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Hydroelectric Dams and the Decline of Chinook Salmon in the Columbia River Basin

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Abstract *The decline of chinook salmon runs into the mouth of the Columbia River in recent decades is thought to be partly attributable to the construction of hydroelectric dams. The purpose of this article is to estimate the magnitude of losses in chinook salmon runs caused by hydroelectric dams, using regression analysis. Such estimates are not only of historical interest but also can potentially affect the extent of efforts to mitigate salmon losses from hydropower operations. Congress has mandated the Northwest Power Planning Council to consider the magnitude of run losses caused by hydroelectric operations in determining the extent of mitigation efforts.*

Keywords Habitat, Northwest Power Planning Council, hydroelectric dams, chinook salmon, smolt production.

Introduction

Chinook salmon runs into the mouth of the Columbia River—runs that historically were among the largest in the world—have declined significantly since the mid-1920s. Theoretically, the decline can be attributed to several causes, including a growth in fishing effort and catch, reducing the stock of returning spawners; a decline in ocean habitat conditions; and a decline in habitat conditions in the Columbia River and its tributaries. Mature chinook salmon migrate upriver to the spawning grounds of their birth, lay and fertilize their eggs in gravel river and stream bottoms, and then die. Juvenile salmon or smolts emerge, spend up to a year in local waters, and then migrate downriver to the waters of the Pacific, where they remain until they mature and repeat the spawning cycle. Although ocean habitat decline is a possible explanation for reduced salmon runs, it can probably be ruled out given that such habitat has been little altered by human activity. This leaves fishing and river habitat alteration as the two possible explanations for declining runs.

Although the problem of habitat decline has been noted by resource economists, little progress has been made in separating out the effects of fishing on salmon runs from the effects of habitat deterioration and alteration (Crutchfield and Pontecorvo 1969, 125). The purpose of this article is to estimate the decline in chinook salmon runs attributable to a major form of habitat alteration on the Columbia River and its tributaries, the construction and operation of hydroelectric dams.

Estimates of the salmon population loss caused by the construction and operation of hydroelectric dams are not only of historical interest but also can potentially have an impact on current public agency programs to mitigate the salmon losses from hydropower operations. The Northwest Power Planning Council was formed by an act of Congress and is mandated to "protect, mitigate, and enhance fish and wildlife affected by the development, operation, and management of hydroelectric facilities" in the Columbia River Basin (Northwest Power Planning Council 1986a, 1). The scale of salmon mitigation projects and the level of expenditures on such projects funded by electricity ratepayers are to be determined, at least in part, by estimates of salmon run losses attributable to hydroelectric dams. A larger loss estimate would result in a more extensive program of mitigation. The council has used hypothetical smolt production figures for the Columbia River basis and adjusted them to account for mortality from dams and the ocean portion of the life cycle to derive estimates of salmon run losses from dams (Northwest Power Planning Council 1986b). By contrast, the purpose of this article is to estimate the loss attributable to dams using econometric techniques and actual historical data on salmon runs and escapement. Once this task is accomplished, estimates from the two approaches can be compared and critically evaluated.

Hydroelectric Development on the Columbia and Snake Rivers

The construction of dams for irrigation and electric power generation on the smaller tributaries of the Columbia date back to the early 1900s (Lavier 1976a). However, dam construction on the mainstem of the Columbia and the middle and lower Snake did not commence until the 1930s. The first dam on the mainstem of the Columbia was the Rock Island Dam, constructed by a public utility district and put into operation in 1933. Construction of the next two dams on the Columbia can be attributed in large measure to the 1920s depression and the attractiveness of large public works projects as a means of creating employment and stimulating economic development. Soon after the 1932 election, the Roosevelt administration authorized the construction of the Bonneville and Grand Coulee Dams (Norwood 1980, 26–40). The Army Corps of Engineers constructed the Bonneville Dam for the purposes of facilitating navigation on the Columbia and generating electric power. The Grand Coulee Dam, on the other hand, was constructed by the Bureau of Reclamation as part of an irrigation project, although the bulk of the revenues to cover the cost of the dam were to be derived from the sale of electricity. The Grand Coulee Dam, placed in operation in 1941, had no fish ladders and thus completely blocked upstream migration of salmon. The Bonneville Dam, placed in operation in 1938, did have fish ladders that were added to the original design only after heated protests from commercial fishing organizations (Netboy 1980, 75). The two dams together would have had trouble marketing the massive amount of electricity they generated had not World War II commenced, dramatically increasing the demand for electricity by a regional aluminum industry created for the war effort (Norwood 1980, 41, 119–128).

Further dam construction was postponed until after the war. Between 1950 and 1969 19 additional dams were constructed on the mainstem of the Columbia and Snake Rivers of which 12 had a significant impact on existing salmon runs (Lavier 1976a). The upper and middle Snake River was blocked from salmon migrations as a result of dam construction. Dams on the Columbia River below the Chief Joseph Dam, located just downstream from the Grand Coulee, were constructed with fish ladders. Dams were constructed by the Army Corps of Engineers, public utility districts, and the Idaho Power Company for the purposes of electricity generation, and in the case of the Corps, also for flood control and navigation (Netboy 72–97).

Even though fish ladders were installed at many dams, dams still constituted a significant barrier to successful upstream and downstream migration of salmon. Adult chinook salmon migrate upstream from the ocean for the purpose of spawning anywhere from three to five years after their birth, returning to the spawning streams from which they originated. Upstream migrants are confronted with the danger of nitrogen poisoning in the waters just below the spillways that become supersaturated with nitrogen (Ebel et al. 1974). In some instances, spawning grounds on the mainstem have been destroyed by the creation of large pools behind dams. Salmon require areas with gravel bottoms and relatively rapidly flowing cool water with a high oxygen content for successful spawning. Pools behinds dams tend to have little perceptible flow, relatively warm water, and silty bottoms as a consequence of a slowing stream flow and a dropping out of silt from the water (Netboy 1980, 37–54, 97–102).

Soon after their birth, Juvenile salmon migrate downstream and out into the ocean. Because of their vulnerability, downstream mortality for juvenile salmon as the result of dams tends to be significantly greater than it does for upstream migrating adults. Normally, downstream migrants face upstream and simply float with the current. This is impossible in the slow-moving pools behind dams forcing the juvenile salmon to expend considerably more energy than they otherwise would during the downstream migration. In addition, the juveniles are highly vulnerable to predators in the still waters of the pools and have trouble discerning the proper direction in which to swim. At the dams themselves, juvenile salmon are faced with mortality from passing through electrical turbines and nitrogen poisoning in the waters below the dam (Netboy 1980, 92–102). Although mortality varies with flow conditions and from one dam to another, fisheries researchers have estimated that upstream mortality for each dam is roughly 5%, and downstream mortality is approximately 20% (Northwest Power Planning Council 1986b, 8).

A Methodology for Estimating Salmon Run Declines from Hydroelectric Development

The methodology used here for estimating the effect of hydroelectric dams on salmon runs is based on a conventional spawner-return model of the following form:

$$R_t = f(S_{t-s}) \tag{1}$$

where R is the number of salmon returning to spawn in time period t from the brood year of spawners S in period $t-s$ (Crutchfield and Pontecorvo 1969, 23–25). In practice, the run in any given year for chinook salmon will be composed of three to four different brood years. Because of diminishing returns to population density on feeding and spawning grounds, the first derivative of the above function is positive and declining and eventually goes negative. The difference between the run into the river R in this model and the number of spawners S for any given year is the number of salmon harvested in the river. For upper river runs (those with destinations above the Bonneville Dam), the escapement of spawners can be readily estimated from dam counts and the total run can be estimated by adding dam counts to the harvest figures.

To take into account losses from dams, the above model needs to be modified. As dams are constructed and put into operation over time, the run must be adjusted downward by the loss resulting from the upstream mortality of spawners and the downstream mortality of smolts that occur at each dam. To accomplish this, successful smolt production and downstream migration M in the absence of dams is assumed to take the following quadratic functional form:

$$M = aS - bS^2 \tag{2}$$

where a and b are positive constants and the time period subscripts are suppressed to simplify the notation. This functional form satisfies the assumption of diminishing returns on the spawning and rearing grounds.

Given the above model and its assumptions, the loss of successful downstream smolt migrants for the first mainstem dam, the Rock Island Dam, which was put into operation in 1933, is equal to

$$[ah_0S - b(h_0S)^2] - d[auh_0S - b(uh_oS)^2] \tag{3}$$

where h_0 is the proportion of the total stock of spawners migrating to locations above the Rock Island Dam, u is the upstream spawner survival rate for passage by a single dam, and d is the downstream smolt survival rate for passage by a single dam.[1] The constants a and b together determine the magnitude of smolt production and downstream migration from a given number of spawners that reach the spawning grounds in the absence of dams. The first bracketed component of Eq. 3 is downstream smolt migration from the area above Rock Island Dam prior to dam construction, the second bracketed component multiplied by d is downstream smolt migration from the same area after the dam is in place, and the difference between the two components is the loss of downstream smolt migration as a result of the dam. In the second bracketed component of Eq. 3 the upstream survival rate is multiplied by the spawner escapement level h_0S because mortality caused by a dam during upstream migration reduces the number of spawners, and the downstream survival rate d is multiplied by the production function as a whole because the downstream mortality occurs sequentially after smolt production has taken place. Equation 3 can be rewritten as

$$ad_0S - bd_0'S^2 \tag{4}$$

where $d_0 = mh_0$, $d_0' = m'h_0^2$, $m = 1 - du$, and $m' = 1 - du^2$.

The loss from the second mainstem dam, the Bonneville Dam, which was put into operation in 1938, is equal to

$$amh_1S - bam'(h_1S)^2 \tag{5}$$

assuming that the Rock Island dam does not exist and that h_1 is the proportion of the total upper river run above the Bonneville Dam. Because the upper river run is defined as the run with spawning ground destinations above Bonneville, h_1 will equal one. Because the Rock Island Dam was already in operation at the time Bonneville was constructed, Eq. 5 needs to be modified. Equation 5 already includes the equivalent of Eq. 4 as the loss above the Rock Island Dam resulting from Bonneville, but to correctly represent the actual loss from Bonneville, it should include only the difference in the loss above Rock Island before and after the construction of Bonneville, which is equal to

$$[a(1 - d^2u^2)h_0S - b(1 - d^2u^4)(h_0S)^2] - [amh_0S - bm'(h_0S)^2] \tag{6}$$

where the first bracketed component is the loss of smolt production from above Rock Island with both Rock Island and Bonneville in operation, and the second bracketed component is the same loss with just Rock Island in operation. The first component incorporates the upstream and downstream mortality from two dams; the second component incorporates such mortalities for just one dam. Equation 5 must be altered to account for the prior existence of Rock Island Dam by subtracting Eq. 4 and adding Eq. 6 in order to come up with the following:

$$ad_1S - bd_1'S^2 \tag{7}$$

where $d_1 = mh_1 - m^2h_0$ and $d_1' = m'(h_1)^2 - m'^2(h_0)^2$.
In the above equations d_i can be viewed as a linear smolt loss rate from the dam in question, and d_i' can be referred to as a quadratic smolt loss rate.

The third mainstem dam, the Grand Coulee, which was put in operation in 1941, lacked passage facilities. Consequently, the remaining runs with spawning ground destinations above the Grand Coulee were completely lost. Given the above notation, the loss is equal to

$$ad_2S - bd_2'S^2 \tag{8}$$

where $d_2 = (1 - m)^2h_1$ and $d_2' = (1 - m')^2(h_2)^2$. The proportion of the run above Grand Coulee must be reduced by mortality associated with the two downstream dams already in operation to arrive at the correct smolt loss rate.

The next mainstem dam on the Columbia, the McNary, was not put into operation until 1953, and resulted in a loss equal to

$$ad_3S - bd_3'S^2 \tag{9}$$

where $d_3 = (1 - m)mh_3 - (1 - m)m^2h_0 - m(1 - m)^2h_2$ and d_3' is the corresponding quadratic loss rate with m' substituted for m and the run proportions squared. The McNary Dam is located above Bonneville Dam but below the Rock Island and Grand Coulee dams. Consequently, the loss in the absence of Bonneville has to be adjusted downward by multiplying through by the factor $(1 - m)$ to account for the prior existence of the Bonneville Dam. Also, the loss figure must be adjusted for the prior existence of both the Rock Island and Grand Coulee dams. This is accomplished by the second and third components of d_3. The second component is the loss from Rock Island Dam taking into account the existence of the Bonneville Dam multiplied by m, the mortality associated with the McNary Dam. The third component is the loss from the Grand Coulee Dam, which already takes into account the Bonneville Dam, multiplied by m, the mortality associated with the McNary.

This same procedure can be followed to calculate linear and quadratic loss rates for each dam on the mainstem of the Columbia and Snake Rivers.[2] A summation of the linear indices (the d_is) can be made for all dams at any given point in time t and can be set equal to D_t. The same can be done for the quadratic indices. Data for D_t, which can be referred to as the aggregate linear loss rate for dams, are presented in Table 1. The following model of the spawner return relationships can now be derived for statistical estimation purposes:

$$R_t = b_1(1 - D_{t-s})S_{t-s} - b_2(1 - D_{t-s}')(S_{t-s})^2 \tag{9}$$

This equation can be put into a return-per-spawner form by dividing through by S_{t-s}:

$$R_t/S_{t-s} = b_1(1 - D_{t-s}) - b_2(1 - D'_{t-s})S_{t-s} \quad (10)$$

This is the functional form used in the estimation procedure described below. This functional form assumes a constant ocean mortality rate, an assumption also adopted by the Northwest Power Planning Council in its work (Northwest Power Planning Council 1986b, 8).

Empirical Results

The empirical results using the model just described are presented in Tables 2–4 for the spring, summer, and fall upper river runs of chinook salmon. In each case the spawner population used is a weighted average of previous spawner escapement levels because a run in any given year is made up of three or four different brood year classes depending on the run. The weights used are taken from Junge and Oakley (1966), an earlier article on the effects of dams on salmon runs.[3] Regression results are presented for three alternative upstream and downstream survival rates (u and d) for individual dams. Fisheries researchers estimate that the typical upstream survival rate for spawners is 95% for a dam with passage facilities, and the typical downstream survival rate for smolt is 80% (Northwest Power Planning Council 1986b, 8). To construct a range of possible survival rates, 25% of the upstream and downstream mortality rates ($1 - u$ and $1 - d$) were added and subtracted from the survival rates estimated by fisheries researchers under the assumption that an error greater than this is unlikely. Note that the goodness of fit changes very little as survival rates for individual dams are changed, suggesting that regression analysis cannot be used to determine which survival rates are the correct ones. For this reason, a range of estimates of salmon losses from dams will be calculated using regression results covering the suggested range of survival rates.

Table 1
The Aggregate Linear Loss Rate for Dams

	Run		
Year	Spring	Summer	Fall
1938–1940	.2721	.2710	.2781
1941–1952	.3403	.3467	.3948
1953–1956	.4813	.4978	.4921
1957	.6050	.6180	.6140
1958	.7243	.7904	.6140
1959–1960	.7289	.7935	.6145
1961–1962	.7754	.8366	.6624
1963–1966	.7781	.8384	.6627
1967	.8570	.9010	.7710
1968	.8781	.9206	.7922
1969–1984	.8925	.9341	.8080

Note. The upstream spawner survival rate for an individual dam is assumed to be equal to .95, and the downstream smolt survival rate is assumed to be .80 in these calculations.

Table 2
Regression Results and Run Loss Estimates: Spring Chinook Upper River Run Return Per Spawner, 1944–1984

	Equations			
	(i)	(ii)	(iii)	(iv)
Individual dam upstream and downstream survival rates	(.95) (.80)	(.95) (.80)	(.9625) (.85)	(.9375) (.75)
Independent variables				
Constant	1.8453 (3.44)	3.6709 (2.68)	1.9017 (3.08)	1.7794 (3.70)
Aggregate survival rate for dams	4.9600 (4.08)	2.5110 (1.31)	4.3637 (3.74)	5.5933 (4.27)
Quadratic survival rate times spawners	−.0509 (−3.62)	−.0555 (−3.87)	−.0445 (−3.61)	−.0579 (−3.62)
Weighted hatchery release		−.0002 (−1.76)		
Ocean troll effort		−.0001 (0.32)		
$\bar{R}^2$	.6564	.6633	.6538	.6583
d.w.[a]	1.73	1.76	1.72	1.75
Mean weighted spawners	78231			
Inriver run loss from dams	93064		87298	97476
Run loss from dams with ocean catch	102370		96028	107233

Note. The figures in parenthesis for Tables 2–5 and 8 are *t*-statistics. The critical value of the statistic for a two-tailed test and a 10% significance level is approximately 1.69. The data sources for run and spawner escapement levels are Fish Commission of Oregon and Washington Department of Fisheries (1971 and 1984) and Oregon Department of Fish and Wildlife and Washington Department of Fisheries (1988). The data sources for hatchery releases are Washington Department of Fisheries (1988b), Oregon Department of Fish and Wildlife (1988), Idaho Department of Fish and Game (1988), and Smith and Wahle (1981). Hatchery release data are unavailable for the Columbia River prior to 1960, and the hatchery release variable is set equal to zero. Because of an inadequate hatchery feeding technology, it is generally though that hatchery releases prior to 1960 were ineffective (Ortmann et al. 1976). The data sources for ocean troll effort are Washington Department of Fisheries (1971, 1982, and 1988a). All these data sources apply to Tables 3–5 and 7 as well.

[a]For all regression equations a first- or second-order autoregressive scheme was used in Tables 2–5 and 8 to deal with a problem of low Durbin-Watson statistics.

The model in Eq. 10 is supported in a slightly modified form by the empirical results presented in Tables 2–4. The coefficient on the aggregate linear survival rate for dams, defined as one minus the aggregate loss rate for dams $(1 - D'_{t-s})$, is statistically significant and positive in all cases, and the coefficient on the aggregate quadratic survival rate for dams times the weighted and lagged spawner escapement level, $(1 - D'_{t-s})S_{t-s}$, is statistically significant and negative in all cases.[4] With only one exception, the constant term is statistically significant and positive, suggesting that it should be

Table 3
Regression Results and Run Loss Estimates: Summer Chinook Upper River Run Return Per Spawner, 1944–1984

	Equations			
	(i)	(ii)	(iii)	(iv)
Individual dam upstream and downstream survival rates	(.95) (.80)	(.95) (.80)	(.9625) (.85)	(.9375) (.75)
Independent variables				
Constant	1.1979 (2.65)	1.2451 (1.24)	1.1312 (2.20)	1.2251 (2.97)
Aggregate survival rate for dams	7.2926 (6.91)	7.2421 (5.14)	6.6666 (6.52)	8.0407 (7.17)
Quadratic survival rate times spawners	−.0783 (−4.31)	−.0784 (−4.21)	−.0668 (−4.20)	−.0912 (−4.38)
Weighted hatchery release		−.0002 (−0.50		
Ocean troll effort		−.00002 (0.05)		
$\bar{R}^2$	.8252	.8205	.8214	.8279
d.w.[a]	1.70	1.70	1.70	1.70
Mean weighted spawners	56738			
Inriver run loss from dams	169550		167933	171213
Run loss from dams with ocean catch	457785		453419	462274

[a]*See note a, Table 2.*

included in the model in all except the one case. This in effect means that Eq. 10 is not exactly the functional form, and that the function represented by Eq. 10 must be shifted up to get the best statistical fit.[5] In the one case where the constant term is statistically insignificant, the model is reestimated dropping the constant term. The result is an improvement in the t-statistics.

Two other variables can potentially influence upper river salmon runs: upper river hatchery releases and ocean troll fishing effort. Spring and fall run smolts are released by a number of hatcheries above the Bonneville Dam. The release of summer chinook smolt is insignificant and is thus not considered here. Hatchery release figures were compiled, weighted according to brood year in a given run, and lagged using the weights described above from Junge and Oakley (1966). The release figures were then adjusted for downstream smolt mortality resulting from passage through dams. In theory, hatchery releases should have a positive effect on runs into the river. As can be seen in Table 4, the coefficient on the hatchery release variable is not statistically significant for the fall run. In the case of the spring run in Table 2, however, the coefficient is statistically significant and negative, suggesting that hatchery releases reduce runs rather than increase them. Because the inclusion of the hatchery release variable in the model results in the linear survival rate being rendered statistically insignificant, and because the correlation between the linear survival rate for spring chinook and the hatchery release variable is equal to −.86, multicollinearity is present between the two variables. Effective hatchery releases increased from zero to a positive number at the same time major dam construction was ending, and at least some hatcheries have been put into operation to mitigate the negative effects of dams on salmon runs (Delarm and Wold 1986).[6] Because the sign of the coefficient on the hatchery release variable is negative in the regression equation, it must be picking up the effects of hydroelectric dam construction and operation rather than the effects of hatchery releases on spring runs. Consequently, the hatchery release variable is dropped from the model. To the extent that hatchery releases in fact do contribute to runs, the estimate of the reduction in runs as a consequence of dams will be biased in a downward direction.

An increase of ocean troll fishing effort should in theory increase the ocean catch and reduce the run into the river and therefore the return per spawner. This hypothesis is not, however, supported by the statistical evidence in Tables 2–4. In all cases the coefficient on ocean troll effort is statistically insignificant. This could be explained by a relatively constant ratio over time between the inriver run and the ocean catch of fish destined for the Columbia River. If the ratio was fairly stable, then ocean fishing effort would not be a determining element in the inriver run.[7]

Further comments are required on the measure of fishing effort used in Tables 2–4. Accurate data on fishing effort is difficult to get. The only series of data available for the entire period that could serve as a proxy for ocean troll fishing effort was the number of commercial ocean troll licenses issued by the state of Washington. A reasonable pre-

Table 4

Regression Results and Run Loss Estimates: Fall Chinook Upper River Run Return Per Spawner, 1944–1984

	Equations				
	(i)	(ii)	(iii)	(iv)	(v)
Individual dam upstream and downstream survival rates	(.95) (.80)	(.95) (.80)	(.9625) (.85)	(.9625) (.85)	(.9375) (.75)
Independent variables					
Constant	1.7087 (3.59)	2.8341 (1.49)	1.5293 (1.49)		1.2251 (2.35)
Aggregate survival rate for dams	8.9649 (3.59)	7.7226 (2.20)	8.1467 (3.36)	11.0640 (6.14)	9.9447 (3.70)
Quadratic survival rate times spawners	−.0425 (−4.04)	−.0447 (−4.19)	−.0367 (−4.10)	−.0375 (−4.12)	−.0484 (−3.90)
Weighted hatchery release		−.00009 (−0.32)			
Ocean troll effort		−.00019 (−0.32)			
$\bar{R}^2$	.6542	.6416	.6560	.6496	.6512
d.w.[a]	1.83	1.81	1.83	1.90	1.84
Mean weighted spawners	138710				
Inriver run loss from dams	413702			663228	390344
Run loss from dams with ocean catch	1592755			2553428	1502824

[a]*See note a, Table 2.*

sumption is that market conditions would be roughly the same along the entire west coast, and thus aggregate effort would probably be roughly correlated to effort for one state. The number of licenses is not the best possible measure of effort because of the possibility of technological change increasing the amount of effort per license. In any event, the ocean troll catch is a positive, statistically significant function of ocean troll effort using the licenses measure, as can be seen in Table 5.

Because most of the ocean troll fishing effort that affects Columbia River salmon runs is expended on the fall run, the fall chinook hatchery release should be a determinant of the ocean troll catch. Unfortunately, the lagged and weighted hatchery release variable and ocean troll effort have a correlation coefficient equal to .81, suggesting the possibility of multicollinearity between the variables. This possibility is supported by Eq. (ii) in Table 5, where adding the hatchery release variable to the regression reduces the significance of the ocean troll effort variable and reduces $\bar{R}^2$ slightly. The correlation between the two variables would be reasonable given that increased effective hatchery releases result in increased runs that would in turn attract increased fishing effort. The vast bulk of the Columbia River hatchery releases occur below the Bonneville Dam and thus could well have a significant impact on the aggregate Columbia River run even though the much smaller upper river releases do not seem to statistically affect the upper river runs.

Table 5

Regression Results for the Ocean Troll Catch: 1944–1984

	Equations	
	(i)	(ii)
Independent variables		
Constant	1806.7	1824.3
	(11.50)	(10.69)
Ocean troll effort	.2706	.1900
	(3.48)	(1.61)
Total Columbia River fall chinook hatchery release (lagged and weighted)		3.1633
		(0.84)
Statistics		
$\bar{R}^2$	.52	.51
d.w.	1.82	1.86

Note. The data sources for the ocean troll chinook are Aro and McDonald (1974), Fry (1951), Milne (1964), Van Hyning (1951), North Pacific Fisheries Commission (1952–1988), and Washington Department of Fisheries (1982). For Oregon and California data prior to 1948 average weights of 11.4 pounds and 11.5 pounds were used, respectively, to convert Oregon and California catch data in terms of weight to numbers of fish. These figures were derived from data available on weight and numbers caught for 1951 to 1973 for Oregon and 1952 to 1973 for Oregon. The years 1949 and 1950 were missing from British Columbia data and were interpolated from data for 1948 and 1951. Data on Japan's catch begins with the year 1952, prior to which it was an insignificant figure. The ocean trawl catch includes Alaska, British Columbia, Washington, Oregon, California, and Japan. The source for the hatchery release data is Delarm and Wold (1986).

The magnitude of the run loss can be estimated using the regression results. This involves using the regression coefficients to calculate the return-per-spawner with and without dams using the mean value of the weighted and lagged spawner escapement variable. The difference in the return-per-spawner figures can then be multiplied by the mean value of the weighted and lagged escapement to derive a loss figure for the inriver run. The total loss due to dams can then be derived by multiplying the inriver run loss by the ratio of the ocean troll catch to the inriver run estimated by fisheries researchers and then adding this figure to the inriver run loss.[8] The run loss estimates are presented for each run in Tables 2–4.

Comparison to the Northwest Power Planning Council Analysis

The run loss estimates generated in this article can now be compared with run losses from dams estimated by the Northwest Power Planning Council in Table 6. The first figure in the table is a total run loss estimate from all causes. The fall figure includes only natural runs, not hatchery runs. The council used several methods for estimating the loss from dams, all of which yielded roughly similar figures (Northwest Power Planning Council 1986b). These included estimates based on the predevelopment run size, the current run size, and potential smolt production. Because the estimates in this article are based on the current run, the current run size estimates by the council are used here as the basis for comparison. These estimates are reproduced in line (ii) of Table 6. The procedure employed to arrive at these estimates was to use known ocean mortality figures to estimate the potential smolt production from existing runs. Smolt production was then distributed to different geographic areas on the basis of relative stream habitat mileage, and adult production was estimated with and without dams using a downstream smolt mortality of 20% per dam and an upstream adult mortality of 5% per dam. This procedure is essentially identical to the approach used in this article to calculate the aggregate loss rate for dams D_t, which is used in turn to statistically estimate losses due to dams rather than to calculate such losses hypothetically.

The figures in line (ii) can be compared to the run loss estimates derived in this article and reproduced in line (iii). For the fall chinook run, the estimates in lines (ii) and (iii) are close. The estimates generated in this article for the fall run may in fact be biased downward because of the inability in the regression analysis to account for the addition of fish to the run from upper river hatchery releases beginning in 1960. The mean effective annual upper river fall hatchery release for hatcheries from 1960 to 1984, lagged and weighted to correspond with the appropriate brood year and adjusted to take into account downstream mortality, was 15,588,000 smolt. Given a 4% ocean survival rate, the average annual addition to the run from hatchery releases would constitute 623,520 fish.[9] Because the regression results do not account for an increase in the run as a result of hatchery releases, the added surviving hatchery fish should be included in the estimate resulting in the adjusted estimate in line (iv) of Table 6. This puts the council estimate just about in the middle of the estimate range derived in this paper. A comparable hatchery release figure for the spring run was 1,803,000, and given a 2% ocean survival figure, this added 36,070 fish to the run.[10] The adjusted estimate for the spring run is also presented in line (iv) of Table 6.

The disparity between the council's loss estimates and those derived in this article for the spring and summer upper river runs are significant. The difference arises primarily because of a difference in methodology. The council implicitly assumed constant returns to additional spawners in the production of adult salmon. This article suggests

Table 6
A Comparison with the Power Planning Council Run Loss Estimates
(Number of Fish)

	Spring Upper River Run	Summer Upper River Run	Fall Upper River Run
Power Planning Council estimates[b]			
(i) Total run loss estimate	404,000–1,817,000	2,475,000–4,538,000	176,000–525,000
(ii) Loss from dams based on current run	888,379	2,253,053	2,386,464
Run loss estimates: this article			
(iii) Run loss estimates based on regression analysis (Tables 2–4)	96,208–107,223	453,419–462,275	1,502,824–2,553,428
(iv) Run loss with hatchery fish included	132,098–143,293	453,419–462,274	2,126,344–3,176,948
(v) Maximum total run without dams based on regression analysis[b]	250,412	631,311	2,578,260
(vi) Maximum inriver run with dams based on regression analysis[b]	149,189	64,469	249,045
(vii) Optimum spawner escapement based on regression analysis[b]	125,448	76,816	145,216

[a]The sources are Northwest Power Planning Council (1986a and b).
[b]The upstream survival rate assumed for an individual dam is .95 and the downstream survival rate assumed in .80.

that there are in fact diminishing returns as indicated by the negative coefficient on the second variable in the regression equations of Tables 2 and 3. Thus, additional spawners beyond some point will actually reduce the size of the run. Moreover, if the regression results are an approximate representation of reality, the spring and summer runs could not return to their historical highs as indicated by the data for the pre-dam theoretical maximum runs, including the ocean catch presented in line (v) of Table 6. The calculation of the maximum run assumes that the optimum spawner escapement level is chosen.[11] In other words, some other form of damage to runs occurred prior to dam construction, reducing the maximum runs obtainable.

Possible forms such damage could take include the construction of irrigation dams in tributaries and the extinction of specific races of salmon that migrate to particular tributaries through overfishing. Some argue that the aggregate chinook salmon harvest level was maintained in the first third of this century by simply shifting fishing effort from the spring chinook run, to the summer run, and then to the fall run as the first two runs declined significantly (Craig and Hacker 1940, 196–1967). Because the fall run had not been as significantly depleted at the beginning of the period during which mainstem dam construction began in the 1930s, the fall estimates in this article are closer to the council's estimates. As can be seen in Table 7, however, the spring and summer inriver runs were already at relatively low levels in the 1940s while the fall run was still fairly large. The council implicitly assumes that spring and summer runs can recover to their historical highs. The historically based analysis of this article suggests that these runs cannot recover to historical highs under current conditions. To change these conditions would require the restoration of upper river runs that have been fished to extinction and the restoration of damaged upper river habitat.

One potential upper river habitat problem that could have reduced runs prior to the construction of mainstem dams was the construction of smaller dams on the tributaries of the Columbia. An estimate of the damage to the aggregate chinook salmon runs from tributary dams constructed over the period 1871–1948 is presented in Table 8. Two variables are included in the model, the magnitude of gill net fishing effort on the Columbia River as measured by the number of gill net boats, and the number of tributary dams. The usual catch-effort models in fisheries economics assumed that catch is a function of effort, but that catch at margin diminishes as effort increases (Crutchfield and Pontecorvo 1969, 29). Several functional forms exhibiting diminishing marginal returns were attempted, and the semi-log form on effort brought the best statistical results. The coefficient on gill net effort is statistically significant and positive in the regression equation, whereas the coefficient on the number of tributary dams is statistically significant and negative, suggesting that such dams reduced salmon runs. According to the regression, each tributary dam reduced the harvest by 14,597 fish. The aggregate loss for the 38 tributary dams is shown in Table 8. Given a 50% catch efficiency, the run loss would be equal to 1,109,372.

Table 7

Columbia River Average Annual Salmon Runs into the River and Weighted Escapement Levels: 1946–1985 (Thousands of Fish)

	Upper River Spring Chinook		Upper River Summer Chinook		Upper River Fall Chinook	
Years	Run	Escapement	Run	Escapement	Run	Escapement
1946–1950	111.2	39.4	74.5	19.9	605.3	158.8
1951–1955	230.2	58.6	117.7	47.1	242.4	130.3
1956–1960	188.0	89.0	180.4	78.2	276.5	91.1
1961–1965	170.5	83.1	101.0	92.7	248.4	150.3
1966–1970	169.5	80.7	89.0	70.2	296.9	132.7
1971–1975	178.8	102.6	59.2	77.6	292.3	150.4
1976–1980	92.7	101.6	38.6	46.3	257.7	143.2
1981–1984	63.1	83.0	25.1	36.2	231.6	135.5

Note. The escapement levels are lagged and weighted so as to correspond to the brood year for the run in question.

Table 8
Regression Results for Early Columbia River Chinook Harvest: 1871–1948

	Equation (i)
Independent variables	
Constant	−143.87
	(1.18)
Gill net effort	219.64
(natural log)	(2.04)
Number of tributary dams	−14.597
	(−2.61)
Statistics	
$\bar{R}^2$	.65
d.w.	1.87
Losses	
Inriver harvest loss from tributary dams	554,686
Run loss from tributary dams (67% catch efficiency)	832,029
Run loss from tributary dams (50% catch efficiency)	1,109,373

Note. The data sources are Beiningen (1976a), Lavier (1976b), Fish Commission of Oregon and Washington Department of Fisheries (1971, and Smith (1979, 108–109). The measure of gill net effort is the number of gill net licenses issued for the Columbia River. Because there are missing years for the license data, arithmetic interpolation was used to fill in missing data.

Conclusion

The total annual loss of chinook salmon resulting from both mainstem and tributary dams is estimated to be somewhere between 3,543,890 and 4,891,897 fish. Because the run loss estimates for the spring and summer runs in this article are less than the Northwest Power Planning Council's, some might argue that salmon loss mitigation efforts ought to be reduced. A closer look at the results in this article suggests the opposite. The data in Table 6 clearly indicate that inriver runs have recently been less than the weighted and lagged spawner escapement levels for both the spring and summer runs, suggesting that the continued existence of these runs is clearly threatened. The regression equations can be used to calculate the optimum level of spawner escapement and the maximum run level that results given the existence of dams. These figures are reproduced in lines (vi) and (vii) of Table 6. The optimum escapement figure for the spring run is close to the maximum run, and because so few spring chinook are caught in the ocean, little can be done to enhance the run in the absence of mitigation efforts that would reduce dam passage mortality or improve spawning ground habitat. The situation appears to be even worse for the summer run, where the maximum inriver run is actually less that the optimum escapement figure. Unless the ocean harvesting of summer chinook is reduced or extensive mitigation efforts are undertaken, the summer run appears to be doomed. The question is as much ethical as it is economic, given that the destruction of the wild spring and summer runs would be essentially equivalent to the destruction of species.

Notes

1. The proportion of the total spawners h_i migrating to the area above a given dam i is assumed in the empirical work to follow to be equal to the proportion of stream miles above the dam available for spawning. The base for calculating this proportion is the total stream miles in the Columbia River Basin above the Bonneville Dam. Lavier (1976b) estimates the 1850 and 1976 stream miles available to spring, summer, and fall chinook by key subregions in the Columbia River basin. The 1850 figure was generally used here where reductions in mileage between 1850 and 1976 were apparently the result of mainstem Columbia and Snake River dams. The 1976 figure was used where reductions were apparently the result of tributary dams.

2. The loss rate calculations for all other dams will be provided by the author on request.

3. Gangmark (1957) attempted to estimate the effect of the Bonneville Dam on salmon runs through analysis of catch per unit effort before and after construction of the dam. He did not detect any significant reductions in salmon runs in his analysis. Junge and Oakley (1966), on the other hand, found a significant reduction in the number of salmon returning to the river per spawner for upriver runs in comparison to downriver runs for the 1950s and 1960s when significant dam construction was undertaken. This study was updated by Beiningen (1976a), and the same results were found. None of these articles used statistical techniques.

4. The linear and quadratic aggregate loss rates are lagged and weighted to correspond with the appropriate brood year. Again, the weights used were taken from Junge and Oakley (1966).

5. The model in Eq. 9 was also tested, but the results were statistically insignificant.

6. Because of an inadequate hatchery feeding technology, it is generally thought that hatchery releases prior to 1960 were ineffective (Ortmann et al. 1976).

7. In theory, the sports catch of chinook along the coast could also reduce the run into the river. Data on chinook sports catch are available only for the full period under analysis here for Washington State. Washington, however, dominates ocean sports fishing for salmon along the Pacific Coast. The sports catch was included in the regressions for the summer and fall upriver run and the fall downriver run, and its coefficient was statistically insignificant in all the equations (Washington Department of Fisheries 1982, 1986). The sports catch was excluded from the spring run equation because of the apparent small contribution of the spring run to the ocean catch (Beiningen 1976b).

8. The rations for the spring, summer, and fall runs are, respectively, .1, 1.7, and 2.85 (Northwest Power Planning Council 1988a, 16). The fall run figure is a weighted average for natural and hatchery fish.

9. This is the ocean survival rate used in Northwest Power Planning Council 1986b, 8.

10. Again, this is the ocean survival rate used in Northwest Power Planning Council 1986b, 8.

11. The optimum escapement level can be chosen by multiplying the regression equations through by the level of escapement S_{t-s} and setting the first derivative of the resulting equation equal to zero.

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