (Fig. 3). The debris that collected at Little Goose and Lower Granite Dams after their construction provided a continual supply of woody material that clogged trashracks, accumulated in the gatewells, and collected throughout the fish facilities. Gatewell orifices and all other components of the bypass systems were continually obstructed by debris. Although debris was constantly in the forebays, attempts were made to remove it from the trashracks. However, the rakes that were used to clear the trashracks were ineffective and instead, large, heavy-steel beams were occasionally lowered down the trashracks in an attempt to push impinged debris to the bottom. As judged by water levels and turbulence in the gatewells, this procedure met with limited success.

To compound problems, when first constructed the fish facilities at Lower Granite and Little Goose Dams had undersized plumbing systems and other poorly designed components through which fish moved. Lower Granite Dam had only 20.3-cm diameter orifices to the bypass system which were often plugged and required continual efforts (usually futile) by fish workers to remove debris to maintain unobstructed flows. During peak collection periods at the collection facilities, workers often required 1 hour, and at times up to 3 hours, to transfer fish from one of the five raceways into a fish transport barge. Occasionally, the 6-inch transfer lines would completely plug with debris and fish. The effect of debris throughout the bypass and collection systems was to increase fish injury, descaling, and ultimately mortality from dam passage (Table 1). Total mortalities at Lower Granite Dam were often so high (personal observations by the authors) that individual dead fish could not be counted. Most often, we kept volumetric estimates (buckets full) of dead fish dipnetted from tail-screens in raceways. The fish not collected at the uppermost dam passed through either the spillway or through the trashracks and then the turbines. Although not measured, the mortality of fish that were not collected at the uppermost dam, but which passed through the debris on the trashracks and then the turbines, probably was higher than that at downstream dams where debris on the trashracks was much less of a problem. For example, in 1979, fish sampled from the gatewells at Little Goose Dam showed far less descaling (a reduction of 50%) after the trashracks at Lower Gran-

Figure 3

Debris in the forebay of Lower Granite Dam, 1979.

Table 1

Average facility-caused descaling and delayed mortality for groups of unmarked and marked Snake River spring and summer chinook salmon, *Oncorhynchus tshawytscha*, smolts collected at Little Goose or Lower Granite Dams from 1972 through 1990. Smolts were held approximately 48 hours before or after truck transport to an area below Bonneville Dam.

Year	Dam	Facility-caused descaling (%)	Unmarked-fish delayed mort. (%)	Marked-fish delayed mort. (%)
Not Transported				
1972	Little Goose	19.6	<1.0; 17.6	21.8
1978	Lower Granite	7.5	20.6	13.8
1979	Lower Granite	5.3		5.0
1980	Lower Granite	4.0	2.2	
1986	Lower Granite	3.7		0.3
1987	Lower Granite	3.3		1.1
1989	Lower Granite	2.3		1.1
1990	Lower Granite	3.6		1.3
Transported				
1972	Little Goose	16.0	12.2	10.0
1973	Little Goose	19.6	15.3	17.2
1975	Lower Granite	13.0		11.5
1976	Little Goose	11.5	3.2	6.1
	Lower Granite	7.0	4.1	4.7
1977	Little Goose	23.9	21.3	42.5
	Lower Granite	26.0	31.4	30.0
1978	Little Goose	20.0	12.7	13.1
	Lower Granite	7.5	11.2	17.1
1979	Little Goose	8.1	19.8	
	Lower Granite	5.3	10.0	
1980	Lower Granite	4.0	1.9	

ite Dam were partially cleared of debris with the steel beam.[4]

Fish passage conditions were particularly bad at Little Goose Dam in 1973 and Lower Granite Dam in 1977 because river flows were so low that little (1973) to no (1977) spill occurred at Snake River dams. Thus, nearly all fish had to pass through trashracks at dams into either the turbines or the debris-laden bypass systems. Additionally, it was not unusual for one or more turbines to operate at full or nearly full capacity for relatively short periods during the evening peak load and then shut down for relatively long periods (authors' personal observations). At other times, one or two turbines were operated at partial capacity for relatively long periods. The slowing or stopping of turbines probably delayed dam passage by reducing or stopping the flow into each turbine and, thus, fish were not attracted to the bypass.

Under these conditions in 1977, 10–14% of spring and summer chinook salmon smolts within 140 m of the forebay at Lower Granite Dam were descaled (a fish was considered descaled if it was missing 10–100% of its scales), whereas fish sampled 400 m to 2 km upstream showed no descaling.[5] These observations suggest that fish were delayed at the dam and that they swam in and out of the debris-covered trashracks, possibly while loads were adjusted or when velocities were insufficient to draw fingerlings completely into the bypasses or through the turbines. For fish that passed into the collection facility, an average of 26.0% were descaled. Under similar conditions at Little Goose Dam, the percentage of fish descaled averaged 19.6 and 23.0% in 1973 and 1977, respectively, probably because they hit something during passage through the trashracks or bypass system. (The high level of descaling observed in 1977 most likely resulted from the fact that fish had previously passed Lower Granite Dam.) When debris partially occluded openings through which fish passed, it not only provided objects that the fish hit but caused increased water velocity through the remaining open area. Thus, fish hit the debris with more force as the amount of debris increased. A fish with external injury, such as descaling, would likely have had internal injury as well. To determine the relationship between descaling percentage (as a measure of total injury) and mortality within a short time period, random samples of bypass fish were collected during some years and held in tanks with flow-through river water. The rate of mortality during approximately 48 hours of holding was measured, and the extent to which this was dependent upon descaling percentage was evaluated. Facility-caused descaling was highly positively correlated with delayed mortality for marked untransported fish (R=0.94, $P \leq 0.002$) and unmarked transported fish (R=0.90, $P \leq 0.007$), whereas it was fairly

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[4] Smith, J. R., G. M. Matthews, L. R. Basham, S. Achord, and G. T. McCabe. 1980. Transportation operations on the Snake and Columbia Rivers, 1979. Report to U. S. Army Corps of Engineering, Walla Walla, WA, 28 p. Northwest Fish. Sci. Cent., NMFS.

[5] Park, D. L., J. R. Smith, E. Slatick, G. M. Matthews, L. R. Basham, and G. A. Swan. 1978. Evaluation of fish protective facilities at Little Goose and Lower Granite Dams and a review of mass transportation activities, 1977. Report to U.S. Army Corps of Engineering, Portland, OR, 60 p. Northwest Fish. Sci. Cent., NMFS.

positively correlated for marked transported fish (R=0.77, $P \leq 0.075$) (Table 1). Too few unmarked untransported groups were observed to examine the correlation. Further, we did not use the limited data because the <1.0% delayed mortality measured in one of the 1973 tests is inexplicable (the NMFS annual report[6] for the year stated that the results were "somewhat surprising," considering that migrants passing the dam suffered, in actuality, a 50% mortality). Although not evident from the summary table (Table 1), in the 1970's most of the descaled fish were missing considerably more than 10% of their scales as compared with present conditions where highly descaled fish are the exception rather than the rule.

Annual survival estimates were lowest for 1973 and 1977 (Fig. 2), the two years with the lowest river flows and the highest levels of descaling at the upper dam. The relatively low survivals may well have been greatly influenced by debris-related problems at the upper dams and were compounded by the low river flows in these two years.

In 1980, the COE began removing debris from the Lower Granite Dam forebay, and in 1981 a permanent debris rake was installed and used for the first time to remove debris from the trashracks (effective rakes to remove debris from trashracks were also built during the 1980's for other dams). In 1983, a temporary boom was placed upstream from Lower Granite Dam to divert new debris away from the powerhouse. The temporary boom was replaced by a permanent structure in 1984. Debris is now diverted away from the powerhouse and removed from the river, and trashracks are systematically cleaned. Additionally, the bypass systems at Lower Granite and Little Goose Dams have been substantially modified and improved. For example, pipe and orifice sizes have been increased so that what little debris enters the systems does not cause problems. Fish and debris separators have been modified so that fish are separated under water and they exit after separation via large flumes rather than small pipes. Descaling and 48-hour delayed mortality in recent years have been much less than those observed in the 1970's (Table 1), even under "relatively" low-flow conditions such as occurred in 1987.

To verify improved migratory conditions for chinook salmon smolts after debris problems had been eliminated or greatly controlled in the Snake River, we compared historic with recent Snake River survival estimates. Survival estimates in the 1970's over a 2- or 3-dam stretch under moderate to high river flows ranged from 33 to 50% (Raymond, 1979). Over a comparable 2-and 3-dam stretch in 1993 and 1994, survival estimates were 77%[7] and 66%[8], respectively. For low-flow conditions, we estimated survival of PIT-tagged (passive-integrated-transponder-tagged) (Prentice et al., 1990) chinook salmon smolts from Little Goose Dam to McNary Dam in 1992 by using Raymond's (1979) techniques for comparing populations of fish that passed both dams. We used 50 and 75% collection efficiency estimates for the two dams, respectively. Flows were similar in 1973 and 1992 (Fig. 4); however, our 1992 survival estimate (which covered three dams and reservoirs, but not the most upstream dam) was 81% compared with 12% for two dams and reservoirs in 1973 (Raymond, 1979).

Discussion and conclusions

The argument for a flow-survival relationship for juvenile salmonid migrants, based on the 1973–79 NMFS yearly point estimates of inriver survival (Fig. 2), is heavily influenced by the low survivals estimated for 1973 and 1977 under low-flow conditions. Low survival of river migrants (both above and through the hydropower system) certainly occurred during the 1973 and 1977 low-flow years. However, the estimated low fish survivals within the hydropower system resulted more likely from fish encounters with debris at dams (encounters which were increased because of low flows and exacerbated by sporadic turbine operations) than from river discharge. Data collected in the past few years on PIT-tagged fish that migrated under low to moderately-low flow conditions, comparable to those in the 1970's, indicated a substantially higher survival of juvenile smolts.

Under present conditions, low flows during the spring migration may not lead to direct losses of migrant fish as high as those in the 1970's within the

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[6] Ebel, W. J., R. W. Krcma, and H. L. Raymond. 1973. Evaluation of fish protection facilities at Little Goose Dam and review of other studies relating to protection of juvenile salmonids in the Columbia and Snake Rivers, 1973. Report to U.S. Army Corps of Engineering, Portland, 52 p. Northwest Fish. Sci. Cent., NMFS.

[7] Iwamoto, R. N., W. D. Muir, B. P. Sandford, K. W. McIntyre, D. A. Frost, J. G. Williams, S. G. Smith, and J. R. Skalski. 1994. Survival estimates for the passage of juvenile chinook salmon through Snake River dams and reservoirs. Report to the Bonneville Power Admin., Portland, OR, 140 p. Northwest Fish. Sci. Cent., NMFS, and Univ. Washington.

[8] Muir, W. D., S. G. Smith, R. N. Iwamoto, D. J. Kamikawa, K. W. McIntyre, E. P. Hockersmith, B. P. Sandford, P. A. Ocker, T. E. Ruehle, J. G. Williams, and J. R. Skalski. 1994. Survival estimates for the passage of juvenile chinook salmon through Snake River dams and reservoirs, 1994. Report to the Bonneville Power Admin., Portland, OR, 174 p. Northwest Fish. Sci. Cent., NMFS, and Univ. Washington.

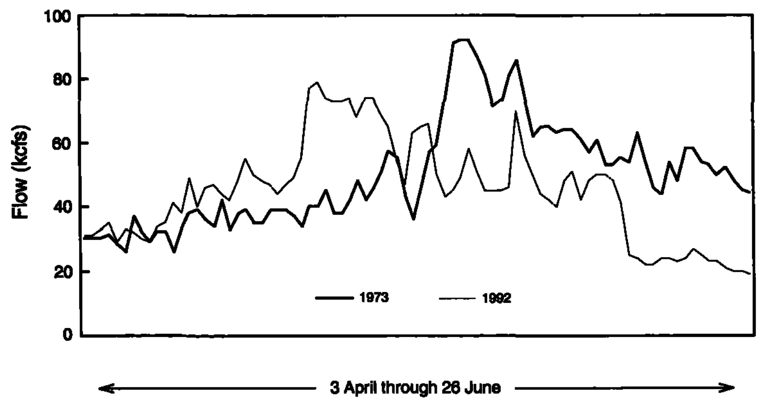

Figure 4

Comparison of 1973 and 1992 Snake River flows during the spring juvenile salmonid seaward migration.

Table 2

Changes in average runoff (in thousands of cubic feet per second) in the Columbia River at The Dalles Dam.

	May	June	July
1926–58	283	353	224
1959–75	250	344	211
1976–91	206	199	132

hydropower corridor, but past research definitely showed that low flows increased travel time (Raymond, 1979). Certainly adult returns of spring and summer chinook salmon have been greatly reduced in most years since the mid-1970's (Matthews and Waples, 1991). This poor return has coincided with a substantial decrease in lower Columbia River flows during the late spring and early summer smolt migrations as a result of completion of storage reservoirs in the upper Columbia River Basin (Table 2). The decreased volume of freshwater entering the estuary and ocean may have delayed entry of fish to the ocean or may have changed the ecology of the system sufficiently to affect predator-prey interactions above and below the trophic level of the juvenile migrant fish and, thus, their survival.

The 1970's juvenile survival estimates made by NMFS in average-to-high flow years also reflected the effects of debris for the proportion of the population that passed through the juvenile collection and bypass systems. These survival estimates are probably lower than those for present passage conditions, even when one accounts for the installation of new bypass systems at dams where they did not exist in the 1970's. Thus, they do not apply to present-day migrants in the Snake and Columbia River hydropower system, and we recommend they not be used by modelers, unless substantial modifications are made to adjust for the errors that we have discussed. We also recommend continued emphasis on research to provide up-to-date survival estimates under present system conditions, because the data gathered to date do not cover a wide range of flows.

Acknowledgments

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