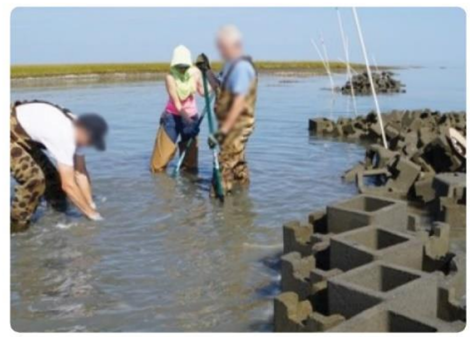

Case Study: Restoration of Aquatic Connectivity in the Hurricane Sandy Coastal Resilience Program

Contract # 5359

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FINAL

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Case Study: Restoration of Aquatic Connectivity in the Hurricane Sandy Coastal Resilience Program

Prepared by Abt Associates, September 2019

Summary

Purpose

This case study forms part of a larger 2019 evaluation of the Hurricane Sandy Coastal Resilience Program (Hurricane Sandy Program) of the U.S. Department of the Interior (DOI) and the National Fish and Wildlife Foundation (NFWF). It provides an analysis of the resilience impacts of aquatic connectivity projects.

Scope

We examined 19 projects in the Hurricane Sandy Program portfolio that were primarily focused on removing dams, improving fish passage, replacing or removing culverts, replacing low-head bridges, and/or improving instream habitat. These activities were designed to reconnect rivers and streams for fish and wildlife use and mitigate storm-related flooding and safety risks.

Findings

Key findings identified using information from archival materials, a survey and interviews of project leads, and peer-reviewed literature include:

- Dam removal and culvert replacement resulted in improved fish access to nearly 370 miles of upstream river habitat, supporting key species in the region.
- While nearly all projects were completed by the time of the evaluation, most were delayed by more than a year due to many factors, including permitting challenges, a loss of landowner cooperation, or the need to avoid harming wildlife with project actions.
- Early improvements in fish passage, water quality, and instream habitat have already been achieved by some projects.
- Dam removal lowered water elevations in project areas, reducing flood risk in nearby areas.
- For a subset of projects, dam removal improved human safety by removing risks associated with recreational activities and catastrophic dam failure.
- The observed ecological benefits of aquatic connectivity projects to date are consistent with expected time lags between restoration and ecological outcomes.
- Long-term ecological monitoring and detailed site-based modeling are needed to understand the full ecological and socioeconomic impacts of aquatic connectivity projects.

Conclusion

Taken together, these findings suggest that **Hurricane Sandy Program investments in improving aquatic connectivity have increased the resilience of natural and human communities close to restored areas.** The program enhanced fish access to a substantial amount of previously inaccessible freshwater habitat, which can improve fish productivity and survival, making those populations more resilient to disturbances. Similarly, people who live, work, or recreate near dams are less likely to be harmed by storms, through either reduced flood risk or improved safety.

1. Introduction

This case study forms part of a larger 2019 evaluation of the DOI and NFWF Hurricane Sandy Coastal Resilience Program (Hurricane Sandy Program). Between 2013 and 2016, the Hurricane Sandy Program, administered through DOI and NFWF, invested over $302 million to support 160 projects designed to improve the resilience of ecosystems and communities to coastal storms and sea level rise.[1] The program supported a wide array of activities, including aquatic connectivity restoration, marsh restoration, beach and dune restoration, living shoreline creation, community resilience planning, and coastal resilience science to inform decision-making. Each of these activities has a distinct impact on ecosystem and community resilience.

DOI and NFWF drafted the following questions to serve as the focus of the evaluation:

1. To what extent did projects **implement activities** as intended? What factors facilitated or hindered project success?
2. What **key outcomes** were realized for habitat, fish and wildlife, and human communities?
3. Is there evidence that investments in green infrastructure are **cost-effective** compared to gray infrastructure?
4. Did investments in tools and knowledge related to resilience **improve decision-making**?
5. What **information is needed** to better understand the long-term impacts of investments in resilience?

The evaluation includes six case studies, each providing a deeper level of analysis on a subset of the projects.

1.1 Purpose

This case study provides an in-depth analysis of resilience activities focused on "aquatic connectivity" and is specifically focused on evaluation questions #1, #2, and #5 (above). For the purposes of this case study, we define ***aquatic connectivity*** **as activities that enhance or re-establish the linkages between stream ecosystems, most typically up- and downstream of an existing dam or culvert that has blocked the free movement of water or aquatic organisms**. More specifically, this case study provides a fuller understanding of the nature and benefits of aquatic connectivity-focused projects, as well as identifying key lessons learned regarding aquatic connectivity project implementation and impact assessment.

1.2 Scope

We examined all 19 projects in the Hurricane Sandy Program portfolio that aimed to re-establish connected waterways and mitigate storm-related flooding and safety risks primarily through the following activities: removing dams, improving fish passage (through sill lowering or fish ladder installation), replacing or removing culverts, or replacing low-head bridges (see Section 3 for a more detailed description of the portfolio of aquatic connectivity projects and Appendix A for a full list of relevant projects).

[1] The evaluation covers these 160 projects. In some cases DOI and NFWF reinvested unspent funds in new, additional projects after the December 2016 cutoff date. These new projects are not included in the evaluation.

1.3 Organization

The remainder of this document is organized as follows:

- Section 2 provides an overview of the methods and information sources used for this case study
- Section 3 provides a detailed overview of the aquatic connectivity projects included in the Hurricane Sandy Program
- Section 4 discusses key case study findings, organized by evaluation question and topic
- Section 5 provides a brief conclusion.

2. Methods Overview

The case study integrates information from the following information sources:

- Archival materials from Hurricane Sandy Program project files (e.g., proposals, interim and final reports)
- A survey of project leads via a web-based instrument
- Interviews with seven project leads (i.e., grant recipients) who led aquatic connectivity projects
- Interviews with NFWF and DOI staff
- Quantitative information provided by project leads in their reports (e.g., miles of upstream river habitat newly accessible to fish)
- Literature searches addressing specific contextual issues (e.g., typical lag time between dam removal and the restoration of key ecological dynamics near and upstream of the dam).

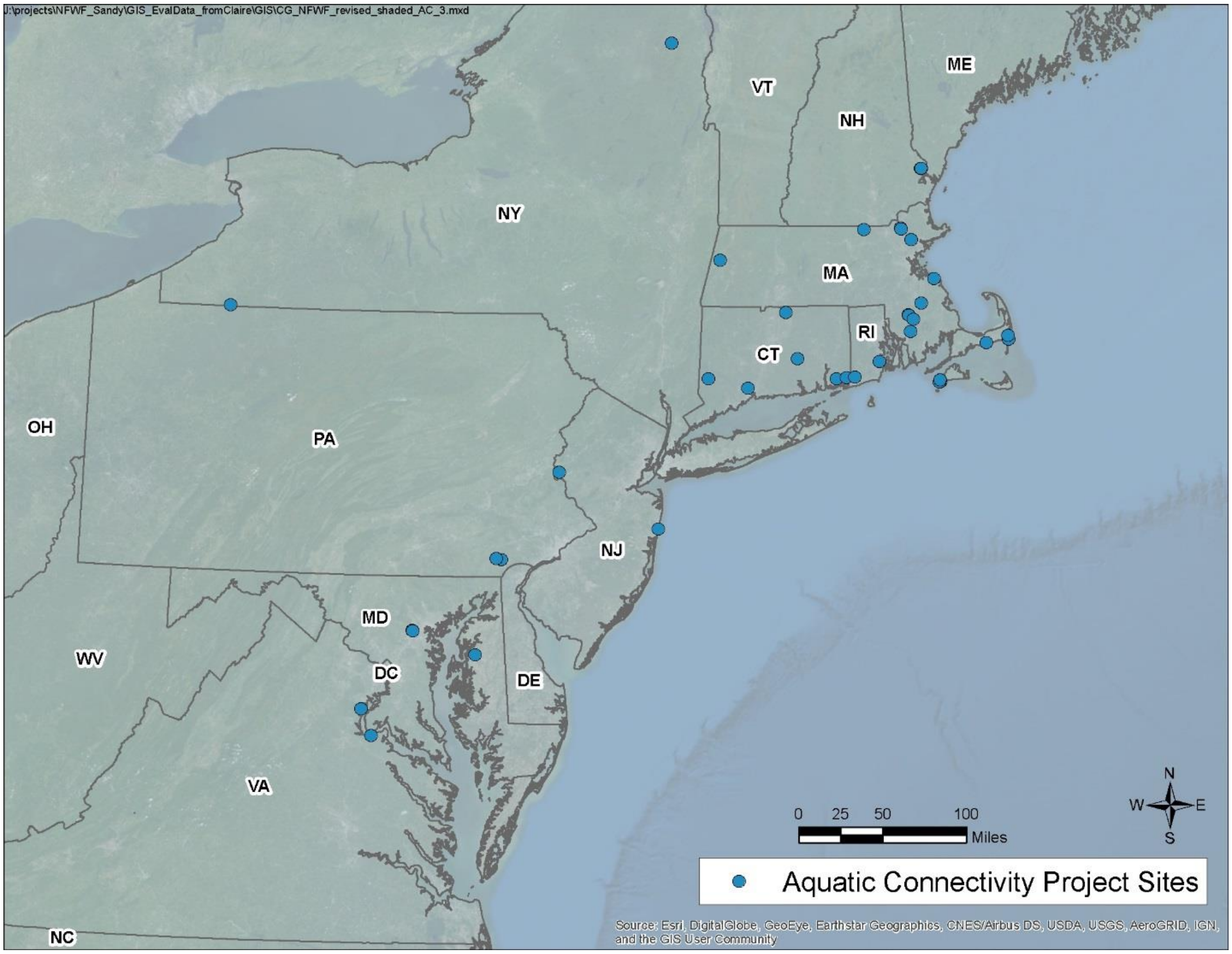
A more detailed description of evaluation methods can be found in Abt Associates (2019).

3. Overview of Projects

Throughout New England and the mid-Atlantic, dams that were once used to power mills, store power for local industries, or generate power are now disused. These dams, while once the center of economic activity for many communities, now degrade habitat and water quality, prevent fish passage to critical upstream habitat, and pose a threat to human property and safety during large storms, during which they can cause flooding and/or fail. In some instances, dams are an attractive nuisance, creating life-threatening conditions for the public. Poorly designed culverts can also prevent fish passage and cause flooding in nearby roadways. Restoration projects in the “aquatic connectivity” category, the focus of this case study, serve to re-establish connected waterways and mitigate storm-related flooding and safety risks primarily by removing dams, improving or replacing culverts or bridges, and improving fish passage.

Nineteen Hurricane Sandy Program projects, located in nine states, focused on the restoration of aquatic connectivity (Figure 1). Of these, 11 projects were administered by the U.S. Fish and Wildlife Service (USFWS) and 8 by NFWF. Most Hurricane Sandy Program aquatic connectivity projects were focused on dam removals, resulting in 23 dam removals overall (see Table A.1). In addition, 10 culverts were either replaced or improved to allow fish passage, one bridge was replaced, and multiple other barriers to fish passage were mitigated (see Table A.2). In addition to the habitat restoration provided by barrier removal, many projects also directly enhanced aquatic habitat, such as by removing sediment that was blocking culverts, or enhancing stream habitat through the placement of natural or artificial fish habitat structures. The dams removed had blocked fish access to upstream habitat for nearly 170 years on average (Figure 2). Overall, the Hurricane Sandy Program invested more than $30.6 million in aquatic connectivity in 19 projects (Table A.3), 3 of which also included other resilience activities; the total funding provided by the program for all of the activities in the 19 projects was $32.9 million.[2]

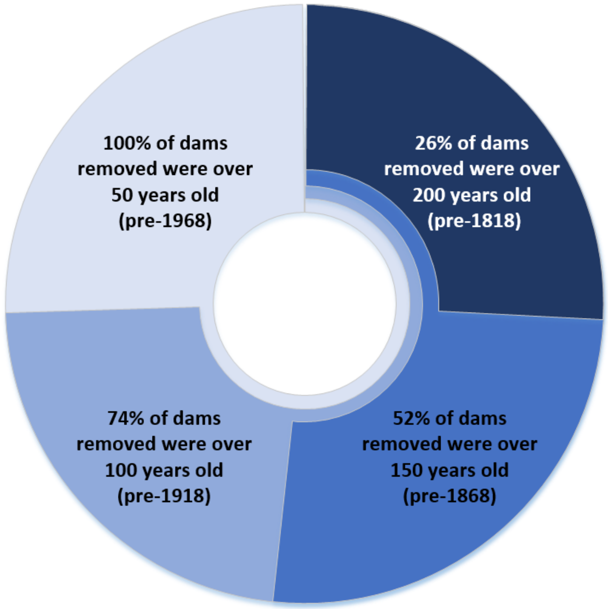
Figure 1. The location of aquatic connectivity restoration activities.[a]



a. Since many projects conducted restoration activities in multiple sites (see Appendix A), the number of aquatic connectivity restoration project sites (dots) in the figure exceeds 19.

[2] Table A.1 presents the amount of project funding specifically allocated to aquatic connectivity activities. For 16 projects, this was the full project funding amount. For three projects, this is a subset of the total project funding. The allocation was based on available project documentation.

Figure 2. Age of dams removed as part of the Hurricane Sandy Program. The dams removed had blocked fish access for decades to centuries.



4. Findings

Topic: Project Implementation (PI)

Finding PI.1: Nearly all projects have successfully completed their proposed activities.

Archival and web-based materials show that 15 out of the 19 projects have been completed,[3] with only 4 projects still in progress. Reviews of contract amendments showed that only one project incorporated a major change of scope, which involved changing the location of the dam removal.

Finding PI.2: A variety of factors delayed the implementation of most projects, including permitting challenges, weather, needed project design adjustments, a loss of landowner cooperation, or the need to avoid harming wildlife with project actions.

While most projects were completed by the end of the evaluation, a range of issues resulted in most projects experiencing significant delays compared to their original completion estimates. The data available through official contract amendments submitted to NFWF and DOI show that 15 of the 19 projects, covering multiple dam removal or culvert replacement sites, requested time extensions, often for a variety of reasons. According to these amendments, **permitting issues** were the most common cause of project delays (noted in contract amendments for eight projects). Multiple project leads in the survey and interviews noted that they found permitting to be a cumbersome and somewhat unpredictable process.

[3] While our evaluation generally provides findings elicited through the review of archival materials received through December 2018, project status information reflects information we gathered through April 2019 (updated project status information was obtained through a supplementary web search in March 2019 and an updated spreadsheet provided by NFWF).

Other reasons for delays included:

- Weather-related effects on restoration activities (noted in contract amendments for six projects),
- Required changes in restoration project design (six projects),
- Landowners rescinding permission to proceed with proposed project activities (four projects), and
- Delaying project activities to avoid harming wildlife during sensitive times of the year (e.g., avoiding construction during the migration or breeding seasons; three projects).

Topic: Project Outcomes (PO)

Below, we discuss the ecological and community-related outcomes achieved through the Hurricane Sandy Program aquatic connectivity projects. We also discuss whether the outcomes observed to date are consistent with expected trajectories of recovery after aquatic connectivity restoration.

4.1 Human Community Outcomes

Finding PO.1: Dam removal and culvert replacements and improvements lowered water elevations in project areas upstream of the former barrier, reducing flood risk.

A key potential benefit of dam removal is permanently reducing flood risk in nearby areas, particularly in urban environments where infrastructure is located close to dams. Dams and undersized culverts or bridges restrict peak flows upstream of the barrier during storms, and thus can cause localized flooding. Modeling done at 16 different Sandy dam removal sites anticipated reduced water elevations in all locations (see Table 1). While the flow conditions at which water elevation was assessed varied among project sites, mean water levels across projects consistently decreased in the area upstream of the former barrier, even during a modeled 100-year flood when the greater amount of water tends to reduce the benefit of the dam removal. Project leads also reported that flood risk was lowered in sites where culvert improvements or replacements widened river spans and improved the conveyance of water downstream (Box 1).

Table 1. Anticipated changes in water elevation upstream of the former dam after dam removal in 16 project sites, based on reported hydraulic modeling of different flow conditions and flood regimes. Negative values indicate a reduction in water elevation, and dashes indicate that no data were available for that simulation.[a]

State	Project ID	Dam name	Difference in water surface elevation before and after project completion (ft)				
			Average flow conditions	2-year flood	10-year flood	50-year flood	100-year flood
CT	NFWF-43378	Springborn Dam	-11.6	–	-12.8	-12.6	–
	USFWS-51	Pond Lily Dam	-7.4	–	–	–	-2.8
	USFWS-21	White Rock Dam	-2	-3	–	–	–
MA	USFWS-9	West Britannia Dam	–	-4.75	–	–	
	NFWF-42671	Balmoral Dam	–	-0.12	–	–	–
		Marland Place Dam	–	-3.42	–	–	-0.07
		Rattlesnake Brook Dam	-3.41	-2.8	-2.22	–	-1.12
		South Middleton Dam	–	-5.65	-3.76	–	-2.29
		Tel Electric Pond Dam	–	–	–	–	-2
		Millie Turner Dam	-5.84	-6.37	-6.6	-6.45	-6.4
MD	USFWS-89	Bloede Dam	–	-20	-21	–	-18
NH	NFWF-41787	Upper Sawyer Mill Dam[b]	–	-5.5	-6	-7	-7.4
NJ	USFWS-94	Hughesville Dam	–	-9.5	–	-9.25	-9.25
Median anticipated reduction in water elevation due to dam removal			**5.0 ft**	**5.1 ft**	**6.3 ft**	**8.1 ft**	**2.8 ft**

a. Data presented are projections for flooding near the dam site from hydraulic modeling done at each dam site prior to removal, as part of the permitting process; only a subset of the modeling results were shared in project reports, and thus we only include these reported data in the table.

b. NFWF did not fund the dam removal, but only funded the design for a future potential dam removal project, due to concerns about sediment contamination.

Box 1. Aquatic connectivity projects reduce future flooding risks and damages.

Projects mitigate flooding risks in locations with historic flooding following major past events

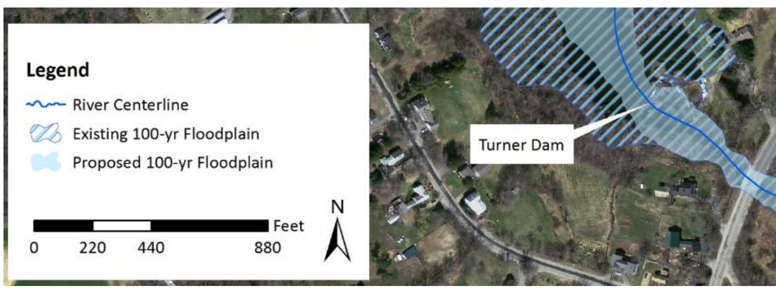
View of Upper and Lower Sawyer Mill dams on the Bellamy River in Dover, NH. The dams are part of a historic, redeveloped mill complex that straddles the river and is currently occupied by business and residents.

Photo source: Project archival materials.

In 2006 and 2010, major storms caused repeat damage and flooding. These dams are also ranked on federal and state inventories as high hazard, posing a threat to public safety in the event of a flood-induced failure.

Photo source: Project-related Request for Quotations.

By reducing size of 100-year floodplains, dam removals decrease exposure to damaging floods



Removal of the Millie Turner Dam on the Nissitissit River, a tributary of the Nashua River in Massachusetts, is expected to decrease the area in the 100-year floodplain and the number of properties potentially exposed to flooding events (left). The dam was also ranked as a high hazard dam in poor condition.

Photo source: Millie Turner Dam Preliminary Design for Removal, Final Report, Appendix A.

Replacing and "right-sizing" narrow culverts increased water conveyance and decreased flooding

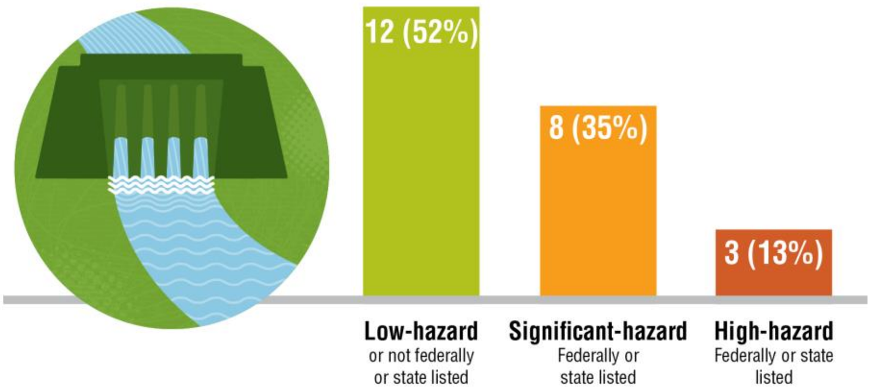
Replacing narrow culverts with a wider bridge improved water conveyance and minimized the risk of flooding. One project performed replacements at six sites; one culvert replacement at New Bridge Brook in Wilmington, NY (above) widened the river span from 4 linear feet to 22 linear feet. The project noted resulting improvements in tidal hydrology, water quality, and vegetation.

Source: Project final report.

Finding PO.2: For a subset of projects, dam removal improved human safety.

Many dams removed through the Hurricane Sandy Program were disused and deteriorating dams. These deteriorating dams could fail during storms, posing significant hazards to the safety and well-being of downstream communities and businesses. Three of the dam sites in the Hurricane Sandy Program were listed as high hazard by either federal or state authorities, and eight were listed as moderate hazard (Figure 3).[4] Thus, the removal of these 11 dams improved human safety for those who live, work, or recreate close to these sites. Furthermore, dams of any hazard and condition rating can pose direct, life-threatening hazards to swimmers and others who recreate near them (Kobell, 2015). For example, at least 9 dam-related deaths occurred since the 1980s at Bloede Dam, which was removed with support from the Hurricane Sandy Program and multiple other funders (USFWS, 2018).

Figure 3. Count of dams removed listed as low, significant, or high hazard on federal or state dam inventories.



Sources: MA ODS, 2012; Ipswich River Water Association, 2014; USFWS, 2015b, 2015c, 2017; RI DEM, 2017; CT DEEP, 2019; MD DE, 2019; USACE, 2019.

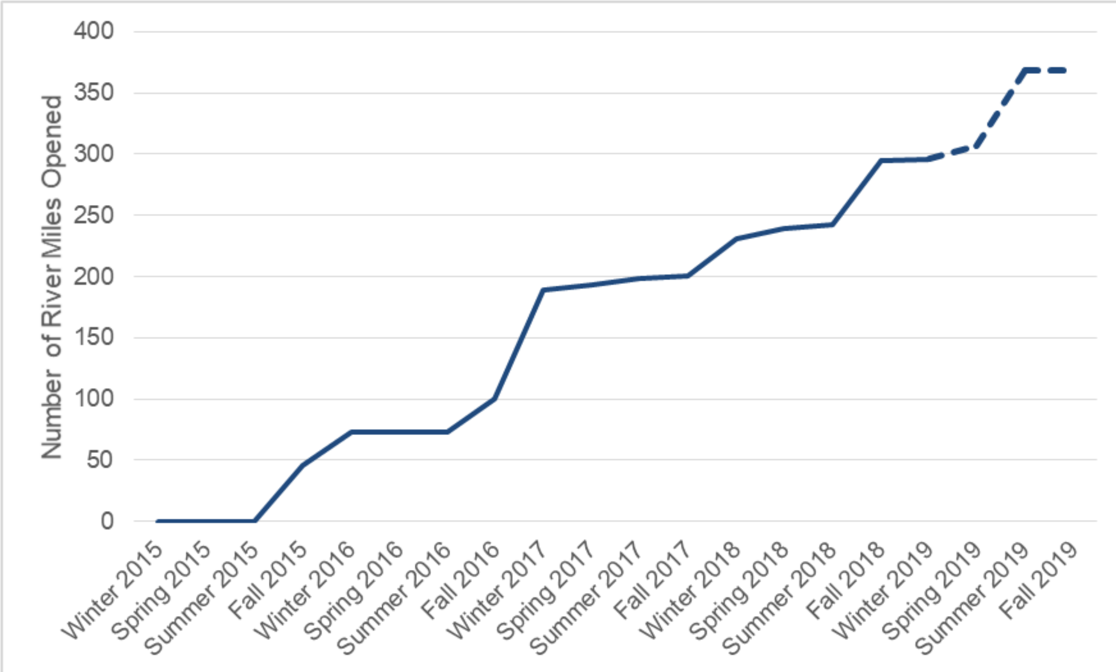
4.2 Habitat, Fish, and Wildlife Outcomes

Finding PO.3: Dam removal and culvert replacement/improvement resulted in improved fish access to nearly 370 miles of stream habitat, supporting key species in the region.

Project lead-reported data show that dam removal and culvert replacement/ improvement have resulted in fish gaining access to just over 368 miles of habitat that had been inaccessible to diadromous fish for decades to centuries (Figures 2 and 4; Tables A.1 and A.2 in Appendix A). This tally represents a minimum estimate of improved habitat access, as most project leads reported only mainstem river miles opened and did not include tributaries (see Tables A.1 and A.2).

[4] Hazard classifications vary between federal and state dam inventories. In general, a high hazard potential indicates that dam failure would result in probable loss of life and extensive property damage, a significant hazard potential indicates that dam failure would result in no probable loss of human life but could result in property damage, and a low hazard potential indicates that dam failure would cause no loss of human life and minimal property damage.

Figure 4. Minimum river miles opened through aquatic connectivity projects over time.



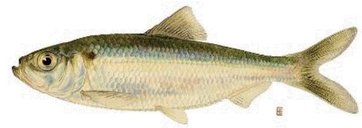
Dashed line indicates dams scheduled to be removed after the completion of this evaluation.

The literature suggests that access to this new habitat could be critical to sustaining and growing populations of a wide range of fish that utilize freshwater rivers and streams during part of their life cycle. For example, project leads noted four representative species that would benefit from their aquatic connectivity projects: alewife (*Alosa pseudoharengus*), American eel (*Anguilla rostrata*), American shad (*Alosa sapidissima*), and blueback herring (*Alosa aestivalis*) (see Box 2). All four species use river and stream habitats for feeding, reproduction, resting, or migrating, and therefore would potentially benefit from improved access to freshwater habitat (ASMFC-1 through ASMFC-4, Undated). Removing dams before they fail can also prevent the destruction of critical fish habitat. Furthermore, 11 of the dams removed had been identified as high priority[5] for removal by the Northeast Aquatic Connectivity Assessment Tool, which identifies where removals of barriers to fish passage are likely to provide the most ecological benefits (Martin and Apse, 2011).

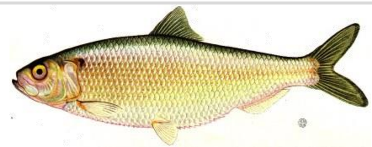
[5] All dams in this tool are reported in 5% tiers; these 11 dams were ranked in the top 20% for their potential benefit to diadromous and resident fish if removed or bypassed.

Box 2. Examples of representative species likely to benefit, or that are already benefiting, from aquatic connectivity projects.[a, b]

Alewife is a common species that migrate from the ocean to upstream rivers and lakes to spawn. It is a crucial component of the marine and freshwater food chains, serving as prey for larger commercial fish and other wildlife. River herring stocks (which include both alewife and blueback herring) are at near historic lows coast-wide. Alewife and other migratory fish populations are depleted due to historical overfishing, habitat fragmentation and loss, and other factors.



Blueback herring migrate from saltwater into freshwater to spawn, and serve as prey for bass and other large recreational and commercial species. As noted above, river herring stocks are at near historic lows coast-wide.



American shad, a staple food for pre-colonial Native Americans, were historically over-harvested in the mid-Atlantic region and serve as an important forage fish for larger fish. Stocks are currently at all-time lows.

American eel are an important prey species for commercial fish. A catadromous species that lives in freshwater and migrates to saltwater to spawn, they have the largest range of any fish species in North America. American eel stocks are depleted, due to historical overfishing, habitat loss, and other factors.

a. Drawings not to scale.

b. See Finding PO.4 and Box 3 for observed improvements in fish utilization of restored aquatic habitat.

Sources: USFWS (2015a), State of Maine Department of Marine Resources (2016), ASMFC-A and -B (2019), Chesapeake Bay Program (2019), ASMFC-1 through ASMFC-4 (Undated).

However, the ultimate impact of any given aquatic connectivity project on aquatic populations will depend on the nature of the intervention (e.g., dam removal, culvert replacement), the amount and quality of habitat available upstream of the project site, the size and age distribution of the preexisting population, and the size and depth of the river (Pess et al., 2008, 2012) as well as factors external to the project that affect the population (at-sea predation, for example). In the Information Gaps section below, we provide a more in-depth discussion of the information needed to determine the long-term impact of aquatic connectivity projects.

Finding PO.4: Early improvements in fish passage, water quality, and instream habitat have already been achieved by some projects.

While most aquatic connectivity projects were only recently completed at the time of our evaluation, some have already achieved improvements in fish passage, instream habitat, water quality, and fish use of upstream habitat. For example, shad and herring were quickly observed in habitats upstream of dam removals in New Jersey and Massachusetts (see Box 3). At the Norton Paper Mill Dam removal site, a project lead noted in an interview that the dam removal quickly flushed out sediment and debris that had accumulated behind the dam for decades, exposing rocks and boulders, and making the upstream habitat similar to historical conditions. In addition, 10 aquatic connectivity projects not only restored habitat through barrier removals, but also worked to directly improve instream habitat through removing sediment, planting riparian vegetation, or installing fish habitat structures. These types of habitat improvements can provide benefits to fish immediately following restoration, though their full benefits may not be realized for many years (see Finding PO.5 below for a more detailed discussion of timelines of ecosystem recovery post-restoration).

Box 3. Fish outcomes observed to-date.

Shad return to the Musconetcong River, NJ, following the Hughesville Dam removal

The Hughesville Dam was a river-spanning, 15-foot high safety hazard and impediment to fish passage on the Musconetcong River. Following its removal in 2016, American shad were reported upstream for the first time since upstream passage was blocked in 1768. "The return of shad, a benchmark species indicative of the overall health and diversity of a waterway, is an exciting milestone," said the Department of Environmental Protection's (DEP) Commissioner Bob Martin. "This achievement is the direct result of an ongoing partnership among state and federal agencies, nonprofit groups, and dam owners – all committed to making this beautiful waterway free-flowing again."

Source: NJ DEP Press Release, June 15, 2017.

Herring return to the Shawsheen River, MA, following the Balmoral and Marland Place dam removals

Balmoral and Marland Place dam removals were both completed around January 2017. The following spring, Emerson professor Jon Honea organized 46 volunteers to help count herring swimming upstream of these sites in the Shawsheen River. A total of 95 herring were observed, suggesting an estimated season run size of ~ 425 herring. The high-quality breeding habitat upstream from these dams had previously been inaccessible for almost 200 years.

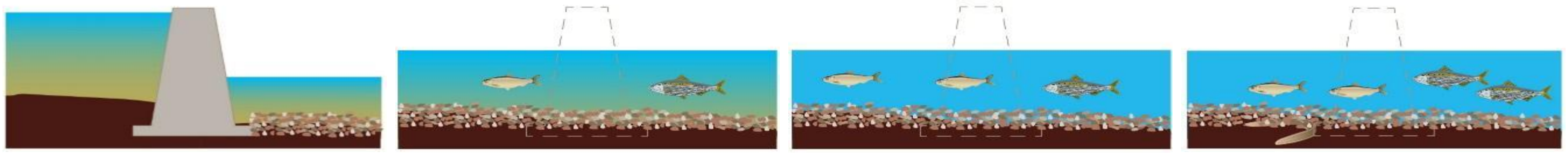
Source: Lyman, 2017.

4.3 Trajectories of Outcome Achievement

Finding PO.5: Observed ecological benefits of aquatic connectivity projects to date are consistent with expected time lags between construction of the restoration project and long-term ecological outcomes.

The ecological and socioeconomic benefits of many projects funded through the Hurricane Sandy Program will take time to materialize after restoration activities are completed. To better understand and convey the potential timing of the achievement of key outcomes, the Abt Associates (Abt) evaluation team developed conceptual timelines of recovery after restoration using information from key peer-reviewed articles in combination with professional judgment from our team's subject matter experts (Figure 5).

Figure 5. Description of short-, medium-, and long-term outcomes related to aquatic connectivity, fish, and flooding.



Realization timeframe[a]	Year 0 (pre-project)	Short-Term (1–2 years) Outcomes 2017–2021	Mid-Term (3–5 years) Outcomes 2019–2024	Long-Term (10+ years) Outcomes 2026+
Connectivity	Barrier alters hydraulics, traps sediment.	Flow continuity and sediment transport/redistribution begin immediately; water temperature changes; historic/rocky substrates may be exposed.	Sediment redistribution continues, exposure of historic/rocky substrate, restoration of historic flow conditions begins, water temperature changes; pioneer riparian vegetation establishes.	Channel morphology, and sediment dynamics continue to improve, some streams may require storm events to approach pre-dam conditions; mature riparian vegetation begins to return.
Fish	Habitat does not support diadromous fish, lake/warm water species typically inhabit areas upstream of the dam.	Diadromous fish species may begin to return/recolonize upstream habitats, some initial macroinvertebrate die-off due to sediment redistribution.	Diadromous fish continue to re-colonize and re-establish, some populations increase.	Native diadromous fish continue to return, rate and degree of recovery varies with geomorphology and recovery rate of other biota and other factors.
Flooding Reduction	Barrier or risk of failure can cause flooding.	Immediate elimination of risk of failure, reduction in inundation risk.	Water flows begin to approach reference condition, additional decrease in floodplain area upstream of the former dam.	Water flows continue to approach reference condition, additional decrease in floodplain upstream.

a. Assuming projects completed between 2016 and 2019.

Sources: **Connectivity:** Bednarek, 2001; Doyle et al., 2005; Tullos et al., 2014; Foley et al., 2017a, 2017b. **Fish:** Bednarek, 2001; Catalano et al., 2007; Marks et al., 2010; Foley et al., 2017a, 2017b. **Flooding:** professional judgment. Some elements on diagram courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/).

Early observations of key outcomes for some projects are generally consistent with what the literature and Abt team experts identified as likely trajectories of key outcomes over time. As noted above, project leads have already observed fish passage and reduced water temperatures at many dam removal sites, and modeled projections of water surface elevations show reduced flood risk after dam removal. However, as noted in Figure 5, final outcomes for dam removal may take 10 years or more to materialize. This suggests that for projects implemented from 2015–2019, long-term outcomes for even the most successful projects are not likely to be fully realized until approximately 2025–2030.

More specifically, hydraulics, sediment mobilization and redistribution, and aquatic species population recovery may all begin immediately following dam removal. However, the timing and degree of recovery are influenced by many factors, including river management, the presence of other dams, geomorphic conditions, and existing biological communities (e.g., Bednarek, 2001; Doyle et al., 2005; Foley et al., 2017a, 2017b). For example, some rivers and dams may require a high-flow year in the water body to completely redistribute impounded sediments (Foley et al., 2017b). In addition, riparian vegetation, which can influence flow, sediment transport, and geomorphic features, may take many decades (30 years or more) to fully recover (Doyle et al., 2005).

Similarly, diadromous fish often migrate upstream of the former impoundment within one year following a dam removal (e.g., Catalano et al., 2007; Foley et al., 2017a, 2017b). However, full recovery of diadromous fish populations and historical riverine fish assemblages can take decades. A wide range of factors influence population recovery (as opposed to migration by individuals), including geomorphic conditions, temperature, flow, riparian habitat, pressure from non-native species, and the recovery of other aquatic species such as macroinvertebrates and mussels (Bednarek, 2001; Doyle et al., 2005; Marks et al., 2010), as well as factors beyond the project site, such as at-sea effects, and other environmental conditions. The dynamics of recovery are also important to consider. Ecological recovery after dam removal is a complex and non-linear process, with some ecosystem components often recovering more quickly, or more fully, than others (Doyle et al., 2005).

Topic: Information Gaps Regarding Resilience Impacts (IG)

Finding IG.1: Long-term ecological monitoring is needed to understand the full impact of aquatic connectivity projects.

As noted earlier in the case study, dam removal is known to have a range of benefits to fish that utilize streams for refuge, foraging, and reproduction. However, as described in Finding PO.5 above, there is typically a significant lag time between restoration activities and the full realization of ecological outcomes related to fish and other wildlife. More specifically, it is likely to take many years for fish to successfully re-establish reproduction in areas that have been inaccessible to them for decades to centuries (Doyle et al., 2005). Because our evaluation ended soon after most projects were finished and before six of them were completed, our team was not able to ascertain whether medium- or long-term outcomes have been realized. In addition, monitoring to determine whether such outcomes are achieved was not included in the restoration proposed for projects in this program, as such monitoring is typically beyond what funders of restoration activities support.

To address this information gap, NFWF and DOI are supporting efforts to assess longer-term fish, habitat, and water quality outcomes in a subset of sites. More specifically, eight aquatic connectivity projects will be undertaking field measurements of fish abundance, assemblage, and migration patterns. Data collection is currently in its early phases and will last from spring 2018 through 2023. These additional data will help improve understanding of how riverine and adjacent systems can rebound after restoration and the long-term benefits of aquatic connectivity projects.

Finding IG.2: Detailed modeling is needed to fully understand the impact of dam removal and/or culvert replacement on flood risk in nearby communities.

As noted under Finding PO.1 above, 16 different projects modeled the anticipated impact of dam removal on water surface elevation, suggesting that flood risk has been reduced in these sites. However, these modeling efforts did not include detailed analyses of how changes in water elevation directly impact nearby infrastructure. This information gap prevents a full understanding of the flood mitigation benefits associated with dam removals completed through the Hurricane Sandy Program. In addition, the models are based on project designs, but have not been re-run after construction to predict future water elevations once the dams have been removed.

However, NFWF and DOI are supporting inundation modeling in a subset of sites to better characterize and quantify flood risk reduction in project sites over the long-term. More specifically, a joint USFWS- and USGS-led effort is performing HEC-RAS modeling for 9 of the 23 different dam removal sites. The output from these models will be used to create detailed inundation maps of nearby communities and to compare inundation patterns before and after dam removal. This will offer clear, quantifiable insights regarding the flood risk benefits provided through dam removal under different flow scenarios. NFWF and DOI are also supporting long-term monitoring to understand the impacts of project-related flooding reduction on human health and well-being, transportation, critical facilities, and recreation.

5. Conclusion

Investments that the Hurricane Sandy Program made in improving aquatic connectivity have increased the resilience of natural and human communities close to restored areas. The program enhanced fish access to a substantial amount of previously inaccessible freshwater habitat, which can improve fish productivity and survival, making those populations more resilient to disturbances. Similarly, people who live, work, or recreate near dams are less likely to be harmed by storms, through reduced flood risk and improved safety. While the flood risk and safety benefits of dam removal are apparent immediately after project completion, the full ecological benefits of dam removal, including population and ecosystem resilience to storms, may not materialize for many years. Further monitoring and assessment is needed to understand the long-term benefits and costs of these types of interventions.

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Appendix A. Project Summaries

Table A.1. Dam removals completed by aquatic connectivity projects in the Hurricane Sandy Program.

State	Project ID	Dam name	Main river name	Height (ft)	Year built	Removal date by season	Minimum river miles opened
CT	USFWS-79	Norton Paper Mill Dam	Jeremy River	20	1726	Fall 2016	17
CT	USFWS-53	Hyde Pond Dam	Whitford Brook	5	1814	Fall 2015	4.1[a]
CT	USFWS-68	Flock Process Dam	Norwalk River	14	1850	Summer 2018	3.5
CT	NFWF-43378	Springborn Dam	Scantic River	26	1890	Fall 2017	2.6
CT	USFWS-51	Pond Lily Dam	West River	6	1794	Winter 2016	2.6
MA	NFWF-42671	South Middleton Dam	Ipswich River	10	1953	Summer 2019	57
MA	NFWF-42671	Millie Turner Dam	Nashua River	10	1750	Fall 2015	40[a]
MA	USFWS-9	West Britannia Dam	Mill River	8	1824	Winter 2018	30
MA	NFWF-42671	Cotton Gin Dam	Satucket River	10	1820	Winter 2017	13
MA	NFWF-42671	Barstowe's Pond Dam	Taunton River	8	1920	Spring 2018	8
MA	NFWF-42671	Rattlesnake Brook Dam	Taunton River	4	1882	Fall 2016	7
MA	NFWF-42671	Hunters Pond Dam	Bound Brook	5	1820	Summer 2017	5
MA	NFWF-42671	Tel Electric Pond Dam	Housatonic River	20	1933	Summer 2019	4.8
MA	NFWF-42671	Balmoral Dam	Shawsheen River	6.8	1920	Spring 2017	2.1
MA	NFWF-42671	Marland Place Dam	Shawsheen River	12.5	1920	Spring 2017	2
MD	USFWS-89 and NFWF-43834	Bloede Dam	Patapsco River	34	1907	Fall 2018	52[a]
MD	USFWS-89	Centreville Dam	Corsica River	5	1933	Fall 2015	2
NH	NFWF-41787	Upper Sawyer Mill Dam	Bellamy River	15	1880	Spring 2019	11
NH	NFWF-41787	Lower Sawyer Mill Dam	Bellamy River	18	1935	Fall 2018	
NJ	USFWS-94[b]	Hughesville Dam	Musconetcong River	17	1889	Fall 2016	1[b]
RI	USFWS-21	Bradford Dam	Pawcatuck River	6	1819	Winter 2017	70[a]
RI / CT	USFWS-21	White Rock Dam	Pawcatuck River	6	1770	Spring 2016	
RI	USFWS-21	Shady Lea Mill Dam	Mattatuxet River	5	1820	Spring 2018	0.5

a. For these projects, project leads stated the total of both mainstem and tributary miles opened. Minimum river miles opened from other projects may also include improved access to tributaries with important fish habitat, but these data were not reported.
b. This project also funded improvement of a culvert. See the Wreck Pond site in Table A.2.

Table A.2. Culvert replacements, bridge replacements, and fish passage improvements completed by aquatic connectivity projects in the Hurricane Sandy Program.

State	Project ID	Site name	Activity	Activity date by season	Minimum river miles opened	Other aquatic connectivity restoration activities
NY	NFWF-42874	Ausable Watershed	Replaced 4 culverts with fish-friendly structures.	Winter 2016	24	Not reported
MA	NFWF-43322	Herring Creek	Dredged sediment to restore tidal flows; restored herring and eel migration route (blueback herring and American eels) and spawning grounds for crabs (Atlantic horseshoe crabs).	Winter 2019	0.3	Not reported
PA	NFWF-43759	Brandywine River Watershed	Restored floodplain wetlands to store overbank flow and reconnect floodplains.	Winter 2015	N/A	1.6 acres of floodplain reconnected. Also completed riparian restoration and in-channel habitat restoration.
NY	NFWF-44022	Allegany Reservoir and River	Restored hydrological connections of landlocked nursery and wetland areas to the Allegany Reservoir through debris removal; mitigated 7 fish barriers.	Winter 2016	Not reported	15 acres of restored hydrology, and mitigation of 7 fish barriers, including culverts and dams.
MA	USFWS-11	Muddy Creek Wetland	Replaced two culverts with a bridge and open channel.	Spring 2015	Not reported	Restored a mix of approximately 55 acres of estuarine and subtidal wetlands.
MA	USFWS-33	Parkers River Watershed	Replaced 1 bridge with a larger span structure and replaced 2 culverts.	Winter 2019	1.04	Restored 60 acres of salt marsh, improved 93 acres of fish and shellfish habitat in the tidally influenced Seine Pond, and improved migratory fish passage to 63 acres of spawning habitat.
VA	USFWS-34	Quantico Creek	Restored streambank above a culvert to eliminate sediment build-up.	Winter 2017	6.25	Not reported
NJ	USFWS-94	Wreck Pond	Created bypass box culvert and reconstructed berm and dune system over the new culvert.	Fall 2016	2	Not reported

Table A.3. Aquatic connectivity projects supported through the Hurricane Sandy Program. This table presents the amount of project funding specifically allocated to aquatic connectivity activities. For 16 projects, this is the full project funding amount; and for three projects, this is a subset of the total project funding. The allocation was based on available project documentation. All dollars rounded to the nearest hundred.

Project identification number	Project title	Project state	Project lead organization	Award amount	Reported matching funds
NFWF-41787	Restoring Bellamy River's fish passage and reducing flooding through removal of two fish barriers, New Hampshire	NH	New Hampshire Department of Environmental Services	$550,000	$168,100
NFWF-42671	Enhancing seven communities, ecosystems, and infrastructure resiliency by removing seven fish barriers, Massachusetts	MA	Fish and Game, Massachusetts Department of/ Division of Ecological Restoration	$4,039,200	$1,461,200
NFWF-42874	Ausable watershed flood mitigation and fish passage restoration, New York	NY	The Nature Conservancy	$620,000	$188,500
NFWF-43322[a]	Enhancing Wampanoag Tribe of Gay Head's land resiliency in Martha's Vineyard, Massachusetts	MA	Wampanoag Tribe of Gay Head	$268,000	$92,800
NFWF-43378	Restoring fish runs and fragmented trout populations by removing a fish barrier, Connecticut	CT	State of Connecticut	$2,800,000	$1,000,000
NFWF-43759	Reducing flood impacts and restoring habitat in the Brandywine River watershed, Pennsylvania	PA	Stroud Water Research Center	$1,515,000	$250,000
NFWF-43834	Increasing community and ecological resiliency by removing a Patapsco River fish barrier, Maryland	MD	American Rivers, Inc.	$2,480,000	$5,677,000
NFWF-44022	Reconnecting and restoring the Allegany Reservoir, New York	NY	The Seneca Nation of Indians	$350,000	$226,400
USFWS-11	Muddy Creek wetland restoration project, Chatham, Massachusetts	MA	U.S. Fish and Wildlife Service	$3,762,000	$438,600
USFWS-21[a]	Aquatic connectivity and flood resilience in Connecticut and Rhode Island: Removing the White Rock and Bradford dams, assessing the Potter Hill Dam fishway on the Pawcatuck River, and removing the Shady Lea Mill Dam in North Kingstown	Multi: CT, RI	U.S. Fish and Wildlife Service	$2,294,300	$1,229,000
USFWS-33[a] (-43 in final report)	Parker River Tidal Restoration Project	MA	U.S. Fish and Wildlife Service	$3,718,000	$568,600

Project identification number	Project title	Project state	Project lead organization	Award amount	Reported matching funds
USFWS-34	Aquatic connectivity and flood resilience in Virginia: Replacing the Quantico Creek culvert in Dumfries	VA	U.S. Fish and Wildlife Service	$330,800	$900,000
USFWS-51[a]	Aquatic connectivity and flood resilience: Pond Lily Dam removal, West River, New Haven, Connecticut	CT	U.S. Fish and Wildlife Service	$661,500	$238,800
USFWS-53[a]	Aquatic connectivity and flood resilience: Hyde Pond Dam removal, Whitford Brook, Mystic, Connecticut	CT	U.S. Fish and Wildlife Service	$551,300	$3,200
USFWS-68	Aquatic connectivity and flood resilience: Flock Process Dam removal, Norwalk River, Norwalk, Connecticut	CT	U.S. Fish and Wildlife Service	$970,000	$169,000
USFWS-79	Aquatic connectivity and flood resilience: Norton Mill Dam removal, Jeremy River, Colchester, Connecticut	CT	U.S. Fish and Wildlife Service	$727,700	$52,000
USFWS-89[a]	Aquatic connectivity and flood resilience in Maryland: Removing the Centreville Dam in Centreville and the Bloede Dam in Catonsville	MD	U.S. Fish and Wildlife Service	$1,212,800	$5,400,000
USFWS-9[a]	Aquatic connectivity and flood resilience: West Britannia and Whittenton Dam Removals, Mill River, Taunton, Massachusetts	MA	U.S. Fish and Wildlife Service	$650,000	$837,000
USFWS-94[a]	Aquatic connectivity and flood resilience in New Jersey: Removing the Hughsville Dam in Pohatcong and restoring the Wreck Pond inlet and dune in Sea Girt and Spring Lake	NJ	U.S. Fish and Wildlife Service	$3,050,000	$3,718,000

a. Denotes a project for which long-term monitoring funding has been secured through NFWF and DOI.