Passing Judgment on Fish Passage Technologies
HSA 10-5 The Economics of Oil and Energy
April 7, 2016

Introduction

For millennia, the Elwha River in Washington was the annual spawning site of a vibrant array of salmon and trout species. This changed in the early 1900s, when the Elwha and Glines Canyon dams were built across the river.[1] The installations wreaked havoc on the river's fish. Confused salmon were annually seen repeatedly bumping their heads against the bases of the dams in a futile attempt to find a path to their historic spawning grounds.[2] The salmon population plummeted 98%,[3] and the Lower Elwha Klallam Tribe, which lived along the river, lost the supply of fish they once relied on.[4] In 1995, Congress judged that the environmental damage caused by the dams was too great and ordered their removal.[5] When the removal was carried out, the results were dramatic. After just a couple years, Chinook salmon had returned to the river to spawn, and animals such as birds which feed on salmon grew in number and began showing signs of greater health.

What made people decide that saving fish merited a $26.9 million[6] removal project? Fish play an essential role in the health of river ecosystems, and dams can have a catastrophic effect on fish populations. As the world focuses ever more on finding renewable energy sources, hydropower stands out as an environmentally friendly candidate. The devastating toll a hydropower dam takes on fish populations, however, shows that hydro is not so green after all.

Superficially, hydropower appears to be an attractive energy source which is both renewable and cost effective. Fig. 1[7] ranks hydropower as cheaper than conventional coal, nuclear, and almost all other renewable energy sources. Many developing nations, primarily located in Asia and South America, are considering hydropower as a potential solution to their rising energy needs.[8] Unfortunately, below hydropower's attractive exterior lurk substantial environmental costs, one of which is the devastation of fish populations which can no longer freely navigate the river. In order to decide whether hydropower is a viable contributor to a nation's clean energy future, it is important to determine how serious these environmental dangers are and how easily they can be mitigated. This paper discusses the challenges

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[1] "Elwha River Restoration." *National Park Service* n.d. https://www.nps.gov/olym/learn/nature/elwha-ecosystem-restoration.htm.
[2] Blumenthal, Les. "Will Dam Removal Return Life to Elwha?" *The Olympian*. 2010. http://www.theolympian.com/news/politics-government/article25251595.html.
[3] Lieb, Anna. "The Undamming of America." *PBS*. 2015. http://www.pbs.org/wgbh/nova/next/earth/dam-removals/.
[4] Nicole, Wendee. "Lessons of the Elwha River: Managing Health Hazards during Dam Removal." *Environmental Health Perspectives* n.d. http://ehp.niehs.nih.gov/120-a430/.
[5] "Elwha River Restoration."
[6] "Frequently Asked Questions - Olympic National Park." *National Park Service* n.d. https://www.nps.gov/olym/learn/nature/elwha-faq.htm.
[7] "Levelized Cost of New Electricity Generating Technologies." *Institute for Energy Research* n.d. http://instituteforenergyresearch.org/studies/levelized-cost-of-new-generating-technologies/ .
[8] Conca, James. "The Hidden Cost Of Hydroelectric Power." *Forbes*. 2014. http://www.forbes.com/sites/jamesconca/2014/11/04/the-hidden-cost-of-hydroelectric-power/#57a2241e114e.

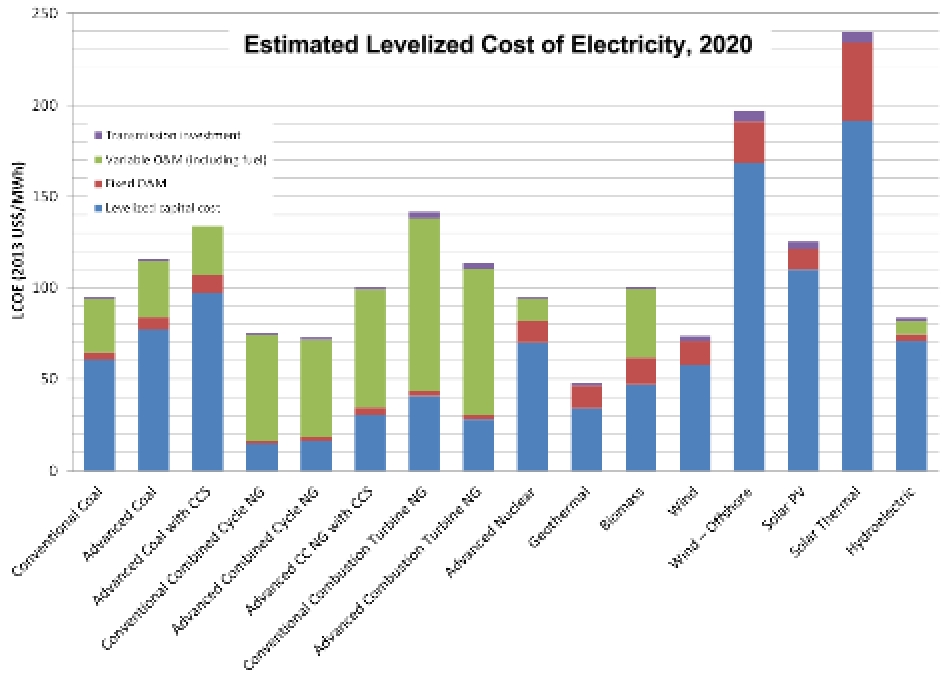


Figure 1: Cost of various conventional and renewable energy sources, estimated from the Energy Information Administration's 2015 Annual Energy Outlook.

involved with implementing fish passage technologies and evaluates how environmentally friendly hydropower is in this area.

Why Fish Passage Matters

A hydropower dam without an effective fish passage program can upset an entire ecosystem. Pacific salmon, for instance, are an important food source for 137 other species. As they migrate upriver to spawn, they transport marine minerals. In fact, trees on the banks of spawning rivers gain 22-24% of the nitrogen in their foliage from nutrients transported by salmon and grow three times as fast as trees on rivers where salmon do not spawn.[6] Healthy tree growth in turn prevents erosion of soil along river banks, which prevents excess sediments from changing the nutrient composition of the water. When a dam prevents fish from playing their key role, the entire ecosystem suffers.

Many fish are also central to the economy. Pacific salmon, for instance, support a $3 billion fishing industry which involves over 10,000 jobs per year.[6] Although it is difficult to attach a number to the value of saving a fish given the variety of economic, cultural, and environmental considerations, a study which estimated the marginal cost of steelhead trout in various Oregon rivers found that a single fish was valued at approximately $149, and in one river was worth as much as $456. These high price values reflect how connected fish welfare is too human welfare; when fish populations disappear, humans are harmed too.

Fish Passage: Problems and Solutions

Without effective fish passage techniques, hydroelectric dams (shown in Fig. 2[9]) disrupt the passage of fish up and down the river. These dams pose the most severe threat to populations of anadromous fish such as salmon, which spend their lives in the ocean but annually migrate upstream to breed. Without

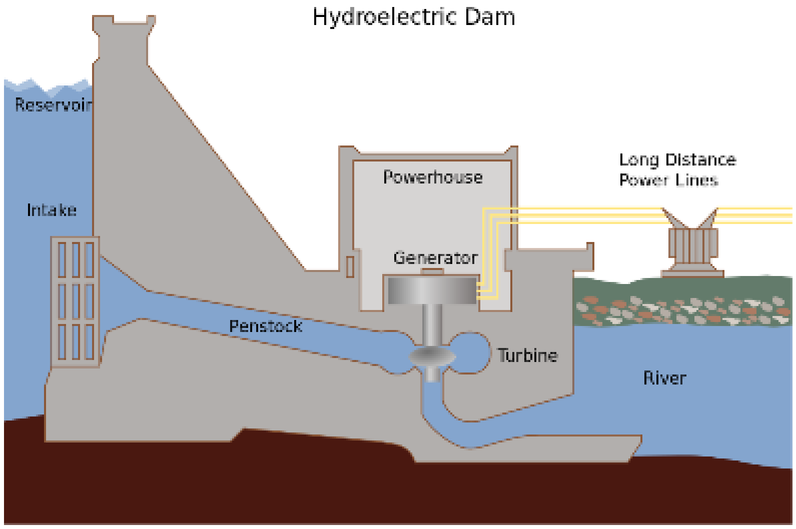


Figure 2: Diagram of a conventional hydropower dam.

upstream fish passage technologies, many fish cannot find their way to breeding grounds and are unable to reproduce. If fish do find themselves above the dam, navigating the dam heading downstream can be equally difficult. Fish are sucked into turbines, where steel blades kill them or tear off their scales. Even those not directly hit by the turbine may suffer barotrauma - potentially fatal physical harm from the rapid change in barometric pressure between the bottom of the reservoir and the surface-level water on the far side of the dam. To adjust to the new pressure, the fish's swim bladder swells rapidly and may rupture.[10]

To address these issues, an array of fish passage technologies have been implemented to transport fish upstream or downstream. Most upstream fish passes can be categorized as variations on fish ladders (see Fig. 3)[11] or fish elevators, which crowd fish into a small container and lift them over the dam. Downstream fish passes include bypass pipes or sluices which carry the fish safely to the other side of the turbine.

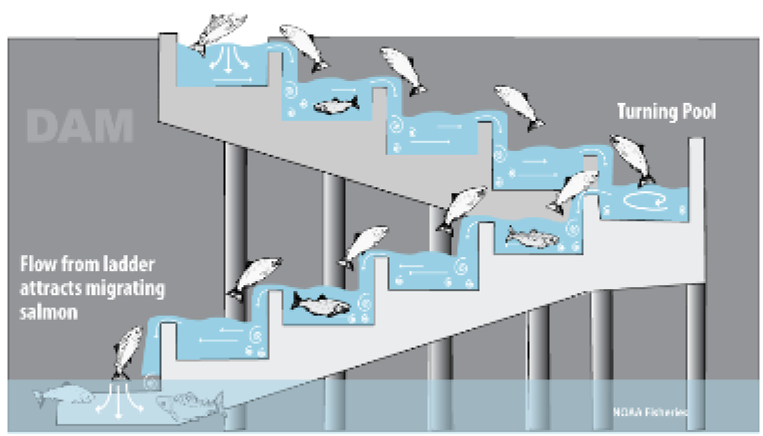


Figure 3: A salmon fish ladder. Fish ladders are generally species-specific.

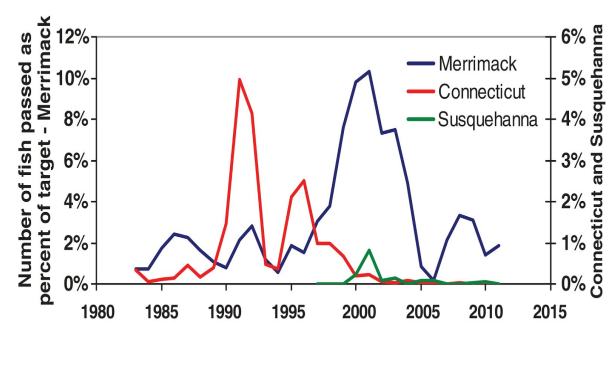
[9] Tomia. "Hydroelectric Dam." *Wikiversity*. 2007. https://en.wikiversity.org/wiki/Power_Generation-hydro_Power .
[10] DOE/Pacific Northwest National Laboratory. "Making Dams Safer for Fish around the World." *ScienceDaily*. 2014. https://www.sciencedaily.com/releases/2014/04/140414140802.htm.
[11] NOAA Fisheries. "Fish Ladders." *National Oceanic and Atmospheric Administration* n.d. http://www.westcoast.fisheries.noaa.gov/fish_passage/about_dams_and_fish/fish_ladders.html.

Fish are directed to these bypasses through cues such as sounds and lights. Alternatively, dams can periodically release water through a spillway over of the dam, carrying fish over as well.

The Big Question: Is Fish Passage Working?

Although there are a variety of options available for fish passage, it remains a complex problem, and there is no guarantee any particular solution will be effective in any given environment. Since fish are essential to our environment and economy, it's crucial that hydropower dams pass enough fish to maintain healthy populations. We have to ask ourselves one big question: is fish passage working?

Assessing whether fish passage at a dam is effective isn't easy. Although individual dams often record how many fish pass their dam, there is no centralized location where the data is collected to determine the cumulative impact on species which must navigate rivers blocked by multiple dams. In 2013, fish ecologist Jed Brown led a team which conducted a study of several dams along three major East-coast rivers.[12] His results, summarized in Fig. 4, were not reassuring. The team found that "[fish passage] targets are being missed by orders of magnitude. The goal at the first Connecticut River dam is 300,000 to 500,000 fish. There, the mean for those same years was 86. And for the Susquehanna, the goal is 5 million river herring spawning above the fourth dam, which passed an average of seven herring from 2008 to 2011."[13] The study reached a grim conclusion: fish passage technologies are not effective. Unless the industry can rethink fish passage, hydropower can never become a truly environmentally friendly power source.



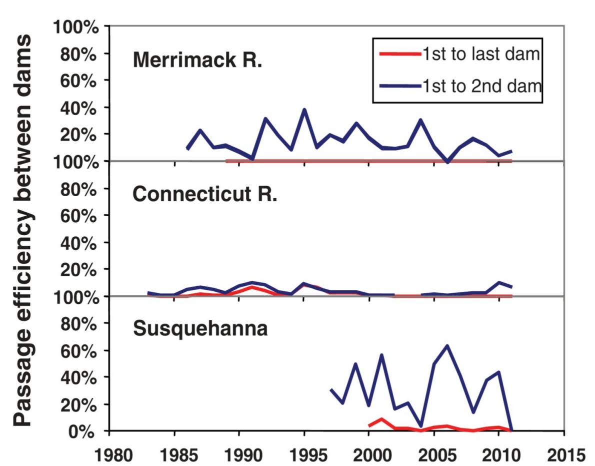


Figure 4: Data from Brown's research on fish passage along three major East Coast Rivers. No river passes more than 12% of its target, and almost no fish could navigate over every dam.

Brown's study focused primarily on problems with upstream fish passage, but the extent of the harm to fish stretches far beyond his findings. Fish are often killed by large drops over spillways or being funneled through transport pipes at high speeds. This danger extends to mature fish and juveniles alike.

[12] Adams, Jill U. "Fish Ladders and Elevators Not Working." *Science*. 2013. http://www.sciencemag.org/news/2013/01/fish-ladders-and-elevators-not-working.

[13] Adams, Jill U. "Fish Ladders and Elevators Not Working."

The proportion of adults which do not make it back down to the ocean is so great that, according to one of the authors of Brown's study, "We've taken species that spawn more than once in their lives and turned them into one-time spawners."[14] Juveniles face the additional challenge of arriving in a timely manner. If juvenile salmon, for instance, do not swim to the ocean within 15 days, they may lose the ability to switch from freshwater to saltwater when they arrive. Unfortunately, the process of discovering bypasses through a series of dams takes so long that many young fish lose this vital race against time. On the Snake River, for example, a downstream journey which took three days on the undammed river currently may take up to 39 days, a delay which results in a 95% juvenile salmon mortality rate.[15] Dams, it seems, serve as slaughterhouses for fish in both directions.

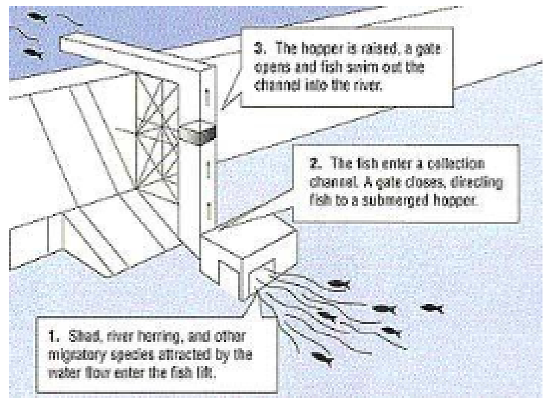


Figure 5: A fish lift

A second persistent failure of fish passages is their inability to accommodate a wide range of species. Many fish passes, especially fish ladders, are designed to suit the needs of one species, typically salmon, shad, or herring.[16] When other species try to pass the dam, however, the fish passes often fail miserably. Ladders built for salmon and other powerful fish used to jumping into headwaters frequently cannot successfully provide passage for fish such as sturgeon and bass, which have weaker swimming skills and very little jumping ability.[17] This problem is avoided with fish lifts and elevators like that in Fig. 5,[18] but even these are only effective if they can transport fish in a timely manner without injuring them in the process. Elevators are not suitable in all instances; shad, for example, cannot use fish elevators easily because of their susceptibility to "stress and damage" and "because they tend to migrate in extremely large and concentrated shoals at irregular intervals."[19] Since each species has unique physiology and behavior, there is no one fish passage solution appropriate for every species, and some species get sadly neglected. Freshwater fish are especially frequently overlooked since they typically do not undergo massive migrations up and down the river. However, research shows that a significant number of freshwater fish are still caught in turbines. These fish are more likely to be endangered than others; in fact up to a third of the world's freshwater fish species may be classified as "threatened."[20] Although it is tempting to design fish passages solely for the most numerous species, to prevent extinctions and preserve biodiversity, fish passage must serve all species in the river.

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[14] Kraft, Amy. "Upstream Battle: Fishes Shun Modern Dam Passages, Contributing to Population Declines." *Scientific American*. 2013. http://www.scientificamerican.com/article/upstream-battle-fishes-shun-modern-dam-passages-population-declines/.

[15] "Dams and Migratory Fish." *International River s*n.d. https://www.internationalrivers.org/dams-and-migratory-fish.

[16] Brown, Jed, Karin E Limburg, John R Waldman, Kurt Stephenson, Edward P Glenn, Francis Juanes, and Adrian Jordaan. "Fish and Hydropower on the U.S. Atlantic Coast: Failed Fisheries Policies from Half-Way Technologies." *Wiley Online Library*. 2013. http://onlinelibrary.wiley.com/doi/10.1111/conl.12000/full.

[17] Kraft, Amy. "Upstream Battle: Fishes Shun Modern Dam Passages, Contributing to Population Declines." *Scientific American*. 2013. http://www.scientificamerican.com/article/upstream-battle-fishes-shun-modern-dam-passages-population-declines/.

[18] "How Fish Lifts Work." *Safe Harbor Water Power Corporation* n.d. http://www.shwpc.com/fishlift.html.

[19] Travade, F., and M. Larinier. "FISH LOCKS AND FISH LIFTS." *Knowledge and Management of Aquatic Ecosystems Journal*. 2002. http://www.kmae-journal.org/articles/kmae/pdf/2002/04/kmae2002364s102.pdf.

[20] Gray, Richard. "Third of Freshwater Fish Threatened with Extinction." *The Telegraph*. 2011. http://www.telegraph.co.uk/news/earth/wildlife/8672417/Third-of-freshwater-fish-threatened-with-extinction.html

Addressing the Problem

This destruction of fish populations is not inevitable, and there are four key areas where hydropower could be improved. The first is to identify areas in need of further research. Hydropower experts have found that "A noticeable asymmetry still exists between salmonids and non-salmonids fish passages in terms of information, research funds availability, human resources, availability of technological tools, etc."[21] Conducting research into improving ways to accommodate a wider variety of species in more scenarios could minimize the most persistent failures of fish passes. Some of these issues are already being tackled. The Bureau of Reclamation, for instance, is currently offering a $20,000 prize for innovative new downstream fish passage ideas in a competition beginning March 31, 2016.[22] However, many areas in need of more research remain. For instance, researchers were puzzled to find that American shad easily climb fish ladders on the West Coast but have unusual trouble finding and using fish ladders on the East Coast.[23] This is just one of many instances in which a fish passage solution which proved effective in one instance fails miserably in a different environment. Figuring out how ecological, physiological, and behavioral factors affect how fish use passages is essential to determining which fish passage technology is appropriate in any given situation.

The second change which would help address failures in fish passage would be an improved strategy for measuring and enforcing fish passage effectiveness. Currently, the Federal Energy Regulatory Commission requires that dams seeking a renewal of their 30-50 year license implement some form of fish passage and report on how many fish are successfully passed.[24] Even though individual dams record this information, it was not until 2013 that Jed Brown's team of scientists combined information on all the dams along one river and discovered that reality was falling disturbingly short of fish passage goals. Regularly performing this type of analysis as part of a comprehensive program to record fish passage efficiency for the river as a whole could provide the hydropower industry with a more accurate impression of the effects dams are having on fish populations. With a centralized location where data from all dams along a river was analyzed together, policymakers could better judge whether fish passage goals are realistic and effective, enforcers hold deficient dams responsible for doing their part to protect vulnerable species on the river.

If the environmental problems associated with dams cannot be solved, a third way to improve hydropower might be to turn to microhydro, which runs water through turbines without damming the river, as shown in Fig. 6.[25] There are some disadvantages of this technology compared to large hydro, including lower power generation capacity and seasonal fluctuations in electricity production, costs are fairly low both economically and environmentally. Discussing the full range of benefits and challenges of micro hydro is outside the scope of this paper.

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[21] "FISH PASSAGE 2015 Abstracts Review." *University of Massachusetts Amherst*. 2015. https://fishpassage.umass.edu/sites/default/files/FP2015/Fish%20Passage%202015%20Abstracts%20Overview.pdf.

[22] Bureau of Reclamation. "Downstream Fish Passage at Tall Dams." *U.S. General Services Administration* n.d. https://www.challenge.gov/challenge/downstream-fish-passage-at-tall-dams/ .

[23] Adams, Jill U. "Fish Ladders and Elevators Not Working." *Science*. 2013. http://www.sciencemag.org/news/2013/01/fish-ladders-and-elevators-not-working.

[24] "The Federal Role in Fish Passage at Hydropower Facilities." *Princeton*. 1995. https://www.princeton.edu/~ota/disk1/1995/9519/951907.PDF.

[25] "Micro-Hydro Electric Power." *K.C. Larson, Inc.* n.d. http://www.kclarson.com/Micro-Hydro-Electrical-Power.php.

The fourth and final final way to prevent the slaughter of fish populations is the most extreme. Some hydropower dams inflict such great damage on the environment in comparison with the electricity they provide that removing the dam may be the only environmentally responsible option. The process isn't cheap; the removal of a large dam can stretch into the tens or hundreds of millions of dollars and take years.[26] People must also be wary of the environmental effects of allowing the large amount of sediments which build up behind a dam to wash downstream when the dam is removed. When the Elwha River was undammed, 24 million cubic yards of sediments (the equivalent of 50,000 dump-truck loads) were swept downstream. For the next 3-10 years, "Dramatic increases in turbidity are expected to kill fish and diminish spawning success as well as affect water for drinking, hatcheries, and a paper mill."[27] Despite these environmental costs, dam removal has proved to be largely positive for the Elwha River. Salmon and steelhead are spawning in increased numbers above the dam, and scientists predict that soon river ecosystems and the beaches around them will be healthier than while the dam was present. In cases like this, dam removal may be the only option to save a sickly ecosystem and may justify the economic and environmental costs.

Conclusion

Colonial accounts used to marvel at rivers "running silver" with millions of migrating fish.[28] Today, these same rivers struggle to support only a sliver of those historic numbers. As an industry, hydropower is not doing enough to protect these vulnerable species. Even at the occasional fish-friendly dam, hydropower still might not be clean. Fish passage is only one item on hydropower's environmental rap sheet, which includes silting of riverbeds and changes to the temperature, nutrient content, and oxygen concentration of water.

The existence of these environmental costs doesn't mean that the world should permanently abandon hydropower as an energy source. Hydroelectric power has the ability to provide enormous amounts of urgently-needed cheap electricity for people in developing nations, and it reduces greenhouse gas emissions from burning fossil fuels. If we can discover ways to mitigate the most harmful aspects of hydropower, then perhaps hydro can benefit people across the globe. Before hydropower can have a prominent future in an increasingly environmentally conscious world, however, it must leave smaller ecological footprint... and fin-print.

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[26] Lieb, Anna. "The Undamming of America." *PBS*. 2015. http://www.pbs.org/wgbh/nova/next/earth/dam-removals/.

[27] Nicole, Wendee. "Lessons of the Elwha River: Managing Health Hazards during Dam Removal." *Environmental Health Perspectives* n.d. http://ehp.niehs.nih.gov/120-a430/.

[28] Waldman, John. "Running Silver: Restoring Atlantic Rivers And Their Great Fish Migrations." *Amazon*. 2013. http://www.amazon.com/Running-Silver-Restoring-Atlantic-Migrations/dp/0762780592.