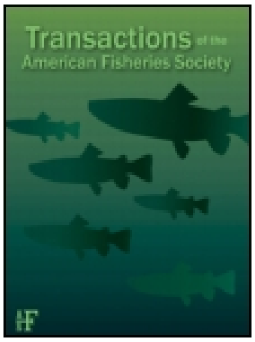

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ARTICLE

Quantifying Cumulative Entrainment Effects for Chinook Salmon in a Heavily Irrigated Watershed

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Abstract
Pacific salmon *Oncorhynchus* spp. experience multiple small-scale disturbances throughout their freshwater habitat, but the cumulative effect of these disturbances is often not known or not easily quantifiable. One such disturbance is water diversions, which can entrain fish and alter streamflow regimes. Threatened Lemhi River (Idaho) Chinook salmon *O. tshawytscha* smolts encounter 41–71 water diversions during their out-migration. We used passive integrated transponder tag data to model the entrainment rate of Chinook salmon smolts as a function of the proportion of water removed by an irrigation diversion. Under median-streamflow conditions with unscreened diversions, the estimated cumulative effect of the diversions was a loss of 71.1% of out-migrating smolts due to entrainment. This is a large potential source of mortality, but screening is an effective mitigation strategy, as estimated mortality was reduced to 1.9% when all diversions were screened. If resources are limited, targeting the diversions that remove a large amount of water and diversions in locations with high fish encounter rates is most effective. Our modeling approach could be used to quantify the entrainment effects of water diversions and set screening priorities for other watersheds.

Pacific salmon *Oncorhynchus* spp. are an integral component of Pacific Northwest stream ecosystems but have experienced extensive population declines due to habitat alteration, stocking practices, hydropower development, and climate (Ruckelshaus et al. 2002; McClure et al. 2003). Most salmon recovery plans include strong recommendations for improving habitat conditions; the actions implemented based on these recommendations typically consist of small projects at multiple locations throughout the spawning and rearing habitat of a population. Salmon biologists are working to determine methods for quantifying the effects of local, small-scale habitat disturbances and restoration efforts at the population level (Bartz et al. 2006; Honea et al. 2009; Roni et al. 2010). Quantification of population-level effects is challenging, but one important habitat disturbance that may be quantifiable is the direct effect of irrigation diversions on the out-migration success of juvenile salmonids.

Water diversion for irrigation is a major threat that is currently faced by fish populations (Rosenberg et al. 2000). Water diversion can alter streamflow regimes and entrain fish in irrigation canals (Gebhards 1958; Post et al. 2006). Although

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the importance of streamflow alteration is receiving greater research attention (Poff and Zimmerman 2010), the direct effects of entrainment by water diversions are not as well studied. For a fish population, the entrainment effect of any individual diversion may be minimal, but the cumulative effects of multiple diversions could be considerable.

Entrainment is the process by which fish travel into irrigation canals at a water diversion. The fate of entrained fish depends on whether the diversion is screened. In an unscreened diversion, fish will enter the irrigation system and likely die; if the diversion is screened, fish are bypassed and returned to the main river channel (Zydlewski and Johnson 2002). The few studies of individual diversions have reported entrainment rates ranging from 1% to 79% (Carlson and Rahel 2007; Gale et al. 2008). It is challenging to quantify the number of fish that are entrained at a single diversion, and estimating the population-level effect is even harder. As a result, entrainment studies have mainly been conducted for nonmigratory species at one or a few diversions (Schrank and Rahel 2004; Unwin et al. 2005; Post et al. 2006). Despite the lack of quantified effects, managers have long recognized the potential for irrigation diversion entrainment to have a substantial negative effect on fish populations. As a result, fish screens were built as early as the 1890s, although they were often discontinued due to high maintenance costs (Clothier 1953). Screens are still expensive to build and maintain, but they are becoming a common conservation practice. Similar to the negative effects of diversions, the benefits of screening have not been well quantified at the population level (Moyle and Israel 2005; but see Gale et al. 2008).

The goal of this study was to evaluate the effect of entrainment due to water diversion for migrating Chinook salmon *O. tshawytscha* smolts and the benefit conferred by screening those diversions. We used Lemhi River (Idaho) Chinook salmon as a case study, because the Lemhi River basin experiences extensive withdrawals of water due to irrigation diversions. Our objectives were to (1) explore how entrainment varied with diversion rate and variation in streamflow, (2) predict fish mortality in the Lemhi River basin for unscreened and screened scenarios, and (3) evaluate various management approaches to the prioritization of screening efforts.

METHODS

Study Site

The Lemhi River is a tributary to the Salmon River in central Idaho (Figure 1). Its watershed encompasses about 3,300 km^2 of forest, rangeland, and irrigated land. The climate is semiarid, with cold winters and warm summers. Precipitation generally increases with elevation (22–115 cm/year) and primarily falls as snow. Melt from mountain snowpack is the predominant source of streamflow, but the Lemhi River basin also has groundwater inputs that modify the influence of annual freshets. Diversions occurred in the Lemhi River basin as early as 1855, and today there are over 250 gravity-fed irrigation diversions. These diversions reduce streamflow in the Lemhi River and its tributaries to the extent that most tributaries are disconnected from the main stem (Tire et al. 2011). Screening of water diversions began in 1958 (Schill 1984), and currently most of the water diversions on the Lemhi River and its large tributary (Hayden Creek) are screened. However, there are still many unscreened diversions on the other tributaries.

The Lemhi River basin historically supplied productive spawning and rearing grounds for Chinook salmon, but the population has experienced substantial declines in the last 50 years. The population is part of the Snake River spring–summer Chinook salmon evolutionarily significant unit, which is listed as threatened under the Endangered Species Act. Due to its size and location, the Lemhi River population is considered a key population for the recovery of this evolutionarily significant unit (ICTRT 2007). Spawning currently occurs primarily in the upper Lemhi River and Hayden Creek (Figure 1). We use the term "upper Lemhi River" to refer to the main-stem Lemhi River above the confluence with Hayden Creek; the term "lower Lemhi River" refers to the main-stem Lemhi River below the confluence with Hayden Creek. Chinook salmon in the Lemhi River basin have demonstrated three migration life histories within the same cohort: (1) out-migration during the first spring after emergence as age-0 early smolts; (2) downstream migration during the fall as age-0 fall parr and subsequent overwintering in the lower Lemhi River and Salmon River; and (3) out-migration during the next spring as age-1 smolts (Bjornn 1978; Lutch et al. 2003). In this study, we focused on age-1 smolts, which represent one of the common migration strategies.

Geospatial Model

We used a spatially explicit GIS-based simulation model to assess the effects of diversion entrainment on Lemhi River Chinook salmon smolts. We first identified the location and size of each diversion in the watershed. We then developed a model to estimate the probability that a fish would be entrained at a diversion. Finally, we routed fish through the stream network, with individuals removed at each diversion based on the modeled probability of entrainment.

Water diversion locations.—We obtained all points of diversion (PODs) in the Lemhi River basin and the associated water rights data from the Idaho Department of Water Resources (IDWR; Figure 1). For each POD, we summarized the total amount of legal water withdrawals and provided this value as a new attribute. Many of the PODs in the IDWR database have been consolidated into a single diversion for screening purposes, so in the final analysis we only considered the list of irrigation diversions and associated fish screens developed by the Idaho Department of Fish and Game (IDFG) Anadromous Fish Screen Program. Each of these diversions has a screen design discharge that corresponds to the maximum discharge that can be diverted. Lemhi River gage data are not available at every POD; thus, to estimate streamflow, we modeled natural streamflow (low [Q_{80},

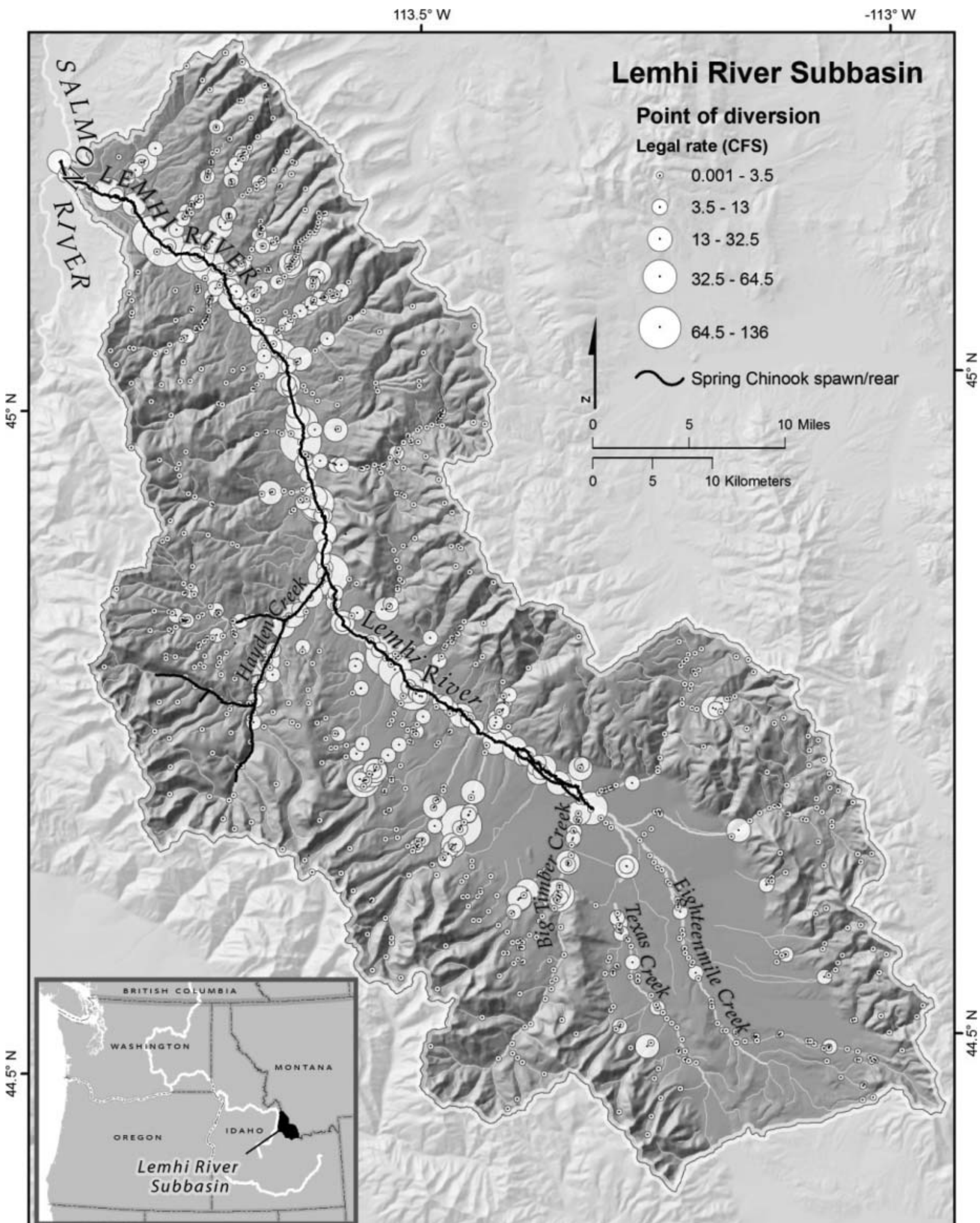

FIGURE 1. Map of the Lemhi River basin, Idaho. Each point of diversion is denoted by a circle; the size of the circle represents the legal rate of water diversion in cubic feet per second (CFS; 1 CFS = 0.03 m^3/s) for that site. Areas where spring Chinook salmon spawn and rear are highlighted in bold.

i.e., the flow level that was exceeded 80% of the time], median [Q_{50}], and high [Q_{20}] streamflows under no-diversion conditions, estimated on the basis of watershed characteristics) and then subtracted the cumulative water rights upstream of the POD, accounting for the fact that some of the diverted water would return to the Lemhi River via return flow (percent return flow estimated based on gage data; see Appendix).

Entrainment rate.—The IDFG Anadromous Fish Screen Program has monitored fish entrainment since 2003 by installing automated passive integrated transponder (PIT) tag readers on fish screen bypass pipes. The PIT tag interrogation stations (Biomark, Inc., Boise, Idaho) documented the movement of PIT-tagged fish (tagged as part of the routine IDFG monitoring program) through fish screen bypasses on two to four diversions from 2003 to 2008.

To estimate the probability that an individual fish would be entrained at a monitored irrigation diversion, we examined records of smolts out-migrating during spring (March 1–June 30) 2003–2008 (PTAGIS 2011). We did not include fall-tagged parr; although some of these individuals actively migrate downstream and out of the Lemhi River basin, others hold over for the winter in the lower reaches of the Lemhi River. Separate release cohorts of fish were created for each irrigation diversion with a PIT tag detector because the detector dates of operation varied. For each release cohort, we created capture histories for individual fish and used the Cormack–Jolly–Seber model (Cormack 1964; Jolly 1965; Seber 1965) to estimate joint detection and survival probabilities. We assumed that the probability of detection at a fish bypass was the same as the probability of entrainment; however, detection efficiencies are potentially less than 1.0 at every site, so the resulting entrainment probabilities are actually minimum estimates.

We related these entrainment probabilities to the average daily proportion of streamflow that was diverted during the migration season at the monitored diversion site (Table A.1). The daily proportion of streamflow diverted was calculated on the basis of daily Lemhi River streamflow at each monitored diversion site (estimated from the nearest streamflow gage) and the daily estimated discharge that was diverted by the irrigation diversion. The discharge diverted was unknown and was predicted using a step function based on historic values from an evaluation of diversion operation plans (DHI 2003). If streamflow at a diversion site was low ($<Q_{80}$), diverted flow was set to half the historic average diverted flow. If streamflow was average (between Q_{80} and Q_{20}), diverted flow was set to the historic average. If streamflow was high ($>Q_{20}$), diverted flow was set to the historic maximum diverted flow.

The diversion sites differed in their physical characteristics such that entrainment might vary with the location and orientation of the irrigation diversion or the timing of water diversion; however, those characteristics are not necessarily static and could not be quantified and modeled. In an attempt to remove some of this variation in the data while still preserving the average relationship between entrainment probability and proportion of streamflow diverted, we modeled the average of the entrainment probabilities across sites within years. This reduced the data to six data points (one for each year; Table A.2).

The model relating entrainment rate to the proportion of streamflow diverted was fitted using weighted least squares, with the weights equal to the inverse of the estimated variances of the mean entrainment probabilities on the logit scale. We assumed that if no streamflow was diverted at a given site, then no fish would be entrained in that irrigation diversion; likewise, we assumed that if 100% of the streamflow was diverted at a given site, then all passing fish would be entrained at that site. To impose these constraints in our models, we used the logit transformation ($\text{logit}[x] = \log_e[x/\{1-x\}]$) for both the entrainment probability estimates and the proportion of flow diverted. On the logit scale, the model for entrainment probability at a diversion site for a cohort of fish in a season (p_i) as a function of the proportion of streamflow diverted at that site ($pdiv_i$) was

$$\text{logit}(p_i) = \beta_0 + \beta_1 \text{logit}(pdiv_i) + \varepsilon_i. \quad (1)$$

Here, ε_i represents random error terms that are assumed to be normally distributed with a mean of 0 and a variance of σ^2 on the logit scale. We used weighted least squares to fit the models, with the weights being equal to the inverse of the estimated variances of the entrainment probability estimates on the logit scale. Weighting in this way allowed observations with more precise entrainment probability estimates to have more influence in the model fit. Due to the unknown time of passage for individual undetected fish, there was a large amount of missing information on the proportion of streamflow diverted, thus precluding the use of commonly used capture–recapture models that allow individual covariates (e.g., Lebreton et al. 1992).

Fish routing.—The final stage in the model was simulating fish loss to or passage by the irrigation diversions. Since many of the PODs have been consolidated for screening purposes, we considered the diversions that were monitored and screened by the IDFG Anadromous Fish Screen Program. For these diversions, the most accurate estimate of discharge diverted is related to fish screen design, as each fish screen has a maximum design discharge that corresponds to the maximum diverted discharge. During May, spring runoff is still below peak, and there is not enough water for all water users to exercise their full water rights; therefore, we used an estimated water diversion equal to 75% of design discharge. The percentage is likely to vary with streamflow conditions, but we kept it constant for comparison purposes.

To examine fish routing, we focused on stream reaches used by Chinook salmon smolts and the arrangement of irrigation diversions within these occupied reaches. We used spawning and rearing data developed by IDFG that describe salmon use by reach, and we modified the habitat quantity to be expressed as stream area. We divided all reaches in currently occupied rearing streams into 200-m segments and inserted each irrigation diversion into its correct position within this network. The predicted proportion of smolts in each segment was assumed to be equivalent to the proportion of stream area. Starting from the upstream-most position, we routed fish downstream, adding smolts at new reach segments and removing smolts at diversions based on entrainment estimates.

We compared the simulated effects of entrainment for screened and unscreened scenarios under low, median, and high May streamflow conditions. If an irrigation diversion was unscreened, it was assumed that a smolt would not survive entrainment, and survival was set at 0.01. If a diversion was screened, survival was set at 0.99 because a previous laboratory study showed that survival rates at screens were greater than 0.99 for juvenile Chinook salmon (Swanson et al. 2004). In addition to the current situation, in which all diversions on the mainstem Lemhi River are screened, a series of potential screening management strategies was tested, including screening based on location, diversion rights, or entrainment rates.

We estimated SEs of predicted total survival using Monte Carlo simulation. For each of 10,000 iterations, a slope and an intercept for the entrainment rate model were drawn from a multivariate normal distribution with the mean vector equal to the estimated model parameters from the regression model for entrainment rates (Table 1) and with the covariance matrix equal to that for the estimated model parameters, both on the logit scale. In addition, within each iteration, each diversion site had a separate random error term that was drawn from a normal distribution with a mean of 0 and a variance that was equal to the estimated residual variance from the regression model—that is, for each diversion site, within each iteration the predicted entrainment rate was

$$\hat{p}_{h,i} = \text{logit}^{-1}(b_{0,h} + b_{1,h}\,pdiv_i + e_{h,i}), \qquad (2)$$

where h is the index for simulation iteration, i is the index for irrigation diversion site, b_0 and b_1 are simulated regression parameters, $pdiv$ is the logit-transformed proportion of water diverted, and e is the random error term. We ran the entrainment calculator for each iteration of the simulation, and we recorded the resulting cumulative total survival values. The SD of those 10,000 total survival values was used as the SE of predicted total survival.

TABLE 1. Parameter estimates and associated P-values for a weighted linear regression relating the probability of Chinook salmon smolt entrainment to the proportion of streamflow removed by an irrigation diversion in the Lemhi River basin, Idaho. The P-values are two-sided; $pdiv$ is the proportion of streamflow diverted.

Coefficient	Estimate	SE	t	P
Intercept	−0.560	0.238	−2.356	0.0780
Logit($pdiv$)	0.907	0.150	6.062	0.0037

Simulation Model to Estimate Multiple Entrainment Events

When irrigation diversions are screened, an individual fish may be entrained multiple times; this could increase stress and travel time. To estimate how many times a fish is entrained and bypassed, we ran a Monte Carlo simulation. In the simulation, each time a fish encountered an irrigation diversion a random number between 0 and 1 was generated; if the number was less than the probability of entrainment for that diversion, the fish was assumed to be entrained. The probability of entrainment was the value from the previous analysis under median May conditions. The number of times each individual fish was entrained and bypassed at a diversion was counted, and the simulation was run for 10,000 fish. The simulation used only the 41 screened irrigation diversions that all smolts encounter as they pass through the lower Lemhi River; therefore, this simulation provided a minimum estimate of multiple entrainment rates.

RESULTS

The weighted linear regression yielded convincing evidence that the mean estimated entrainment probability for a Chinook salmon smolt was associated with the mean proportion of streamflow diverted ($P = 0.0037$; Table 1; Figure 2). The proportion of fish entrained was slightly less than the proportion of streamflow diverted; variability in the proportion of fish entrained increased as the proportion of streamflow diverted increased (Figure 2). Based on this relationship, the modeled entrainment rate at individual irrigation diversions was relatively low: on average, the percentage of smolts entrained at an individual diversion was 4% under high-streamflow conditions,

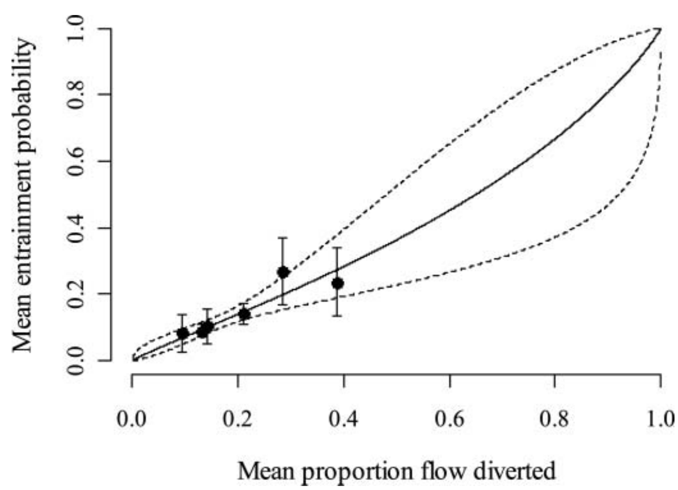

FIGURE 2. Estimates of mean (± SE) entrainment probability for Chinook salmon smolts versus the mean proportion of streamflow diverted at irrigation diversions within the Lemhi River basin, Idaho, 2003–2008. Entrainment probabilities are means of the monitored diversion sites for each year. The solid line is from the weighted regression described in Table 1; dotted lines represent the 95% confidence interval.

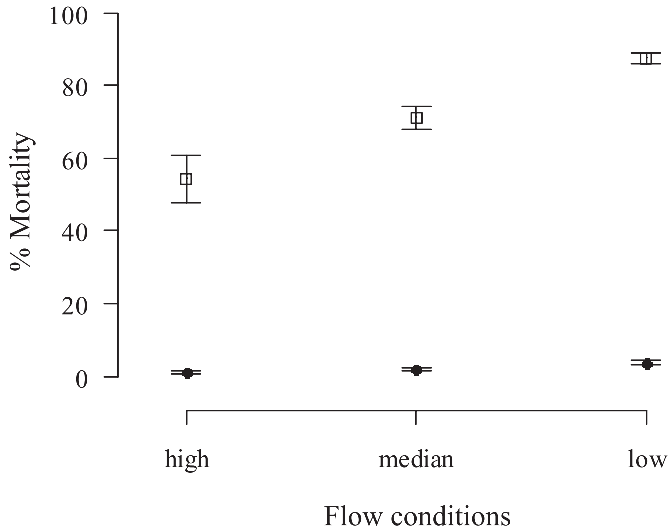

FIGURE 3. Entrainment mortality (mean ± SE) during the Chinook salmon smolt out-migration under scenarios of unscreened (open squares) and screened (shaded circles) irrigation diversions and high (Q_{20}), median (Q_{50}), and low (Q_{80}) streamflow conditions.

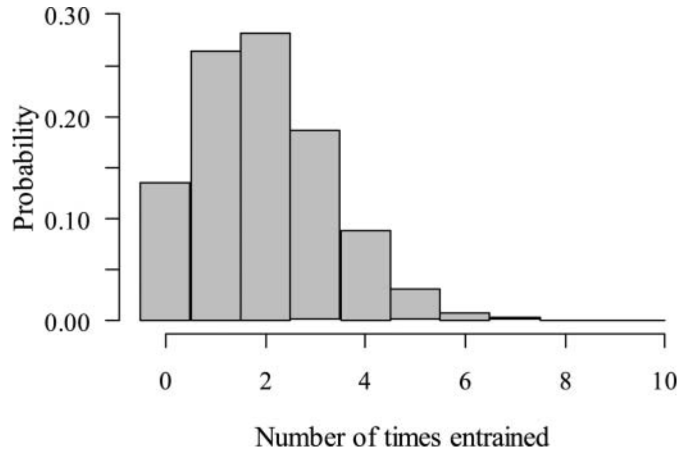

FIGURE 4. Probability of zero, one, or multiple entrainment events for a Chinook salmon smolt as it passes through the 41 irrigation diversions in the lower main-stem Lemhi River. Probability was estimated with a simulated run of 10,000 fish.

6% under median-streamflow conditions, and 10% under low-streamflow conditions. The maximum estimated entrainment rate for a single diversion was 45% (low-streamflow conditions), and the minimum entrainment rate was less than 1%.

Estimated cumulative effects under scenarios of unscreened irrigation diversions were high. Under median May streamflow conditions, 71% of migrating smolts would be lost to entrainment in irrigation canals (Figure 3). This percentage increased to over 88% during low-streamflow conditions. During low streamflow, a greater proportion of the water was diverted, resulting in higher entrainment rates (Figure 3). Under high-streamflow conditions, smolt mortality decreased to 54% (Figure 3). Under scenarios in which diversions were screened, mortality dropped to between 1% and 4% for all streamflow conditions.

For the scenarios involving screened diversions, we assumed very low mortality with entrainment (1%), such that a fish could become entrained multiple times. Most fish were entrained one or two times while passing through the 41 irrigation diversions in the lower Lemhi River (Figure 4). Approximately 12% were never entrained, and about 15% were entrained four or more times.

Screening of all irrigation diversions resulted in a decline in smolt mortality from 71.1% to 1.9% (Table 2). Screening of the diversions located on the main-stem Lemhi River resulted in large reductions in Chinook salmon smolt mortality (7.7% mortality), while screening only the diversions within the tributaries had little effect (70.4% mortality). Screening the largest irrigation diversions was more important than screening the smaller diversions; however, even when all diversions greater than 0.14 m^3/s (5 ft^3/s) were screened, there were still effects (9.6% mortality). Screening of diversions based on entrainment probability (i.e., proportion of water diverted) also decreased mortality, but even when the 40 diversions with the highest entrainment rates were screened the mortality rate was still 39.6% due to the other unscreened diversions. When approximately 40 diversions were screened based on their location or on the amount of discharge diverted, mortality dropped to 28.7% and 26.0%, respectively (Table 2).

DISCUSSION

Irrigation is the largest use of freshwater in the United States, and much of this water is obtained through diversion from

TABLE 2. Potential screening management strategies for irrigation diversions and the associated predictions of entrainment mortality of Chinook salmon smolts under median May streamflow conditions. The screening scenario based on entrainment probability involves screening those diversions with the highest entrainment probabilities under median May streamflow conditions.

Screening scenario	Diversions screened (*N*)	Mortality (%)
None screened	0	71.1
All screened	89	1.9
Screening based on location		
Main-stem Lemhi River	70	7.7
Lower main-stem Lemhi River	41	28.7
Lemhi River tributaries	19	70.4
Screening based on water rights		
>0.57 m^3/s (20 ft^3/s) diverted	22	42.5
>0.28 m^3/s (10 ft^3/s) diverted	42	26.0
>0.14 m^3/s (5 ft^3/s) diverted	70	9.6
Screening based on entrainment probability		
Top-10 diversions	10	66.6
Top-20 diversions	20	59.6
Top-40 diversions	40	39.6

natural streams and rivers (Hutson et al. 2004). The effect of this extensive network of irrigation diversions on fish populations is not well known. In this study, we evaluated the direct effects of diversion structures on Chinook salmon smolts in a heavily irrigated watershed. Although most individual irrigation diversions only entrained a small proportion of migrating smolts, the predicted cumulative effect of water diversion on smolt out-migration survival was substantial. However, the direct effects of diversions were successfully mitigated by a comprehensive screening program. The methods developed for this study can provide an approach for quantifying the effects of irrigation diversions and setting screening priorities in other watersheds.

We found a consistent relationship between the proportion of streamflow diverted and the entrainment rate. Our relationship differed from the expected S-shaped curve that describes a scenario in which very few fish are entrained at low water diversion rates, entrainment increases sharply as more water is diverted, and entrainment reaches nearly 100% at high water diversion levels (Moyle and Israel 2005). However, in our study, the average proportion of streamflow diverted at any individual irrigation diversion was generally less than 50%, and a sharp increase in entrainment could be possible when the majority of water is flowing into an irrigation canal. As a result, our entrainment curve likely provides a conservative estimate of entrainment at high levels of water diversion. Due to the large number of irrigation diversions, we used the same entrainment curve for all diversions, but the relationship will likely differ between diversion sites. Other factors that could affect entrainment rates include fish species and life history, the configuration of the irrigation diversion, the timing of water diversion, and the physical location of the irrigation diversion site (Schrank and Rahel 2004; Bahn 2007; Grimaldo et al. 2009; Svendsen et al. 2010). Bahn (2007) found that the best predictors of entrainment rate for irrigation diversions were the amount of discharge diverted and the upstream slope. For studies that are focused on the effect of only a subset of specific water diversions, individual entrainment curves should be calculated that take into account the unique characteristics of each irrigation diversion site. Diversion-specific streamflow and water diversion rates would allow further refinement of the model.

We found that the entrainment effect of a single irrigation diversion was low, with only 6% of smolts entrained by an individual diversion on average. However, the cumulative effects of irrigation diversions for the population were considerable; 71.1% of migrating smolts were entrained under median-streamflow conditions. A 71% entrainment rate is equal to the percentage of age-0 westslope cutthroat trout *O. clarkii lewisi* that were entrained during downstream movement in Skalkaho Creek, Montana (Gale et al. 2008), but is much higher than rates observed in other studies (Schrank and Rahel 2004; Post et al. 2006; Carlson and Rahel 2007). The higher entrainment rate in our study is attributable to the fact that we considered obligatory migrants in a basin with many irrigation diversions. In the Lemhi River basin, the strong effects are driven by the number of diversions, although several of the irrigation diversions divert large amounts of water and have high individual entrainment rates (25–45% [depending on streamflow] if unscreened). It is possible for one irrigation diversion to have considerable effects; in the Yellowstone River, one diversion accounted for more than half of all nonfishing mortality in saugers *Sander canadensis* (Jaeger et al. 2005).

In this study, we focused only on smolt out-migration, but many juvenile Chinook salmon out-migrate as parr during the previous fall. Differing migration strategies expose cohorts to varying risks in relation to the management of irrigation withdrawals and streamflow. For parr that migrate all the way to the Salmon River during fall, entrainment rates should be lower because the amount of irrigation withdrawal decreases in October and November. For parr that overwinter in the lower Lemhi River and continue their out-migration during the next spring, entrainment rates in the upper Lemhi River would be lower, and entrainment rates in the lower Lemhi River would be comparable to those of smolts. In the six monitored irrigation diversions, parr entrainment was lower than smolt entrainment, with 1–12% of tagged parr entrained in a monitored irrigation diversion during a given year (2003–2007) in comparison with 6–34% of smolts (C.D.W., unpublished data). Although the movement patterns during migration are straightforward, parr and smolts could also be moving locally and encountering irrigation diversions multiple times before migration, increasing the probability of entrainment. Future studies should incorporate all life history types and non-migration-related movement.

In addition to providing estimates of entrainment, our approach allowed us to quantify the effectiveness of screening measures in the Lemhi River basin. The basin has undergone an intensive screening program, and at this point all irrigation diversions that are likely to be encountered by Chinook salmon smolts during out-migration are screened. Screening has been shown to be an effective management tool (Gale et al. 2008), but there are still few studies that quantify the potential benefits of screening, especially at the population level or for out-migrating anadromous fish (Moyle and Israel 2005). Our modeling approach showed that the screening of irrigation diversions can reduce mortality during smolt out-migration from 50–90% to 1–4%. This result is useful for evaluating the vast amount of resources invested in screening. Screening of an irrigation diversion in the Lemhi River basin costs, on average, \$3,600–4,600 per 0.03 m^3/s (= 1 ft^3/s) of diversion capacity. The average design discharge for an irrigation diversion in this basin is about 0.42 m^3/s (15 ft^3/s), but the largest diversions divert almost 1.7 m^3/s (60 ft^3/s). In addition to the cost of building diversion screens, the IDFG employs full-time seasonal workers to clean and maintain the screens in the Lemhi River basin. Results from this study could be combined with cost estimates to conduct cost–benefit analyses for proposed screening projects.

By examining various screening strategies, the model provides support for current methods of prioritizing screening efforts. In the Lemhi River basin, screening the irrigation diversions that divert more water and that are located on the main stem will save more smolts than the screening of smaller diversions along the tributaries. The results suggest that screening based on the size of the diversion was a consistently good strategy. Screening of the diversions with the highest entrainment probability (based on proportion of water diverted) was not as effective as expected because many of these diversions were located higher in the watershed and thus encountered fewer fish. Due to the varying physical characteristics of individual irrigation diversions, these general guidelines should be supplemented with a targeted approach aimed at diversions that may have high entrainment rates attributable to the timing of water withdrawal or to the diversion configuration. In the Lemhi River basin, it was necessary to screen almost all of the diversions potentially encountered by smolts for maximum effect. To reduce mortality to less than 10%, screening was required for approximately 70 of the 89 irrigation diversions encountered by smolts during their out-migration. Our models focused on Chinook salmon, which primarily spawn and rear in the main stem, but for species that are highly migratory tributary spawners (e.g., steelhead *O. mykiss*, bull trout *Salvelinus confluentus*, and westslope cutthroat trout), screening of diversions on the tributaries may be much more important. The Lemhi River basin has over 100 unscreened diversions on the tributaries, possibly creating negative effects for other species.

The model assumed very high survival (99%) for smolts that encountered screened irrigation diversions, but the assumption was based on a laboratory study that only considered screen mortality. In the field, there may also be non-screen-related mortality: for example, the fish could experience mortality when exiting the bypass pipes if they exit into poor-quality habitat or into a pool with waiting predators. The estimates also do not account for the potential fitness costs of being entrained or for the possibility that the majority of fish will be entrained more than once. Multiple entrainments can result in increased travel time, which is associated with decreased survival during out-migration (Scheuerell et al. 2009). Harnish (2007) found the median entrainment time to be 7 d, but the estimate was for nonmigratory fish (westslope cutthroat trout juveniles) without the downstream-directed movement of out-migrating Chinook salmon. In addition, the experience could be stressful or could alter behavior. Studies on delta smelt *Hypomesus transpacificus* found that plasma cortisol concentrations increased during exposure to fish screens, indicating increased physiological stress (Young et al. 2010). Thus, our estimates of mortality are probably minimum estimates. Given the high likelihood that a smolt will be entrained multiple times in a screened system, future studies should explore other possible sources of mortality and nonlethal effects.

Irrigation diversions are potentially a significant source of mortality for out-migrating smolt populations due to entrainment effects. Our results suggest that these effects can be successfully mitigated by screening, although the effects of multiple entrainments in screened diversions on travel time and stress require further study. While diversion screening is widely viewed as important, this is one of the first studies to quantify the benefits at the population level. In addition, our approach allows a comparison of the costs and benefits of various screening approaches, which can help managers to prioritize the limited funds dedicated to restoration efforts. This study also highlights the importance of evaluating the cumulative effects of small-scale disturbances and restoration efforts.

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APPENDIX: ESTIMATION OF LEMHI RIVER STREAMFLOW FOR EACH POINT OF DIVERSION

To estimate Lemhi River streamflow at each point of diversion (POD), we first modeled what the natural hydrology would be if there was no water diversion ($Q_{undiverted}$). For each POD, we subtracted the cumulative legal water rights upstream of the POD (ΣWR), taking into account that the proportion of water rights utilized (i.e., the diversion fraction [DF]) might be less than 1.0 and that some water would be returned via return flow (RF):

$$Q_{diverted} = Q_{undiverted} - [\Sigma WR \times DF \times (1 - RF)]. \quad (3)$$

We used locations with available gage data as a check on our estimates.

Natural hydrology ($Q_{undiverted}$) was estimated by using StreamStats, a program developed by the U.S. Geological Survey (water.usgs.gov/osw/streamstats/idaho.html). StreamStats provides streamflow statistics based on basin characteristics and assumes no anthropogenic hydrologic alterations. We used StreamStats to calculate monthly hydrological indices (exceedance probabilities Q_{20}, Q_{50}, and Q_{80}) for 20 locations, and we regressed the indices against watershed area (km^2). Watershed area was calculated using the drainage area provided in the U.S. Geological Survey's National Hydrography Dataset, and a proximity function was used to assign each diversion to its nearest National Hydrography Dataset stream reach. For all monthly hydrologic indices, the relationship with watershed area (ranging from 40 to 3,100 km^2) was well described by a power function: $y = ax^b$ ($R^2 \geq 0.94$). For each diversion location, we calculated watershed area and used the regression equations to get an estimate of natural hydrology under low (Q_{80}), median (Q_{50}), and high (Q_{20}) streamflow conditions. Due to the large number of locations (>200), we did not directly use StreamStats for all PODs. The Lemhi River has a substantial natural groundwater component that was not captured in the StreamStats analysis. To correct for this, we examined the difference between the predicted median StreamStats streamflow and the median streamflow from gage data for winter months, when diversion was not occurring. We added 0.85 m^3/s to streamflow in Lemhi Big Springs Creek, 1.42 m^3/s to streamflow in Hayden Creek, 1.70 m^3/s to streamflow in the upper Lemhi River, and 2.55 m^3/s to streamflow in the lower Lemhi River. For the analysis, we focused on May streamflow because May is the time period during which smolt migration and water diversion are both occurring.

We calculated the ΣWR impacting a POD by using GIS to compute the aggregated values above each diversion. We did not include extra-high water rights in these values. Under median-streamflow conditions, we assumed that 100% of the legal diversion rights ($DF = 1.0$) were exercised; however, for high- and low-streamflow conditions, we adjusted the proportion of subtracted ΣWR to match gage data. Under high-streamflow conditions, water rights owners have high water rights, which were not included in the ΣWR calculation. Therefore, under high-streamflow conditions, we set the diversion rate at 150% of ΣWR. For some individual diversions, 150% of legal water rights was more than the diversion ditch could handle, but at a larger scale 150% of ΣWR was comparable to the cumulative maximum capacity of the diversion ditches. During low-streamflow conditions, water rights owners will probably not be able to utilize their full water rights; this is especially true for junior water rights owners, who are mainly located along the upper Lemhi River and the tributaries. We set the diversion rate equal to 50% of ΣWR for the tributaries and upper Lemhi River and to 70% of ΣWR for the lower Lemhi River. For high- and low-streamflow conditions, percentages were chosen so that predicted streamflow matched that calculated from gage data.

Not all of the diverted water is lost from the system; a proportion will return to the stream through surface and groundwater flow (i.e., *RF*). We chose *RF* fractions so that predicted median May streamflow hydrology matched the median May streamflow levels at the locations for which gage data were available. The *RF* was 65% for the upper Lemhi River, 75% for the lower Lemhi River, and 72% for all other areas. These values are within the range (50–99%) of reported *RF* fractions for a study of individual diversions (DHI Water and Environment, Inc. 2003). We assumed the same *RF* fractions for low- and high-streamflow conditions.

TABLE A.1. Detection and covariate data for cohorts of Chinook salmon smolts released into the Lemhi River, Idaho, 2003–2008. Detection sites are the irrigation diversions that were equipped with passive integrated transponder tag readers. First day of release is given as the day of year (January 1 = day 1).

Year	Detection site	Number of fish released	Estimated entrainment probability: Mean	Estimated entrainment probability: SE	First day of release	Streamflow (m^3/s)	Proportion of streamflow diverted
2003	L03	202	0.109	0.039	113	5.72	0.172
	L03A	202	0.109	0.039	113	5.88	0.105
	L09	119	0.051	0.035	135	7.88	0.113
2004	L03	196	0.535	0.054	105	0.91	0.647
	L03A	350	0.106	0.024	95	0.72	0.279
	L08A	174	0.105	0.035	106	1.31	0.459
	L09	35	0.200	0.127	128	3.67	0.160
2005	L03	203	0.552	0.053	97	2.12	0.405
	L03A	218	0.079	0.029	95	1.85	0.238
	L08A	141	0.203	0.050	104	2.71	0.295
	L09	98	0.238	0.066	111	3.63	0.200
2006	L03	175	0.156	0.037	113	6.24	0.143
	L06	119	0.083	0.036	116	6.26	0.414
	L30	119	0.183	0.050	116	6.99	0.075
2007	L03	128	0.064	0.036	107	6.82	0.091
	L06	251	0.039	0.019	86	5.34	0.260
	L30	142	0.208	0.056	103	6.57	0.075
2008	L03	65	0.027	0.027	114	10.83	0.107
	L30	47	0.138	0.064	120	7.50	0.081

TABLE A.2. Yearly means of detection and covariate data for cohorts of Chinook salmon smolts released into the Lemhi River, 2003–2008. First day of release is given as the day of year (January 1 = day 1).

Year	Number of estimates	Mean first day of release	Estimated entrainment probability		Mean streamflow (m^3/s)	Mean proportion of streamflow diverted
			Mean	SE		
2003	3	120.3	0.090	0.019	6.50	0.130
2004	4	108.5	0.237	0.102	1.65	0.387
2005	4	101.8	0.268	0.101	2.58	0.284
2006	3	115.0	0.141	0.030	6.49	0.210
2007	3	98.7	0.103	0.053	6.24	0.142
2008	2	117.0	0.082	0.055	9.17	0.094