

CALIFORNIA
ENERGY
COMMISSION

**ROADMAP FOR PIER RESEARCH ON
FISH PASSAGE AT CALIFORNIA
HYDROPOWER FACILITIES**

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Executive Summary

The *Roadmap for PIER Research on Fish Passage at California Hydropower Facilities* addresses research and development efforts to facilitate fish movement up and downstream past hydroelectric facilities. In California, hydropower represents approximately 27% of the state's installed generating capacity and supplies approximately 15% of its annual electricity. A substantial portion of this capacity, however, was installed prior to enactment of federal and state environmental protection laws, and therefore, many facilities may not meet modern environmental standards. Furthermore, California's freshwater ecosystems have suffered massive alteration, with many fish populations in precipitous decline, with the result that there is increasing pressure for the hydropower sector to reduce adverse effects on aquatic resources.

For example, it is estimated that 58% of California's freshwater fish species are extinct or are in serious decline. Hydropower's role in the decline of freshwater fisheries in California is well documented. The effects of hydropower on aquatic species and habitats in California include the loss, alteration, and fragmentation of aquatic habitats; degradation of water quality, and the introduction of invasive species.

Fish passage issues—the subject of this roadmap—have received increased attention in recent years because many of California's remaining migratory salmon species have been listed as threatened or endangered. Efforts to protect these species invariably involve fish passage measures past dams and other barriers to increase access to historically used habitat. In addition, as noted above, many populations of California's non-salmon species have seriously declined. Although clearly many of these species are affected by hydropower operation, the benefit of fish passage for many of these species is uncertain.

For non-federal hydropower facilities within the state, fish passage issues will be addressed as part of the Federal Energy Regulatory Commission (FERC) relicensing process. Therefore, the need for accurate, cost-effective tools and methods to assess, design, and implement fish passage measures is immediate—within the next eight years, over 40 facilities (constituting over 3,000 MW in capacity) will have to renew their licenses.

In the short-term (1–3 years), this roadmap recommends that research address the following objectives:

Objective	Projected Cost (\$000)
5.1.1. Develop protocols for fish passage information requirements	120
5.1.2. Evaluate need and requirements for non-salmonid fish passage	450
5.1.3.A. Evaluate technology for upstream fish passage at high dams	350
5.1.3.B. Evaluate use of behavioral technology for upstream passage	150
5.1.4.A. Demonstrate innovative downstream fish passage	550
5.1.4.B. Develop downstream fish passage monitoring guidelines	150
Total	1,770

The PIER-EA Roadmap for PIER Research on Fish Passage at California Hydropower Facilities does not identify mid-term (3–10 year) and long-term (10–20 year) goals at this time.

Roadmap Organization

This roadmap is intended to communicate to an audience that is technically acquainted with this issue. The sections build upon each other to provide a framework and justification for the proposed research and development.

Section 1 states the issue to be addressed. *Section 2: Public Interest Vision* provides an overview of research needs in this area and discusses how PIER plans to address those needs. *Section 3: Background* establishes the context of PIER's work to address fish passage and entrainment issues. *Section 4: Current Research Needs* surveys current fish passage and entrainment projects and identifies specific research needs that are not already being addressed by those projects. *Section 5: Goals* outlines proposed PIER Environmental Area (PIER-EA) activities that will meet those needs. *Section 6: Leveraging R&D Investments* identifies methods and opportunities to help ensure that the investment of research funds will achieve the greatest public benefits. *Section 7: Areas Not Addressed by this Roadmap* identifies areas related to fish passage and entrainment research that the proposed activities do not address.

1. Issue Statement

There is a need to improve our understanding of hydropower generation's effects on the health and stability of California's freshwater ecosystems, as well as to develop cost-effective assessment and mitigation methods that maximize environmental protection and minimize unnecessary curtailment of hydropower generation.

2. Public Interest Vision

The primary mission of the California Energy Commission's Public Interest Energy Research (PIER) program is to conduct research that helps deliver "...environmentally sound, safe, reliable, and affordable electricity..." to California citizens. The mission of PIER's Environmental Area (PIER-EA) is to develop cost-effective approaches to evaluating and resolving environmental effects of energy production, delivery, and use in California, and explore how new electricity applications and products can solve environmental problems.

The PIER Environmental Area Research Plan: Environmental Context and Key Environmental Issues (California Energy Commission 2001) identified hydropower generation's impacts on the natural ecological and hydrological functions of California's aquatic systems as a high priority for research. That effort separated the effects of hydropower generation on California's freshwater ecosystems into three issues: (1) water quality, (2) fish passage, and (3) instream flows. The aim of these three roadmaps is to summarize current research and identify research needs on these issues with the ultimate aim of supporting the development and application of cost-effective methods and technologies for reducing and resolving the negative effects of hydroelectric generation on California's freshwater ecosystems. In addition, this research program is designed to help maintain hydropower's role in California's electricity system, by minimizing unnecessary curtailment of hydropower generation attributable to a lack of scientific understanding or the unavailability of suitable mitigation measures.

This roadmap focuses on fish passage issues related to hydropower generation within California. Hydroelectric power plants and associated dams have contributed significantly to the drastic alteration of California's freshwater ecosystems, and to the corresponding precipitous decline of many of California's inland fisheries. Specifically, hydropower development within the state has led to the destruction and fragmentation of habitat, introduction of exotic species and blockage of migratory fish patterns.

Fish passage issues have received increased attention in recent years, because many of the anadromous fish species in California and elsewhere in the western United States have received, or are being considered for, protection under the Federal Endangered Species Act.

As described in the following section, numerous researchers nationwide have documented a variety of approaches to providing fish passage, with an emphasis on downstream fish passage (Office of Technology Assessment 1995). In California, there has been little research on addressing fish passage needs at hydropower facilities. Now, however, there is a growing recognition that many of California's fisheries are seriously threatened. In fact, it is estimated that 58% of California's freshwater fish species are extinct or are in serious decline (Moyle 2002). Therefore, fish passage issues are becoming even more important. In the near future, additional fish species may also be identified as threatened or endangered, which will force hydropower operators to confront fish passage issues for species they have not addressed before.

Therefore, this roadmap identifies a suite of research opportunities to develop new or enhance existing methods and tools to facilitate fish passage up and downstream past hydroelectric power plants. These research goals focus on several aspects of fish passage needs within California, including:

- development of protocols and guidelines to facilitate fish passage information gathering and monitoring efforts;
- assessment of the fish passage capabilities of new approaches to physical and behavioral barriers to fish during hydropower operation;
- evaluate feasibility and costs associated with fish passage at high dams; and
- evaluate the need for fish passage for non-salmonid anadromous and riverine species, to identify target species and design suitable fish passage facilities for those species that need such facilities.

The recommendations developed for this roadmap are intended to yield products and techniques that enhance fish passage directly, where it is needed; and to provide a foundation for future research and monitoring.

Overall, Californians will benefit from this program through a better balance of resource protection and electricity generation. In particular, this program offers an opportunity to reduce fish losses by facilitating passage and access to additional habitat. In addition, the program presents an opportunity to reduce cost and permitting efforts for operators, agency staff, and other stakeholders, as well as an opportunity to increase consistency and regulatory certainty. California's rich freshwater fishery is a public resource used and enjoyed by millions of residents and visitors, and a vital component in some rural California economies. Healthier and more plentiful freshwater fish and fish habitats would help ensure the stability of that resource. This work would also facilitate industry compliance with state and federal laws designed to protect aquatic resources. Industry and stakeholder participation in the research identified herein would also promote partnerships and cooperation towards solving water quality issues associated with hydropower generation.

3. Background

The term *fish passage*, as used in this roadmap, refers to efforts to facilitate the movement of fish up or downstream past hydroelectric plants, dams, and other obstacles. Although much of this discussion focuses on fish passage technologies, the migratory and swimming behavior and the habitat requirements of the fish species of concern are equally important (Odeh 1999; Clay 1995). Sufficient flows to both attract and sustain fish in their up or downstream passage past hydropower facilities are a basic necessity for successful fish passage; however, PIER is addressing instream flow issues in a separate roadmap (Sale et al. 1991, Sale et al. 1997).

The following sections describe California's hydropower generation sector, discuss why fish passage is a significant concern, and outline upstream and downstream fish passage technologies.

3.1 Hydropower in California

3.1.1 The Role of Hydropower in California's Electricity System

Hydropower is an important component of California's electricity system, representing about 27% of the state's total installed generation capacity. Actual hydropower generation, however, varies greatly in response to hydrologic factors. Between 1990 and 2000, hydropower actually contributed from 9% to 25% of the in-state supply, as a result of annual variations in runoff. In

2001, a drought year, hydropower represented only 10% of the total in-state generation. Over an 18-year period between 1983 and 2001, hydropower represented just over 15% of electricity used within the state, including imports.

The ability to dispatch hydropower on short notice is perhaps an even greater benefit to the state's electrical system than its contribution to the state's overall installed capacity. Unlike many other generation sectors, hydropower units can start up and meet capacity load in a matter of minutes, as well as provide spinning reserve to meet transmission line voltage requirements. Although drought years will reduce overall hydropower production, hydropower continues to play an important role in helping the state meet peak demand. In addition, hydropower plants are highly reliable, generally being available in excess of 90% (EPRI 2001). Although only limited information was available, EPRI (2001) found that the average capacity factor for California facilities was 52%, reflecting both equipment (e.g., outages) and flow limitations. Hydropower also contributes to the state's electricity system by providing low-cost energy. Many hydropower facilities in the state produce electricity at less than 2 cents per kilowatt-hour (kWh).

3.1.2 Distribution of Hydropower Facilities

Hydropower generation takes place on all of the major rivers systems within California. The vast majority of hydropower generation within the state, however, comes from hydropower plants on the thirteen rivers (and their tributaries) that flow into the Sacramento and San Joaquin Rivers and the Tulare Lake Basin (California Energy Commission 2003). Almost 58% of the state's installed hydropower capacity is found within the Sacramento River watershed; almost 41% of the installed capacity is found within the San Joaquin River watershed. Hydropower development on streams and rivers that discharge to the Tulare Lake Basin make up most of the remaining capacity. Although the vast majority of hydropower generation is found within the watershed of California's Central Valley, hydropower plants that can affect the state's freshwater ecosystems are found throughout the state.

3.2 Fish Passage Systems

Both upstream and downstream fish passage systems consist of the up and downstream reach of the river, including the immediate entrance and exit of the structure, as well as the fish passage structure itself (Odeh and Haro 2000). The design of a successful fishway must reflect the behavior of the targeted fish, including their preferred flow characteristics—as well as other environmental conditions (Cada 1998).

Historically in California, all of the large reservoirs, such as Shasta or Folsom, were not provided with up or downstream fish passage. Instead, hatcheries were developed to compensate for lost (upstream) spawning and rearing habitat for salmonid species. Because many California salmon runs are listed as endangered or threatened, the provision of fish passage at these facilities may be revisited. Because of a lack of anadromous fish passage above the major multipurpose reservoirs that ring the Central Valley, many of the hydropower facilities located at higher elevations were not provided with fish passage structures. Of those that do provide fish passage, the focus is on facilitating the movement of trout species.

3.2.1 Upstream Fish Passage Technologies

The aim of upstream fish passage is to conduct fish past the hydroelectric facility without injuring or unduly delaying their movement upstream. Therefore, upstream fish passage requires that fish downstream of the hydro facility are attracted to the entrance of the fishway,

induced (either actively or passively) to pass upstream by use of a fishway, and discharged upstream of the facility.

Historically in California, upstream passage has been developed only for salmon and trout species. Only very recently in the western United States has there been interest in fish passage for other species (Weigmann et al. 2001). In some areas, upstream fish passage is undesirable, because it may allow predators, such as smallmouth bass, access to fisheries.

In California, upstream fish passage at hydroelectric facilities is provided almost exclusively through the use of fish ladders (Cada 1997; Sale et al. 1997). Lifts (elevators or locks), pumps, and transportation operations are used only minimally within the state.

3.2.1.1 Fish ladders

Fish ladders (or fishways) are generally flumes or chutes periodically divided by baffles into a graduated series of pools. Water flows between the pools and baffles through vertical slots, submerged orifices, over free-flow weirs, or through a combination of these measures (Clay 1995). The energy of the water flowing from pool to pool is dissipated in turbulence within the pools. The baffles also determine the water elevation drop, flow velocity—and with pool size—local turbulence levels.

Fish ascend the ladder by swimming over the weirs or swimming through orifices within the baffles (Office of Technology Assessment 1995; Clay 1995). The fish ladders are generally designed to generate flow conditions that are behaviorally and physically favorable to passage of the target species. For example, chum and pink salmon will not leap, and thus prefer fish ladders with orifices or slots. If behaviorally acceptable flow patterns are not generated, the desired fish passage will not occur.

Fish ladders, if properly designed and operated, appear to be a successful method for providing upstream passage (Office of Technology Assessment 1995). Ladder designs with acceptable flow patterns, velocities, water surface drops, and jump heights have been established for salmonids, but not most other species. Optimum design guidelines for other fish species generally are not available; therefore, laboratory and field studies and validation will be necessary for their development. Fish ladders (e.g., pool-and-weir, Denil, Alaska steeppass (ASP), vertical slot, hybrid) have been designed and modified to accommodate strong, weak, bottom, orifice, and surface swimmers—as well as fish that prefer streaming or plunging flows. Because conventional fish ladder designs have been tested experimentally and operated successfully over time for certain species, they are almost generic.

Proper attraction flows are important to the success of ladders, lifts, and fish passage in general. For adult fish, an important feature of any fish ladder is its attraction flow, which mimics the turbulence and water movement of the river and encourages adults to enter and ascend the ladder (Clay 1995). Improper flows mean that fish cannot find passage entrances and migration or that movements are delayed.

- **Conventional fish ladders or fishways.** Conventional ladders can be classified based on their hydraulic design and function as *pool-and-weir*, *vertical slot*, *roughened channel*, *hybrid*, *mechanical*, and *climbing passes* (Office of Technology Assessment 1995). Conventional ladders have been installed in California only at small hydropower and diversion sites (e.g., Red Bluff Diversion Dam on the Sacramento River and the Potter

Valley Dam on the Eel River). As noted above, these fish ladder types have been operated successfully over time.

Natural fishways are constructed to mimic natural channels and flows. Instead of using concrete baffled chutes like conventional ladders, these ladders are built with earth, rock (e.g., rock-ramp fishways), and/or timber to create pools for resting and controlling drops and energy dissipation). Entrance, fishway, and exit design requirements are similar to those for conventional fishways. The gradient of natural fishways tends to be flatter than other fishway types. This low gradient requirement results in long fish ladders that are likely unsuitable for high dam sites, but also may provide options for weaker-swimming riverine species.

Nature-like fishways are more common in Australia (Harris et al. 1998) and Europe (Mader et al. 1998; Parasiewicz et al. 1998; Steiner 1998; Gebler 1998) than in the United States. Some researchers feel that the use of nature-like fishways is constrained by a lack of adequate design guidelines. Specifically, the flow mechanics in these fishways are poorly understood.

In California, a several-thousand-foot-long natural fishway has been considered by the U.S. Bureau of Reclamation (Reclamation) at Red Bluff Diversion Dam on the Sacramento River, to support sturgeon and salmon passage around the dam. Two natural fishways are also being considered for the Farad Dam on the Truckee River in California.

3.2.1.2 Trap-and-lift/haul upstream fish transportation systems

Fish lifts, including elevators and locks, are employed for species that do not use ladders, or at sites where vertical passage heights are excessive. Fish lifts can move fish vertically over high-head dams, greatly reducing physical demands on fish for passage. They have the potential to allow for upstream passage of non-anadromous native fish species that otherwise are not strong enough swimmers to pass through steep, high-flow ladders at high-head dams.

Trap-and-truck operations have been used successfully for moving adults upstream of long reservoirs in which migrants could become lost or disoriented, and in offering interim passage until construction of ladders or lifts is completed. Transportation or lift may be the only feasible passage method at high-head dams. The success of trap and truck techniques hinges on the availability of good methods for collecting and handling fish. Fish separation techniques may be needed to prevent trapping and transport of non-target species. A potential benefit of trap-and-lift/haul upstream fish passages is that they require much less flow than traditional ladders, and may be especially helpful during low-flow periods in California's highly variable hydrologic regime.

- **Applications of trap-and-lift/haul systems in California.** Trap-and-lift/haul operations have been conducted in California at Keswick Dam on the Sacramento River by the U.S. Bureau of Reclamation (David Poore, 2002, pers. comm.) This hydropower facility is the only one in California that uses this technology, but it is used at various non-hydropower dams in the state.

3.2.1.3 Archimedes and helical pumps

Pumps (particularly Archimedes and helical designs) effectively lift fish with minimal injury and mortality (Helfrich et al. 2000; McNabb et al. 2000). Primarily, they have been used to support

fish exclusion bypass operations and management at aquaculture facilities. Injury potential and possible vertical lift are functions of pump design, size, and rotational speed. Based on known technology, the maximum injury-free lift that could be supplied by pumps is about 33 feet. Fish avoid entering pumps, so intake designs must yield effective collection and passage without avoidance and delay. The Archimedes pumps generate intake velocities that juvenile salmonids cannot hold against, thus preventing passage delays (Week et al. 1989).

The Bureau of Reclamation is undertaking an extensive experimental program using helical and Archimedes pumps at the Red Bluff Diversion dam. This program aims to determine the extent of injury and/or mortality to juvenile Chinook salmon passing through these pumps. Testing results indicate that pump passage is a minimal source of mortality.

Fish released to the riverine environment can be disoriented, making them more susceptible to predation, which is one reason resource agencies prefer fishways, which allow fish to move of their own volition.

3.2.2 Downstream Fish Passage Technologies

There are three aspects to successful downstream fish passage: (1) moving fish safely downstream past dams, (2) preventing or reducing fish entrainment in turbine intakes, and (3) reducing fish migration times—especially through reservoirs (Office of Technology Assessment 1995). Although the first two aims are closely related and applicable to all hydro facilities where fish passage is desired, the third aspect is mainly applicable to facilities with large reservoirs. In comparison to upstream passage, a wide range of approaches to downstream fish passage is available (Office of Technology Assessment 1995, Coutant and Whitney 2000). Nonetheless, no single downstream passage technology is appropriate for all sites and situations. This may explain why most of the research and development conducted in the last 20 years has focused on downstream fish passage issues.

The first aim of downstream fish passage is to conduct downstream-migrating fish safely past dams and other obstacles. The focus in California is to ensure the movement of juveniles of the different anadromous salmon species from tributaries and major streams and rivers to the ocean. Because many of these species are identified as threatened or endangered by the state or federal government, the goal is to provide 100% passage. In California, when downstream fish passage is provided, it most often incorporates the use of a physical screen to exclude fish from the penstock (see description later in this section).

Two factors in particular contribute to further fish mortality at the power house and below the dam. First, fish may be killed, injured or disorientated as a result of turbulence, pressure changes, and/or other stresses. Mortality or injury is especially associated with fish that pass through the turbines (see discussion below). The second factor is known as *gas bubble disease*, which results from the supersaturation of nitrogen and other gases when water is spilled over a dam or passed through outlets. Nitrogen bubbles can form within the blood and tissue of fish found in this supersaturated water. This condition may adversely affect swimming performance and can result in death. In the Pacific Northwest, gas bubble disease is considered one of the contributing factors to anadromous salmon decline. In California, however, the authors are not aware of any fish kills attributable to gas bubble disease.

The second aim of downstream fish passage is to prevent the passage of fish through the hydropower turbines. For dams without downstream passage, every fish moving downstream must pass through either the turbines or the spillways. Passage through the turbine subjects the

fish to a variety of pressure changes, stresses and direct contact—potentially leading to injury or death. The level of fish mortality attributable to entrainment is influenced by the type and size of the turbine, turbine revolutions, head, environmental conditions, and mode of operation—as well as the size, life-stage, and physiological condition of the entrained fish (EPRI 1987; Cada 2001).

In recent years, a vast amount of research has been conducted on the specific sources of injury and mortality to fish that pass through hydroturbines. Summaries of this research are contained in Cada 1990b, 2001; Cada et al. 1997.

Overall, the mechanisms causing injury or death to fish that pass through turbines include:

- rapid and extreme pressure changes,
- cavitation of vapor bubbles in the water,
- shear stresses,
- turbulence,
- collision with turbine parts, and
- grinding fish between fixed and moving parts.

Fish may also become disoriented after turbine passage. Mesa (1992) as well as others have documented the effects of disorientation leading to increased susceptibility to predation after passage through the draft tube and tailrace (the final portions of turbine system), where large-scale turbulence occurs.

Entrainment mortality rates vary greatly from facility to facility, with mortality rates ranging from 0% to 100% (Bell et al. 1967; EPRI 1987; Cada 2001). Overviews of past studies of general turbine-related fish mortality are provided by EPRI (1987, 1992); Cada (2001); and Whitney et al. (1997). EPRI (1987, 1992) reported that turbine model studies emphasized the important influences of tailwater elevation, cavitation, wicket gate opening, and relative speed at which fish strike turbine blades. The only clear linkage EPRI (1987) found with mortality seems to be that of peripheral runner speed in the case of Francis turbines. Research conducted by Fish and Roth (1995) studied how turbine design and the range of head and flow at a power plant affect fish survival. Of the different hydropower turbines in use, most research on turbine passage focuses on Kaplan turbines. This turbine type is most common in the very large hydropower plants in California. For example, just about every Bureau of Reclamation powerhouse in California uses Kaplan turbines. Smaller hydropower facilities in California use either Pelton or Francis turbines. Although survival after turbine passage through one hydropower facility may be slightly reduced, passage through multiple facilities has a cumulative effect, and can result in a large decrease in survival rates (Cada 1990b,c).

The species, size, life-stage, and physiological condition of the entrained fish also strongly influence entrainment survival (EPRI 1987; Cada 2001). Nietzel et al. (2000) found that of fish entering a shear environment, American shad were the most susceptible to injury; whereas, steelhead and rainbow trout were the most resistant. In addition, smaller fish suffer relatively lower mortality rates, apparently better able to avoid direct contact with turbine blades (Coutant and Whitney 2000). The physiological condition of the fish also greatly influences entrainment survival (EPRI 1987). This influence became apparent during a number of entrainment tests, where handling and transportation of the sample fish strongly affected test results.

Entrainment survival rates are influenced by fish behavior, certainly species-related, but also often on a life-stage, diel, and/or seasonal basis. Coutant and Whitney (2000) provide a useful literature review of published literature on factors affecting fish behavior near or during passage

through the turbines. Such factors include orientation to flow in the forebay and entrance to the turbine, surface orientation in the forebay, and distribution in the intake.

In California, entrainment studies are normally required as a part of the studies mandated for the FERC relicensing process. Such studies normally collect dead fish below the dam and sample fish populations above and below the dam to estimate entrainment mortality and determine population effects, if any. Sampling protocols are determined by site-specific condition. For example, for the Upper American River Project, the Sacramento Municipal Utility District (SMUD) is developing separate entrainment study protocols based upon the depth of the intake. Such studies focus on determining actual entrainment mortality, not mortality rates. Methods of estimating entrainment include netting, hydroacoustic technology, and telemetry counters (EPRI 1987; 1992). The success of such approaches is often dictated by site-specific conditions. Information on entrainment rates and sophisticated population are not usually developed. Mitigation for entrainment impacts generally focuses on physical barrier screens as a method for excluding fish from turbine intakes.

Knowledge about mechanisms causing fish injury and mortality has increased more rapidly in recent years, in large part because of recent endangered fish listings on various stretches of major rivers. This research is discussed in greater detail in Section 4.6.4.

Downstream fish passage technology can be grouped into one of four categories, based upon their mode of action: (1) physical barriers, (2) diversion or structural guidance systems, (3) behavioral guidance devices, and (4) collection systems. The most widely accepted technologies for fish exclusion and guidance are structural methods such as screens (which physically exclude fish from turbine entrainment) and angled bar racks and louvers (which may alter flow patterns and rely on fish behavior for exclusion). Table 1 shows the technologies that are in use in California and elsewhere, and identifies those that are considered experimental.

Physical barrier screening techniques (e.g., drum, traveling, and fixed screens) with bypasses for downstream passage are the most accepted by state and federal agencies for hydroelectric facilities in California and can reduce entrainment in turbines and water intake structures. In comparison, the most common bypass system in the Columbia River system uses submerged traveling and profile wire screens to remove juvenile salmonids from deep turbine intakes (Mighetto and Ebel 1994). Because the focus of downstream fish passage in California is on protecting threatened or endangered species—predominately anadromous ones—physical barrier screens that offer higher passage efficiencies than other approaches are the only readily acceptable fish passage technology within the state. Physical barrier screens are expensive, with initial capital costs easily exceeding \$25.00 per cubic foot per second (cfs) of flow.

Although a wide variety of approaches to downstream fish passage have been developed, physical barrier screens are the only technologies that offer the promise of 100% passage effectiveness, which makes them acceptable to California resource agencies. A major driver behind the evaluation of alternative downstream passage technologies is the high cost of physical barrier screens.

3.2.2.1 Physical barrier screens

Physical barrier screens are devices installed at hydroelectric facilities and other dams to physically preclude passage of fish without injury to the fish. Bypasses are generally provided in conjunction with the screen, to guide the fish around the dam. A variety of screen types are

available; the following discussion reviews those commonly used or that hold promise for use at hydroelectric facilities.

Table 1. Downstream Fish Passage Technologies: Status and Use

Downstream Passage Technology	In Use In California	In Use Elsewhere	Considered Experimental
Physical Barrier Devices			
Drum screen	X	X	
Traveling screen (submersible; vertical)	X	X	
Fixed screen (simple; inclined)	X	X	
Turbine intake (gate well) screen	X	X	
Eicher screen		X	X
Modular inclined screen			X
Barrier net		X	X
Coanda screen		X	X
Structural Guidance Devices			
Angled bar/trash rack		X	
Louver array		X	
Surface collector		X	X
Alternative Behavioral Guidance Devices			
Acoustic array		X	X
Strobe and mercury lights		X	X
Electric field		X	X
Other Methods			
Trapping and trucking	X	X	X
Pumping		X	X
Spilling	X	X	X
Barging	X	X	X
Turbine passage	X	X	

Source: Modified from Office of Technology Assessment (1995).

The primary design consideration for physical barrier screens is that the water must have low velocities through (known as *approach velocity*) and across (known as *sweeping velocity*) the screen, to avoid fish injury. The swimming ability of the target fish will determine the acceptable velocity. Uniform through-screen flow velocities are desirable, because under non-uniform conditions, high-velocity localized areas increase the potential for fish injury and debris accumulation.

In California, the National Marine Fisheries Service (1997) provides screening criteria for anadromous salmon species, and the California Department of Fish and Game (2000) recommends screening criteria for all diversions. These criteria specify acceptable approach and sweeping velocities, screen material, mesh size, and maintenance (cleaning) requirements. To ensure that low approach velocities are met, physical barrier screens are generally large, increasing capital and operating costs.

Physical barrier screens designed and installed in the last 20 years in the Pacific Northwest and California have achieved nearly 100% guidance efficiency (EPRI 1994a, 1999; DOE 1988). They require operation, maintenance, and potentially frequent cleaning, depending on the debris load. Wahl and Einhellig (2000) and Allen et al. (1996) report on numerical models for predicting flow rates through fish screens.

Physical barrier screens are expensive to anchor and install and are affected by flow variations. A review by the Washington Department of Fish and Wildlife (2002) of physical barrier screen costs for a large range of water diversions (most installed in the last few years) greatly exceeded \$4,000 per cfs.

- **Fixed flat-plate screens (diagonal and “V” configurations).** Fixed flat-plate screens consist of a series of flat panels, set between support beams, and placed at an angle to the approach flow. The screen may have a single face or converging faces that form a “V”. A continuous smooth face is maintained along the screen length to minimize obstacles to fish passage and simplify its cleaning.

The screens are set at an angle to the flow, to reduce hydraulic forces that could impinge fish and to establish a sweeping or tangential flow that guides fish along the screen length to the bypass (EPRI 1986, 1994a,b, 1999).

Flat-plate screens are effective barriers that can be designed to exclude specific fish species and sizes. The screen itself has no moving parts, which simplifies the screen support structure and reduces costs. Fish guidance and debris shedding (when the passing flow sweeps debris off the screen) are more efficient at flatter screen angles; therefore, generally angles range from 15 degrees to parallel to flow.

Examples of fixed flat-plate screens on hydropower facilities in California include Beaver Creek Diversion on the North Fork Stanislaus River Hydroelectric Development Project (Northern California Power Agency, maximum flow rate 400 cfs), and the Kilarc-Cow Creek Project on South Cow Creek (Pacific Gas & Electric, maximum flow rate 50 cfs).

- **Turbine intake (gate well) screens.** Turbine intake screens are used at large hydropower facilities on the Columbia and Snake River system (EPRI 1986, 1994a, 1999; Bell 1991). The screen, placed in the turbine intake, intercepts and screens only the upper portion of the intake; therefore, they are most appropriately applied at sites with large intakes where entrained fish are concentrated in the upper portion of the intake.

At sites where the intake screens are the most effective, screens intercept over 75% of smolts entrained by the intake. When fish are not concentrated near the surface, or where entrance flow patterns guide fish below the screens, efficiencies can be less than 30% (INCA Engineers 1999). Intercepted fish are bypassed or transported around the dam. There are no intake (gate well) screen installations in California.

- **Drum screens.** Drum screens—screen-covered cylindrical frames—are placed in the flow with the cylinder axis oriented horizontally (EPRI 1986, 1994a, 1999; Bell 1991). A screen installation can consist of one or a series of cylinders placed end-to-end across the flow section. Seals are placed between the screen and bottom and end surfaces (pier sides or walls). Seal maintenance is a significant operation and maintenance demand. Each installed drum slowly rotates about its axis and operates 65% to 85% submerged. This submergence and rotation allows debris to be carried over the top of the drum and removed by the through flow. Drum screens have excellent debris handling and self-cleaning characteristics; rarely needing supplemental cleaning.

Specific submergence requirements for effective operation limit drum screen use to sites with well-regulated and stable water levels, restricting their use to canal and reservoir sites with no seasonal drawdown. Modern drum screen installations place the drum line at an angle across the flow so fish encounter a continuous, fairly smooth screen facility face. Fish tend to swim along the screen face, influenced by the passing flow, and are guided to bypasses. Through-screen velocities and other design criteria are applied similarly to fixed flat-plate screens.

Research identified no hydropower facilities with drum screens in California. An example of a drum screen on an irrigation installation in California is Reclamation's Tehama-Colusa Canal, with a maximum flow rate of 3,060 cfs.

- **Fixed inclined screens.** Fixed inclined screens consist of non-moving flat plate panels placed on an adverse slope. The full screen surface is submerged so the entire surface is used, even under shallow flow applications. The flow uniformly passes through the screen and sweeps over the length of the screen, guiding fish across the screen surface to a terminal bypass (Locher et al. 1993).

Facilities using these screens have flow-resistant backing behind the screens that generates uniform through-screen velocities, and the screens include cleaning systems (Ott and Jarrett 1992). Although this screen is not commonly used for fish exclusion at hydroelectric sites, the Potter Valley Project on California's Eel River uses a fixed inclined screen.

- **Coanda/inclined screens.** The Coanda screen design uses a concave arc or flat plate panel consisting of wedge wire (Strong and Ott 1988; Bestgen et al. 2001; Wahl 2001). Coanda screens are installed on downstream faces of overflow weirs. Flow passes over the crest of the weir, across a solid acceleration plate, and across and through the screen panel. Flow passing through the screen is collected in a conveyance channel below the screen, while the overflow containing fish and debris passes off the downstream end of the screen. Flow velocities across the face of the screen are highly variable, and are a function of the drop height from the upstream pool to the start of the screen (Wahl 2001). Sufficient flow depths must be maintained over the end of the screen to prevent excessive fish contact with the screen surface.

Flow depths across the screen are shallow, which increases fish exposure to the screen surface. These screens typically require a head drop of several feet. Coanda screens have high flow-handling capacities for their size, are essentially self-cleaning, and have the ability to exclude very fine debris and small aquatic organisms.

Fish impingement on Coanda/inclined screens appears to be a minor concern, compared to impacts from traditional screens, because the sweeping velocity carries fish off the screen immediately. However, because of the high velocities across the screen surface and shallow flow, fish injury and mortality is a concern.

Installations of this screen in California are likely limited to small hydropower facilities (Strong and Ott 1988). Coanda screens are used in California at the Panther Ranch Hydroelectric Project in Shasta County (maximum flow rate 4 cfs); Bear Creek Hydroelectric Project in Shasta County (maximum flow rate 70 cfs); Montgomery Creek

Project in Shasta County (maximum flow rate 120 cfs); and Bluford Creek Hydroelectric Project in Trinity County (maximum flow rate 30 cfs).

Limited biological evaluations have been conducted on the Coanda screen (Buell 2000), and it is not yet considered acceptable for anadromous fisheries in California.

- **Submerged fixed cylindrical screens.** Submerged fixed cylindrical screens (EPRI 1986, 1994a, 1999) incorporate screen concepts that include fully submerged screen modules at the end of turbine flow supply conduits. Designs may include single or multiple screen modules, which allow diversion of larger flow rates (e.g., 120 cfs or more). The fixed screens are fully submerged. Screen-excluded fish remain free-swimming and are not entrained in a structure or converging screen section requiring a bypass. Backflushing (i.e., reversing flows through the screen surface) is generally used for cleaning.

Although more widely used for screening irrigation and process water deliveries, fixed cylindrical screens are used at small hydropower facilities. Because of their use at irrigation and process water intakes, data on their effects on several fish species and developmental stages are available (i.e., screens have been developed to effectively exclude fish eggs and larvae).

These screens are likely applicable only at small hydropower facilities and have been used in California at the Arbuckle Mountain Hydroelectric Project on the Middle Fork of Cottonwood Creek ([maximum flow rate 115 cfs] Ott et al. 1988).

- **Vertical traveling screens.** Vertical traveling screens are mechanical screens composed of panels connected to form a continuous belt (EPRI 1986, 1994a, 1999). The screens function whether stationary, rotating, or traveling. Rotation is required for cleaning. When rotating, the screen moves up on the leading face and down on the back. Supplemental components include cleaning and debris handling equipment and an internal baffle to generate uniform through-screen velocities.

Traveling screen installations are more expensive than other screens and require more maintenance. They function well at sites with severe debris problems. Because of the relatively high costs of these screens, they would likely only be used at larger facilities. No California hydropower facilities use vertical traveling screens.

3.2.2.2 Structural guidance devices

- **Angled bar or trash racks and louvers.** Angled bar or trash racks and louvers consist of arrays of vertical slats placed on a diagonal across a flow field (Bates and Vinsonhaler 1956). Spacing between slats is larger than the width of the fish to be excluded. Thus, they exclude not by creating an absolute barrier to passage, but by generating flow turbulence created by the louver spacing, which fish avoid. Fish maintain position off the rack or louver surface as the passing flow (caused by angled louver placement) guides them along the line to bypasses. Fish response to this flow, however, can vary with species, life stage, and swimming ability (EPRI 1986, 1994a, 1999). Skinner (1974) and Vogel et al. (1991) measured exclusion efficiencies from greater than 90% for juvenile Chinook salmon, striped bass, and white catfish.

Closely spaced bar racks have the potential for fish impingement, particularly for those fish with compressed body shapes or weak swimming ability (EPRI 1994a). Studies

have evaluated louver efficiencies as a function of design parameters, but a specific louver design has rarely been developed for a specific fishery.

EPRI (2001) conducted studies on the use of angled bar rack and louver laboratory for guiding fish (small- and largemouth bass, golden shiners, walleye, channel catfish, shortnose and lake sturgeon, and silver-phase American eels) at water intakes. Angled bar racks and louvers are not used at hydroelectric facilities in California, and because they are not absolute fish-exclusion barriers, it is unlikely that regulatory agencies will accept their use at sites where species are listed as endangered or threatened.

3.2.2.3 Other methods for providing downstream passage

- **Transportation.** Transporting migrating juvenile salmon downstream around dams in trucks or barges reduces the loss of fish in long reservoirs, decreases turbine entrainment, and reduces potential predation at multiple dams and reservoirs. Transportation during low flow periods can significantly reduce the time that juveniles move through the system.

In California, collection and bypass operations have been conducted at sites where migrating juveniles may be stranded. Such operations consist of trapping and then transporting (trucking) the juveniles downstream below the dam. Typically, this strategy is employed during low-flow conditions, such as those at the San Clemente and Los Padres Dams on the Carmel River, but it is used also for facilities without downstream passage, such as on the Shasta River.

- **Spilling.** One option for constructing structures specifically for downstream passage is to operate spillways so fish will locate the spillway and use it instead of the turbines. Because juvenile salmonids concentrate at shallower depths in reservoirs, if spillway releases draw water from near the surface, juveniles will likely pass through the spillway instead of diving to deep turbine intakes (Ransom et al. 1996).

Passing juveniles downstream by spilling is commonly used in the Columbia River Basin. The Army Corps of Engineers and regulatory agencies in the Northwest consider spilling as one of the safest options for moving fish past dams instead of through turbines, but it can result in gas bubble trauma or injuries induced by pressure.

In the Columbia and Snake rivers, flow rates are large and stilling basins are typically not baffled; but at California sites, higher energy and smaller volume stilling basins are more common. Therefore, high-head California dams have an increased potential for fish injury and mortality during spill.

- **Sluicing.** Another downstream passage option similar to spill is to use the dam's ice, debris, and sediment sluice structures for passage. Sluiceways may not be available on the large, high dam facilities in California.

3.2.3 Experimental Downstream Passage Technologies

There is a recognized need for improved downstream passage technologies that are: less expensive to design, install, operate, and maintain; easy to retrofit into existing facilities; and water conserving. Methods under investigation include: improved performance of existing technologies (e.g., surface collectors); development of physical barrier approaches and

behavioral guidance techniques; use of fish-friendly pumps and turbines; and changing generation procedures to reduce risk to fish.

3.2.3.1 Archimedes and helical pumps

As discussed in the Upstream Passage section, pumps (particularly Archimedes and helical designs) lift fish with minimal injury and little mortality (Stone & Webster Engineering Corporation 1977, 1979; Frizell et al. 1996; Week et al. 1989; Helfrich et al. 2000; McNabb et al. 2000). Pumps have been used in conjunction with fish exclusion to return collected fish to natural channels at sites where available water surface elevation or flow conditions are insufficient for effective gravity flow.

Injury potential is a function of pump design, size, and rotational speed. Pumping fish can cause descaling and injury as they travel through the pump and bypass pipe. Fish released to the river can be disoriented, making them more susceptible to predation. Regulatory agencies, such as the National Marine Fisheries Service prefer gravity bypasses, which allow fish to choose whether or not to move. As noted above, Reclamation is conducting extensive studies of helical and Archimedes pumps at the Red Bluff diversion dam.

3.2.3.2 Surface collector technology

Surface collection technology generally consists of floating- or fixed-box conduits to bypass fish around penstocks. These surface collectors are positioned close to turbine or penstock intakes to attract emigrating anadromous juveniles and take advantage of their natural orientation to shallow depths (Giorgi et al. 1999). The fish travel through a bypass conduit to an outfall and into tailrace locations where predation potential is considered low (National Marine Fisheries Service 1995a,b; Johnson, Giorgi et al. 1999). This location may be several thousand feet downstream of large dams. Delay of juveniles in the forebay increases overall migration time, vulnerability to entrainment by turbines, and predation potential.

A concept to guide fish and increase the opportunity for them to locate entrances to surface collector systems is a “trail of turbulence” (Coutant 1998) or turbulent attractant flows (Coutant 2001) in quiescent dam forebays (see Section 3.2.4 on Alternative Behavioral Guidance Methods). This concept has merit, but little is understood about juveniles’ responses to turbulence. Another concept being examined in California at Whiskeytown and Lewistown reservoirs is the possibility of using temperature control curtain technology for smolt surface collection and in-reservoir transfer/passage systems (Vermeyen 2000).

3.2.3.3 High-velocity screens

Most of the screen technologies discussed above rely on a low approach velocity, requiring a large screen surface area. Eicher and modular inclined screens (MIS) are high-velocity screens operating at 8 to 10 feet/second, although velocities of about 6 feet/second are typical (EPRI 1994a,b; 1999). They include a flat screen panel placed on a diagonal within a circular or rectangular cross-sectional conduit. The screen is installed directly in the turbine flow supplying penstock. The screen panel is supported by a pivot-beam that runs across the panel at midsection. As with other concepts associated with angled screen placement, the flow approaching and passing the screen guides fish across the screen surface and to a bypass (Winchell 1990). These screens have been developed through extensive laboratory testing with a variety of fish species, followed by prototype development and field evaluation. These technologies have been successful in guiding certain types and sizes of fish under a range of high-velocity conditions. These screens collect fish only when water is flowing over them (during

power operations) and will not support fish passage when reservoirs are filling and power operations are not occurring.

Approach velocities for this type of screen typically exceed resource agency velocity criteria. Such velocities tend to increase the potential for fish injury. However fish exposure time to the screens is often less than 10 seconds, which minimizes the potential for fish contact. Field and laboratory studies have shown that high survival and low injury rates can be achieved for some fish species and life stages (Winchell and Sullivan 1991; EPRI 1992; Smith 1993, 1997; Amaral et al. 1999).

Pivoting the screen panel about the support beam to a position that generates a backflushing flow cleans the screens. Backflushing may be initiated periodically as part of a routine cleaning operation or may be initiated by monitored pressure drop across the screen. The cleaning operation does not interrupt power generation.

Few high-velocity screen facilities have been developed (EPRI 1992, 1994b; Smith 1993, 1997; Cramer 1997); therefore, operation and maintenance experience with such facilities is limited. Major concerns associated with use of high-velocity screens are descaling from screen contact and impingement. Amaral et al. (1999) states that evaluations for Eicher screens and MIS demonstrate descaling and impingement are less than 5% for most species tested. No high-velocity screen facilities are installed in California.

3.2.3.4 Barrier nets

Barrier nets prevent fish entrainment and impingement at water intakes and work best under low approach velocities, light debris loading, and minimal water action. Net installations are sized to yield low through-net velocities, minimizing impingement and debris fouling. Because nets are oversized, substantial fouling could occur without compromising performance. On the other hand, debris cleaning and biofouling control can be labor intensive (EPRI 1998).

Nets, as a positive barrier, offer a low capital cost option. Their performance is affected by local hydraulic conditions, fish size, and the size and type of mesh used. Barrier nets have been documented to be 100% effective in excluding fish; however, efficiencies generally range from 70% to 100% (EPRI 1986, 1994b, 1999; Guilfoos 1995). Barrier nets do not work well for preventing entrainment of very small fish, where some passage of fish is required, when there is a high debris load, or where icing is a problem.

The authors did not identify any hydropower facilities that use barrier nets to exclude fish in California. Most current barrier net applications are for seasonal use. In California, however, any such application would likely need to be a year-round use, which would make maintenance difficult.

3.2.4 Alternative Behavioral Guidance Methods

Behavioral guidance technologies employ sensory stimuli to elicit behaviors that result in a fish avoiding or swimming away from areas where injury or mortality can occur (e.g., a turbine intake) to an area of safety or toward a fishway. Mechanisms that fish use to respond to auditory stimuli are not well understood, and for certain behavioral approaches, study results are not consistent with what is known about the sound capabilities of the fish species. Behavioral technologies can repeatedly elicit startle responses in fish but have not consistently resulted in consistent movement in a desired direction. Such technologies may be insufficient to guide the

downstream migration of juveniles with poor swimming ability to bypasses that are small, compared to intake or river flow.

Use of behavioral devices may offer lower capital and operating cost options and may partially reduce fish entrainment. Behavioral devices may also offer a fish exclusion option at sites that would be otherwise difficult to screen (such as those at penstock entrances that are positioned at great depth in a reservoir).

3.2.4.1 Sound

Sound is directional, rapidly transmitted through water, is unaffected by turbidity and light changes, and is used by fish for general environmental cues. Sand and Karlsen (2000) suggest that fish use frequencies less than 20 Hz (infrasound) to obtain a wide range of environmental information. Fish may also respond to sound produced by structures such as barrier screens and turbines (Anderson et al. 1989; Nestler and Davidson 1995), as well as other swimming fish (Kalmijn 1989). Different species may respond to only narrow ranges of sound, and there may be day/night differences in responses (Ross et al. 1993, 1996). Unfortunately, dam noises and ambient sounds may mask guidance sounds.

Sonic systems have been applied generally in a prototype or developmental mode for fish avoidance and guidance or exclusion at several hydropower facilities outside California.

Various frequency ranges have been examined, but these can be generally grouped into ultrasonic (above 30 kHz), low-mid frequency (50–900 Hz), and infrasonic (<50 Hz).

- **Ultrasound** Most fish are insensitive to ultrasound, and experimental acoustical barriers based on ultrasound have failed (Carlson 1994; Carlson and Popper 1997; Popper and Carlson 1998). However, some fish species can detect ultrasound (Dunning et al. 1992; Nestler et al. 1992; Astrup and Mohl 1993; Mann and Popper 1997). Based on documented avoidance of ultrasound, acoustic barriers using ultrasound have been effective in reducing entrainment of certain *Alosa* species at a specific site (Ross et al. 1993, 1996).
- **Low-mid frequency sound.** A low-mid frequency concept of playing back fish sounds has been tested at water diversion sites on the Sacramento River (Loeffelman et al. 1991). Results from preliminary tests at the Sacramento River site were inconclusive (Darrel Hayes, 2000, pers. comm.). A prototype sonic barrier that demonstrates behavioral device application was installed and evaluated at the confluence of Georgiana Slough and the Sacramento River (San Luis & Delta-Mendota Water Authority and Hanson 1996; Hanson et al. 1997). The concern was that downstream migrating salmon smolts might be attracted into the slough and diverted from a direct path to the ocean. Experiments examined the ability of the sonic barrier to deflect migrating Chinook smolts in the river away from the slough entrance.

Observed fish guidance and exclusion efficiencies were influenced by flow and hydraulic conditions and ranged from 50% to 80% for typical operating conditions. Observed efficiencies, however, dropped to 8% to 15% during flood events. On occasion, damage occurred to the sound barrier system during flood events.

The low-mid frequency concept of playing back fish sounds (Carlson 1994; Carlson and Popper 1997; Popper and Carlson 1998) has been tested as part of the Columbia River

Acoustic Program (sponsored by the U.S. Department of Energy (DOE) and the U.S. Army Corps of Engineers (COE)). Field test results have been inconclusive.

- **Infrasound.** With Atlantic salmon, infrasound was successful in guiding fish in field experiments, and consistent behavioral responses have been observed in laboratory tests. The Columbia River Acoustic Program has tested this technology on Pacific salmon for more than five years. Carlson (1994) and Sand et al. (2001a) reviewed research on infrasound detection and behavioral responses of fish. Sensitivity to infrasound (linear acceleration) in fish is related to the kinetic component (i.e., vibration of water particles in a sound field expressed as particle displacement, velocity, or acceleration) of sound stimulating otolith organs (Sand et al. 2001b). Several investigators have observed flight and avoidance responses at 10 Hz in juvenile Atlantic salmon (Knudsen et al. 1992) and juvenile Chinook salmon (Knudsen et al. 1997; Mueller et al. 1998, 2001) and 12 Hz in descending silver eels (Sand et al. 2000, 2001a)

The effective range of infrasound is estimated to be 4 to 3 meters, according to Carlson and Campana (1996) and Sand et al. (2001b), respectively. Other researchers have not demonstrated flight and avoidance in salmon (Amaral et al. 2001; Ploskey and Johnson 2001) or rainbow and eastern brook trout (Mueller et al. 2001). Atlantic and Pacific salmon habituate when exposed repeatedly to infrasound (Knudsen et al. 1992, 1994; Mueller et al. 2001), reducing infrasound as a potential deterrent for local, but perhaps not migratory, fish (Knudsen et al. 1994). Sand et al. (2001a,b) mention that an improved infrasound device, fitted with electronics that allow phase synchronization of several units, will soon be commercially available.

Experimental applications of sonic barriers have been evaluated at water delivery sites within California on the Sacramento River at Georgiana Slough, Wilkins Slough, and Reclamation District 1004.

3.2.4.2 Light

Light is directional, transmitted rapidly through water and is not masked by noise, but may be affected by turbidity (Anderson et al. 1988). Light is probably most effective when a strong contrast exists between light and background, such as occurs at night. Fish movements and migrations may be affected by behavioral differences to light conditions. Vogel (1989) and Vogel and Marine (1994) found that juvenile Chinook salmon move downstream at night in the Sacramento and Mokelumne rivers in California.

Incandescent (e.g., mercury) and strobe lights have been tested on different species in the laboratory and field. Species may be attracted or repelled by light (Haymes et al. 1984; Feist and Anderson 1991; EPRI 1992; Nemeth and Anderson 1992; Homa et al. 1994; Johnson et al. 1999); Nestler et al. 1995) and responses of species may vary with fish size, development, and physiology (Fernald 1988; Lythgoe 1988) and other factors.

Incandescent and mercury lights have been applied in a prototype or developmental mode at numerous hydropower facilities outside California to attract fish to safe areas or to bypass entrances. Fish guidance objectives, design, ambient conditions, and observed effectiveness varied widely.

- **Strobe lights.** Strobe lights appear to be more effective than mercury lights in eliciting fish responses (EPRI 1994b). Researchers have conducted several laboratory studies

on juvenile salmonid response to strobe lights (Puckett and Anderson 1987; Nemeth and Anderson 1992). In laboratory tests, juvenile Chinook salmon smolts showed moderate to strong avoidance of mercury and strobe lights (Amaral et al. 1998; Ploskey et al. 1998). Migrating juvenile Chinook salmon respond more readily to strobe lights at dusk, at night, or when migrating to deep water (Amaral et al. 1998), and avoid strobe lights during daytime testing at the water surface (Nemeth and Anderson 1992; Ploskey et al. 1998). Maiolie et al. (2001) found strobe lights effectively dispersed Kokanee away from selected areas and had the potential to effectively reduce numbers of Kokanee near turbine intakes. Kokanee in more than 100 m and less than 25 m of water responded similarly to strobe lights. Strobe lights were most effective in winter, with accompanying high water clarity. Lights may increase use of bypasses and serve as enhancements to conventional trash rack measures.

Mueller et al. (1995) tested infrasound and strobe lights on juvenile Chinook salmon and brook and rainbow trout. Mueller et al. (1995) concluded that under clear water and low ambient light conditions, strobe lights would be more effective than infrasound at eliciting more consistent avoidance responses for juvenile Chinook salmon and rainbow trout. Strobe lights have an effective range of about six meters for juvenile Coho salmon under low ambient lighting (Ploskey and Johnson 1998; Ploskey et al. 1998).

Strobe lights have been applied, generally in a prototype or developmental mode, at numerous hydropower facilities outside California. Fish exclusion and guidance objectives, design and ambient conditions, and observed fish responses vary widely.

3.2.4.3 Electrical barriers

Electrical barriers have been used successively and selectively to prevent upstream passage of fish (Verrill and Berry 1995; Swink 1999) and to guide Chinook salmon into traps (Palmisano and Burger 1988). Results on downstream movements are less conclusive (Hilgert 1992; Bengueyfield 1993; Kynard and O'Leary 1993; Swink 1999). Electrical fields have shown mixed success in guiding fish around obstacles, inlets, or channels and into fishways or target areas (Palmisano and Burger 1988; Kynard and O'Leary 1993; Barwick and Miller 1996). Favorable flow conditions and safety of animals and people are important considerations when considering this technology. Electrical fields are most effective in shallow streams and relatively narrow regions where sufficient field strength can be maintained (EPRI 1994b). Electrical barriers have not been used at hydroelectric facilities in California.

3.2.4.4 Curtain-like barriers (bubble curtains, hanging chains, water jets)

Curtain-like barriers are not physical obstructions—instead, fish passage is discouraged through behavioral avoidance. Such behavioral approaches include bubble curtains (created by compressed air), a curtain of hanging chains, and turbulent jet flow curtains (created by water jets). These curtain-like barriers pass debris, thus minimizing maintenance requirements.

Air bubble curtains have met with limited success in guiding or blocking and diverting fish in the laboratory or field (Kuznetsov 1971; Hocutt 1980; Patrick et al. 1985; EPRI 1999). Water jet and hanging chain curtains have been superficially tested and have not shown consistent results (Office of Technology Assessment 1995; EPRI 1999).

3.2.4.5 Turbulent attraction flows

Coutant (1998, 2001) suggests that the missing component for guiding juvenile salmonids toward and through bypasses (especially surface flow bypasses) is turbulence, which would

attract migrating juveniles. Coutant's (2001) proposal to use induced flow and controlled turbulence as attractant flows offers an alternative way to mimic critical fluid dynamics of rivers in dam forebays and bypasses for downstream migrants.

Coutant (2001) encourages further evaluation in the use of integrated, multi-sensory behavioral guidance systems that incorporate repulsion and attraction. He presents a table of sensory mechanisms, technologies, and references to encourage the design of multi-sensory approaches to integrated fish passage systems. For example, strobe lights and air bubble curtains have been examined together as repellants (Patrick et al. 1985; McCauley et al. 1996). Johnson, Goetz et al. (1999, 2000) describe successful fish passage at Lower Granite Dam on the Columbia River, through a combination of spill (50%), screen diversions (34%), and surface bypass over turbines (12%).

3.2.5 Relative Comparison of Downstream Fish Exclusion Guidance and Passage Technology

Table 2 was developed to summarize key performance and application considerations for the downstream passage fish exclusion, guidance, and passage technology. The ratings are relative. Quantified performance (which is typically influenced by specific site characteristics) is available in the literature cited for each concept in discussions above.

Table 2. Relative Comparison of Downstream Fish Passage Technology

DOWNSTREAM PASSAGE TECHNOLOGY	FISH EXCLUSION OR PASSAGE EFFECTIVENESS	MAINTENANCE REQUIREMENTS	PROVEN TECHNOLOGY	CAPITAL COST
Physical Barrier Devices				
Flat plate screens	○	●	○	\$\$\$
Turbine intake screen	●	●	○	\$\$
Drum screen	○	●	○	\$\$\$
Inclined screen	○	●	○	\$\$\$
Coanda screen	○	○	●	\$\$
Cylindrical screen	○	●	○	\$\$\$
Traveling screen	○	●	○	\$\$\$\$
Structural Guidance Devices				
Angled bar/trash rack	●	●	●	\$\$
Louver array	●	●	●	\$\$
Surface collector	●	●	●	\$\$\$\$
Complements to Technology				
Bypass chute	●	○	●	\$\$\$
Sluiceway / Spillway	●	○	●	\$\$\$\$
Alternative Behavioral Guidance Devices				
Acoustic array	●	○	●	\$
Strobe and mercury lights	●	○	●	\$
Electric field	●	○	●	\$
Other Methods				
Trapping and trucking	●	●	●	\$\$\$\$
Barrier nets	●	●	●	\$\$
Collection and barging	●	●	●	\$\$\$\$
Turbine passage	● to ●	○	●	\$

○ GOOD ● FAIR ● POOR See text for an explanation of the ratings.

The following paragraphs discuss the information in Table 2.

Fish exclusion or passage effectiveness – The fish exclusion column indicates the effectiveness of the concept in preventing entrainment of fish with consideration of fish species, size, and life stage. A rating of “good” indicates that the concept, if properly designed, can be expected to exclude all fish for fry stage and larger, independent of species and size. A rating of “fair” indicates that some fish passage will occur with application of the concept and that this passage may be influenced by fish species and fish size (swimming strength and behavior). A rating of “poor” indicates that either substantial fish passage can be expected or that performance is very uncertain and that substantial passage can be expected dependent on species and size.

For fish passage, a rating of “good” indicates that the approach can be expected to collect and pass the majority of the migrating fish with little or no injury. A rating of “fair” indicates that collection and passage efficiencies may be variable and that there is a potential for significant fish injury and

mortality. A rating of “poor” indicates that collection and passage efficiencies may be low or that the potential for fish injury and mortality may be high.

Maintenance requirements – This comparison indicates operation and maintenance demands that can be expected and sensitivity of the concept performance to correct operation and maintenance. A rating of “good” indicates that minimal operation and maintenance is required to sustain performance. A rating of “fair” indicates that routine (daily to weekly) operation and maintenance attention is required. A rating of “poor” indicates that either the concept includes numerous mechanical features that require substantial maintenance, or that operation of the facility is labor intensive.

Proven technology – This comparison indicates the completeness of concept development and application and is a general indicator of the acceptance of the concept by resource agencies. It can be anticipated that if lower-rated concepts are applied at a specific site, detailed field validation of performance may be required. A rating of “good” indicates that the concept has been widely applied and performance well validated. A rating of “fair” indicates that developmental studies and limited field applications have been conducted but that performance has not been evaluated over a wide range of operating conditions and for a wide range of fish species. A rating of “poor” indicates that performance and workability is uncertain.

Capital Cost – Facility costs are strongly influenced by specific site features. Inflationary effects must also be considered in determining current capital costs based on previous facility developments. Scattered documentation of capital costs can be found in the literature, however costs are routinely not published. EPRI 1986 is a general document that includes comparative cost data. A rating of “\$\$\$\$” indicates that costs are high and that the concept likely includes substantial structures with relatively complex mechanical equipment. A rating of “\$\$\$” indicates moderate to high costs and that significant structures are required and that moderately complex mechanical equipment is included. A rating of “\$\$” indicates that moderate costs are involved and that smaller structures with more simplified mechanical equipment are included. A rating of “\$” indicates that costs are minimized, as is the required structure and equipment.

3.2.5.1 Passage monitoring

Methods of monitoring fish movements include mark-recapture (i.e., capturing fish, marking or tagging them, releasing them, and attempting to recapture them) and radio telemetry (i.e., capturing individual fish, tagging them, and following their movements over long distances or through passage structures). For example, juvenile salmonids, implanted with passive integrated transponder (PIT) tags, are monitored remotely after they are released from fish hatcheries or as they pass through specially designed facilities at hydroelectric dams (Peven and Mosey 1999). Modified mark-recapture techniques are promoting more precise estimates of downstream passage mortality (Heisey et al. 1992; Mathur et al. 1996) and spillway and bypass survival (Heisey et al. 1996). These techniques have provided much information on movements, but little understanding as to why fish are moving.

Widely recognized riverine fish movements (Office of Technology Assessment 1995) include dispersal (e.g., passive fry dispersal with flow, active fry or juvenile dispersal mediated by competition, and specialized dispersal with patchy resources); habitat shifts (e.g., microhabitat shifts related to life stage, seasonal movements between summer and winter habitat, and daily movements for resting and feeding); spawning migrations (e.g., movements between lakes and rivers and multidirectional movements when spawning and rearing habitats are dispersed); homing movements (i.e., returning home after displacement by floods or capture and release), and home range movements (e.g., daily movements related to territorial defense and feeding).

Based on monitoring, some fish species appear to move great distances; whereas, others seem somewhat sedentary. However, studies indicate that rather than a species exhibiting such definite patterns of little or great movement, it seems that portions of populations within a species (changing over time and developmental stage) may exhibit great or little movement (Solomon and Templeton 1976; Northcote 1978; Harcup et al. 1984; Heggenes et al. 1991; Hesthagen 1988; McBride 1993; Gowan et al. 1994).

- **Telemetry tagging technologies.** Telemetry allows researchers to track individual fish through passage structures and develop accurate estimates of the passage of representative subsets of marked fish. Radio tags, sonic (acoustic) tags, and PIT tags are telemetry tagging technologies used to study the behavior of fish approaching or swimming near a dam, or using various passage routes through the hydropower facility. Radio transmitters work best on surface-oriented fish swimming in calm freshwater. Sonic tags operate over a limited range, work poorly in areas of background noise, and require underwater hydrophones. According to Steig et al. (1998), acoustic tags give a precise three-dimensional position for individual juvenile routes in large hydropower forebays. Adaptation of PIT tags for fisheries applications had been a major advance in fish monitoring (Haro et al. 1999). These small electronic packages (the size of a large grain of rice) are inserted into a fish's body cavity. Each is programmed with a unique code that allows tagging date, location, fish size, and other information to be recorded. Passive integrating transponder tag monitoring devices can be placed at bypass systems and dams.
- **Netting.** Netting is most commonly used to measure turbine entrainment. Full tailrace netting is the preferred technique. The Office of Technology Assessment (1995) described problems with netting and factors that can influence data interpretation. If netting is used, estimates of netting efficiency are essential to interpret data. EPRI (1992) has suggested that netting efficiencies of 85% to 100% are necessary for certain nets.
- **Hydroacoustic technologies.** Acoustical systems have been used for more than 20 years to study fish movement. Hydroacoustic technology or sonar uses a transducer to alternately transmit a known frequency (e.g., sound waves at 40–500 kHz) into the water and record the returning waves that bounce off objects (Ransom 1991; Dawson et al. 1997). This technology can function continuously over months to count target-sized fish without harm or delay. When marking individual fish is not feasible because of size, threatened or endangered status, or other factors, hydroacoustic monitoring allows individual tracking through large volumes of water without handling or marking individuals.

In entrainment studies, researchers generally use echo integration, echo counting, or target tracking. Echo tracking and target tracking count individual fish; whereas, echo integration estimates fish biomass over time. These technologies can determine temporal distribution of entrainment; determine spatial distribution of fish when entering a forebay, power canal, or intake; identify swimming velocity and trajectory; evaluate different bypass and screen alternatives (Skalski et al. 1996); and evaluate many other factors. Netting and hydroacoustics may be combined, or their effectiveness as sampling techniques can be compared. Ransom et al. (1996) found similar results between hydroacoustic and net catch estimates at Columbia River Basin dams.

Hydroacoustics (single-beam, multiple-beam, and scanning split-beam hydroacoustics) have provided valuable data on entrainment and numbers entrained—as well as on individual responses to hydraulic and other environment conditions in hydropower forebays, penstocks, and bypass entrances (Skalski et al. 1993; Iverson et al. 1996, 1999). Improved spatial resolution and three-dimensional fish tracking capabilities make the split-beam technique more useful than either single- or dual-beam acoustic techniques for monitoring escapement and behavior at most sites, according to Ransom et al. (2000). Ehrenberg and Torkelson (1996) describe various applications and expected performance of acoustic systems that combine dual-beam and split-beam techniques with target tracking.

Hanks and Ploskey (2000) tested transducer locations and orientations, to maximize detectability of fish and identify important sampling considerations for increasing the accuracy of fish passage and guidance efficiency estimates.

- **Remote recording (videotaping and resistance counters).** Remote recording allows for unbiased, long-term observation of fish passage (and hence timing and patterns of movements), but only at one point, and individual fish usually cannot be identified. Fish movements can be monitored at ladders or other passage structures with counters or advanced video monitoring. Hiebert et al. (2000) compared the effect of infrared and visible illumination to determine delay rates and delay times of migratory Chinook salmon, Coho salmon, and steelhead trout in the fish ladder viewing chamber, using advanced video monitoring.

A promising, powerful new tool for observations in fisheries work is the Dual-Frequency Identification Sonar (DIDSON). This acoustic camera permits the user to observe fish behavior and fish numbers unobtrusively, at a distance of up to 10 to 12 meters, regardless of water clarity.

- **Computer modeling.** Computer modeling such as computational fluid dynamics (CFD)—a three-dimensional numerical computer modeling technique—is often used by engineers to obtain detailed flow field characteristics, such as water velocities and pressures, within a hydraulic system (e.g., Sinha et al. 1999; Smith and Larock 1997). Computational fluid dynamics is an economical and fast way to determine flow behavior in the hydraulic system, and complements the use of traditional hydraulic physical models (Sinha et al. 1999). Recently, CFD mathematical models have been used to provide highly detailed and fairly accurate simulations of flow characteristics near hydropower projects to assist in fish passage studies (Meselhe and Odgaard 1998).

Like hydraulic physical models, CFD simulations enable studies of varying flow conditions, using different structural and hydraulic designs. These simulations can be obtained quickly and relatively inexpensively, and simulations are conducted before constructing costly passage systems that may be very difficult to modify, if modifications are needed. Superimposing information about individual fish movements on the output from numerical models allows more precise understanding of fish behavior and their reactions to certain hydraulic conditions. This technique can lead to a greater understanding of fish behavior near dams and provide criteria that could improve passage facilities.

3.3 The PIER Focus

Existing methods, tools, and data are currently inadequate to address fish passage at California's hydropower facilities. Part of the mission of PIER is to conduct and fund research in the public interest that would otherwise not occur. The issue of fish passage at California hydropower plants is one such issue. PIER-EA intends to address this topic through its own targeted research and to attract collaborators that will share data and work with PIER-EA to develop mitigation strategies.

PIER-EA is also developing roadmaps to address the water quality aspects of hydropower generation and instream flow issues. Whenever possible, PIER-EA will coordinate these programs and seek outside collaborators to leverage funding and avoid overlapping research.

4. Current Research and Research Needs

4.1 The Need for Hydropower Research and Development in California

In California, the majority of hydropower research and development efforts addressing hydropower have focused on enhancing generation, because hydropower is a mature technology that does not require the research and development support provided to other renewable generation technologies, such as wind or biomass. Furthermore, very little new hydropower generation has been added in California in the last 20 years. New hydro capacity that has been brought online, or is likely to be brought online, is the result of generation capacity added to existing water diversion and transmission structures, such as pipelines and canals (EPRI 2001).

The hydropower sector, which represents approximately 27% of the state's installed electrical capacity, is considered a mature technology, and therefore has received significantly less research support than other renewable technologies. However, hydropower generation is currently forced to meet new environmental standards, as a result of the drastic decline in the state's freshwater fisheries and efforts to protect and restore salmon habitat under the Endangered Species Act. In addition, more than 3,600 MW of installed hydropower capacity will be subject to relicensing by the FERC between 2002 and 2010. Even more capacity will be up for relicensing in the succeeding decade. To maintain hydropower capacity that will help meet the state's rising electricity needs and improve aquatic habitat at the same time, targeted research must be conducted to resolve pressing fish passage and entrainment issues.

Within California, there are well over 300 hydropower plants that may have no, slight, or significant effects on aquatic species and communities. The effects of any one facility on aquatic species depend on the resources and hydrology present and on the hydropower plant's design and operating parameters. The majority of these facilities are licensed or exempted from a license by FERC. Licenses are issued by FERC for 30 to 50 years. Over half of the hydropower

facilities within the state were licensed prior to 1970. That means that many of these facilities were permitted prior to the enactment of National Environmental Protection Act or the Endangered Species Act. Given that less than 12% of hydropower facilities in the western United States (excluding the Pacific Northwest) include fish passage facilities, this topic will be an important component in many relicensing cases.

Between 2002 and 2010, 42 hydropower projects within the state will undergo FERC relicensing, representing approximately 3,600 MW of installed capacity. Many of these projects consist of several power plants and dams. The need for upstream and downstream fish passage will be evaluated for each of these projects. It is likely that many of the hydro plants lacking fish passage today will be required to provide it; and for those plants that have fish passage facilities, the efficiency of that fish passage will be evaluated and modifications and/or new fish passage facilities will be required.

Federally owned facilities, such as those operated by the Bureau of Reclamation, are not under FERC authority. However, because a number of the state's anadromous species are listed as threatened or endangered; these facilities will have to address fish passage issues as well.

Dam removal has become a serious consideration for numerous California dams, as a result of aging dam infrastructure, the need for alternative approaches to river management, and concern over fish passage. The cost and effectiveness of the removal are important criteria for determining whether a dam should be removed. Although a small number of dams have been removed in California, no hydropower facilities have been decommissioned. Several hydropower facilities in the state, however, mainly on Battle Creek and the Klamath River, are being considered for decommissioning.

4.1.1 The Need for Fish Passage Research

Aquatic ecosystems in California have undergone (and continue to undergo) massive alteration, with well over half of the state's native freshwater fish species either extinct or in serious decline (Moyle 2002). For example, anadromous salmon have been eliminated from approximately 5,700 miles of their historic habitat in the Central Valley. In most cases, the habitat remaining to these species is of much lower quality than the habitat lost, and is subject to continuing degradation from a variety of factors. The major contributing factors to the overall decline in the state's freshwater fishery include, in order of importance: (1) dams, including water diversions; (2) habitat modification; (3) pollution; (4) introduction of alien species; (5) hatcheries; and (6) exploitation (Moyle 2002).

A key effect of dams—and the focus of this roadmap—is the blockage of fish movement. For example, completion of Shasta Dam on the Sacramento River and McCloud Dam on the McCloud River contributed to the extirpation of bull trout (*Salvelinus confluentis*) in California by excluding salmon (its major food source) from the drainage, altering its habitat, and degrading downstream water quality—in particular by introducing inhospitable water temperatures and severing the connection between habitats used by adults and juveniles. Although the focus of fisheries restoration and, in particular, provision of fish passage in the western United States is on anadromous fish,¹ dams may interfere significantly with non-migratory fish movement, such as non-migratory bull trout, as well.

¹ Anadromous fish are those that migrate from freshwater to the sea and return to spawn and die.

Without fish passage facilities, fish are generally unable to pass upstream of a hydropower dam; whereas, downstream passage may be possible if fish pass safely through turbines and sluiceways or over spillways. Supplying passage facilities for anadromous species such as salmon is generally acknowledged as important for species sustainability. Much of our knowledge and data on the influences of dams and fish passage are based on experience with salmonids (Bell et al. 1972; Williams and Matthews 1995; Whitney et al. 1997; Muir et al. 2001). Mrakovcich (1998) analyzed watersheds in western states (including California) where stocks of spawning salmon occur. Her study concluded that the more dams that exist below watersheds where salmon spawn, the less healthy the salmon stocks are. McClure et al. (2001) found that dams can differ widely with respect to salmon passage and opportunities for increased population growth. They proposed a decision framework based on systematic regional examinations of hydropower operations using matrix models or other approaches to compare suites of recovery actions or risk factors. Clearly, restoration of our anadromous fisheries encompasses much more than fish passage by hydroelectric facilities, yet for the hydroelectric industry in California, it is a major issue.

4.2 Assessment of Fish Passage Needs in California

4.2.1 Fish Passage Inventory and Assessment

There is a lack of information on the type of fish passage facilities in use at hydroelectric plants in the state or the efficiency of these facilities. The FERC is undertaking a program to inventory fish passage facilities at all FERC-licensed hydropower plants nationwide, and is also attempting to determine fish passage success. Within California, the California Department of Fish and Game, the Department of Water Resources, Caltrans, the National Marine Fisheries Service, and the California Coastal Conservancy—as well as several counties—are all undertaking inventories of barriers to anadromous fish passage. In addition, a California Energy Commission survey of hydropower operators is requesting information on fish passage facilities. Much of this research being conducted by other state agencies such as the efforts being undertaken by Caltrans (Hayes, 2002, pers. comm.), focuses on all fish passage barriers, such as road culverts. The National Marine Fisheries Service, however, is conducting an inventory of fish passage facilities at hydropower plants within California. This inventory is intended to be coupled with facility and water body information and applicable study results in a GIS system (Edmondston, 2002, pers. comm.).

Research Need

1. In light of agency databases being developed, the authors are not recommending fish passage inventory and assessment as a high priority.

4.3 Fish Passage Requirements

4.3.1 Fish Passage Needs

The need for upstream and downstream fish passage will be evaluated for each FERC relicensing project. For those power plants with fish passage facilities, the efficiency of fish passage will be evaluated and alternative passage technologies considered. Generally, such studies are prepared independently by each licensee and for each project, with only limited collaboration. This process is time consuming, inefficient, and leads to regulatory uncertainty with sometimes conflicting or ambiguous study requests.

As a result, there is a need to standardize study requirements. Standardizing study requirements may reduce costs and streamline the licensing process by reducing redundancy, minimizing ambiguity, and reducing the likelihood that studies will need to be repeated or that

results will be disputed. Standardized study requirements will also provide enhanced regulatory certainty if applicants know ahead of time what likely study requirements will be. Standardized study requirements should focus on the technical and biological feasibility of fish passage and on the compatibility of resource management goals and objectives.

An important element of this effort will be to provide a standardized method for evaluating the ability of existing fish passage facilities to allow successful up or downstream movement. Specifically, this effort would recommend standardized approaches to fish monitoring, especially for approaches to estimating entrainment injury and mortality.

In evaluating fish passage requirements, regulators must balance between the benefits of providing fish passage and the costs associated with the development and maintenance of fish passage facilities. Accurate cost and benefit information will improve this process. In addition, alternative mitigation measures, such as off-site habitat enhancement, may be possible. Costs and benefits associated with such approaches should also be identified.

Research Needs

1. There is need to develop a standardized protocol that can be used to determine what information is necessary to fully evaluate fish passage needs during the FERC relicensing.
2. There is a need to develop criteria to assist in weighing the costs and benefits of fish passage measures as well as alternative approaches to fish passage, such as habitat restoration.

4.4 Enhancement of Fish Passage in California

Both upstream and downstream fish passage can be partitioned into three elements: (1) attraction to a structure of interest (e.g., a fishway or downstream bypass); (2) the passage (i.e., movement through the structure); and (3) post-passage effects (i.e., stress, exhaustion, instantaneous and delayed mortality, injury, and susceptibility to predation).

Research should evaluate and resolve performance criterion for the design and assessment of fishways in California (e.g., the requirement could be that the fishway needs to pass at least 95% of the size range of each migratory life stage of each species).

4.4.1 Predictive and Descriptive Models for Hydraulic Simulations and Associated Fish Passage

Models that describe and predict flows in front of, through, and out of fish passage structures can provide a better understanding of the hydraulic forces fish confront in attempting to navigate these facilities. Computational fluid dynamics models could be used to simulate 3-D velocity distributions near powerhouses, turbine intakes and forebays, and the spillway channel. Hydraulic information from the CFD models could be used to design fish passage systems like prototype surface collectors and to investigate potential linkages between project operations and adult migrant fallback. CFD-modeled velocities and turbulence, in combination with hydroacoustics and radio telemetry tracking, could promote understanding of how fish and amphibians respond to the physical environment.

Research Needs

1. CFD modeling represents an excellent tool to simulate velocity distribution, design fish passage systems, and improve understanding of passage system effects on fish. Because this modeling technique is a well-developed technology, however, the authors are not

recommending support for research using CFD, except as a tool to evaluate research meeting other research goals and objectives identified in this roadmap.

4.4.2 Fish Passage for Anadromous and Riverine Species

Many of California's native non-salmonid anadromous species, such as the Pacific lamprey, have been adversely affected by dams and other barriers, leading to loss of suitable habitat. For other, non-anadromous species, referred to as *riverine fish*, populations and habitats have been fragmented by dam construction, with many localized populations being extirpated. The Department of Fish and Game have identified several of these species as species of special concern. As habitat continues to be lost, the number of these riverine species likely to receive state and/or federal protection will increase. Many of these riverine species, although not migratory, may still move quite a distance up and downstream, and that movement can be blocked by hydropower facilities. Identification of riverine fish species that would benefit from the provision of fish passage—as well as the identification of fish passage requirements for these species—will allow better management of these fish populations and potentially prevent the need for further Endangered Species Act regulatory action.

The East Bay Municipal Utility District is conducting fish passage research at Woodbridge Dam on the lower Mokelumne River. The utility is monitoring the types and numbers of non-anadromous native and introduced fish attempting to move upstream via a fish ladder (Woodman, 2002, pers. comm.). Although certain species, such as pikeminnow can navigate the ladder, others, such as the Sacramento splittail, enter the ladder but do not pass all the way through. Efforts at the University of California, Davis, Center for Aquatic Biology & Aquaculture (CABA) and at the UC Davis Hydraulics Laboratory fish treadmill have been attempting to determine riverine fish swimming performance and water diversion screening criteria.

Research Needs

Research needs in this area for non-salmonid anadromous species—as well as for riverine species—should include determining sustained and burst swimming speeds and other behavioral factors necessary for designing suitable fish passage facilities.

1. There is a need to identify which riverine species would most benefit from the provision of fish passage.
2. For those riverine species that are identified as benefiting the most from fish passage facilities, research needs to evaluate life-stage specific swimming ability and examine other behaviors that would affect fish passage relative to environmental conditions (e.g., light intensity, water velocity).
3. The suitability of current fish passage technologies for non-salmonid anadromous and riverine fish species needs to be evaluated with any necessary modifications to this technology identified.
4. Research to identify new approaches to fish passage for these species is also needed.
5. There is a need to develop standardized protocols for fish passage monitoring, especially for turbine passage survival. The emphasis should be on establishing protocols for telemetry use.

4.5 Upstream Fish Passage

Upstream fish passage technologies are generally available and widely applied for anadromous salmonid species. Although fishways designed for passing salmonids have often been of little benefit to non-salmonid species, research efforts under Section 4.2 (Assessment of Fish Passage Needs in California) should address these needs. Currently, the major upstream research focus is on the hydraulics of fishways in general and on nature-like fishways in

particular. In California, the issue is whether upstream passage should be provided for high dams such as Oroville. As noted above, for most of the high dams in California, hatcheries were built as mitigation in lieu of providing fish passage. Although the use of hatchery fish to sustain populations is a controversial issue, it is uncertain to the authors whether fish passage at high dams will ever be required in California. Nonetheless, this topic deserves further research.

For such facilities, elevators, lifts, trap and haul, or tunnels may be the only practical approach. The issue therefore becomes how to provide fish passage over high dams to provide access to spawning areas and other habitats without injuring fish and while excluding predators.

In addition, there is a need for further research on the use of behavioral approaches to facilitate upstream fish passage. Although the focus of most behavioral approaches has been on downstream fish passage, such approaches may be useful in guiding fish to upstream fish passage structure such as fish ladders, elevators and traps.

Research Need

1. Further research is needed in identifying the costs and issues associated with upstream fish passage at high dams. Specific issues include ways to allow fish passage for target species while minimizing the introduction of predators into upstream areas.
2. There is also a research need for innovative approaches to facilitating upstream fish passage, such as the use of turbulent flows to guide fish to upstream fish passage facilities.

4.6 Downstream Fish Passage

4.6.1 Downstream Passage Through Large Reservoirs

A concern that has been identified is the delay and/or loss of downstream anadromous juveniles through large reservoirs. Adapted to running water (lotic) conditions, the downstream migrating juveniles may find themselves disoriented and more susceptible to disease and predation in the calm (lentic) water conditions found in larger reservoirs.

Research Needs

1. Because California's larger dams do not provide upstream passage, this topic is not a research priority issue for California.

4.6.2 Downstream Fish Passage Monitoring

Methods of evaluating fish losses (e.g., combined immediate and delayed effects of fish injury, disorientation, stress, mortality, and predation) during downstream passage through turbines and over individual and multiple dams have been enhanced with the development of the Hi-Z turbo tags² and other monitoring and modeling approaches.

Research efforts associated with entrainment on the Columbia and Snake Rivers and the Department of Energy's fish-friendly turbine program have greatly increased our understanding of the hydraulic stresses that fish experience when they pass through turbines or in a severe hydraulic environment.

² Hi-Z turbo tags are specially designed balloons that contain a gas-producing chemical. They are attached to a fish prior to release, and once activated, the balloon inflates, causing the fish to float to the surface for retrieval.

Current methods for evaluating passage at large facilities are: release and recapture by tailrace netting, release and recapture by balloon tagging, and radio tagging and telemetry. However, all of these methods can be expensive and labor-intensive for large-scale hydropower facilities.

Research Needs

1. Given the state of the technology for identifying entrainment effects and the ongoing research efforts to address this issue, the authors are not recommending this as a high research priority.

4.6.3 Turbine Survival and Turbine Passage Effects

Passage through a hydropower turbine subjects fish to a variety of pressure changes, stresses, and direct contact—potentially leading to injury or death. In recent years, a vast amount of research has been conducted on the specific sources of injury and mortality to fish that pass through hydroturbines. Summaries of this research are contained in Cada 1990a, 2001; Cada et al. 1997; and others.

Research Need

1. Given the extensive research program on this issue, mainly conducted in the Columbia Basin, the authors do not see this as a research priority for California.

4.6.4 Fish-Friendly Turbines

Fish mortality associated with passage through a turbine has both direct and indirect components. Direct mortality occurs immediately, such as when a fish is struck by a turbine blade; whereas, indirect mortality occurs when a fish dies from an injury incurred during passage, stress incurred during passage, or subsequent predation on stressed, injured fish.

Major research is under way by turbine designers, biologists, and plant operators in an effort to understand the mechanisms for fish injury in hydraulic turbines and associated water passage structures (Ellis et al. 1999). Cada and Rinehart (2000) and Cada (2001) describe the recent and planned research and development activities across the United States related to survival of fish entrained in hydroelectric turbines. Ventikos et al. (1999) summarized recent results from ongoing research efforts aimed at developing advanced CFD methods that are capable of assessing and improving the environmental comparability of hydropower installations. The U.S. Army Corps of Engineers has developed a research program to study the physical causes of mortality of fish passing through turbines in the Pacific Northwest (Ferguson 1993). The program will develop biological criteria that could be incorporated into the design of turbines, providing safer passage environments for fish.

The Advanced Hydropower Turbine System (AHTS) program was created in 1994 by the U.S. Department of Energy, the Electric Power Research Institute, and the Hydropower Research Foundation (Cada et al. 1997; Hecker et al. 1997; Sale et al. 1997; Cada et al. 1999; Cook et al. 2000). The program's main goal is to develop new turbine designs that can produce hydroelectricity without adverse environmental effects such as fish entrainment/ impingement or degradation of water quality. Two research contracts were awarded based upon conceptual designs. One was by Alden Research Laboratory, Inc. and Northern Research and Engineering Corporation, who provided a conceptual design for a new turbine runner. The second, to the Voith team, produced new fish-friendly design criteria for Kaplan and Francis turbines.

Research Need

1. Given the scope of the AHTS research and development program, the authors conclude that this not a high priority research program for California.

4.6.5 Physical Barrier Approaches to Downstream Fish Passage

The most widely used technologies for fish exclusion and guidance are structural methods such as screens and angled bar racks and louvers. Physical barrier screening techniques with bypasses for downstream passage are most accepted by California and federal agencies, and can prevent entrainment in turbines and water intake structures. These screen structures, which are generally preferred by regulatory agencies, can be expensive, typically require significant maintenance, and may not be well suited for application at specific sites. However, alternative approaches fall far short of the guidance efficiencies provided by physical barrier screens (EPRI 1986). Coutant (2001) urges the integration of both attraction and repulsion behavioral approaches for better performance and to match environmental and species variability.

Research Need

1. Innovative behavioral approaches to successfully steer fish away from intake structures are a high research priority. There clearly are numerous research opportunities regarding behavioral approaches to fish protection at hydropower plants, however, given regulatory constraints and costs, the authors must question whether these efforts would be acceptable to agencies and the industry in California. Therefore, the priority for research in behavioral approaches is those coupled with physical approaches to ensure successful implementation. Such research efforts could include the use of a behavioral approach, such as sound or bubble curtains, to reduce fish impingement on flat plate screens.

5. Goals

The goal of the *PIER Research on Fish Passage at California Hydropower Facilities* roadmap is to identify and prioritize research needs for fish passage under current hydropower operations in California. The goal of the PIER-EA fish passage research is to help California benefit from reduced impacts on fish from hydropower plant passage and entrainment issues.

The achievement of this goal depends on the ability of researchers to assess the current status of fish passage technologies and methods, and to develop, test, and implement economical, effective fish exclusion and passage technologies for hydropower plants. As a result, the state will benefit from healthier aquatic ecosystems and more robust fishing and tourism industries.

The goals developed for these roadmaps are based on the information summary and synthesis developed in previous sections, from discussions with agency and utility staff and responses to a Bureau of Reclamation questionnaire.

The proposed objectives describe the activities needed to reach the objective and the critical factors needed for success. Objectives identified for the short term are mainly efforts that are the necessary first step to address specific issues.

The PIER program recognizes that very little state-specific work has been conducted and disseminated in these areas. However, whenever possible, PIER-EA will identify existing efforts and form partnerships to leverage resources.

5.1 Short-term Objectives³

5.1.1 Fish Passage Requirements

A. Develop protocols for fish passage information requirements.

Activities needed: (1) Develop a prioritized list of important factors in determining the need for fish passage, and if necessary, the type of fish passage needed. (2) Based on a review of current and past FERC relicensing cases (as well as on other efforts), identify the relative importance of the different criteria. (3) Apply the fish passage and criteria and weighing factors to actual fish passage evaluations. (4) Evaluate the use of decision support models to facilitate application of the fish passage criteria.

Critical Factors for Success: Agency, utility and other stakeholder acceptance of standardized criteria for determining fish passage information needs

5.1.2 Fish Passage Enhancement

A. Identify and gather information for fish passage for non-salmonid anadromous and riverine species.

Activities Needed: (1) Based upon existing information, identify native non-salmonid anadromous and riverine species adversely affected by a lack of suitable fish passage. (2) For these species, identify existing information on swimming speeds and other behavioral factors that influence fish passage. (3) Through laboratory and/or fieldwork, collect important information necessary to design and operate fish passage facilities for these species.

Critical Factors for Success: Monetary and staff support for project

5.1.3 Upstream Fish Passage

A. Modify existing technology for upstream passage at high dams in California.

Activities needed: (1) Continue expedited schedules to design and install passage and passage improvements to fish ladders—including modifications of exits, additional ladders, and auxiliary water systems for attraction flows. (2) Where feasible, continue to encourage development and implementation of reintroduction programs. (3) Maximize in-river passage survival of adults by minimizing delay and reducing pre-spawning mortality.

B. Use behavioral approaches to facilitate upstream fish passage.

Activities needed: (1) Locate a demonstration site with existing upstream fish passage. (2) Develop and install behavioral control at the site. (3) Design and implement rigorous experiments to evaluate the biological, operational, and hydraulic performance of the control as appropriate, refining the design as required. (4) Document testing results.

Critical Factors for Success: Access to sites, hydropower operator and regulatory agency participation

³ *Short-term* refers to a 1–3 year time frame; *mid-term* to 3–10 years; and *long-term* to 10–20 years. The activities specified in the roadmap are projected to begin sometime within the designated time frames, and the duration of actual projects may be less than the entire term specified.

5.1.4 Downstream Fish Passage

A. Validate and demonstrate innovative approaches to physical or behavioral barriers that effectively exclude fish during power operation.

Activities needed: (1) Locate a demonstration site at a small hydro facility. (2) Develop and install a physical or behavioral barrier at the site. (3) Design and implement rigorous experiments to evaluate the biological, operational, and hydraulic performance of the barrier as appropriate, refining the design as required. (4) Document testing results.

Critical Factors for Success: Access to sites, hydropower operator and regulatory agency participation

B. Develop downstream fish passage monitoring guidelines.

Activities Needed: (1) Identify important criteria for determining fish passage effectiveness and the relative weight of each of these factors. (2) Develop criteria for the use of different fish monitoring technology, such as hydroacoustics, PIT tagging, and others. (3) Evaluate the criteria against published literature and through field testing.

Critical Factors for Success: Access to appropriate sites

Table 3. Short-term Budget

Objective	Projected Cost (\$000)
5.1.1. Develop protocols for fish passage information requirements	120
5.1.2. Evaluate need and requirements for non-salmonid fish passage	450
5.1.3.A. Evaluate technology for upstream fish passage at high dams	350
5.1.3.B. Evaluate use of behavioral technology for upstream passage	150
5.1.4.A. Demonstrate innovative downstream fish passage.	550
5.1.4.B. Develop downstream fish passage monitoring guidelines	150
Total	1,770

No mid-term or long-term fish passage objectives have been identified.

6. Leveraging R&D Investments

6.1 Methods of Leveraging

Much of the work identified in this roadmap would be collaborative with other entities; PIER-EA would either co-fund projects by other entities, or use outside funds to support PIER-EA efforts.

6.2 Opportunities

Co-sponsored efforts are already under way with the Center for Aquatic Biology and the State Water Resources Control Board. Co-sponsorship opportunities are likely with National Marine Fisheries Service, the Department of Fish and Game, Southern California Edison (SCE), Pacific Gas and Electric (PG&E) and academic institutions. Each of these organizations is interested in addressing fish passage and entrainment issues.

7. Areas Not Addressed by This Roadmap

This roadmap addresses issues associated with fish passage at hydropower facilities in California. Areas not addressed by this roadmap include fish passage at other types of facilities, habitat restoration efforts, and flow determination issues. Specifically, fish movement and migration associated with flow releases are being addressed in a separate research effort.

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9. Personnel Communications

Edmonston, Steve. 2002. National Marine Fisheries Service. Personnel Communication with Joseph O'Hagan

Hayes, Darryl. 2002. Personnel Communication with Joseph O'Hagan. CalFed.

Poore, David. 2002. Personal Communication with Mary Orland. Bureau of Reclamation.

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