Environmental Mitigation Technology for Hydropower:

Summary Report on a Summit Meeting Convened by Oak Ridge National Laboratory, the National Hydropower Association, and the Hydropower Research Foundation

Washington, DC

June 2-3, 2010

Introduction

Hydroelectric power production is largely free of several major classes of environmental impacts associated with non-renewable energy sources. Unlike fossil-fueled power plants, hydroelectric generation does not emit toxic contaminants (e.g., mercury) or sulfur and nitrogen oxides that can cause acidic precipitation. Inundation and decomposition of vegetation by the reservoir can cause the release of greenhouse gases, e.g., methane and carbon dioxide, but the significance of this source greatly depends on the age, size, and geographic location of the reservoir and the amount of vegetation and soil carbon flooded. Hydroelectric power provides an opportunity to reduce the production of air pollutants and greenhouse gases when compared to power produced by the combustion of fossil fuels or biofuels.

Similarly, hydroelectric power plants generate few solid wastes. Land may be required for the disposal of material dredged from reservoirs or waterborne debris, but the amounts of land needed are very small compared to that needed for the continuing disposal of coal ash and slag. Similarly, hydropower production does not create hazardous or radioactive wastes that require safe, long-term storage facilities. Many other environmental impacts associated with the overall fuel cycles of other energy sources are minor or non-existent for hydroelectric power. These externalities include impacts associated with resource extraction (e.g., coal mining, oil drilling), fuel preparation (e.g., refining), and transportation (e.g, oil spills, other accidents).

Although hydroelectric power plants have many advantages over other energy sources, they also have potential environmental impacts (Table 1). Most of the adverse impacts of dams are caused by habitat alterations. Reservoirs associated with large dams can inundate large areas of terrestrial and river habitat. Diverting water from the stream channel or curtailing reservoir releases in order to store water for future electrical generation can dry out streamside (riparian) vegetation. Insufficient water releases degrade habitat for fish and other aquatic organisms in the river below the dam. Water in a reservoir is stagnant compared to that in a free-flowing river. Consequently, water-borne sediments and nutrients can be trapped, resulting in the undesirable proliferation of algae and aquatic weeds (eutrophication) and a change in water quality in the reservoir and in reservoir releases. In some cases water spilled from high dams may become supersaturated with nitrogen gas resulting in gas-bubble disease in aquatic organisms inhabiting the tailwaters. Hydropower projects can also affect aquatic organisms directly. The dam can block upstream movements of fish, which can have severe consequences for anadromous fish (e.g., salmon, steelhead, American shad), catadromous fish (e.g., American eels), or riverine fish that make seasonal migrations to spawn (e.g., sturgeon and paddlefish). Fish moving downstream may be drawn into the power plant intake flow (entrained). Entrained fish are exposed to physical stresses (pressure changes, shear, turbulence, strike) as they pass through the turbine that may cause disorientation, physiological stress, injury, or mortality.

Table 1. Potential environmental benefits and adverse impacts of hydroelectric power production.

Benefits	Adverse Impacts
No emission of sulfur and nitrogen oxides	Inundation of wetlands and terrestrial vegetation
Few solid wastes	Emissions of greenhouse gases from flooded vegetation at some sites
Minimal impacts from resource extraction, preparation, and transportation	Conversion of a free-flowing river to a reservoir
Flood control	Replacement of riverine aquatic communities with reservoir communities
Water supply for drinking, irrigation, and industry	Displacement of people and terrestrial wildlife
Reservoir-based recreation	Alteration of river flow patterns below the dam
	Loss of river-based recreation and fisheries
Reservoir-based fisheries	Desiccation of streamside vegetation below the dam
Enhanced tailwater fisheries	Retention of sediments and nutrients in the reservoir
Improved navigation on inland waterways below the dam	Development of aquatic weeds and eutrophication
	Alteration of water quality and temperature
	Interference with upstream and downstream passage of aquatic organisms

In order to accelerate the development of environmentally sound hydroelectric power production, it will be important to resolve and/or mitigate the environmental impacts that limit its deployment. A group of 28 experts on the environmental impacts of hydropower met in Washington, DC on June 2-3, 2010 to share information about how environmental mitigation is being applied to hydropower projects. Participants in the Environmental Mitigation Technology Summit (EMTS) meeting came from diverse backgrounds, including developers, environmental and engineering consultants, resource and regulatory agency personnel, and government laboratory scientists and engineers. Facilitated discussions considered the state of knowledge about key impacts associated with hydropower, technological and operational measures currently used to address the impacts, approaches for monitoring and evaluating the effectiveness of environmental mitigation measures, and the research and development (R&D) needed to improve the effectiveness and reduce the cost of mitigation measures (Table 2).

This report is a summary of the presentations and discussions that took place during the EMTS meeting.

Mitigation Issues

Participants considered the major environmental issues that frequently require mitigation at hydropower projects. Although there is a long list of particular environmental issues that may affect individual sites, the most common mitigation needs continue to relate to the provision of fish passage, environmental flow releases, and adequate water quality within the reservoir and in the water discharged into the tailrace. These general topics were identified in advance, and speakers were asked to make presentations about the status of mitigation in order to facilitate discussions. A final session of the meeting was devoted to other environmental issues. In the following sections, each environmental issue is described and a summary of the discussions related to environmental mitigation technologies is provided.

Fish Passage

***Environmental Issue* –** Hydropower projects can affect aquatic organisms directly by impeding their migration, blocking their movement upstream and/or downstream, and indirectly by altering the flow patterns and water quality conditions to which they respond. In addition to the blockage caused by the dam, flowing streams are changed to reservoirs, in which the average depth and cross-section are increased and the velocities of water flowing through that reach are decreased. The rate of downstream transport of aquatic invertebrates and drifting fish can be slowed when water velocities upstream of hydroelectric dams are substantially reduced or when a large proportion of the stream is diverted for hydroelectric generation.

Most hydropower dams pose a physical barrier to upstream-migrating fish. Fish migrate upstream for a variety of reasons, including to return to natal areas to spawn (e.g., adult salmon,

Table 2. Agenda for the Hydropower Technology Summit Meeting on Environmental Mitigation held in Washington, DC.

DAY ONE – June 2, 2010	
Time	*Agenda Item*
8:00 AM	**Introduction and Direction to Participants**
8:15 to 8:45 AM	**Overview of mitigation issues, their role in hydropower licensing, and their costs**
8:15 am to Noon	**1. FISH PASSAGE** • The status of upstream fish passage research • Downstream passage through hydropower systems • The potential of fish-friendly turbines: what is known, needed R&D, applicability. • ***Facilitated discussion of alternative views***
	Lunch
1:00 pm to 4:30 pm	**2. ENVIRONMENTAL FLOWS** • Overview of environmental flows issues for sustainable river management • The Instream Flow Council, their recent survey of methods, and state agency perspectives • Validation of methods and the role of adaptive management • ***Facilitated discussion of alternative views***
4:30 pm to 5:00 pm	***Charge to attendees for next day***

DAY TWO – June 3, 2010	
8:00 am to 8:30 am	**Review of Day One**
8:30 am to 10:00 am	**3. WATER QUALITY –** • Aerating turbines and other mitigation experience at the Osage project • Supersaturated dissolved oxygen (SDOX) technology • Water temperature issues • ***Facilitated discussion of alternative views***
	Break
10:15 am to Noon	**4. OTHER ENVIRONMENTAL ISSUES –** • Discussion about hydropower impacts to terrestrial systems, recreation, and/or any important issues not covered earlier • Discussions will consider the state of knowledge about the impacts and mitigation measures, the value of cumulative/basin scale impact assessments and ecological risk assessment, and innovative • ***Facilitated discussion of additional issue not yet covered***
Noon	**Lunch**
1:00 pm to 2:00 pm	***Continue discussion, final thoughts from speakers and audience, and outline next steps***
2:00 pm	**Adjourn Meeting**

steelhead, American shad), to complete their freshwater rearing period (e.g., juvenile American eel), or to feed. Many freshwater fish move seasonally between large rivers and their tributary streams. These migration routes may be blocked by dams, eliminating large areas from production of fish.

Fish that migrate downstream past hydropower projects have three primary routes of passage. They may be 1) drawn into the power plant intake flow (entrainment) and pass through the turbine, 2) diverted via bypass screens into a gatewell and to a collection facility or the tailrace, or 3) passed over the dam in spilled water. Entrained fish are exposed to physical stresses (e.g., rapid changes in pressure, shear, turbulence, blade strike) that may be injurious. In the best conventional turbines up to 5% of turbine-passed fish may be injured or killed, and mortalities in some turbines may be 30% or more. Several new advanced turbine concepts have been tested or are under development that may reduce mortality of turbine-passed fish to 2% or less. Non-turbine passage routes pose some risk to fish as well. Weak swimmers, such as juvenile lamprey and small resident fish may be impinged or injured upon contact with bypass screens. The design and location of outfalls from fish bypasses are also critical to minimize exposures of bypassed fish to predatory fish in the dam tailrace. Fish that pass via the spill of high-head dams are subjected to extremely high and variable water velocities, may be abraded by contact with the dam face, and may collide with submersed structures below the dam, including those designed to dissipate the high energy of spilled water. However, project spills may reduce residence time of migrating fish immediately above the dam during which they are vulnerable to predators in the reservoir. Thus, design of the entire project from forebay entrance to tailrace exit affects the safe and efficient passage of fish.

Mitigation Measures for Fish Passage – In a survey conducted by the U.S. Department of Energy (DOE) in 1994, 9.5% of hydropower projects licensed by the Federal Energy Regulatory Commission had installed upstream fish passage mitigation measures (aka fishways). These include fish ladders, fish elevators, and trap-and-haul operations. Of these, fish ladders were the most common technology, accounting for 62% of the installations. Costs for construction and operations and maintenance varied greatly, mainly related to the size of the project. There had been relatively little effectiveness monitoring of the upstream passage measures.

The majority of fishways in North America have been designed for efficient upstream passage of salmonids, especially anadromous salmon. However, other species of fish may not respond similarly to these fishways because of their unique behaviors. For example, adult white sturgeon may be too large to navigate certain designs. The upstream passage of adult lamprey is also poor relative to the number of fish that approach a project. Effectiveness of fishways is less well understood for catadromous fish (eels) or many freshwater species. In most cases it would be desirable for constructed fishways to pass a greater diversity of fish.

A relatively new upstream passage design is the nature-like bypass, which is based on simulating natural stream characteristics, using natural materials, and provide suitable upstream (and downstream) passage conditions over a range of stream flows for a wide variety of fish species and other aquatic organisms. Nature-like bypasses have been implemented most commonly in Europe, but a few examples can be found in the United States (mainly Minnesota). Despite their seeming multiple advantages, nature-like bypasses have not been comprehensively studied. For example, it is not known whether these devices will allow the passage of a wide variety of U.S. fish species or will function reliably under wide ranges of flows over many years. Perhaps because of these uncertainties, agencies in the Northeastern U.S. may be reluctant to approve their use.

Downstream passage of fish has been a more difficult problem to resolve, but advances in turbine designs and in the techniques for measuring fish passage conditions and fish survival are encouraging. Improved, more precise measurements can lead to better “fish-friendly” turbine designs, offering the possibility of using passing more water through the turbines in order to generate more electricity, while causing lower fish passage mortality. Initial tests of the Minimum Gap Runner (a major refinement of the conventional Kaplan turbine) at the Wanapum Dam showed good fish survival and increased energy production. A pilot scale (1/3 size) laboratory model of the Alden turbine demonstrated excellent survival of turbine-passed fish, but the design has not yet been tested at full scale in the field. Other fish-friendly turbine designs have been conceptualized for a range of hydraulic heads and environmental settings. All these advanced turbines would benefit from testing and validation of the expected benefits at field sites.

A variety of other ideas related to the mitigation of fish passage issues were brought out in the EMTS meeting but not discussed in detail: 1) Although the two installations of Eicher screens in the Pacific Northwest are seemingly effective for safely keeping fish out of turbines, they are not accepted as proven by NOAA. 2) Downstream passage options and needs for the American eel are poorly known, although fish tests of the pilot scale Alden turbine showed excellent survival. 3) The value of trap-and-haul operations for transporting fish (in lieu of more permanent fishway structures) should be reconsidered, especially for American shad, sturgeon, and other species that are reluctant to use ladders or that may suffer mortality through a series of dams and reservoirs. 4) In some South American hydropower projects (and perhaps also in the United States), improvements in upstream fish passage may be negated by inadequate upstream spawning habitat, degraded water quality, and/or poor subsequent downstream passage through the reservoir and dam. The need for upstream passage should be carefully considered if downstream passage cannot be guaranteed. 5) The effective passage of fish through reservoirs as well as turbines is an unresolved issue. We need to learn how to synchronize fish movement through storage reservoirs and mainstem reservoirs with hydraulic retention times and power production needs. The success of the Baker Lake “fish gulper” may provide a useful example for other settings. 6) There is a continuing need to further develop technologies and measurement/monitoring techniques that quantify fish passage conditions and fish passage survival. Many of these techniques are being developed in the Columbia River Basin, and it would be valuable to transfer these tools to other settings across the U.S. Potentially, a type of "lending library" of equipment and expertise might be an efficient form of technology transfer. The conclusions drawn from earlier fish passage studies, using less precise/accurate techniques, should be re-examined.

Environmental Flow Releases

Environmental Issue – Hydropower storage reservoirs can retain enough water that the river below the dam dries up. Similarly, diversion projects withdraw water from the river, pass it through a canal or pipeline, and return it to the river downstream from the powerhouse. In both types of hydroelectric projects, stream flows and aquatic habitats in a portion of the river are greatly or entirely reduced. This may eliminate fish and invertebrates that were residing in the affected reach and constrain the movements of migratory fish. Over the long term, reductions in flood flows by the dam may alter sediment dynamics and riparian communities that both depend on periodic high flows.

Mitigation Measures for Environmental Flows – The provision of environmental flows (releasing a predetermined amount of water down the river channel) is often required to sustain the other instream uses of water, including maintenance of fish and wildlife communities, streamside vegetation, recreation, aesthetics, water quality, and navigation. Providing flows downstream from a storage reservoir or hydroelectric diversion is simple; water can be spilled from the dam instead of diverted to a pipeline or stored in a reservoir. A greater problem is determining the quantities and schedules of environmental flow releases. Because releasing water to support multiple uses below the dam frequently makes that water unavailable for generation of electricity, hydropower operators are interested in providing sufficient, but not excessive, releases.

Methods have been developed to ascertain the instream flow requirements of many of these uses, but the needs of biological resources are often difficult to assess. A wide variety of instream flow assessment methodologies are available to help determine how much water needs to be released to maintain aquatic and riparian communities. The number of environmental flow assessment methodologies exceeds 100, and they range from simple, desktop calculations (e.g., Aquatic Base Flow Method) to methodologies that may require considerable site-specific field work (e.g., the Physical Habitat Simulation Models associated with the Instream Flow Incremental Methodology). The number of available methods appears to be proliferating, rather than converging into a small set of well-understood and validated approaches. A large number of methods is acceptable as long as there is a rationale or guidance on what method to use in what setting. A recent survey by the Instream Flow Council found that states and provinces do not need more models, but rather need more funding and public and regulatory support. Small hydropower projects often have smaller impacts on the environment (and smaller financial resources), and should be able to use simpler methods if the agencies agree. It would be useful to develop models that can be applied widely within a river basin or region in order to minimize the site-specific studies; regional flow-ecology relationships might be ascertained. Whatever method is chosen, a water routing model for the river basin that everyone understands is a necessary starting point.

A shortcoming of most environmental flow assessment methods is the lack of validation. That is, uncertainties remain in the relationships between predicted physical habitat created by the flow releases and the aquatic and riparian biological communities downstream from the dam. Known costs of environmental flow releases would be more supportable if the benefits could also be quantified, but the few validation studies that have been carried out suggest that particular flow releases yield a positive response in some ecosystem characteristic and a negative response in others. The simple application of unvalidated assessment methods could be supplanted by modeling that is oriented toward hypothesis testing. Output of the modeling should be a flow regime that meets varying ecosystem needs over a daily, seasonal, and annual time frame (recognizing that under unaltered flow regimes habitat is not a static value, but is stochastic/variable). Environmental monitoring should focus on good, comprehensive, representative ecosystem endpoints, potentially based on an understanding of where the "bottlenecks" for biological populations or ecosystem function occur.

Among the environmental mitigation areas discussed in the EMTS meeting, the determination of appropriate environmental flow releases might be the most amenable to adaptive management approaches. Compared to mitigation measures like fish ladders or fish-friendly turbines, the developers and agencies agreeing to initial flow releases are not committing to large construction costs or the installation of hardware that is difficult to remove or alter. Rather, environmental flow releases can be altered relatively easily to test hypotheses and to optimize environmental benefits and power production. That said, there is a poor understanding of the value of adaptive management for determining sufficient, but not excessive, flow releases. Industry and agencies would benefit from guidance on applying adaptive management to this issue. As an example of such guidance, the Instream Flow Council has published a book that provides detailed descriptions of 8 specific case studies of riverine ecosystem management, examples of monitoring techniques and adaptive environmental assessment and management, and a comprehensive discussion of advancing the state-of-the-practice for instream flow studies. In a larger sense, it would be beneficial to the industry if support was restored for the further development and validation of flow assessment methods, for example, a reinvigoration of the U.S. Fish and Wildlife Service's support of the Instream Flow Group and the Habitat Evaluation Procedures.

Water Quality

Environmental Issue – The most common water quality issues associated with hydroelectric power production are changes in temperature and dissolved oxygen concentrations in the water released from the dam. Reservoirs in temperate regions often become thermally stratified, especially if they are deep or sheltered from the wind. Many hydroelectric turbine intakes withdraw water from the depths of the reservoir, and summer water temperatures in the discharged water are lower than would occur in the free-flowing river. The opposite situation may occur in the winter. Altered water temperatures in the tailwaters have profound effects on aquatic organisms. Cold water discharges in the summer can slow the growth rates and reduce productivity of fish and aquatic invertebrates, but they can also allow the establishment of a coldwater fishery in areas where the natural rivers are too warm. Conversely, warm water discharges in the winter can speed the metabolic rate of aquatic insects and fish eggs, so that they develop and emerge before the appropriate season.

Thermal stratification can also decrease the concentrations of dissolved oxygen in the water discharged from the reservoir. The relatively stagnant bottom waters are isolated from the processes of atmospheric diffusion and wind mixing that replenish dissolved gases at the surface. Plant and animal respiration, bacterial decomposition of organic matter, and chemical oxidation can all act to progressively remove dissolved oxygen from bottom waters. This situation may be exacerbated by the input of high levels of oxygen-consuming organic materials that enter the reservoir from the watershed upstream. Turbines that withdraw from the bottom may discharge water that is low in dissolved oxygen, affecting the aesthetic qualities (taste, odor and appearance), communities of aquatic organisms, and waste assimilation capacity of the tailwaters. Adequate levels of dissolved oxygen (at least 5 mg/L in most waters) are necessary not only for aesthetic qualities (taste and odor) but also to support a balanced community of aquatic organisms.

Mitigation Measures for Water Quality – There are many methods available to increase dissolved oxygen concentrations in reservoirs and tailwaters, including aerating reservoir forebay waters with air or oxygen, installing advanced aerating turbine runners, and constructing aeration weirs in the tailrace below the dam. Innovative approaches continue to be developed – presentations included a new technique of mixing hyper-oxygenated water with deoxygenated discharges and a successful R&D effort to model, install, and test an aerating Francis runner at a hydropower project in Missouri. The effectiveness of dissolved oxygen enhancement measures is easily determined by compliance monitoring. Many of these mitigation measures have proven effective, and costs can be readily determined. At some sites it may be valuable to design tailrace weirs not only to increase dissolved oxygen concentrations, but also to assist in dampening flow fluctuations (reduce ramping rates) from turbine discharges.

Water temperature alteration is a problem at many projects, particularly where fisheries are limited by discharges from large reservoirs. Depending on the region, water released from reservoirs may be unnaturally cold or warm. There is a need to improve our understanding of the biological responses to these altered temperatures, based on comprehensive look at historical literature. In some cases, outdated and potentially inaccurate "gray" literature is being used to condition licenses. Improved knowledge, using the most recent, peer-reviewed studies, might lead to more flexible water quality standards or permit conditions. These documents and the supporting data could be put in a publicly accessible clearinghouse to help make better licensing decisions and to move toward standard practices. A comprehensive study of temperature effects by DOE (or some other objective organization), based on updated literature, would be helpful to both industry and regulators.

Other Environmental Issues

Other environmental issues discussed at the EMTS meeting included:

1) ***Terrestrial impacts* –** There is a need to reinvigorate the Habitat Evaluation Procedures (HEP) and find a home for them so that further development can be fostered. Can the work being done on climate change inform hydropower mitigation?

2) ***Recreation* –** There is no particular need for technological fixes or R&D to mitigate hydropower impacts to recreation, but there is a need to better integrate recreational flow releases (for fishing, whitewater sports, etc.) into the methods used to set environmental flows.

3) ***Gravel/sediment restoration* –** We need to develop a better way to restore gravels captured by the impoundment than front end loaders and trucks. Research on techniques to pass gravel through a reservoir so that it would be available to support downstream spawning and other habitats would be useful. This is a different issue than the flushing flows that may be needed to remove fine sediments from the substrate below an impoundment. Complexity of the channel should be maintained, and this includes retention of large woody debris that constitutes aquatic habitat.

4) ***Site selection methods* –** Guidance for selecting potential hydropower sites that have minimal environmental issues is needed, especially for new, small projects. It is difficult for a developer to consult with the agencies early about good sites or environmental issues, because that public consultation reveals development plans that competitors may use to their advantage. Consequently, unless the regulations governing site preference are changed, many developers will collect as much information about a site as they can before making their plans public with the filing of a license or permit application with the Federal Energy Regulatory

Commission (FERC). Related to this need, the FERC has a small hydro website that can be used to assist potential applicants in site selection. The Northwest Power Planning Commission maintains a geospatially referenced list of protected areas, and such databases may be available in other parts of the country. The U.S. Forest Service has information on river reaches that are classified or under consideration for Wild and Scenic Rivers status.

General R&D Needs Related to Environmental Mitigation

Several environmental mitigation R&D needs were briefly discussed that are not related to any particular environmental issue. These included:

1) Quantified Mitigation Plans - Development and guidance of the use of quantified metrics to compare the effectiveness of mitigation measures and to help arrive at negotiated settlements. These plans should be robust and flexible (in light of the vagaries of natural systems).

2) Separate the impacts of the dam from impacts of hydropower operation

3) Cumulative impacts of multiple projects within a river basin.

4) Guidance on methods for expressing the non-power values of rivers, to allow for comparison to the more easily quantified power generation benefits.

5) Development, promotion, and training in the use of standardized tools to get the right mitigation measures in place faster.

6) Creation of a publicly available clearinghouse to store and analyze existing data on environmental impacts and environmental mitigation measures. This need was identified for each of the areas considered: fish passage, environmental flow releases, and water quality. A clearinghouse should have clear criteria for inclusion of data, emphasizing recent, peer-reviewed work. At the least, this could involve linking websites from different organizations to make information more readily accessible. The use of existing data and analyses can reduce the cost of mitigation decisions and could support comprehensive reviews of the environmental issues.