fisheries management **feature**

Untested assumptions: effectiveness of screening diversions for conservation of fish populations

ABSTRACT

Diversions from streams are often screened to prevent loss of fish. Because construction of fish screens competes for scarce dollars with other fish conservation projects, the widely accepted premise that fish screens protect fish populations merits thorough examination. We reviewed literature on fish screen projects in California's Central Valley, where there are over 3,000 diversions. We found few studies that even attempted to evaluate the effectiveness of screens in preventing losses of fish, much less declines in fish populations. The limited published literature suggests that this lack of evaluation is typical throughout the western United States, despite millions of dollars spent annually on screens and their maintenance. Nevertheless even small diversions can be important sources of fish mortality, given their large number and the combined volume of water they divert. The impact on fish populations of individual diversions is likely highly variable and depends upon size and location, as demonstrated by evaluations of cooling water intakes for power plants. Studies are needed to determine which diversions have the greatest impact on fish populations in order to set priorities for screening, to make the best use of limited public funds available for restoration and conservation, and to provide scientific support for effective screening policies.

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One of the most common fisheries management practices in North America is placing screens across diversions that withdraw water from streams for irrigation, power production, and other types of human consumption. The primary purpose of screening is to prevent loss of fish in order to maintain fish populations for sport and commercial fisheries and to prevent extinction of species listed under state and federal endangered species acts. Despite extensive literature on the construction and engineering of fish screens, there is little quantitative analysis of how screening diversions affects fish populations. Fisheries agencies have historically not evaluated effectiveness of fish screens because screening seems so obviously beneficial to fish. Leitritz (1952), in a review of fish screens in California, does not mention a need to evaluate their effectiveness except in terms of screen design. Odenweller (1994), in a popular article on fish screens, answers the question "Why are they necessary?" only with "Fish screens are necessary to prevent loss of fishery resources at water diversion sites." The implication is that without screens, fisheries will be diminished or lost. This attitude is reflected in a textbook of fisheries management published by the American Fisheries Society (Kohler and Hubert 1999). In this book, fish screens are mentioned just twice in single sentences, e.g., "Fish screens are used to keep fishes out of particular reaches of streams or to keep game fishes or endangered species from entering irrigation diversion canals…."(p. 424). Treatment is similarly minimal or even absent in other texts on fisheries management (e.g., Welcomme 2001). A recent review of fish screen performance criteria stated only that fish screens should be "built, operated, and maintained to protect aquatic life, while allowing for other beneficial uses of the waters that are diverted (McMichael et al. 2004:10)." No population-level biological criteria are provided, except to point out that declines in anadromous fishes are associated with increased diversions of water.

Despite this lack of evaluation of effectiveness of most fish screens in achieving their primary purpose, screens are generally required for power plants and other large diversions and often for smaller diversions as well. In states where a high percentage of the water is diverted for agriculture or urban use, fisheries agencies generally have policies that all or most diversions should be screened (McMichael et al. 2004). From a fisheries perspective, this seems like good policy. Implicit in this policy is the precautionary approach to fisheries management (Dayton 1998) that a diversion should be assumed to harm fish populations unless it can be proven otherwise. The problem lies in the cost both of constructing fish screens and in maintaining them. Even small screens can cost thousands of dollars to build and large ones can cost several million dollars, with substantial annual maintenance costs. Construction costs alone are typically $5,000–6,000 per acre foot of water screened and may be much higher (for example, see www.wdfw.wa.gov). While costs may be borne by the diverters, more often they are either shared or paid fully by state or federal governments. For example, over a 15-year period, government agencies spent about $76 million on fish passage structures (mainly screens) in the Yakima River basin in Washington alone, with maintenance costs estimated to be over $4.2 million/year (McMichael et al. 2004). Given the scarcity of funds to implement fish conservation and recovery, it is important to determine when spending conservation dollars on fish screens is an effective investment for improving imperiled fish populations and fisheries. Considering the millions of dollars spent annually on fish screens nationwide, but especially in California and the West, the lack of systematic analyses of their effectiveness by fisheries biologists is a serious oversight.

This article is the result of an investigation made by the senior author on behalf of the Independent Science Board of the CALFED Ecosystem Restoration Program (ERP, http://calwater.ca.gov/Programs/EcosystemRestoration/InterimScienceBoard/ISB_ReportOnFishScreens.pdfwer). CALFED was created as a joint state-federal effort to resolve endangered species and other issues that were affecting the reliability of California's water supply, with hundreds of millions of dollars appropriated for restoration and other activities (CALFED 1999; Moyle 2000). Fish screening projects quickly became a major priority (see below). We therefore investigated the evaluations of existing fish screen projects in the Sacramento-San Joaquin River system of central California to see if we could gain insights into the value of proposed projects. A major goal was to see if sufficient information existed to determine whether fish screen projects provide major benefits to fisheries and endangered species.

Basic questions

Basic questions for which we sought answers were:

- **How many fish, and what species and life stages, are entrained by unscreened diversions?**
- **Given expected losses in the absence of screens, what are the likely population consequences of screening the remaining unscreened diversions, particularly for listed or declining species?**
- **What is the relationship between fish entrained in unscreened diversions and amount of water diverted?**
- **Is it more beneficial to fish populations to selectively screen diversions based on size, location, and mode of operation?**
- **Are alternatives to fish screens to reduce impacts of diversions on fish used?**
- **Are there detrimental effects of screening, including changes in fluvial and riparian processes or enhancement of predation on species of concern?**
- **Given the above considerations, how do additional screens compare with other potential restoration actions in a cost:benefit analysis?**

Our approach was to first review available studies on fish screens in the Sacramento and San Joaquin rivers and their tributaries, and in the Delta, the freshwater portion of the San Francisco Estuary where the two rivers meet. One reason for confining our study to this area is that we quickly discovered that most of the relevant studies were unpublished and usually not even available on the Internet. Our failed attempts to find similar reports for other regions using the Internet and library searches suggested that local knowledge was crucial for this review. In any case, the sheer number and variety of diversions in

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Head gate to a diversion off Shackleford Creek, in the Scott Valley, California, which is a spawning and rearing stream for threatened coho salmon. There is a fish screen just below the head gate, out of the picture.

the Central Valley indicates that it is a good region to conduct a "test case" evaluation of the literature.

Diversions in the Central Valley

There are at least 3,356 diversions in or on the Sacramento and San Joaquin rivers, their tributaries, and the Delta (Herren and Kawasaki 2001); 98.5% of these diversions are "either unscreened or screened insufficiently to prevent fish entrainment" (Herren and Kawasaki 2001:343). Most of the diversions are small (intake pipe diameters less than 1.02 m or less than 7.1 m^3/s; 73% have less than 1.4 m^3/s capacity). In general, the larger the diversion, the more likely it is to be screened. Out of 767 diversions with measured intake capacity, 61% with a capacity of over 7.1 m^3/s, 19% with a capacity between 2.8 m^3/s and 7.1 m^3/s, and about 12% with a capacity of less than 2.8 m^3/s were screened (D. White, NOAA Fisheries, Santa Rosa, CA, pers. comm., 2003). In addition, small diversions on small tributary streams can take a high percentage of the flow and are often subject to screening if the stream is regarded as important for spawning of anadromous fish. A further problem is that poorly maintained screens may not be fully functional.

Diversions are widely assumed to kill large numbers of fish, especially migratory fish such as salmon and steelhead. Thus, 11 of the 32 top priorities for protecting anadromous fish in the Central Valley streams, listed in the California Department of Fish and Game's (CDFG) 1993 action plan, are for screening or installing "fish protective devices" on diversions. Likewise, the Ecosystem Restoration Program Plan (CALFED 1999) lists unscreened diversions as an important stressor on populations of salmon and other fishes and indicates elimination of unscreened diversions should be a high priority action. To keep fish, especially juvenile salmonids, from being lost in these diversions, the state of California enacted fish screen requirements under three sections of the CDFG Code (Odenweller 1994), which outline screening responsibilities of CDFG and diverters based on the size of diversion and date of construction. In addition to state requirements, NOAA Fisheries and U. S. Fish and Wildlife Service (USFWS) often require screening to protect fish species listed as threatened or endangered under the Endangered Species Act (ESA), the Federal Power Act, and the Fish and Wildlife Coordination Act (see http://swr.ucsd.edu/hcd/fishscrn.htm). A major justification for screening under the ESA is that any removal of individuals of threatened or endangered species by a diversion constitutes "take" under section 4(d) of the ESA and must be prevented, even if there is no demonstrable effect on the species at the population level. For the most part, fish screens required by federal agencies are paid for with federal funds, especially through the Anadromous Fish Restoration Program of the USFWS (USFWS 1999).

The establishment of CALFED made additional state and federal money available for new and improved screens and by 2000, around $20 million in funds (12.5% of the total dollars spent by the ERP) had been allocated to screening projects. In 2001, over $11 million was appropriated for fish screen work (7 projects), including a $6 million project to replace existing screens on one large Sacramento River diversion and $1.8 million to screen small diversions on the river. In 2002, there were 17 applications for ERP funds related to fish screens, totaling over $55.6 million. Overall, for legal and historic reasons, most fish screens in California are paid for with public funds. Without such funds, most diversions go unscreened despite the obvious economic benefits accruing to the users of water from each diversion and despite the perceived harm to fish populations.

Methods

The California literature review was conducted in March–June 2001 and mainly located studies done prior to 2000. The first step was a cross-database search of the California Digital Library for publications containing any of the title words "California fish screens." This library has a search function that enables a coarse but rapid search of 47 digital databases. Our search identified 19 databases that contained at least one article with California fish screens in the title. The articles located in these databases were then segregated into categories based on topic. Because we were interested specifically in the effects of screening projects on fish, additional searches were conducted by examining the bibliographies of articles located in the computer search as well as through personal contacts. The ability of our search to find large numbers of reports in the gray literature suggests that it caught all major studies relating to the Central Valley and at least a representative sample of other studies. For the purposes of analysis, we divided the studies into the following categories:

1. **General reviews** included reports and documents on current screening programs, the history of fish screens, screening policy, surveys of fish conservation devices, and reviews of the many different types of fish screens.
2. **Facility reports** included all articles concerned with design, construction, operation, and maintenance of fish protection facilities.
3. **Fish losses** included all field studies and estimates of fish losses due to diversions, including predator control studies.
4. **Economic costs** included an estimate of screening costs for water diversions in the region and a report on economic costs to the State Water Project of environmental protection and mitigation measures.

5. **New technology** included technical design documents and evaluation reports on screen designs and various technical alternatives to fish screens.
6. **Laboratory studies** were mostly behavioral or physiological studies on the responses of fish to screens or other devices.

Once we sorted the literature into the above categories, we further refined the search to screens based on size and location of diversions. We concentrated on finding studies that evaluated diversions of less than 7.1 m^3/s in the Sacramento-San Joaquin Delta and Suisun Marsh (both part of the San Francisco Estuary) and riverine diversions of all sizes in the Central Valley. We then conducted a follow-up review of the published literature to provide further insights into the effectiveness of fish screening projects in protecting fish populations.

Results

General results

We identified 255 articles, primarily in the gray literature, related to California fish screens. Most reports (153, 60%) discussed some aspect of the operation and design of facilities. Thirty-six (14%) articles dealt with some aspect of evaluating losses of fish to diversions in relation to screening, while 34 (13%) dealt with alternatives to fish screens (new technology). Of 36 reports on fish losses, only 15 were related even vaguely to the effects of fish screens on fish populations in rivers and streams, the category of most interest here. Six were studies of small diversions in the Delta and Suisun Marsh. The rest (15) dealt with losses at the immense state and federal pumping plants in the south Delta, which have their own special problems (so are not treated further here). Other categories were general reviews of screening and fish passage problems and technology (22), laboratory studies (4), and economic evaluations of screening (2).

For comparison with our results, we examined the bibliography maintained by the Delta Fish Facilities Study Program (http://iep.water.ca.gov/cvffrt/references.htm), which listed 75 reports spanning the years 1959–1986. Thirteen reports (17%) dealt with some aspect of loss of fish to diversions in rivers and to small diversions in the Delta. Five of the 13 were not found in our search because they were interoffice memoranda or draft reports.

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A fish screen on a major irrigation diversion from the Scott River, in the Scott Valley, California. The screen is designed to return juvenile coho salmon and steelhead back to the river.

Riverine diversions

Of the 15 reports on riverine diversions, 9 dealt with large diversions on the rivers. Most (7) of these concerned Red Bluff Diversion Dam on the Sacramento River, the largest of the diversions with very special problems related to its size. Two dealt with the Hallwood-Cordua diversion on the Yuba River but did not provide estimates of the numbers of fish lost to the diversions or saved by screening. Two were studies of predation losses in relation to fish screens prompted by indications that some screens increased predation rates on juvenile Chinook salmon (*Oncorhynchus tshawytscha*) by providing holding areas for predatory fish. Both were inconclusive.

Hallock and Van Woert (1959) was the only publication we found that attempted a fairly broad evaluation of fish losses to unscreened diversions. This paper is not particularly rigorous in its analysis (no statistics, limited data summaries), but it did attempt to evaluate losses of salmon to diversions of various sizes from both the Sacramento and San Joaquin rivers over a 3-year period, mainly by using fyke nets to sample water at the diversion point or by sampling irrigation canals behind the diversions. Their findings, based on data summaries in their tables, include: (1) more fish were lost to large diversions (based on pipe diameter) than small ones, although no relationship between size and numbers lost was developed; (2) total numbers of salmon lost in the diversions was surprisingly small and was attributed to low overlap of agricultural diversion season with the main periods of salmon out-migration; (3) numbers of all fish lost to individual diversions was highly variable among diversions and through time, but was often quite low; (4) many species were entrained but most abundant were, in order of abundance, common carp (*Cyprinus carpio*), Sacramento sucker (*Catostomus occidentalis*), white catfish (*Ameiurus catus*), small centrarchids (mainly *Lepomis* spp.), and Chinook salmon. Only Sacramento sucker and Chinook salmon are native species. Hallock and Van Woert (1959) concluded "…appreciable losses of salmon in irrigation diversions now occur at few places on the [Sacramento] river itself above Meridian. Individually, most of the small irrigation diversions do not destroy many young salmon and steelhead. Collectively, however, they do take considerable numbers (p. 245)." "The 1955 studies on the San Joaquin River show that all of the large diversions sampled…are destroying appreciable numbers of salmon fry. This is not surprising, since between 20 and 40 percent of the entire river flow is pumped into irrigation canals during the period when salmon are migrating downstream…" (p. 252). "Appreciable numbers," in the latter case, meant an estimated 1.5–12.0 juvenile salmon/hour of diversion or approximately 31,000 fish for the entire season in the three largest diversions sampled. Along the Sacramento River, about 9,000 total hours of fyke netting in 23 diversion canals yielded about 1,600 juvenile salmon, with a total estimated loss of less than 4,000 salmon for the season. Catches for common carp and Sacramento suckers were appreciably higher.

Overall, Hallock and Van Woert (1959) indicated that despite the mixed results from the surveys, all diversions should be screened because of cumulative effects. The authors also indicated that they thought (without documentation) diversion losses were probably much higher in tributaries and results from the main rivers were therefore not representative of the problem.

In a study published after our literature search was completed, Hanson (2001) reported experimental Chinook salmon losses at a large diversion on the Sacramento River that diverted about 1% of the river's flow. When he released large numbers of marked, hatchery-reared juvenile Chinook salmon above the diversion, only 0.05% were entrained, a result similar to an earlier study on another diversion. As Hanson (2001) points out, his use of hatchery fish, his release methods, and the particular configuration of the diversion limit the generality of his results.

Delta diversions

Diversions in the Delta and estuary have been studied more intensively than those in the rivers, mainly by the California Department of Water Resources because of potential effects on striped bass (*Morone saxatilis*), Chinook salmon, and other species. Allen (1975), in a brief study, concluded that loss of striped bass eggs and larvae through small diversions was proportional to the number of fish in the river and the amount of water being diverted. Pickard et al. (1982) studied one large diversion in Suisun Marsh, just downstream of the Delta. They netted the diversion for an unspecified number of hours on 12 days over a 6-month period, and captured over 14,000 fish of 27 species. The most abundant species were natives: delta smelt (*Hypomesus transpacificus*), longfin smelt (*Spirinchus thaleichthys*), threespine stickleback (*Gasterosteus aculeatus*), and Chinook salmon. No attempt was made to extrapolate to total number of fish lost. Losses of all species continued after the diversion was screened (due to openings in the screen, which were later repaired) but at much lower numbers.

Spaar (1994) evaluated four small diversions in a "pilot" study and found that larvae were entrained at roughly their densities in the associated sloughs, with species captured more or less in proportion to their numbers in the sloughs as well. Screening one diversion significantly reduced numbers of fish being lost through that particular diversion. The most abundant fish in her study were all alien fishes: shimofuri goby (*Tridentiger bifasciatus*), threadfin shad (*Dorosoma petenense*), western mosquitofish

(*Gambusia affinis*), white catfish, and bluegill (*Lepomis macrochirus*). Most fish were captured as embryos and larvae although small numbers of juveniles were captured as well. Although the three diversions studied were estimated to entrain over 3 million eggs and larvae in a season; over 85% were those of shimofuri goby (invading explosively at the time, 1992) and threadfin shad (an abundant alien planktivore). In a three-year follow-up study, Cook and Buffaloe (1998) concluded they could not develop quantitative estimates from their study because of sampling problems. They nevertheless noted (p. 13), "The results of this study…suggest that small-scale diversions…can entrain a large diversity of fish species…The actual number of entrained fish can be large." They noted that benthic fishes were more likely to be entrained than pelagic fishes, although threadfin shad and striped bass were commonly captured. Only a few individuals of native delta smelt, splittail (*Pogonichthys macrolepidotus*), and Chinook salmon were captured; most fishes taken were nonnative, warmwater fishes.

Nobriga et al. (2004) conducted a more intensive study of fish entrainment in three diversions (pipe diameter 61 cm; two screened, one unscreened) in the lower Sacramento River, over two 3-day periods in July 2000 and 2001. They found that large numbers of larval and postlarval fishes were entrained in the unscreened diversion but that most (>99%) were small alien species, mainly threadfin shad and gobies. The small numbers of native fish entrained included a few delta smelt, listed as a threatened species under the ESA. The numbers of smelt captured was low despite their abundance in trawl samples from the adjacent river, which suggested they had low entrainment rates because they generally avoid inshore waters (Nobriga et al. 2004). This study indicated that vulnerability of fish to diversion varied among species, size, time of day and, possibly, the ebb and flow of tides. While the study showed that the screens reduced diversion of fish by 99%, the impact of the unscreened diversion on fish populations was likely small because of its small size in relation to the river from which the water was being drawn.

What is lacking is the means to prioritize screening projects, aside from size and location, or to find alternatives to them.

The single most intensive effort to sample diversions, however, took place in Suisun Marsh, where water is diverted into freshwater marshes managed for waterfowl hunting (CDFG 1998). Eight small diversions were sampled using fyke nets over 24-hour periods, for a total of 439 days, mainly during periods when species of interest (delta smelt, juvenile Chinook salmon) were mostly likely to be present. About 21,000 fish were captured (average of 2 fish/hr), mostly prickly sculpin (*Cottus asper,* 50%), threespine stickleback (42%), and shimofuri goby (5%). About 68% of all these fish were caught in one diversion over a 52-day period; this same diversion caught only 3 juvenile Chinook salmon. The rest of the 106 salmon captured came from one other diversion, which over an 80-day period also captured most of the remaining 32% of the fish taken in the study. The prickly sculpins captured were all small juveniles. Both sculpins and sticklebacks are abundant throughout the marsh (Matern et al. 2002). The report did not present any conclusions, basically summarizing data without analysis. The data indicate, however, that most diversions in the marsh are likely not diverting many fish and are having a negligible impact on fish populations.

Comparative studies

A conventional literature search using various literature databases at the University of California, Davis library did not reveal many relevant studies, especially on small agricultural diversions that are the most numerous diversions in California and the western United States (but see Nelson and Beckman 1979). Internet searches also revealed few studies or reports that provided some indication of the numbers of fishes saved by screening agricultural and urban diversions. The best and most numerous published studies are those that relate to the impacts of fish entrainment and impingement on cooling water diversions for power plants. Although Cada and Sale (1993) reported that most (79%) such projects lacked monitoring of their impacts on fish populations, some fairly comprehensive studies have been completed in this area (Dixon et al. 2003). One of the most extensive evaluations was for a large power plant on the Hudson River (papers in Barnthouse et al. 1988). These studies detailed the stock dynamics and distribution patterns of fish species of interest when they were most susceptible to diversion. According to Klauda et al. (1988: 320) "…power plant operations could not be convincingly implicated as a major source of mortality that was clearly distinguishable from other abiotic factors. Perhaps the power plants had no effect or perhaps 10–15 years of intensive studies were not long enough for any effects of power plants on fish populations to be manifested." Savitz et al. (1998) examined impingement and entrainment of fishes on the intake of a power plant in Lake Michigan and reviewed reports for similar plants. They concluded the diversion, and others like it, had little impact on fish populations because of locations of the intakes (in deep water) and low numbers of fish taken. Similar results were found for power plants on the Ohio River and the Delaware Estuary, although diversions into a power plant on the California coast apparently had a negative impact on the local population of at least one fish species (Dixon et al. 2003).

For power plants diverting water for cooling, a number of quantitative models have been developed to predict impacts: the Empirical Transport Model (Boreman et al. 1981), the Production Foregone Model (Rago 1984: Jensen et al. 1988), and the Recruitment Foregone Model (Jensen 1990). The Empirical Transport Model attempts to estimate mortality of different age classes in relation to their non-uniform physical and temporal distribution in the waterway in relation to the intake site. The Production Foregone Model attempts to distinguish the relative importance of different life history stages in terms of lost fish production, in order to determine the relative value of screening adult and juvenile fish versus reducing entrainment of larval fish.

Because these two types of models require large amounts of data, they do not seem to have been used very frequently. A less data-hungry approach is the Recruitment Foregone Model, which estimates how many fish would have been lost to the adult population as the result of entrainment. Using this model, Jensen (1990) estimated that even entrainment of millions of embryos and larvae of yellow perch (*Perca flavescens*) had little impact on perch populations in western Lake Erie. Other models are presented in Dixon et al. (2003). Apparently, no attempt has been made to apply such models to diversions in California and the western United States, or to develop more appropriate models for use in evaluating small riverine diversions.

Discussion

Clearly, the effectiveness of fish screens in preventing fish losses in the Central Valley has not been well evaluated, especially at the population level. Not only are there few studies that were made prior to screening, but there are even fewer studies that demonstrate how well existing screens are working. The reports we located are primarily in-house documents by agency staff that have gone through little or no outside review. The few evaluations available focus on large in-river diversions, on the large state and federal pumping plants in the Delta, and on small Delta diversions. Not surprisingly, there are at best only limited answers to the questions posed in the introduction. Our cursory review of the published literature suggests that this problem is not unique to the Central Valley but is typical of most areas.

In the absence of screens, how many fish, and what species and life stages, are entrained by the remaining unscreened diversions? There is no doubt that at times large numbers of juvenile salmonids and other species of concern are entrained by diversions, especially by large diversions and by small diversions on tributaries important for spawning and rearing. Yet the quantification of this phenomenon is very poor. The few studies that exist tend to find that alien species or abundant natives (e.g., Sacramento sucker) are the principal species diverted, especially in small ($<1.1\ m^3/s$) diversions, which remain the majority of those unscreened. Most diversions that have been perceived to be major problems (mainly large riverine diversions) appear to have been screened. The existing information suggests that diversions that remove only a small proportion of the water available, especially on mainstem rivers and in backwater areas such as Suisun Marsh, have low or no impact on fish populations although little definitive can be said about this issue until studies are undertaken to evaluate both individual and cumulative impacts. Indeed it is possible that a small individual diversion at the right time and place could have a major negative impact on a rare or endangered species.

Given expected losses in the absence of screens, what are the likely population consequences of screening all unscreened diversions, particularly for listed or declining species? As indicated, quantitative answers to this question cannot be given based on existing data. Answers that are given are reflected well in the list of benefits of screening diversions on small streams given by J. Bybee of National Marine Fisheries Service in an unpublished memorandum to the CALFED Ecosystem Restoration Program in response to an earlier version of this report (20 June 2001):

"First, installed fish screens remove the potential legal burden of taking an ESA listed fish. Second, a screen complements habitat restoration in particular watersheds and is a vote of confidence that increased fish production in a small stream is not in vain. Third, fish screens will probably be identified as an action in Recovery Plans. Fourth, steelhead occur in these small streams, often year round, being subjected to entrainment continuously during the diversion season. Fifth, fish screens are probably also effective in keeping more than listed fish in the streams; certain other species of fish and macroinvertebrates of importance to the ecosystem are also saved."

Implicit in this answer is the importance of saving fish and invertebrates as individuals, regardless of population consequences, for largely social and legal reasons. In addition, it incorporates the precautionary approach that a diversion should be assumed to harm fish populations unless it can be proven otherwise. The latter is perhaps the best reason for screening but it still does not remove the need for evaluation studies.

What is the relationship between fish entrained in unscreened diversions and amount of water diverted? Surprisingly, this seems to be poorly understood. The only regional study of which we are aware is that of Kozlowski (2004) who evaluated the take of juvenile steelhead (*O. mykiss*) by a large diversion on the Yuba River, in which all fish diverted were captured in a trap in the canal and returned to the river. He found that the number of steelhead taken by the diversion was virtually zero when the diversion was taking less than 15% of the total river flow. Numbers rose dramatically when the diversion took 25–35% of the flow. The relationship between the fish captured and the amount diverted was not linear and day-to-day capture rates were highly variable, depending on factors such as phase of the moon and temperature (Kozlowski 2004). This study suggests that the relationship between the amount of water diverted and the number of fish entrained, while generally positive at higher levels of diversion, is fairly complex, with high seasonal and year-to-year variation. This relationship is amenable to modeling, provided adequate experimental and empirical data exist, which would seem worth pursuing as a way to better understand cumulative effects of diversions.

Is it more beneficial to selectively screen diversions based on size, location, and mode of operation? At a gross scale, the answer to this question is a fairly obvious "yes." However, once the diversions known to be major problems for fish are identified and screened, there are still several thousand left in the Central Valley. While the CALFED Ecosystem Restoration Program's Fish Screen and Ladder Construction Technical Panel includes specific criteria in their evaluation of projects for funding, adequate data do not appear to exist to make decisions based on much beyond intuition and experience (i.e., professional judgment, which, however, should not be discounted in importance). Rarely are pre-screening data on fish entrainment available to determine the positive consequences of screening, although such information is important for determining population level impacts through lost recruitment. What information exists suggests that specific diversions differ widely in their impacts on fish populations and that many small diversions have little or no impact (e.g., Jensen 1990: Savitz et al. 1998)

Are alternatives to fish screens to reduce impacts of diversions on fish used? For the most part, it appears that decisions to reduce entrainment of fishes in diversions are to screen or not to screen. Alternatives, such as changing the timing of water diversion, adjusting the diversion volume in relation to the presence or absence of fish of concern, or relocating the place of diversion do not seem to be used or even considered. The fact that McMichael et al. (2004) found that all fish screens they evaluated over a 4-year period experienced multiple performance problems suggests the value of considering alternatives to screening.

Are there detrimental effects of screening, including changes in fluvial and riparian processes or enhancement of predation on species of concern? Negative impacts of a fish screen installation are rarely considered although it is at least possible that areas around fish screens may attract predatory fishes because of the abundance of small fishes and the presence of low-velocity holding areas (Hall 1980). Because fish screens require that intake locations be fixed, they can also result in the "hardening" of stream banks above and below each site, and even across the river from it, to protect the structure from fluvial processes (erosion, deposition). These problems are likely of small concern either because the problems exist mainly around existing large diversion structures or because they can be handled by the proper design of new screening facilities. However, hard information to support this conclusion is lacking.

Increasingly, fisheries are being managed using models that take into account uncertainty. It should be possible to develop and apply such models to the impacts of unscreened diversions on fish populations.

Given the above considerations, how do additional screens compare with other potential restoration actions in a cost:benefit analysis? This should be an important consideration because both the costs of screening and the costs of other ecosystem restoration actions are high and funds are limited. We suggest that each screening project should have a well-defined benefit to fish populations as demonstrated by careful studies. We recognize that this is a problem for regulating diversions under the "take" provisions of the ESA, but even here flexibility is desirable. Funds used for fish screens may have higher benefits to listed species if spent on other projects.

Conclusions

Most new screening projects in the Central Valley today are built to keep diverters from potentially killing individuals of endangered species (mainly spring run Chinook salmon, winter run Chinook salmon, Central Valley steelhead, and delta smelt), although the desire to protect fisheries is also an important rationale. We simply do not know if screening every diversion or even any particular diversion will make a difference to fish populations, even those of listed species. Some screens may even be detrimental because of predation on juvenile salmon and other fish around the structure, or because they require modification of natural habitats for installation. Screening large diversions may have slowed population declines or even prevented extinctions of local populations of salmon and other fishes but considerable uncertainty remains over the cumulative contribution of screening towards improving fish populations. Overall, the impact of diversions on fish has not been evaluated in Central California since Hallock and Van Woert (1959), a study with results that are equivocal. Costs of constructing new screens and replacing and maintaining old ones are high, so evaluations of new projects, especially for small diversions on large rivers, in terms of both local and cumulative impacts on fish populations is in order.

It is important to recognize that we are not saying that diversions, even small ones, are unimportant as sources of mortality for juvenile salmon and other fishes, including endangered species. Given their large number and volume of water diverted, diversions clearly can entrain large numbers of fish and potentially impact fish populations. Fish screening and/or operating diversions to minimize the loss of fish can be important conservation tools. What is lacking is the means to prioritize screening projects, aside from size and location, or to find alternatives to them. A prioritization scheme should be based at least in part on the contribution of the diversion to the cumulative loss of fishes to the system and the impact of this contribution on fish populations, especially those of declining species. Such an evaluation is needed to determine priorities for spending limited funds available for fish conservation and endangered species recovery.

Recommendations

Until the basic questions posed above are answered and uncertainty is reduced, it does not seem appropriate to use public funds to provide new screens for most diversions (especially small diversions on large rivers) unless the projects have a strong evaluation component to them, including intensive before and after studies. Under an adaptive management framework, the "before" study should be evaluated by independent experts to see if the diversion does harm to fish populations, either individually or cumulatively. It is appropriate that regulatory agencies work with the philosophy that diversions, especially large diversions, are doing harm to fish populations unless it can be proven otherwise and it should be incumbent on the diverters to prove lack of harm. However, because many diverters are not legally obligated to screen diversions and funds for conservation projects are limited using public funds to screen diversions whose impacts are likely to be low (based on size, location, and timing of diversions) seems inappropriate. It is appropriate for public funds to pay for studies on subjects such as the population benefits of screening small diversions, the cumulative effects of existing unscreened diversions, the effects of individual diversions (screened or unscreened) that are perceived to have a serious impact on fish populations, and the development of models that can address these issues. We clearly need more information on how diversions affect fish populations and on the most effective strategies to deal with negative impacts, if we are to make most effective use of scarce conservation dollars. Increasingly, fisheries are being managed using models that take into account uncertainty. It should be possible to develop and apply such models to the impacts of unscreened diversions on fish populations.

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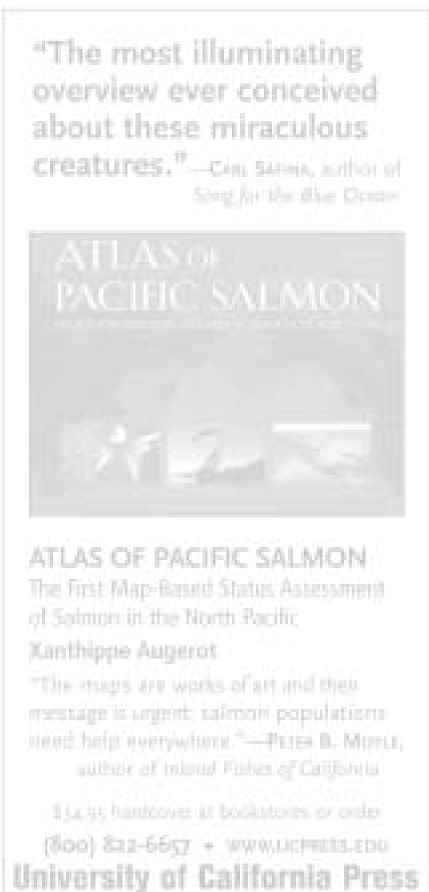
References

Allen, D. H. 1975. Loss of striped bass eggs and young through small agricultural diversions in Sacramento-San Joaquin Delta. CDFG Anadromous Fisheries Branch, Sacramento, Administrative Report 75-3:1-12

Barnthouse, L. W., R. J. Klauda, D. S. Vaughn, and **R. L. Kendall.** 1988. Science, law, and Hudson River power plants. American Fisheries Society Monograph 4, Bethesda, Maryland.

Boreman, J., C. P. Goodyear, and **S. W. Christensen.** 1981. An empirical methodology for estimating entrainment losses at power plants sited on estuaries. Transactions of the American Fisheries Society 110:253-260.



Cada, G. F. and **M. J. Sale.** 1993. Status of fish passage facilities at nonfederal hydropower projects. Fisheries 18(7):4-12.

CALFED. 1999. CALFED Bay-Delta Program Strategic Plan for Ecosystem Restoration. CALFED, Sacramento.

CDFG (California Department of Fish and Game). 1998. 1997-1998 sampling report for the diversion monitoring program, a component of the Suisun Marsh Diversion Screening Program. Unpublished report for Suisun Resource Conservation District: 1-18. Sacramento.

Cook, L., and **L. D. Buffaloe.** 1998. Delta agricultural diversion evaluation summary Report, 1993-1995. Interagency Ecological Program for the San Francisco Bay/Delta Estuary Technical Report 61. Sacramento, California.

Dayton, P. K. 1998. Reversal of the burden of proof in fisheries management. Science 279:821-822.

Dixon, D. A., J. A. Veil, and **J. Wisniewski, editors.** 2003. Defining and assessing adverse environmental impact from power plant impingement and entrainment of aquatic organisms. A. A. Balkema Publishers, Lisse, The Netherlands.

Hall, F., Jr. 1980. Ultrasonic tracking of striped bass and Sacramento squawfish near fish facilities. California Department of Fish and Game Anadromous Fisheries Branch, Sacramento, Administrative Report 80-1:1-12.

Hallock, R. J. and **W. F. Van Woert.** 1959. A survey of anadromous fish losses in irrigation diversions from the Sacramento and San Joaquin rivers. California Fish and Game 45:227-293.

Hanson, C. H. 2001. Are juvenile Chinook salmon entrained at unscreened diversions in direction proportion to the volume of water diverted? Pages 331-341 *in* R. L. Brown, ed. Contributions to biology of Central Valley salmonids, Volume 2. California Department of Fish and Game Fish Bulletin 179.

Herren, J. R., and **S. S. Kawasaki.** 2001. Inventory of water diversions in four geographic areas in California's Central Valley. Pages 343-355 *in* R. L. Brown, ed. Contributions to biology of Central Valley salmonids, Volume 2, CDFG Fish Bulletin 179.

Jensen, A. L. 1990. Estimation of recruitment forgone resulting from larval fish entrainment. Journal of Great Lakes Research 16:241-244.

Jensen, A. L., R. H. Reider, and **W. P. Kovalak.** 1988. Estimation of production forgone. North American Journal of Fisheries Management 8:191-198.

Klauda, R. J., L. W. Barnthouse, and **D. S. Vaughn.** 1988. What we learned about the Hudson River: journey towards an elusive destination. American Fisheries Society Monograph 4:316-328.

Kohler, C. C., and **W. A. Hubert (editors).** 1999. Inland fisheries management in North America. American Fisheries Society, Bethesda, Maryland.

Kozlowski, J. F. 2004. Summer distribution, abundance, and movements of rainbow trout (*Oncorhynchus mykiss*) and other fishes in the Lower Yuba River, California. M.S. Thesis (Ecology), University of California, Davis.

Leitritz, E. 1952. Stopping them: the development of fish screens in California. California Fish and Game 38:53-62.

Matern, S. A., P. B. Moyle, and **L. C. Pierce.** 2002. Native and alien fishes in a California estuarine marsh: twenty-one years of changing assemblages. Transactions of the American Fisheries Society 131:797-816.

McMichael, G. A., J. A. Vucelick, C. S. Abernethy, and **D. A. Neitzel.** 2004. Comparing fish screen performance to physical design criteria. Fisheries 29(7):10-16.

Moyle, P. B. 2000. Restoring aquatic ecosystems is a matter of values. California Agriculture 54(2):16-25.

Nelson, W. R., and **L. G. Beckman.** 1979. Entrainment of ichthyoplankton by irrigation withdrawal systems. U.S. Fish and Wildlife Service Biological Services Program FWS/OBS-79/16.

Nobriga, M., Z. Matica, and **Z. Hymanson.** 2004. Evaluating entrainment vulnerability to agricultural irrigation diversions: a comparison among open-water fishes. American Fisheries Society Symposium 39:281-295.

Odenweller, D. 1994. Screens protect fish from diversions. Outdoor California, September-October 1994:24-26.

Pickard, A., A. Baracco, and **R. Kano.** 1982. Occurrence, abundance and age of fish at the Roaring River Slough Intake, Suisun Marsh, CA during the 1980-1 and 1981-2 diversion seasons. Interagency Ecological Study Program, Technical Report 3. Sacramento, California.

Rago, P. J. 1984. Production forgone: an alternative method for assessing the consequences of fish entrainment and impingement losses at power plants and other water intakes. Ecological Modeling 24:79-111.

Savitz, J. , L. G. Bardygula-Nonn, R. A. Nonn, and **G. Wojtowicz** 1998. Impingement and entrainment of fishes within a high volume-low velocity deep water intake system on Lake Michigan. Journal of Freshwater Ecology 13:165-169.

Spaar, S. 1994. Delta agricultural diversion evaluation 1992 pilot study. Interagency Ecological Program for the San Francisco Bay/Delta Estuary Technical Report 37. Sacramento, California.

USFWS (U.S. Fish and Wildlife Service). 1999. Central Valley Project Improvement Act anadromous fish screen program: program description. USFWS, Sacramento, California.

Welcomme, R. L. 2001. Inland fisheries: ecology and management. Fishing News Books, Blackwell Science, Oxford.