Passing Judgment on Fish Passage Technologies

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Introduction

For millennia, the Elwha River in Washington was the annual spawning site of a vibrant array of species of salmon and trout. 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. Each year, confused salmon were seen bumping their heads against the bases of the dams in a futile attempt to migrate upriver to their historic spawning grounds.[2] The salmon population plummeted 98%,[3] depriving the Lower Elwha Klallam Tribe of the supply of fish they once relied on.[4] Eventually, Congress judged that the environmental damage caused by the dams was too great and ordered their removal in 1995.[5] The results were dramatic. After just a couple years, salmon had returned to the river to spawn, and animals such as birds which feed on fish 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,

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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.

hydropower stands out as an environmentally friendly candidate. The devastating toll a hydroelectric dam takes on fish populations, however, shows that hydro is not so green after all.

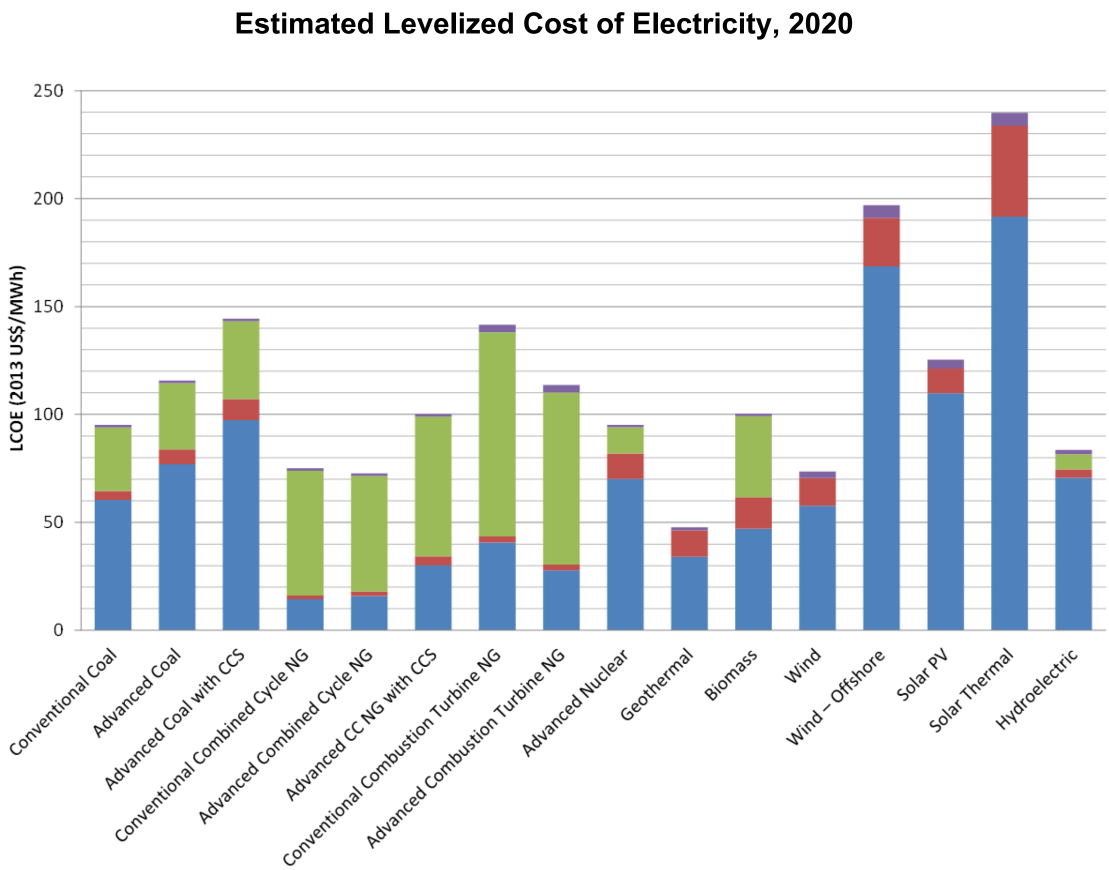

Figure 1: Predicted 2020 cost of various conventional and renewable energy sources, estimated from the Energy Information Administration's 2015 Annual Energy Outlook.

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. Recognizing the economic benefits, many developing nations, primarily located in Asia and South America, are considering hydropower as a potential

[7] "Levelized Cost of New Electricity Generating Technologies." *Institute for Energy Research* n.d. http://instituteforenergyresearch.org/studies/levelized-cost-of-new-generating-technologies/ .

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 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[9] other species. As they migrate upriver to spawn, they transport marine minerals. In fact, trees on the banks of spawning rivers gain 22-24%[10] 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 billion-dollar fishing industry which involves tens of thousands of jobs per year. Although it is difficult to attach a numerical value to a fish's life given the variety of economic, cultural, and environmental considerations needed, a study which estimated the marginal value of steelhead trout in various Oregon rivers found that the preservation of a single fish was valued at an

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[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.

[9] Ed Hunt. "137 Species Rely on Pacific Salmon." *Salmon Nation* n.d. http://www.salmonnation.com/fish/137species.html.

[10] Bakke, Bill. "Salmon Create Their Own Habitat." *Native Fish Society*. 2015. http://nativefishsociety.org/wp-content/uploads/09-September-CONSERVATION-AND-SCIENCE-REPORT2.pdf.

average of $149 and in one river was worth as much as $456. These high price values reflect how connected fish welfare is to human welfare; when fish populations disappear, humans are harmed as well.

Fish Passage: Problems and Solutions

Without effective fish passage techniques, hydroelectric dams (shown in Fig. 2)[11] disrupt the passage of fish up and down the river. These dams pose the most severe threat to anadromous

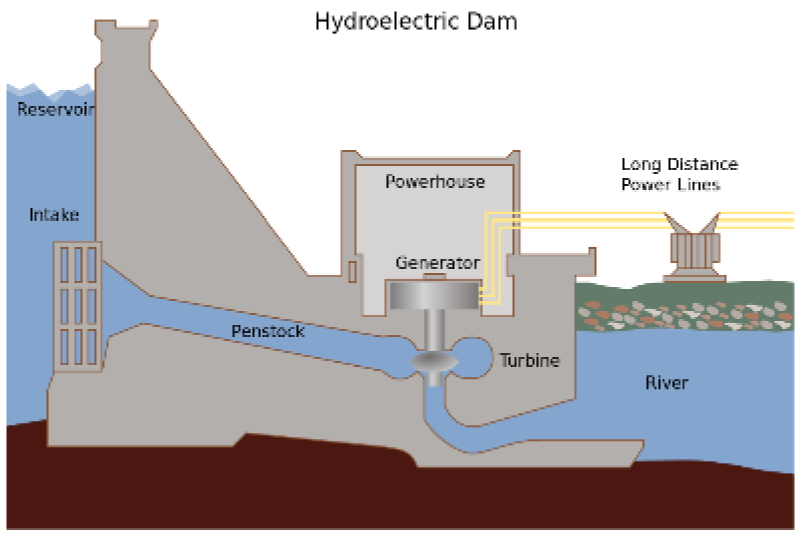


Figure 2: Diagram of a conventional hydropower dam.

fish such as salmon, which live in the ocean but annually migrate upriver to spawn. Without upstream fish passage technologies, many fish cannot find their way to breeding grounds and are unable to reproduce. Even if fish do manage to pass the dam, returning 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, causing internal injuries including eyes bulging and the stomach

[11] Tomia. "Hydroelectric Dam." *Wikiversity*. 2007. https://en.wikiversity.org/wiki/Power_Generation-hydro_Power .

bursting through the mouth.[12] Without some form of fish passage, dams effectively become fish graveyards.

To address these issues, an array of fish passage technologies have been implemented. Most upstream fish passes can be categorized as variations on fish ladders (see Fig. 3)[13] or fish elevators, which crowd fish into a small container and lift them over the dam. Downstream fish passes include cues such as lights, sounds, and bubbles which direct fish to bypass pipes or sluices which carry them to the other side of the turbine. Alternatively, dams can periodically release water through a spillway over the dam, carrying fish over as well.

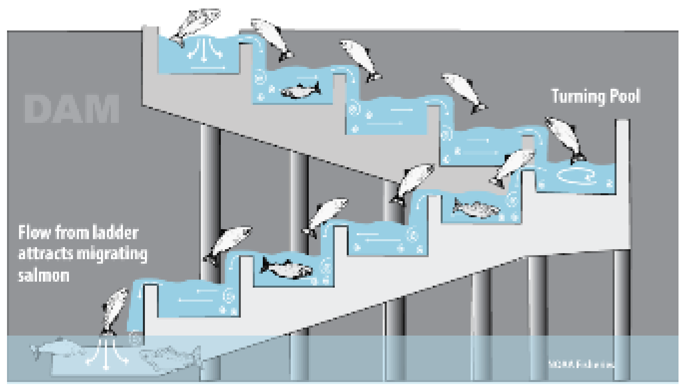


Figure 3: A salmon fish ladder. Fish ladders are generally species-specific.

The Big Question: Is Fish Passage Working?

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

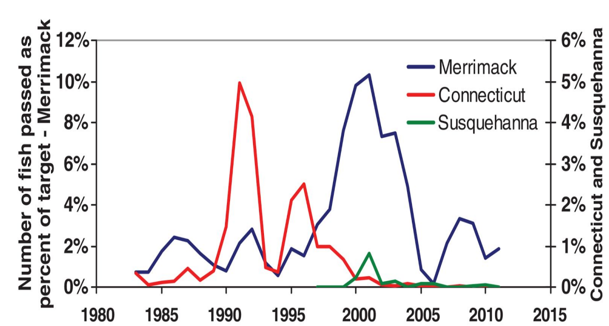
Assessing the effectiveness of fish passage at a dam is not easy. Although individual dams often record how many fish pass their dam, there is no centralized location where the data is collected to determine the cumulative impact on species which must navigate rivers blocked by multiple dams. In 2013, fish ecologist Jed Brown led a team which conducted a study of several dams

[12] Roach, John. "Fish-Friendly Dams? Scientists Race to Reduce Turbine Trauma." *NBC*. 2014. http://www.nbcnews.com/science/environment/fish-friendly-dams-scientists-race-reduce-turbine-trauma-n79936.
[13] 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.

along three major East-coast rivers.[14] 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."[15]

The study reached a grim conclusion: fish passage technologies are not effective.



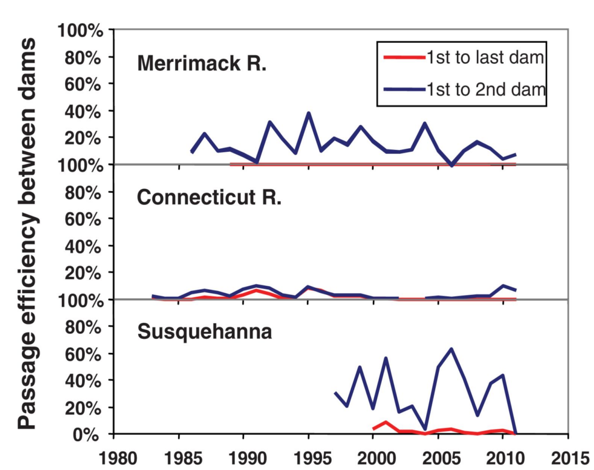


Figure 4: Data from Brown's research on fish passage along three major East Coast Rivers. No river passes more than 12% of its target, and almost no fish could navigate over every dam.

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 attempting to navigate the dam heading downstream 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. The proportion of adults which do not make it back down to the ocean is so great that, according to one author of Brown's study, "We've taken species that spawn more than once in their lives and turned them

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

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

into one-time spawners.”[16] 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.[17] Fish populations cannot sustain such heavy losses in the long run. Unless the industry can rethink fish passage, hydropower can never become a truly environmentally friendly power source.

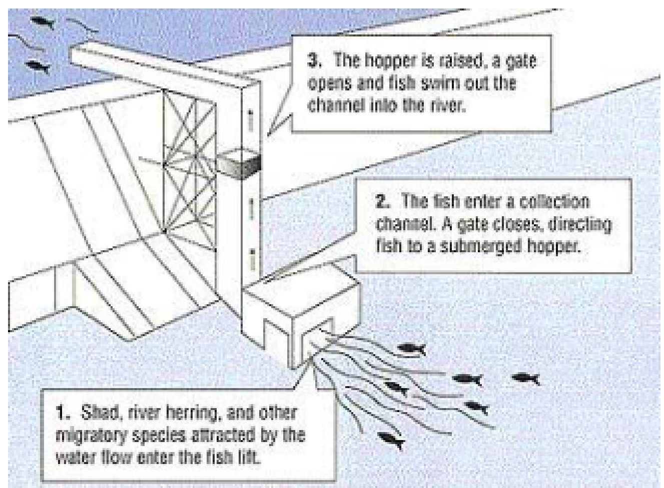


Figure 5: A fish lift

Another 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.[18] 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 weaker fish such as sturgeon and bass, which have very little jumping ability.[19] This problem is avoided with

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[16] 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/.
[17] “Dams and Migratory Fish.” *International Rivers* n.d. https://www.internationalrivers.org/dams-and-migratory-fish.
[18] 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.
[19] 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/.

fish lifts and elevators like that in Fig. 5,[20] 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 they migrate in large shoals.[21] When this dense group of shad reaches the fish elevator, there are too many fish present to be transported in a timely manner. 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 are classified as "threatened."[22] 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.

Fixing Fish Passage

Though preserving fish populations in dammed rivers is a complex issue, there are key improvements which would improve fish passage at dams. 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."[23] Conducting research

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

[21] 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.

[22] 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

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

into improving ways to accommodate a wider variety of species could help protect less numerous, potentially endangered species. Some research challenges 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 which began March 31, 2016.[24] 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.[25] 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.

Another change which could 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.[26] 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 a 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 is analyzed together, policy-makers could better judge whether fish passage goals are realistic and effective, and enforcers could hold deficient dams responsible for doing their part to protect vulnerable species on the river.

[24] 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/ .
[25] Adams, Jill U. "Fish Ladders and Elevators Not Working." *Science*. 2013. http://www.sciencemag.org/news/2013/01/fish-ladders-and-elevators-not-working.
[26] "The Federal Role in Fish Passage at Hydropower Facilities." *Princeton*. 1995. https://www.princeton.edu/~ota/disk1/1995/9519/951907.PDF.

When Fish Passage Can't Be Fixed

In some situations, there may be no practical method of achieving cost-effective and reliable fish passage at an environmentally destructive dam. This may be the case because the dam in question is simply too large, because the reservoir above the dam has such slow-moving water that fish cannot easily find their way out of the reservoir to continue their journey upstream, or simply because collected empirically shows that efforts at fish passage are failing. Some hydropower dams inflict such great damage 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.[27] People must also be wary of the environmental effects of removing the dam. Silt and sediments which build up behind the dam, for instance, can kill fish and diminish water quality.[28] Mitigating this environmental damage, for instance by installing water treatment plants, further increases dam removal costs.

Despite these environmental costs, dam removal has proved to be largely positive for many people and ecosystems along rivers where dams were successfully removed. It is difficult to determine when the benefits will outweigh the costs. Costs vary widely based on the size and location of the dam, as well as the extent of the restoration program after the removal of the dam. Benefits of dam removal are equally difficult to estimate. While some tangible benefits can be easily estimated (such as increased fishing revenues), others, such as the value of the preservation of an endangered species or the restoration of an ecosystem, are far harder to estimate. To give a rough estimate of how costly dam removal is, I will examine the costs and benefits of removal of the Klamath River Dams.

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

[28] 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/.

In April 2016, California governor Jerry Brown signed an agreement ending the years-long controversy over the Klamath Dams.[29] Since the first dam was erected in 1922, the passage of salmon, steelhead, and lampreys was completely blocked. The Karuk and Yoruk tribes living in the Klamath River Basin were not consulted when the dams were installed. These tribes, who were known as the "Salmon People,"[30] were cut off from the salmon which were a central part of their economy, nutrition, and culture.[31] The removal of the dams will reopen 420 miles of the river, hopefully increasing salmon populations, bolstering the river ecosystem, and restoring salmon runs for the Indian tribes.

To roughly estimate of the cost of such a large project, I divided the removal costs into three major costs: forfeited hydropower generation revenue, the cost of physically removing the dams, and the cost of monitoring and mitigating environmental damage caused by the dam removal.

The foregone hydropower profit can be modeled as

$$Lost\ Profit\ =\ (years)[(theoretical\ capacity)(capacity\ factor)(Electricity\ cost) - (O\&M\ cost)].$$

Variable Descriptions

Years - number of years until the end of the hydropower dam's lifetime

Capacity - maximum theoretical power capacity which the dam could produce

Capacity factor - proportion of the maximum capacity which is actually produced

Electricity price - the price the hydropower electricity is sold for

O&M cost - operations and maintenance costs

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[29] Mapes, Jeff, and Cassandra Profita. "Klamath Dam Removal Plan Revived By States And Feds." *Oregon Public Broadcast*. 2016. http://www.opb.org/news/article/klamath-dam-removal-plan-revived/.

[30] Minard, Annie. "Busting Up Klamath River Dams Could Be Boon to Tribes and Salmon." *Indian Country Today Media Network*. 2011. http://indiancountrytodaymedianetwork.com/2011/09/27/busting-klamath-river-dams-could-be-boon-tribes-and-salmon-54018.

[31] Gertz, Emily J. "Removal of 4 Dams to Reopen 420 Miles of Historic Salmon Habitat on Klamath River." *EcoWatch*. 2016. http://ecowatch.com/2016/04/07/dam-removal-klamath-river/.

First, we can estimate the remaining years of operation for each dam. Hydropower dams have an expected lifetime of 50-100 years.[32] All four of the Klamath dams have already passed the 50 year marker, and some are nearing their 100th anniversary (half will turn 100 within the decade). I will assume that each of these dams will each last 100 years from the date they were built until when they must be dismantled or undergo substantial costly repairs.

The capacities of the four dams are listed in Table 1. The capacity factor, the fraction of the theoretical capacity which is typically produced, is about 0.5 at an average dam,[33] but since the dams are so old and have not been upgraded with newer technology, I predict that the capacity factor will be lower - potentially around 0.3. This quantity is multiplied by the price of electricity. I have estimated this cost as 16.32 cents per kWh,[34] the average price of California electricity produced by PacifiCorp, the company which owns the dams.

According to the International Renewable Energy Agency, the operations and maintenance (O&M) costs of a hydropower dam are approximately 1-4% of the initial startup fees.[35] Because these dams are so old, I predict that maintenance fees will be near the upper end of this range. Therefore, these calculations assume that O&M costs are 4% of the installation costs of similarly sized hydropower dams, which cost approximately 1500 USD/kW.[36] Substituting values into our equation, we can solve for the lost hydropower revenue for each of the four dams. Results are summarized in Table 1.

[32] "Advantages of Hydroelectric Power Production and Usage." *U.S. Geological Survey*. 2016. http://water.usgs.gov/edu/hydroadvantages.html
[33] "Renewable Energy Technologies: Cost Analysis Series: Hydropower." *International Renewable Energy Agency*. 2012. http://www.irena.org/documentdownloads/publications/re_technologies_cost_analysis-hydropower.pdf.
[34] "Residential Price Comparison." *Pacific Power*. 2014. https://www.pacificpower.net/about/rr/rpc.html
[35] "Renewable Energy Technologies: Cost Analysis Series: Hydropower." *International Renewable Energy Agency*. 2012. http://www.irena.org/documentdownloads/publications/re_technologies_cost_analysis-hydropower.pdf.
[36] "Renewable Energy Technologies: Cost Analysis Series: Hydropower." *International Renewable Energy Agency*. 2012. http://www.irena.org/documentdownloads/publications/re_technologies_cost_analysis-hydropower.pdf.

Table 1: Breakdown of the Costs/Benefits of Dam Removal							
Dam	**Year Built**	**Dam Height**	**Dam Length (ft)**	**Maximum Power Capacity (MW)**	**Remaining Years**	**Lost Hydropower Profit (2012 USD)**	**Removal Costs (2012 USD)**
J.C. Boyle	1958	68	692	98	42	1,518,000,000	31,000,000
Copco 1	1922	135	410	20	6	44,000,000	6,000,000
Copco 2	1925	33	335	27	9	90,000,000	5,000,000
Iron Gate	1962	189	740	18	46	305,000,000	11,000,000
					TOTALS	1,957,000,0000	53,000,000
Cost estimation data for the four dams. The columns in blue are confirmed information about the dams, all found in the Klamath Dam Removal Overview Report for the Secretary of the Interior. The columns in green are estimations.							

A second major cost involved in dam removal is the cost of physically removing the facilities. To estimate the cost of removing these four dams, I predicted that there would be a positive correlation between project cost and size of the dam (crest length times head height). After deriving a linear best-fit line based on data from several other removed dams,[37] I estimated that the combined cost of removing the four dams will be approximately $53 million. Breakdowns of the removal costs for each dam are listed in Table 1.

A third and final major removal cost is the money used to monitor the environmental impact of the project and take any necessary mitigation measures (for instance, dredging the river to minimize deterioration of water quality and its impact on both fish and humans. The Klamath Dam Removal Overview Report for the Secretary of the Interior estimates that these amount to

[37] "Dam Removal Costs." *University of Rhode Island* n.d. http://www.edc.uri.edu/restoration/html/tech_sci/socio/costable3.htm.

35% of the removal costs of the project.[38] We can calculate that these environmental costs are about $19 million. Summing these costs, we get a total cost of approximately $2.03 billion.

To predict the tangible benefits of restored fish populations, I will estimate potential increased fishing revenue. This number comes from multiplying a reasonable wholesale cost per pound of chinook salmon, $4.50/lb,[39] by an estimated 25 lbs per salmon[40] to get $112.50/fish. The Klamath Dam Removal Overview Report for the Secretary of the Interior reports that the population of Chinook salmon (one of the most commonly harvested species in the river) declined 88-95% from historical levels.[41] Since estimates say the population of Chinook salmon has declined to about 142,200,[42] we can estimate that historically there were about 2.8 million fish. If we assume that each year 5% more fish return than the previous year until we return to historical levels and that each year 5% of the present fish are harvested, then over the course of 50 years (the estimated amount of time until the end of the lifecycle of the newest of the four dams), people would gain approximately $171 million. Table 2 summarizes the costs and benefits of the project, showing that overall dam removal would result in a net $1.9 billion cost.

Table 2: Overall Costs/Benefits of Dam Removal	
Forfeited Hydropower	-$1,957,000,000
Dam Removal	-$53,000,000
Environmental Protection	-$18,000,000
Increased Fishing Revenue	$171,000,000
Total	-$1,857,000,000

Total estimated costs/benefits over 50 years of removing the Klamath River Dams.

[38] "Dam Removal Costs." *University of Rhode Island* n.d. http://www.edc.uri.edu/restoration/html/tech_sci/socio/costable3.htm.
[39] "Alaska Salmon Price Report."*Seafood Market Bulletin*. 2013. http://www.alaskaseafood.org/industry/market/January2014SMB/salmon-price-report.html.
[40] "Chinook Salmon." 1996. http://www.psmfc.org/habitat/edu_chinook_facts.html.
[41] "Dam Removal Costs." *University of Rhode Island* n.d. http://www.edc.uri.edu/restoration/html/tech_sci/socio/costable3.htm.
[42]Houston, Will. "Poor Season Forecast for Klamath Chinook Salmon." *Times Standard* n.d. http://www.times-standard.com/article/NJ/20160305/NEWS/160309925.

Initially, these cost calculations suggest that the removal of the Klamath Dams is unfeasible. Over 50 years, increased revenue from fishing would only regain about 8% of the costs of removing the dam. In terms of quantifiable economic costs and benefits, dam removal appears to be an extreme and impractical measure. However, in many situations, there may be the substantial costs and benefits beyond those considered in my limited cost estimation. This is certainly true in the case of the Klamath Dams. If not removed, the dams would have needed to have been relicensed almost immediately, and the dam owners would still have been forced to expend huge amounts of money on implementing new infrastructure to meet the FERC's modern fish passage and environmental protection requirements. Some of the cost/benefit models created even estimate that the cost of upgrading the dams could be millions of dollars more expensive than removing them. The intangible benefits of removing the dams has also probably been underestimated. The Klamath Dam Removal Overview Report for the Secretary of the Interior estimates over $15 billion[43] in "nonuse value" of a restored open river - even if an individual does not intend to directly benefit from the restoration of the river, they may still value the open river for its beneficial effect on fish, ecosystems, or people in communities along the river. Although in this case it appears that special circumstances surrounding the Klamath Dams make dam removal a feasible option, in most cases this cost estimation is probably a more reliable estimate of the true costs and benefits in consideration. Dam removal is a costly option which is only likely to be practical as a last resort on rivers where implementing fish passage is especially costly or infeasible. Although effective fish passage would certainly be a more attractive option, in some situations, this may be the best choice we have.

Conclusion

Colonial accounts used to marvel at rivers "running silver" with millions of migrating fish.[44] 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

[43] "Chinook Salmon." 1996. http://www.psmfc.org/habitat/edu_chinook_facts.html.
[44] 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.

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, however, does not mean that the world should permanently abandon hydropower. Hydroelectric power has the ability to provide enormous amounts of urgently-needed cheap electricity for people in developing nations, and it prevents 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. Until then, however, some dams may have to be removed to protect river ecosystem and fish populations. 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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