# Fish and hydropower on the U.S. Atlantic coast: failed fisheries policies from half-way technologies

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## Abstract

Globally, diadromous species are at risk from fragmentation by damming of rivers, and a host of other anthropogenic factors. On the United States Atlantic Coast, where diadromous fish populations have undergone dramatic declines, restoration programs based on fishway construction and hatcheries have sustained remnant populations, but large-scale restoration has not been achieved. We examine anadromous fish restoration programs on three large Atlantic Coast rivers, the Susquehanna, Connecticut, and Merrimack with multiple mainstem hydropower dams, most with relatively low generating capacity. Mean passage efficiencies through fishways on these rivers from the first dam to the spawning grounds for American shad are less than 3%. The result is that only small fractions of targeted fish species are able to complete migrations. It may be time to admit failure of fish passage and hatchery-based restoration programs and acknowledge that significant diadromous species restoration is not possible without dam removals. The approach being employed on the Penobscot River, where dams are being removed or provided the opportunity to increase power generation within a plan to provide increased access to habitat, offers a good model for restoration. Dammed Atlantic Coastal rivers offer a cautionary tale for developing nations intent on hydropower development, suggesting that lasting ecosystem-wide impacts cannot be compensated for through fish passage and hatchery technology.

## The problem of half-way technologies

Lewis Thomas in *Lives of the Cell* (1974) defined half-way technologies in medicine as "...the kinds of things that must be done after the fact, in efforts to compensate for the incapacitating effects of certain diseases whose course one is unable to do much about." Frazer (1992) applied the concept to sea turtle conservation where hatchery-raised individuals are released into the wild rather than addressing the causes of sea turtle decline. We consider an analogous case on the U.S. Atlantic Coast where half-way technologies have been employed to restore diadromous (freshwater-sea) migratory fish populations that have been severely reduced by the presence of dams.

## Fishways and hatcheries as half-way recovery technologies

Historically, Atlantic drainages supported runs of about one-dozen diadromous fishes, including Atlantic salmon *Salmo salar*, American shad *Alosa sapidissima*, alewife *A. pseudoharengus*, blueback herring *A. aestivalis*, Atlantic sturgeon *Acipenser oxyrinchus*, sea lamprey *Petromyzon marinus*, and American eel *Anguilla rostrata*. As the Industrial Revolution progressed, most rivers were blocked with mainstem dams to provide power (Hall *et al*. 2011), and consequently many runs of diadromous fishes became extirpated or greatly reduced (Gephard and McMenemy 2004; Hall *et al*. 2012; Stolte 1981). In response to the declines, states passed laws beginning in the late 1700s that required fish passage at dams. Unfortunately, these early attempts to provide passage were unsuccessful at maintaining or restoring populations, as were repeated efforts through the early 1900s. Most recent attempts to restore anadromous fish populations using fishways (fish ladders or fish lifts) began in the 1960s, mandated by project relicensing requirements of the Federal Energy Regulatory Commission (Gephard and McMenemy 2004) with the objective of providing access to historical spawning grounds (Schroeder *et al*. 2002). The fishways were intended to pass alosines, such as river herring (alewife and blueback herring) and American shad, as well as Atlantic salmon. Additionally, large-scale hatchery operations introduced hundreds of millions of fry through stocking programs. Currently, Atlantic salmon and Atlantic sturgeon are listed and river herring and American eel have been petitioned for listing under the U.S. Endangered Species Act.

## Evaluation of management policies: fish passage and hatcheries

On the U.S. Atlantic Coast, mainstem dams on larger rivers are primarily used by private companies to generate electricity from hydropower, and are generally expected to maintain passage of diadromous species at some target level. A simple metric to gauge the effectiveness of fish passage facilities at dams is to measure their efficiency at passing fish. In systems with multiple dams, system-wide efficiency evaluates the number of fish that reach their most upstream spawning destination versus those that pass the first dam. High efficiencies at mainstem dams are critical in passing anadromous populations to historical spawning areas in sufficient numbers to sustain robust abundances.

Fish passage efficiency data for large Atlantic Coast rivers (Fig. 1; see Supporting Information) show that, despite using modern engineering approaches, fishways have been largely ineffective. Of American shad that passed the first dam, on average 4%, 16%, and 32% passed the second dam in the Connecticut, Merrimack, and Susquehanna Rivers, respectively. System-wide efficiencies for these three rivers in recent years have been <3%. Similar poor upstream passage efficiency has been noted for fishways in Europe (Larinier and Travade 2002), South America (Agostinho *et al*. 2007; Oldani and Baigún 2002; Oldani *et al*. 2007), and Australia (Mallen-Cooper and Brand 2007). Low passage efficiency and delays accrued at fishways impose significant energetic costs that reduce American shad survival (Castro-Santos and Letcher 2010) and therefore iteroparity (repeat spawning). The phenomenon of reduced repeat-spawning and consequent decreased mean size and age of adult American shad has occurred in the Connecticut River, resulting in lower population fecundity and probably lower annual recruitment (Leggett *et al*. 2004) in addition to the lost production from obstructed access to spawning grounds.

Spawning may occur below the first dam in some of these systems. For example, the first dam in the Connecticut River is at rkm 140 and may be a reason that this river tends to maintain somewhat robust shad returns at the first dam. Persistence of shad runs, albeit at low levels, is an indication that spawning is occurring below or between dams with fishways. Still, low passage efficiency reduces the population size contributing to between dam spawning. Ironically, the most robust runs of American shad in North America occur on the Columbia River, on the U.S. Pacific Coast where they are an exotic species, introduced from the U.S. Atlantic Coast. High abundances in the Columbia may be due to factors such as a release from native predators. Additionally, whereas the Columbia River has multiple mainstem dams with fishways, the first dam is very far upstream (Bonneville Dam at rkm 235) relative to the Atlantic Coast rivers considered here. Thus, while the large shad population may indicate that there is ample spawning habitat below the first dam on the Columbia River, this situation contrasts greatly with the rivers considered here. In the first 235 river kilometers there are 5, 3, and 4 hydropower dams on the Merrimack, Connecticut and Susquehanna rivers, respectively. Additionally, river flow on the Columbia is actively managed to enhance anadromous fish migration (Committee on Water Resources Management 2004). Furthermore, while American shad have done well in the Columbia, a number of other diadromous species have not (Ferguson *et al*. 2011).

Alternatively, Pompeu *et al*. (2012) argue that a positive trend in abundance of returning fish is a better metric to gauge the capacity of a fishway to maintain viable populations than passage efficiency. Although we do not disagree with this concept in principle, the purpose of the fishways highlighted here is to allow a large proportion of the fish to migrate to historical spawning areas, which is not happening. Additionally, while trends in American shad returns to the first dams are more or less static, they are much below stated restoration targets and historical levels (Fig. 1).

  

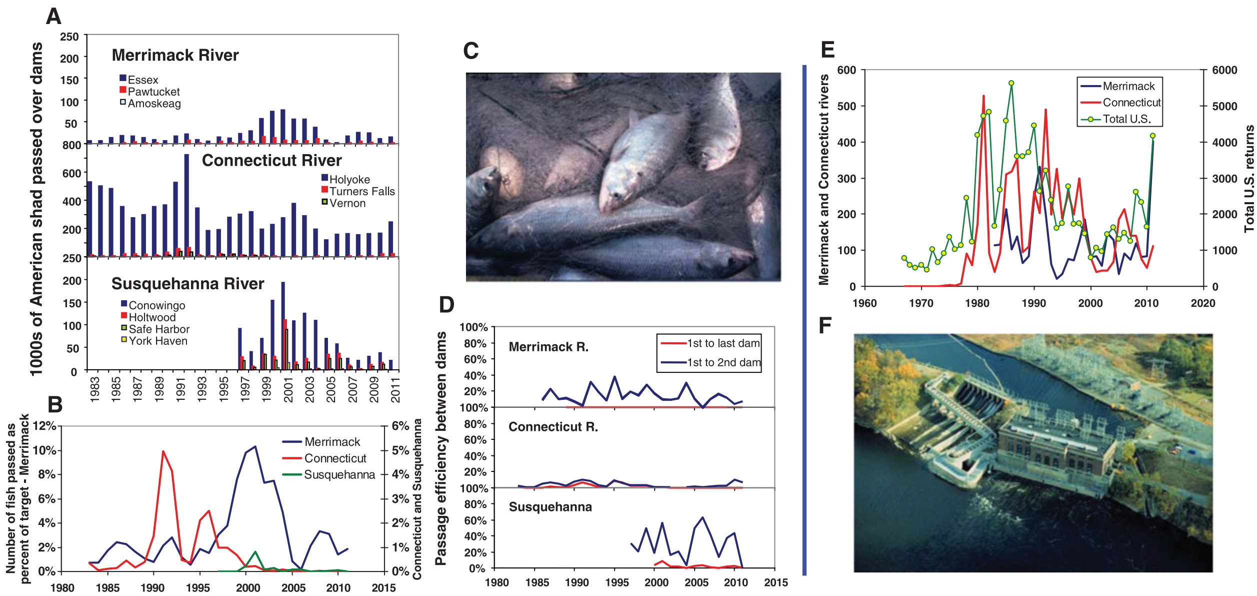


**Figure 1** Aspects of three failed restoration projects that targeted American shad (left-hand graphs), and two that targeted Atlantic salmon (graph on the right). The Susquehanna River, at 715 km and draining 71,225 $km^2$, is the largest river on the U.S. Atlantic Coast; the Connecticut River, the largest river in New England, is 640 km long and drains 29,138 $km^2$; and the Merrimack River is 177 km long and drains 13,000 $km^2$. (A) American shad upstream passage. Blue bars are counts at farthest downstream dams, followed by red, green, and yellow. No passage data are available at Turners Falls Dam (Connecticut River) in 2003, as passage was not monitored that year. (B) American shad passage efficiencies, calculated as the number of fish passed relative to stated restoration targets: Merrimack (target 744,083 American shad at Essex Dam, farthest downstream), Connecticut (target 750,000 American shad at Vernon Dam, third mainstem dam from the sea), and Susquehanna (target 2 million American shad at York Haven Dam, furthest upstream that passes shad). See Supporting Information for dam locations. (C) American shad (photo: K. Limburg). (D) Mainstem passage efficiencies between the most seaward dams and second most seaward dams (blue line), and between the most seaward dams and the furthest upstream dams for which alosine passage data are available (red line) on the Merrimack (Essex Dam–Pawtucket Dam–Amoskaeg Dam), Connecticut (Holyoke Dam–Turners Falls Dam–Vernon Dam) and Susquehanna (Conowingo Dam–Holtwood Dam–York Haven Dam). (E) Total Atlantic salmon returns (individual fish) to the Merrimack and Connecticut rivers and total Atlantic salmon returns to all U.S. rivers. (F) Cabot Station hydropower plant and fishway, Turners Falls, Connecticut River (photo: A. Haro, USGS).

Atlantic salmon restoration efforts have not yielded self-sustaining populations in any eastern U.S. river despite federal spending of hundreds of millions of dollars and the involvement of seven federal hatcheries (see Supporting Information). Although the pitfalls of relying on hatcheries for salmonid restoration have been detailed elsewhere (Hilborn 1992b, 1999; Levin *et al*. 2001), hatchery production has staved off extinction in a few rivers, albeit at the expense of genetic integrity (Lage and Kornfield 2006). In fact, in 2012 the United States Fish and Wildlife Service acknowledged lack of success in the hatchery-stocking component of the Connecticut River salmon restoration effort and terminated the program after 45 years. Unfortunately, solutions to poor passage success at mainstem dams, the cause of the original salmon extirpation from the system (along with overfishing), were never effectively addressed and will continue to impede any diadromous species restoration efforts.

Investments made to improve Atlantic salmon and shad stocks, which have been met by general failure, did not consider impacts on the full suite of diadromous species during fishway and hatchery intervention. For example, Atlantic sturgeon, striped bass *Morone saxatilis* American eel and rainbow smelt *Osmerus mordax* will not use conventional fishways (Gephard and McMenemy 2004), and thus these species may require specialized fishways, such as those specifically designed to pass elvers. Additionally, functioning fish passage facilities can be susceptible to failure during high flow periods. In 2005 and 2006, fishlifts in the Merrimack and Connecticut rivers were closed for much of the spawning season, resulting in low passage numbers; this also occurred in the Susquehanna River in 2011.

Similar to upstream passage, downstream passage is frequently problematic and, in some instances, seaward migrating adults and juveniles can be killed by attempting to pass through turbines (Kostecki *et al*. 1987; Mathur *et al*. 1994; Stier and Kynard 1986; Taylor and Kynard 1985). Even when downstream passage facilities are available, survival rates of migrating fish can be low (Blackwell *et al.* 1998) due to mechanical damage (Ferguson *et al.* 2008) or the increased predation that occurs as down migrating fish pass through chokepoints (Blackwell and Juanes 1998). The technology used for downstream fish passage often is ineffective or is not considered cost-effective by power companies (Novak *et al.* 2003; Pelicice and Agostinho 2008).

## The option of dam removal

An alternative to continued dependence on the status quo is dam removal. Fishes move readily to habitat opened through dam removal, resulting in increased diversity and abundances (Hart *et al.* 2002). Hydropower facilities do provide socioeconomically valuable outputs, but power production is only modest in Northeast U.S. river systems (see Supporting Information). In contrast, U.S. Pacific Coast hydropower plants generate large amounts of electricity, with some producing more than 1000 MW. The lower hydroelectric dams on the Merrimack, Connecticut, and Susquehanna rivers have a mean generating capacity of 14, 34, and 279 MW, respectively (two dams on the Susquehanna River have relatively higher capacities of 418 and 572 MW). Hydropower is valuable for meeting peak demand with reserve capacity and stabilizing the entire eastern U.S. electrical grid. Large capacity pumped-storage hydroelectric plants exist behind the second dam on the Connecticut River and first dam on the Susquehanna River. However, even in the Columbia and Snake Rivers with large power production, a federal judge recently struck down a salmon recovery plan due to deficient restoration actions (Service 2011a), reflecting greater recognition that under federal law, the onus and responsibility is on dam owners to ensure adequate passage. Thus, despite orders of magnitude greater power generation and economic importance, a compelling case for targeted dam removal can be made on the basis of poor fish passage and ineffective management plans alone (Ferguson *et al.* 2011; Service 2011a).

## Political and institutional impediments to dam removal on atlantic coast rivers

As fisheries resources dwindle, natural resources management agencies come under greater pressure to restore them, more funding is applied to the problem, more agency personnel are hired, and it becomes difficult to dismantle ineffective fish passage and hatchery programs (Hilborn 1992a, 1999). Many of these restoration programs, dependent upon institutionalized application of traditional technologies, have set goals which decades of efforts have demonstrated are unreachable (see Supporting Information). The result is displacement of primary restoration goals and greater agency emphasis on maintaining the organization (Warner and Havens 1968), on the ancillary benefits of these programs, such as education and outreach, and on providing additional recreational fishing opportunities—all of which overshadow the original intent of the restoration programs. Further, these programs along with stocking and trucking of individuals around dams will depend on annual efforts to remain successful and costs incurred are generally born by the public. Ironically, the third dam on the Merrimack has an educational center based around anadromous fish restoration, but in a typical year no anadromous fish pass through the facility.

There are political, economic, and social problems with advocating the removal of dams: hydropower is considered a renewable energy source, sediments stored behind dams would need mitigation of any environmentally deleterious impacts, and recreational activities that developed around the new river configuration would need to be addressed. Dam removals require a large one-time cost that can be significant, and the issue of who (e.g., taxpayers, rate payers, utility companies) should bear the cost of removal is frequently contentious (Stephenson 2000). Given uncertainties, and the controversial nature of assigning monetary values to ecosystem products like fishes not to mention the services they provide (Ziv *et al.* 2012), it is difficult to conduct an economic cost-benefit analysis on dam removal. However, monetizing ecosystem values may not be necessary for participants to support dam removals and ecosystem restoration (Gowan *et al.* 2006).

## The way forward

Historically, most of these rivers had Atlantic salmon runs on the order of tens of thousands (Stolte 1981), American shad runs on the order of millions (Lyman 1866; Mansueti and Kolb 1953; Stevenson 1899), and river herring runs on the order of millions or more likely tens of millions (Smith 1899). The reliance on half-way technologies, in concert with overfishing and diminished water and habitat quality has led to population reductions of 95 to 99%, with some extirpations (Limburg and Waldman 2009). However, overfishing is being curtailed by fishery management plans implemented by the Atlantic States Marine Fisheries Commission, and water quality has improved as a result of the implementation of the Clean Water Act (e.g. Kauffman *et al.* 2011). Mainstem river habitat quality would increase dramatically if dams were removed, as impoundments formed behind dams alter the natural flow regime and diminish habitat for anadromous and other native species (Poff *et al.* 1997). For example, there is evidence that drifting eggs and larvae can disappear in the lentic areas of impoundments, and never move downstream (Pompeu *et al*. 2012).

Population goals for restoration are rarely approached, and therefore fall well short of historic baselines. Mean passage of river herring at the first dam on the Merrimack, Connecticut and Susquehanna rivers from 2008 to 2011 fell to relict levels of 706, 86, and 7 fish, respectively. Atlantic salmon returns to the Connecticut and Merrimack Rivers are on the order of a few hundred or fewer fish despite decades of restoration efforts (Fig. 1E). The presence of dams limits each population's resilience, which magnifies impacts from other factors including incidental catch in fisheries, genetic bottlenecks, impaired habitat quality beyond that caused by dams, and climate change. It may be time to admit failure of fish passage and hatchery-based restoration programs and acknowledge that ecologically and economically significant diadromous species restoration may not be possible without dam removals.

Dam removal is not a new idea. Many tributary dams have been removed, but mainstem dam removals are rare (Service 2011b). The Edwards Dam on the Kennebec in 1999, and Embrey Dam on the Rappahannock in 2004 are the only mainstem dams on large (i.e. longer than 150 km) Atlantic Coast rivers to be removed through 2011. Dam removals have resulted in rapid re-colonization by anadromous fishes in the Kennebec (Crane 2009; MDMR 2004) and eels in the Rappahannock River (Hitt *et al*. 2012), and other hydrological and water quality improvement (Hart *et al*. 2002) in reopened rivers. We support this and the novel, whole ecosystem-based approach pioneered on the Penobscot River, Maine. A multi-partner trust was established to purchase three dams, remove the two lower-most dams, construct a fish bypass around the third dam, and give the dam owner the opportunity to increase generation at six existing sites. The result is maintenance of more than 90% of current energy generation while allowing unobstructed access to 100% of historical downriver habitat for sturgeons and striped bass and greatly improved access to nearly 1,600 km of upriver habitat for Atlantic salmon and alosines.

If real progress is to be made in diadromous fish restoration, mainstem hydropower dams need to be removed. Though dam removal may be expensive, it contrasts with the economic and ecosystem services lost due to reduced diadromous fish populations, and the hundreds of millions of taxpayer dollars spent on restoration without producing any measureable success. Due to the extrinsic factors referenced above, we cannot guarantee that dam removal will fully restore diadromous fish populations to historical levels. Thus dam removal may be a necessary, but potentially insufficient condition, for restoration. We believe the burden of proving that dams are not negatively impacting migratory fish populations should be on the dam owners, not on the public.

Methods for prioritizing the removal of fish passage barriers (or not building dams) have been reviewed elsewhere, and can vary from scoring and ranking to GIS approaches to optimization modeling (Kemp and O'Hanley 2010). Optimization modeling has been applied to river systems with hydropower dams (Kuby *et al*. 2005; Kemp and O'Hanley 2010). However, Kuby *et al*. (2005) did not believe that their work was appropriate for making policy relevant recommendations. Nunn and Cowx (2012) describe a simpler approach for prioritizing passage improvements/dam removals for diadromous fish that entails developing matrices that include data on fish stock status, passage efficiency at individual barriers, the difficulty of passage upstream to each barrier and the quality and quantity of habitat upstream to each barrier.

Dams pose a significant threat to global aquatic biodiversity, particularly impacting diadromous taxa of the Clupeiformes, Anguilliformes, Petromyzontiformes (Liermann *et al*. 2012). As the United States struggles to balance hydropower and fish restoration policy, there are numerous projects slated for construction throughout the developing world. China, Lao People's Democratic Republic (Laos) and Cambodia are on the verge of constructing 200, including 11 mainstem, dams in the Mekong River, the second most biodiverse freshwater system and host of the world's most productive inland fishery (Ferguson *et al*. 2011; Grumbine and Xu 2011; Ziv *et al*. 2012), and 151 dams planned in the Amazon River basin threaten highly migratory species (Finer and Jenkins 2012). In an effort similar to Brazil's focus on the Amazon, both Argentina and Chile have committed to a series of dams throughout Patagonia to meet future energy needs through hydropower. The Atlantic Coast, and indeed U.S. diadromous fish populations in general, offer a cautionary tale for developing nations, suggesting that lasting ecosystem-wide impacts cannot be compensated for through fish passage and hatchery technology. Given the enormous reliance on diadromous fishes as a source of protein in the developing world, loss of this "provisioning by nature" will likely have severely disruptive consequences on local societies.

Just as in the case of the Ridley sea turtle, U.S. river restoration efforts have relied on half-way technologies that are impeding measureable improvement of populations. Society must confront difficult, unavoidable tradeoffs among fish restoration, renewable power production and dam removal costs, and find compromises that ensure adequate fish migration to promote a long-term recovery of diadromous species. If society does not do so, and continues to promote the illusion of a "win-win" with dams and fish passage, we run the risk of losing diadromous species and further unraveling the connections between watersheds and marine ecosystems that provide important life support services to humans.

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## Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

**Table S1:** Merrimack River (Dams in Massachusetts and New Hampshire)

**Table S2:** Connecticut River (Dams in Massachusetts, New Hampshire and Vermont)

**Table S3:** Susquehanna River (Dams in Maryland and Pennsylvania)

**Table S4:** Restoration target species

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