Dam Removal in the USA: Effects on River Water Quality

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STAGNANT WATER BODIES POLLUTION

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Chapter 2

DAM REMOVAL IN THE USA: EFFECTS ON RIVER WATER QUALITY

Michael A. Kruge

ABSTRACT

Dam removal decisions should ideally be made after a thorough cost-benefit analysis. If dam obsolescence, structural safety, harm to fisheries, maintenance costs, and reservoir eutrophication are among the primary concerns, decommissioning would likely be favored. On the other hand, dams provide considerable benefits including water storage for agricultural and urban consumption, renewable electricity generation, support of navigational canal systems, flood control, and lakes for recreation. Because of these competing factors and interests, dam removal decision-making in the United States is often a slow process fraught with controversy, as in the case of the Klamath River.

Dams provided mechanical water power essential for mills during the Industrial Revolution, notably on the Passaic River (New Jersey). The 1973 demolition of an old industrial dam at Fort Edward (New York) infamously spread toxic polychlorinated biphenyls (PCBs) downstream in Hudson River sediments, requiring costly remediation and providing a cautionary tale. More recently, carefully planned removals of obsolete dams (on the Cuyahoga, Elwha, and Naugatuck Rivers) were completed without serious environmental impairment, particularly when operators performed a gradual, staged demolition of the dam after the reservoir had been drained. A similarly cautious approach proved successful at the Clark Fork River Superfund site (Montana), even with the serious additional complication of heavily contaminated reservoir sediments requiring removal for off-site disposal. Minor run-of-river dams in urban areas have been removed without significantly affecting sediment contamination levels.

Keywords: dam removal, environmental management, reservoir sediment, PCB and heavy metal contamination, hydropower, Clark Fork River, Cuyahoga River, Elwha River, Hudson River, Klamath River, Naugatuck River, Passaic River

1. ASPECTS OF HISTORICAL DAM USE IN THE USA

Prior to European colonization, millions of North American beaver dams formed ponds and wetlands, strongly impacting local ecology (Butler and Malanson, 2005). Aboriginal fishing weirs, some built of stone, commonly diverted river flow and provided reliable sources of food (Lutins, 1992). The arrival of northern European settlers induced profound landscape transformations. Since beaver pelts were highly prized by the fashion industry of the time, the animal's numbers were severely reduced by over-trapping. Abandoned beaver dams were left to disintegrate, thereby altering the environment (Butler and Malanson, 2005). Colonial farmers gradually cleared the once extensive forests to create pasture and cropland, affecting vegetation, stream drainage, runoff, and sedimentation. Dams impounded many streams, forming reservoirs for mechanical waterpower harnessed to drive modest grain and lumber mills.

The onset of the Industrial Revolution in the late 18th century saw the construction of larger dams, exploiting the abundant water resources in the Northeast and producing waterpower for a variety of increasingly sophisticated machinery. Water wheels turned pulleys with arrays of leather belts in multistory mills, driving devices such as saws, drills, and looms. Slater's Mill on the Blackstone River in Pawtucket (Rhode Island) was among the first of these mechanized factories, established to produce textiles in 1792 (NPS, 2006)

Table 1. Location of case study dams shown in the figures, arranged from east to west.

Dam	River Longitude (°W)	State	Latitude	(°N)
Anaconda	Naugatuck	Connecticut	41.5709	73.0554
Fort Edward	Hudson	New York	43.2685	73.5979
Great Falls	Passaic	New Jersey	40.9155	74.1817
Manatawny Creek	Manatawny	Pennsylvania	40.2511	75.6555
Munroe Falls	Cuyahoga	Ohio	41.1416	81.4368
Milltown	Clark Fork	Montana	46.8675	113.8860
Link River	Klamath	Oregon	42.2383121.8053	
Iron Gate	Klamath	California	41.9310	122.4423
Elwha	Elwha	Washington	48.0948	123.5567

Alexander Hamilton was the first treasury secretary of the United States and an early advocate for commerce and industry in the newly independent country.

He formed the Society for Establishing Useful Manufactures in 1791 in a major, pioneering development of the Industrial Revolution in North America. As the site for its operations, the Society founded the city of Paterson at the Great Falls of the Passaic River in New Jersey (Figure 1). An impoundment fed an intricate system of canals and raceways (Figures 1 and 2) that were gradually constructed over the next half century. Mills and factories sprang up along the raceways, harnessing the waterpower to produce goods as diverse as silk and locomotives. In the later half of the 19th century, steam powered factories were constructed as new technologies replaced direct use of waterpower. However, a further advance saw a renewed interest in the power of moving water with the construction of a 5 MW electrical generating station at the foot of the falls in 1914, upgraded to 11 MW in 1986 and still in use today (Figure 1). As the 20th century progressed, the fortunes of Paterson declined; it is no longer the center for "useful manufacturing" that it once was (NPS, 2006). To honor its industrial heritage, the Paterson Great Falls National Historic Park has recently been established (Mroz, 2009).

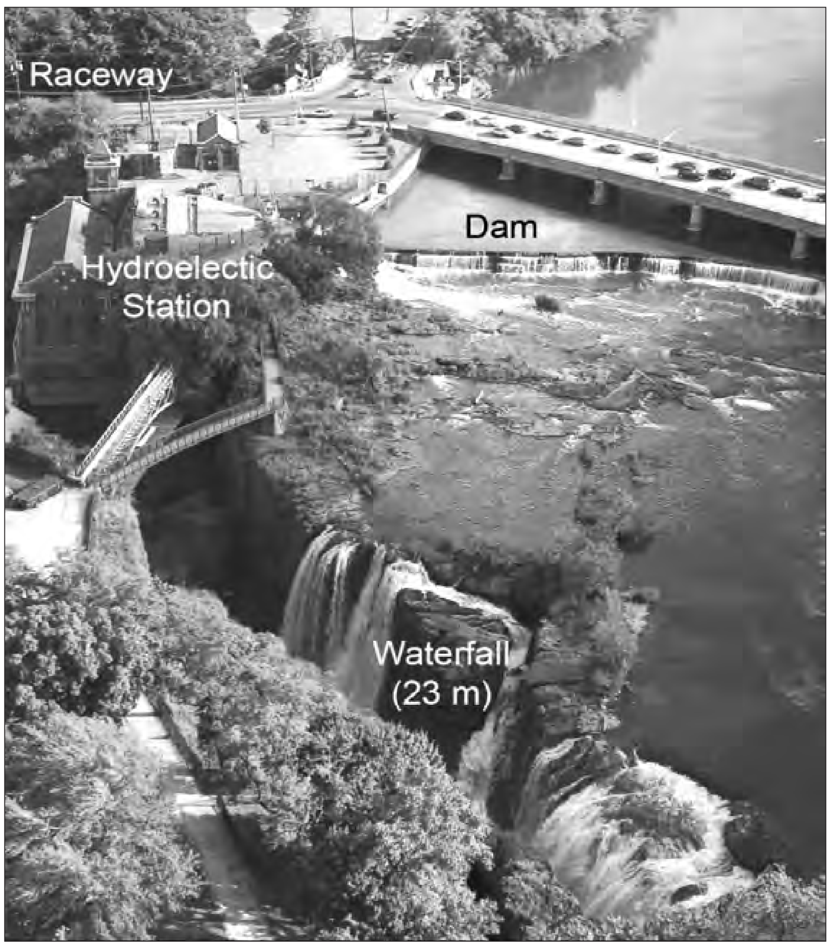

Figure 1. Aerial view of the Great Falls of the Passaic River (Paterson, New Jersey) in March, 2004. See Table 1 for location of this site as well as the others illustrated in the figures. Photo: Mike Peters, Montclair State University. Used with permission.

Figure 2. Remnants of the raceway system in Paterson (April, 2015). Note the sluicegate at the right which served to admit water from the upper canal at the top of the image. The circular pattern in the bricks on the wall of the industrial building on the left marks the former entrance of the rotating driveshaft. Photo: M. Kruge.

2. BENEFICIAL AND DETRIMENTAL CONSEQUENCES OF DAM CONSTRUCTION

While the direct use of mechanical waterpower is largely obsolete, dams of all sizes yield many other benefits. Among these are hydroelectric power, flood control, water supply for populations and irrigation, navigational improvements, and recreation (Bowman *et al.*, 2002). Out of the estimated 2.5 million dams in the USA, only about 3 % produce hydroelectricity (Maclin and Sicchio, 1999; Sternberg, 2006). Since some of these are very large (e.g., Grand Coulee and Hoover Dams), hydroelectric dams collectively account for about 10 % of the U.S. water reservoir volume (Sternberg, 2006) and produce about 6 % of the country's electric power (EIA, 2015). The ongoing, multi-year drought in California highlights both the value and vulnerability of the state's massive water projects, essential for agricultural and urban users alike (Jones, 2015).

Notwithstanding the evident benefits provided by dams, awareness of their undesirable side effects has increased in recent years ((Bednarek, 2001; Bowman *et al.*, 2002; Chatterjee, 1997; Chouinard, 2014), brought to international public awareness by the controversial construction of the colossal Three Gorges Dam in China and the attendant forced population resettlements (Khamsi, 2005; Sternberg, 2006). Concerns about dams are often over public safety and economics as well as their ecological impact.

Dams and their reservoirs have a finite lifespan of about a century (Doyle *et al.*, 2003; 2005). The impounded reservoir gradually fills with sediment over many years, reducing the volume available for water storage and potentially blocking the entrance to the penstock in the case of hydroelectric dams. Aging, deteriorating dams may also be hazardous, since a catastrophic structural failure could lead to loss of life and property. The costs involved in maintaining, repairing or replacing an old structure could exceed its economic benefits. In some cases, an old dam may have been long abandoned by its owner, making governmental agencies responsible by default for its upkeep (Burroughs *et al.*, 2009; Doyle *et al.*, 2003; Graf *et al.*, 2010; Lovett, 2014; Maclin and Sicchio, 1999; Wyrick *et al.*, 2009).

The "ecological health" of a river is increasingly viewed as a public good (Bowman *et al.*, 2002). Noxious algae may bloom in the stagnant water of a reservoir (Armengol and Salgot, 2013; Oliver *et al.*, 2014). Salmon and other anadromous fish suffer if dams block their spawning migration routes. Fish hatcheries, trucking of fish around dams, and construction of elaborate "fish ladders" mitigate this problem, but juveniles swimming downstream may still be caught in turbine intakes of hydroelectric dams (Tucker, 2001). Habitats created by artificial lakes may benefit non-native organisms to the detriment of indigenous species (Pejchar and Warner, 2001). Balancing the harm to fish populations against the benefits provided by dams remains a highly-charged sociopolitical issue (Tollefson, 2008). Nonetheless, the idealized vision of a free-flowing river is increasingly an impetus for removal of aging and obsolete dams (Nijhuis, 2014).

3. ENVIRONMENTAL MANAGEMENT: DAM REMOVAL DECISION-MAKING

Environmental management decisions to remove individual dams must be made carefully and on a case-by-case basis. Dam removal may itself produce undesirable consequences. A prime concern is the potential for the mobilization of contaminated sediments that may have accumulated behind a dam. Reservoir sediments, particularly if fine-grained, may sequester significant amounts of organic carbon, the disturbance of which could produce emissions of the greenhouse gases implicated in global climate change. The removal of a hydroelectric dam is at odds with current policies promoting greater use of renewable energy sources. The loss of an esthetically-pleasing artificial lake could instigate homeowner opposition, reduce property values, discourage tourism, and alter well-established local ecology (Bednarek, 2001; Graf, 2005; Pacca, 2007; Pejchar and Warner, 2001; Wyrick *et al.*, 2009).

When evaluating a dam for removal, environmental managers should carefully analyze financial, ecological, and social costs and benefits. Governmental agencies charged with preliminary evaluation and final decision-making may be underfunded and understaffed, so in practice the ideal procedure may not always occur. Nonetheless, better results are achieved when empirical data are collected and synthesized. Expectations should be tempered since a dam may leave a long-term geomorphological imprint; even after barrier removal, the river may not reassume its pre-dam form (Doyle *et al.*, 2005). Systematic procedural schemes have been proposed to optimize the decision-making process. The first step is to clarify the objectives by cataloging the benefits of keeping and of removing the dam. Secondly, the ecological, economic, and public safety issues must be identified. Are there indications that the dam is causing habitat degradation and that its removal would likely lead to improvement? Is the dam obsolete or is it still performing its originally intended functions? Thirdly, environmental, legal, and social data should be collected. Is there a potential for contaminant release? Fourthly, hydrological and geomorphological computer modeling can be important in predicting the likely river channel behavior after dam removal. After these steps have been completed to the fullest extent possible, an informed decision can be taken. If dam removal occurs, then environmental monitoring and assessment should continue to alert the community to any unforeseen problems, as well as to increase the scientific knowledge base to aid in future projects (Bowman *et al.*, 2002; Doyle *et al.*, 2003; Pejchar and Warner, 2001; Tuckerman and Zawiski, 2007). There is still a paucity of well-documented dam removal case studies, limiting the current predictive capabilities of the scientific community (Sawaske and Freyberg, 2012).

To best balance the competing ecological and economic factors, environmental managers should consider the entire drainage basin, rather than individual dams in isolation. The removal of a few carefully selected dams within a river system may significantly improve fish migration while preserving water storage and hydroelectric benefits (Doyle *et al.*, 2003; Kuby *et al.*, 2005; Null *et al.*, 2014).

As previously indicated, mobilization of contaminated reservoir sediments is of prime concern in dam removal projects. Common industrial inorganic contaminants include lead, cadmium, copper, zinc, arsenic, and mercury. Persistent organic pollutants are often hydrocarbons released by spills or combustion of fossil fuel, as well as pesticides, herbicides, and other manufactured substances. These compounds characteristically increase in concentration in animals higher up the food chain. For example, salmon can transport highly toxic polychlorinated biphenyls (PCBs) as they migrate in river systems (Janetski *et al.*, 2012). To evaluate the extent of contamination, sediment samples from the surface of the reservoir bed should be taken and submitted for chemical analysis. For larger projects or in cases in which there is reason to expect more extensive pollution, sediment cores should be also be taken. These will permit the evaluation of deeply buried sediments likely to be eroded and dispersed downstream as the active river channel reestablishes itself after dam removal. If sediment concentrations of inorganic and/or organic contaminants exceed regulatory limits, reservoir sediments will likely have to be dredged for treatment or safe disposal off-site prior to decommissioning the dam. After dam removal, sediments in the former reservoir and downstream will require continued monitoring to assure that the contamination been properly controlled (Cantwell *et al.*, 2014; Davidson *et al.*, 2005; Evans and Gottgens, 2007; Roberts *et al.*, 2007).

4. DAM REMOVAL CASE STUDIES

4.1. Fort Edward Dam, Hudson River (New York)

In 1817, during the early phase of the Industrial Revolution, a 9 m high dam had been built across the Hudson River at Fort Edward, New York (Chatterjee, 1997), some 260 km upstream from New York City. Many decades later, the General Electric company (GE) established two electronic capacitor factories on the east bank of the river just north of the dam (Figure 3A). Polychlorinated biphenyl (PCB) oils were important components in capacitors and transformers due to their stability at high temperatures. While the factories were in operation (1947-1977) GE discharged an estimated 590 tonnes of waste PCB oil into the Hudson River, much of which accumulated in the sediments impounded behind the dam (USEPA, 2012). Meanwhile, the dam's operators determined that the aging barrier was deteriorating and demolished it in 1973, evidently giving little thought to the consequences and believing that "the river will take care of itself" afterwards. In the immediate aftermath of dam removal logs and other flotsam impeded navigation downstream. Unfortunately, a more serious, long-term problem also arose – the exposure and dispersal of the PCB-laden sediments (Chatterjee, 1997).

Around the time that the Fort Edward dam was demolished, there was a growing awareness of the hazardous nature of PCBs due to their toxicity, carcinogenicity, and persistence in the environment. The New York State Department of Environmental Conservation made the first governmental response in the Fort Edward case, initiating a lawsuit against GE in 1975 and instituting a ban on fishing in the affected river zones the following year. During this time the GE factories continued to function (Figure 4). The first federal government action came in 1977, when the recently-inaugurated U.S. Environmental Protection Agency (USEPA) pronounced a general ban on the manufacture of PCBs and thus GE's plants were obliged to cease operations. In 1980, the United States Congress developed a program to remediate hazardous waste sites by passing the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) to be administered by the USEPA. This is commonly called the Superfund act, since the financing for remedial work is supposed to be provided via pooled funds collected from the parties responsible for pollution (USEPA, 2012).

The contamination concerns provoked by the removal of the Fort Edward dam are twofold. Comparing Figures 3A and 3B, it is evident that draining the reservoir exposed large areas of sediment, namely the light-colored patches marked by X's in Figure 3B (USEPA, 2012). These remnant deposits have high levels of PCB contamination, but remain a fairly localized hazard. However, PCB-contaminated sediments in the riverbed were also able to migrate downstream after the removal of the barrier in 1973, especially during intense storm events (Schneider *et al.*, 2007). In its lower reaches, the Hudson River is an estuary, such that sediments can migrate back upstream with the flood tide. After decades of PCB residence in this complex fluvial/estuarine regime, the net result is that the river is contaminated all the way down to its mouth in New York City harbor (USEPA, 2012).

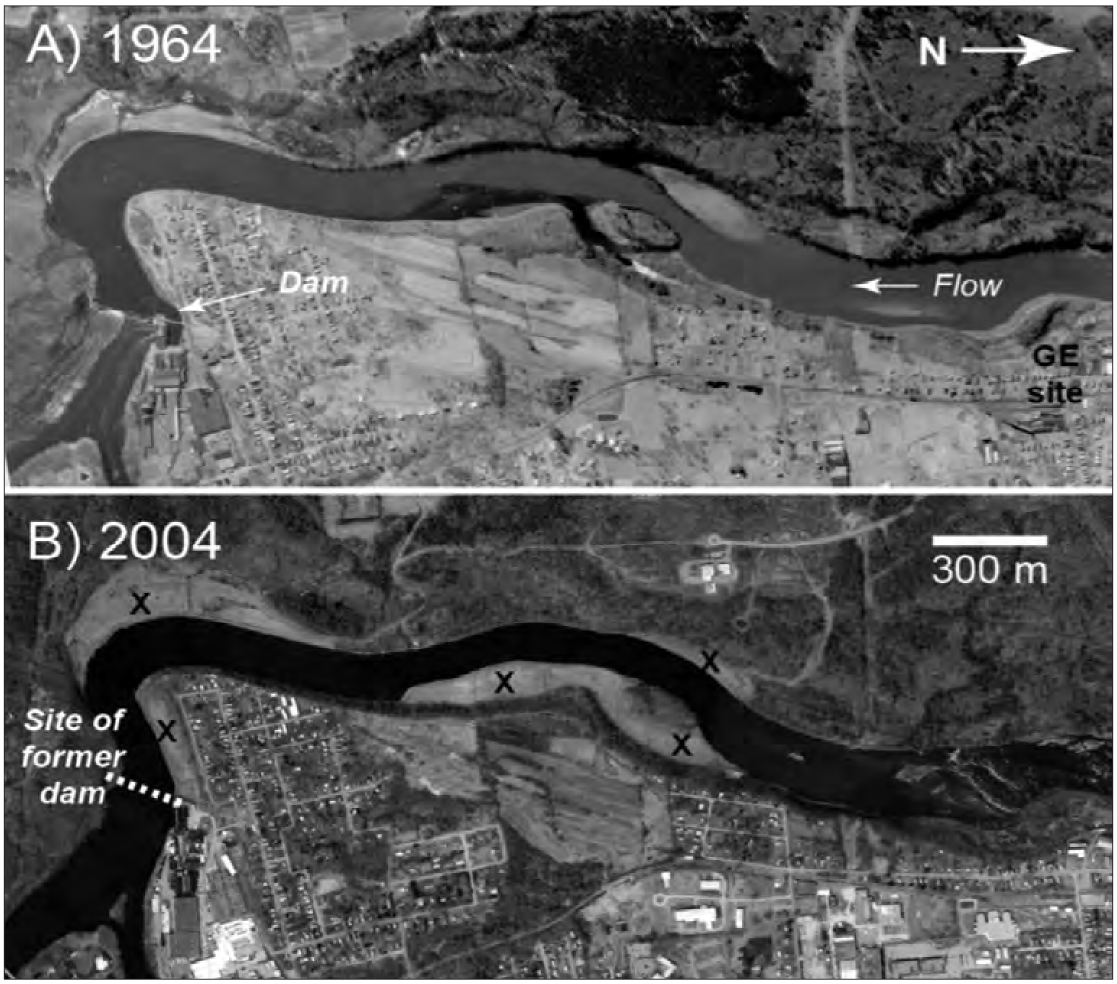

Figure 3. Aerial views of the Hudson River at Fort Edward (New York). A) Image from 1964 while the dam (at left) was in place, downstream from the General Electric capacitor factory (at right). Map imagery: United States Geological Survey. B) The same area in 2004 showing the site of the former dam. Light colored zones marked with black X's are the PCB remnant deposit sites exposed by the draining of the reservoir. Map imagery: Google Earth, New York GIS.

The USEPA initially placed the Hudson River site on the Superfund list in 1984 (Figure 4), with the goal of capping the remnant deposits (Figure 3B) with resistant materials to prevent their erosion and to close to affected areas to limit human exposure. The agency initiated a reassessment of the situation in 1989, considering that the PCB-laden sediments in the river channel also merited attention. After a protracted legal battle with GE fraught with controversy and the formulation of a remediation plan, dredging of riverbed sediments finally commenced in 2009. A second, ongoing phase began in 2011 (Revkin, 2009; USEPA, 2012). An estimated 3 million tonnes of sediment will be removed, at a cost of about US $460 million to GE. Barges take the dredged material to a nearby large-scale processing facility established by GE to be dried (without decontamination) and loaded onto railroad cars. Trains are hauling the sediment over 3000 km to hazardous waste disposal sites in the western United States (USEPA, 2012) where local disposal site operators evidently welcome the it as a revenue source (McKinley, 2009). The extreme consequences of careless pollution combined with poorly planned dam decommissioning provide a cautionary tale — the counter example to be continually evoked during future dam removal discussions (Doyle *et al.*, 2003).

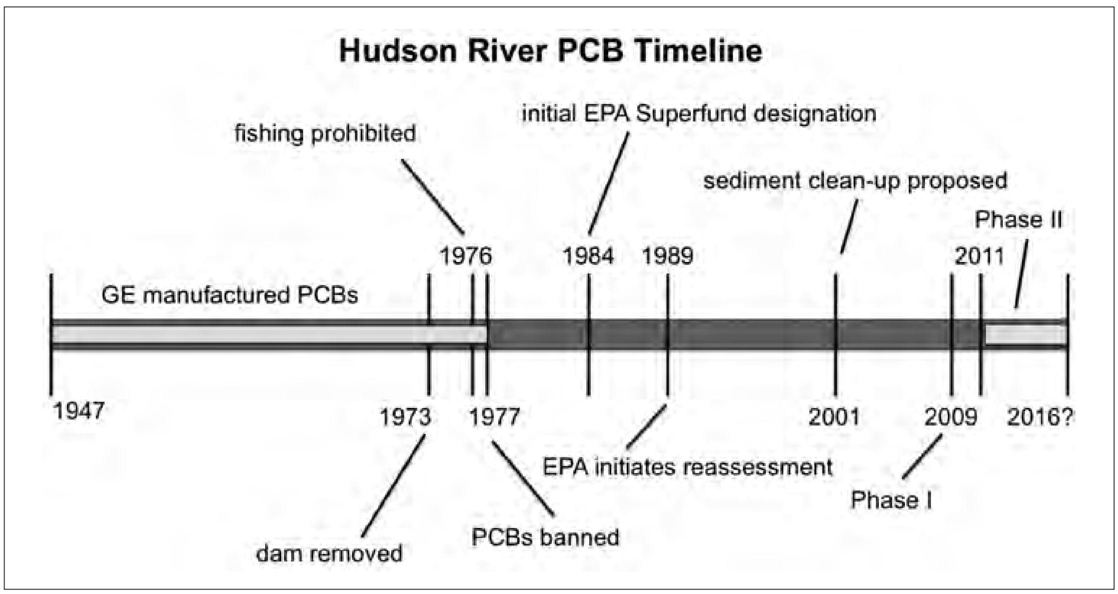

Figure 4. Timeline showing the key dates in the history of Hudson River polychlorinated biphenyl (PCB) contamination and cleanup. Data source: USEPA (2012).

4.2. Munroe Falls and Related Dams, Cuyahoga River (Ohio)

Ohio's Cuyahoga River attained notoriety in 1969 when its oily surface caught fire in the industrial city of Cleveland. The ensuing public outcry stimulated the nascent environmental movement in the United States and was one of the key events leading to the creation of the USEPA and the passage of the federal Clean

Water Act in the 1970's (Tuckerman and Zawiski, 2007). Located approximately 80 km upstream from Cleveland, the original Munroe Falls dam was constructed in 1817 to provide mechanical water power to lumber, flour and paper mills. This wooden dam was replaced by a 3.7 m high, 44 m wide arcuate masonry structure in 1902 (Figure 5A), creating a reservoir that extended 7 km upstream. Inspections in 1995 indicated that the dam, no longer serving its original purpose, was deteriorating and it was consequently decommissioned in 2005 (Peck *et al.*, 2007). Unlike the industrial metropolis of Cleveland, the watershed surrounding the dam site is predominantly suburban, agricultural, and forested (Rumschlag and Peck, 2007). Nonetheless, impaired water quality and habitat, along with sediment contamination, were evident. Geomorphological, geochemical, and ecological studies preceded and followed the Munroe Falls dam removal to assess the likelihood of environmental problems arising from the project, as well as to monitor changes to the river system afterwards (Peck *et al.*, 2007; Rumschlag and Peck, 2007; Tuckerman and Zawiski, 2007).

River channel profiling revealed that erosive down-cutting was primarily localized in the deepest parts of the former reservoir, reaching the pre-dam river bed surface only one month after dam removal, while the reservoir sediments on the margins remained largely in place. Remobilized sediments were transferred down the river below the site of the former dam, significantly altering river bed morphology and sedimentology (Rumschlag and Peck, 2007). Similar observations were made in a decade-long geomorphological study of the effects of the Stronach dam removal on the Pine River in Michigan (Burroughs *et al.*, 2009). The reestablished Cuyahoga River channel occupies about 30% of the width of the reservoir above the dam site (Figures 5A, B); the reclaimed land was repurposed as a public park (Figure 5C).

The Munroe Falls reservoir illustrated the classic effects of decades-long impoundment (Peck *et al.*, 2007). Concomitant with the increased water depth behind the dam (Figure 6A) and reduced stream flow velocity, muddy deposits extended a kilometer upstream (Figure 6B). In addition, the reservoir muds were highly enriched in organic matter, due to the relatively stagnant water conditions (Figure 6C). As mentioned previously (Section 3), this sequestered carbon is subject to alteration after the lake has been drained, potentially releasing greenhouse gases. Radiometrically-dated core samples taken in reservoir prior to dam removal provided a detailed record of the environmental history at the site. The sedimentology and trace metal contents indicated that episodic flood events had mobilized industrial contaminants from upstream sites, but resulted in levels that were unlikely to be significantly bioavailable (Peck *et al.*, 2007).

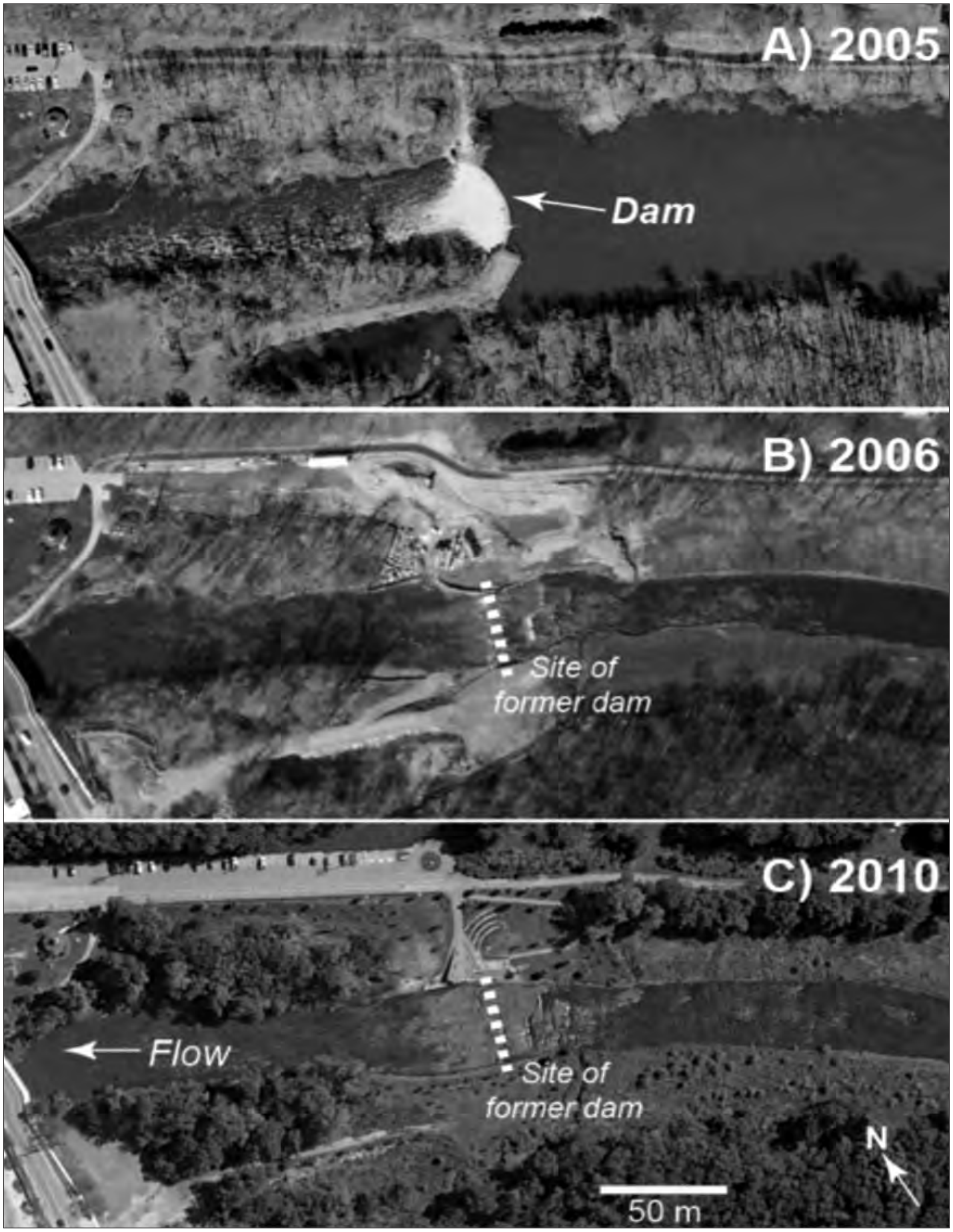

Figure 5. Sequence of aerial images of the Munroe Falls dam site, Cuyahoga River (Ohio). Map imagery: Google Earth, State of Ohio/OSIP. A) View in the year 2005 prior to the removal of the dam. B) View in 2006 shortly after dam removal. C) View in 2010 showing completed landscaping and public park.

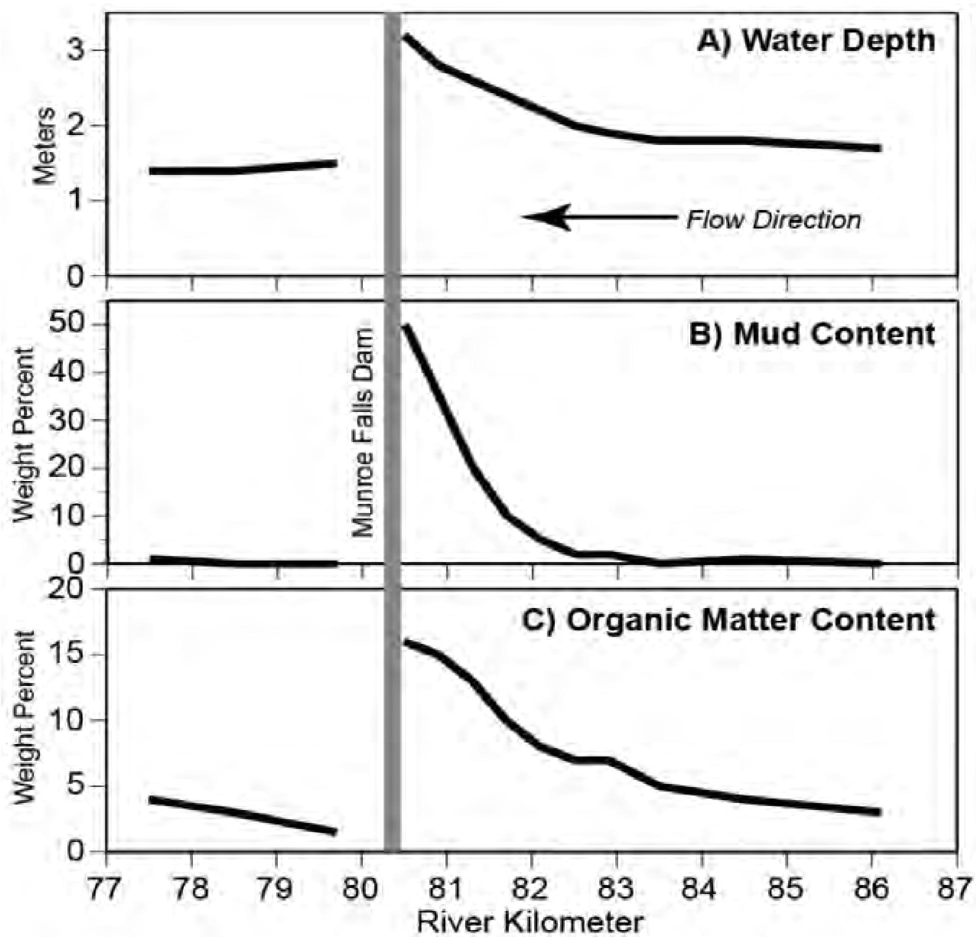

Figure 6. Conditions between river kilometers 77 and 87 prior to the removal of the Munroe Falls dam, Cuyahoga River (Ohio). Data from Peck *et al.* (2007). A) Water depth in the main channel above and below the dam. B) Proportion of mud in the sediment (grain size < 63 μm, normalized on an organic matter-free basis). C) Proportion of organic matter in the sediment, as measured by the loss-on-ignition method.

The stagnant water conditions behind the Munroe Falls dam and the companion Kent dam 8 km upstream led to seasonal hypoxia in the reservoirs, impacting aquatic life. The 19th century Kent dam was one of the oldest arched masonry dams in the United State. The desire for a free-flowing river was at odds with the need for the preservation of this historic structure. After a series of formal community meetings, governmental agencies devised a compromise plan to divert the principal streamflow around the arched dam, which was left in place as an artificial waterfall (Tuckerman and Zawiski, 2007). With the removal of the Munroe Falls dam and the bypass of the Kent dam, summer dissolved oxygen levels improved markedly, exceeding the regulatory standard (Figure 7).

The taller (17 m) Gorge dam, in a more urbanized reach of the Cuyahoga River 8.5 km downstream of former Monroe Falls dam, is being evaluated for demolition. The Gorge dam was completed in 1912 to impound cooling water for a coal-fired electrical generating station, as well as to produce hydroelectricity. With the closure of the power plant, the dam is no longer needed. The muddy, organic-rich, anoxic sediment accumulated beneath the reservoir's lentic water hosts methanogenic bacteria and is enriched in heavy metals, coal, and coal combustion products. To preclude downstream contamination, it is clear that these reservoir sediments will have to be dredged for disposal prior to dam removal. A concern remains that a cleaner, free-flowing Cuyahoga will increase sedimentation downstream and necessitate more frequent navigational dredging of Cleveland's lakefront harbor at the mouth of the river. Watershed modeling and sedimentation rate studies based on radiometrically-dated cores taken in the reservoir predict that increases in sediment load transported downstream would be minimal (Mann *et al.*, 2013). Systematic consideration of the potential consequences of obsolete dam removal provides a sensible course for the environmental management of a river restoration project, such as that ongoing along Ohio's Cuyahoga River.

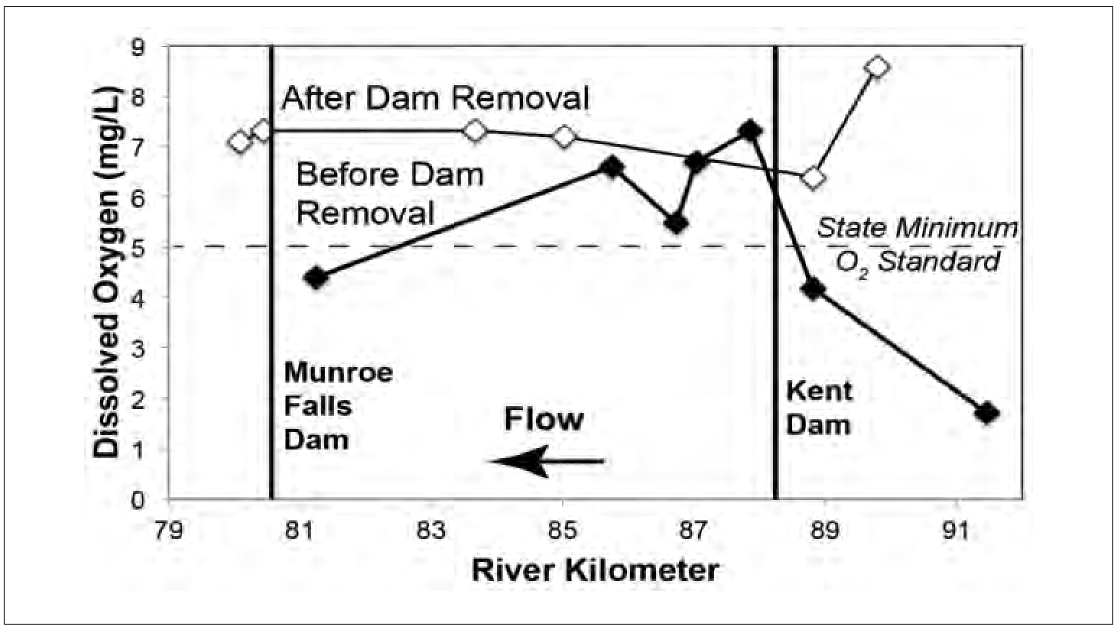

Figure 7. Mean summer (month of August) dissolved oxygen concentrations in Cuyahoga River water before and after the removal of the Munroe Falls and Kent dams. Data from Tuckerman and Zawiski (2007).

4.3. Small Dam Remova l Examples, Northeastern United States

The case of the aging industrial Munroe Falls dam is one of the many such examples of modestly sized dams removed or considered for removal. There are some 42,000 minor "run-of-river" dams in the in the United States (mostly in the East), so called because they are so low that water normally overflows their crests and the river margins are typically not inundated by the reservoir. Nonetheless, they form barriers to fish movement, impeding stream connectivity. Multi-year fish population monitoring before and after the careful, gradual removal of the small (1.5 m high, 25 m long) run-of-river Zemko dam on the Eightmile River in rural Connecticut documented enhancement to the fluvial habitat (Poulos *et al.*, 2014). While it is obvious that major dams impounding large reservoirs strongly impact their environments, the geomorphic effects of small structures are less evident. A study of four small run-of-river dams in Illinois noted that the barriers have only minor effects on channel morphology, as well as sediment accumulation and grain-size distributions. Recognizing this generalization, environmental managers should nonetheless be mindful of site-specific variability prior to decommissioning a small dam (Csiki and Rhoads, 2014). Even if the removed dam was a small one, the stream channel may not necessarily reassume its pre-dam form (Doyle *et al.*, 2005). Continued pollutant discharges (such as those from combined sewer overflow systems in older North American cities) will likely mean that dam elimination alone will not be sufficient to improve river quality, as was documented after the removal of a 2 m high barrier in an urban area on Ohio's Olentangy River (Zhang *et al.*, 2014). Although a dam may be small, it is prudent to consider the possibility of contaminant remobilization and flooding hazard prior to decommissioning. An evaluation of the 2.5 m high run-of-river Secor Dam on the Ottawa River (Ohio) concluded that there would be minimal impacts and the dam owners approved its removal (Roberts *et al.*, 2007).

Even though contaminants may be present in the river system, the removal of a small dam may have little net impact on them. Sediments above and below the 2.5 m high run-of-river Manatawny Creek dam were analyzed for polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and trace metals both before and after the dam was removed. Manatawny Creek is a fourth-order stream flowing into the Schuylkill River in southeastern Pennsylvania. While the results indicated that concentrations of some contaminants were elevated, the dam removal made little difference (Figure 8). The dam was demolished in two stages to reduce the likelihood of sudden impact, but concerns were lessened upon noting that its reservoir did not contain much of the fine-grained sediment likely to trap contaminants (Ashley *et al.*, 2006). Similar results were reported in a study of the removal of a 1.5 m high run-of-river dam in an urbanized reach of the Pawtuxet River (Rhode Island), with little change observed in PAH and PCB concentrations (Cantwell *et al.*, 2014).

The reservoirs of small (< 3 m high) relic 19th century mill dams in southern New Jersey became suburban homesites in recent decades, with residents attracted by the esthetic pleasure of lakefront living. However, the aging, privately-owned dams were in many cases found to be structurally deficient and potentially hazardous to life and property. To their consternation, the owners (i.e., the lakefront residents) were instructed by state authorities to make expensive repairs or remove the dams to prevent catastrophic failure. The owners protested, concerned by the high cost of reinforcing the structures, yet fearing loss of property values and lifestyle degradation if their lakes were drained. Such environmental management conundrums might be resolved more readily by educating the stakeholders while remaining respectful of their concerns (Wyrick *et al.*, 2009).

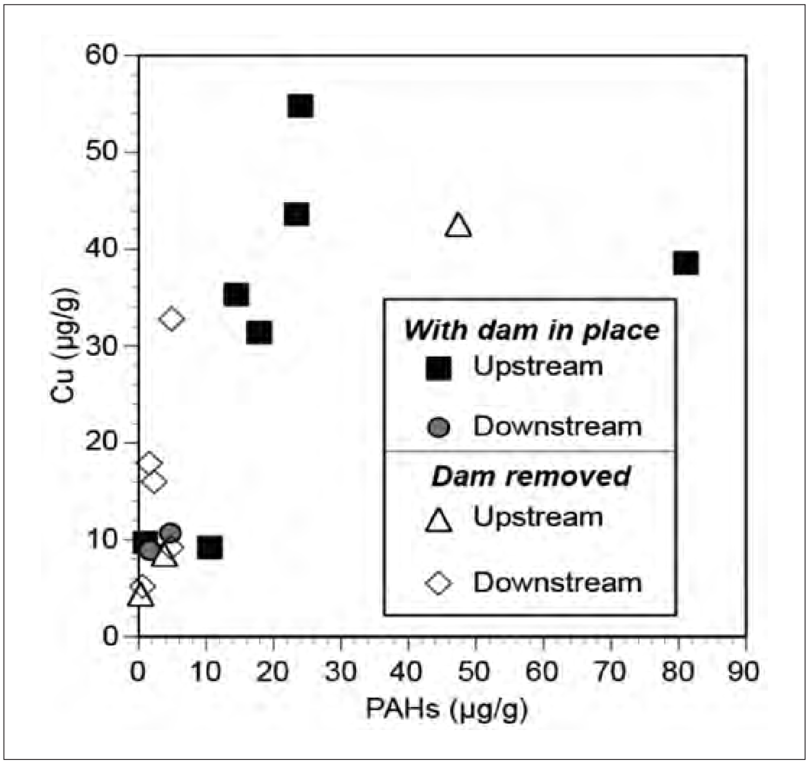

Figure 8. Concentrations of contaminants in the sediments of Manatawny Creek (Pottstown, Pennsylvania) upstream and downstream of the dam site, before and after dam removal. Copper and total polycyclic aromatic hydrocarbons (PAHs) are shown as examples of inorganic and organic contaminants, respectively. Data from Ashley *et al.* (2006).

The Naugatuck River (Connecticut), a major tributary of the estuarine Housatonic River, was once known for its abundance of anadromous fish, particularly *Alosa spp*. With the advent of the Industrial Revolution, fish migration was impeded by the dams built to serve the new mills. These water-powered facilities evolved into heavy industrial complexes by the early 20th century, giving the Naugatuck its reputation as "Connecticut's dirtiest river". By the century's end, the condition of the river was beginning to improve as a result of environmental regulations, closure of the factories due to global economic shifts, and public concern. Dams were removed or by-passed with hopes for ameliorating fish habitat (Howard, 1999). As one of eight dams involved in the ongoing Naugatuck River restoration efforts, the Anaconda dam (Figure 9A) was removed in 1999.

Standing 3.4 m high and 100 m long, it was deteriorating and hazardous. After extensive sediment analysis, the broad spillway on its east side was to be opened and impounded sediments removed to prevent their remobilization. Before these plans could be implemented, a strong storm breached the dam at the spillway. It had to be dismantled quickly, under an emergency decree, to prevent erosive damage to a municipal sewer main. The river soon reestablished itself, scouring a slightly sinuous channel down to the pre-dam riverbed on the east side of the former reservoir (Figure 9B), nearing an equilibrium state in only four years. Much of the reservoir sediment on the west side remains in place as a dewatered, vegetated floodplain, naturally armored over time with coarse sediment. The urgent spillway demolition precluded completion of the planned sediment testing. PAHs were detected, but in relatively low concentrations, likely due to the predominance of coarse-grained deposits. In the years since dam removal, fish populations have increased and recreational angling is now possible (Wildman and MacBroom, 2005).

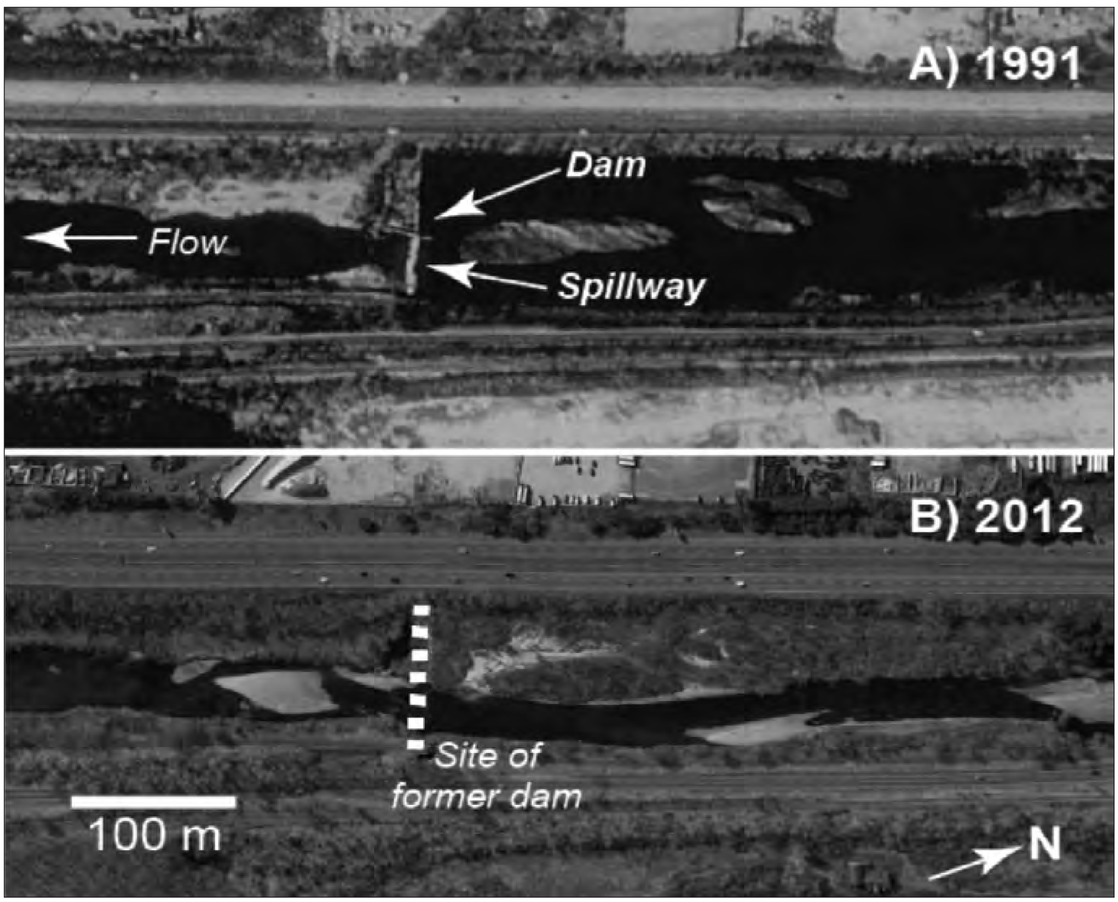

Figure 9. Sequence of aerial images of the Anaconda dam site, Naugatuck River (Waterbury, Connecticut). Map imagery: Google Earth, U.S. Geological Survey. A) View in the year 1991, with dam in place. Note the wide spillway along the eastern half of the dam. B) View in 2012, after removal of dam.

4.4. Consideration of dam removal, Klamath River (Oregon and California)

The early to middle 20th century witnessed the construction of large dams in the western United States (often by state and federal government agencies or by private concerns on leased government lands) to store water primarily for agricultural and urban consumption and for hydroelectric power. Large dams can strongly impact their environments, for example by limiting peak discharges, simplifying the fluvial geomorphology downstream, and by impeding fish migration (Graf, 2006). The Klamath River extends for over 400 km in southern Oregon and northern California. The lower 300 km stretch passes unrestricted through rugged, mountainous terrain, while the valley of the upper 100 km reach is the site of the Klamath River Hydroelectric Project, with six dams between 7 and 53 m in height. In spite of their hydroelectric power (163 MW combined generating capacity) and water supply benefits, the lower four Klamath dams are being considered for removal (GEC, 2006; PacifiCorp, 2011; Stillwater, 2008) . These dams are among the reasons postulated for the declining stocks of commercially-valuable anadromous fish (*Oncorhynchus spp.*) in the Klamath River (NOAA, 2015; Oliver *et al.*, 2014).

In the predominantly rural upper Klamath River valley, another primary concern is poor water quality (Sullivan *et al.*, 2013). This stretch of the river suffers from low dissolved oxygen and high ammonia levels, as well as seasonally elevated pH in the relatively stagnant waters of the reservoirs. The total nitrogen concentrations rise upstream, above river kilometer 350 (Figure 10A). A similar trend is seen for chlorophyll pigment levels (Figure 10B), which provide a proxy indicator for the amount of algal biomass in the water. Excess nutrients (nitrogen and phosphorus) from both point and non-point sources stimulate noxious summer blooms of cyanobacteria and diatoms in the lentic impounded waters (Kann and Asarian, 2006; Oliver *et al.*, 2014; Sullivan *et al.*, 2013). For the uppermost stretch (above river kilometer 375) dam removal is not being contemplated. Instead, possible remedies could include more stringent controls on wastewater treatment plant effluents, diversion of the uppermost stream through a wetland for passive filtration, and periodic physical removal of suspended particulate matter in the water column (Sullivan *et al.*, 2013). Upper Klamath Lake (constituting the headwaters, just above river kilometer 400) is natural, but its level is regulated and it is itself subject to algal blooms, further complicating the water quality problem (Kann and Asarian, 2006; Oliver *et al.*, 2014).

The four dams between river kilometers 300 and 370 (Iron Gate, Copco Nos. 1 & 2, and J. C. Boyle) have been evaluated for removal. The Iron Gate and Copco No. 1 reservoirs are the largest and contain predominantly muddy sediment. If this fine-grained material is released, the resulting turbidity could impair downstream habitat. The sediment was shown to have only insignificant levels of industrial contaminants, thus the concern is simply the large volume of impounded silt and clay (GEC, 2006; Stillwater, 2008). A gradual release would likely mitigate the problem, for example, by demolishing the smaller J.C. Boyle and Copco No. 2 dams first, then slowly draining the larger Iron Gate and Copco No. 1 reservoirs prior to removing their dams (Stillwater, 2008). Extensive sediment dredging is not practical in this case. Environmental managers commissioned a demolition plan and price estimate (GEC, 2006) as part of the cost/benefit analysis. The impact of elevated nutrient levels (N, P) on downstream habitat should also taken into account prior to dam removal (Oliver *et al.*, 2014). In 2010, stakeholders including the federal government, Oregon and California state agencies, Native American tribal representatives, and the hydroelectric leaseholder PacifiCorp signed the Klamath Hydroelectric Settlement Agreement, which provides a procedural framework for the possible removal of the four dams by 2020. Many controversial details remain unresolved and the Agreement is still awaiting approval by the U.S. Congress (Fimrite, 2009; NOAA, 2015; PacifiCorp, 2011).

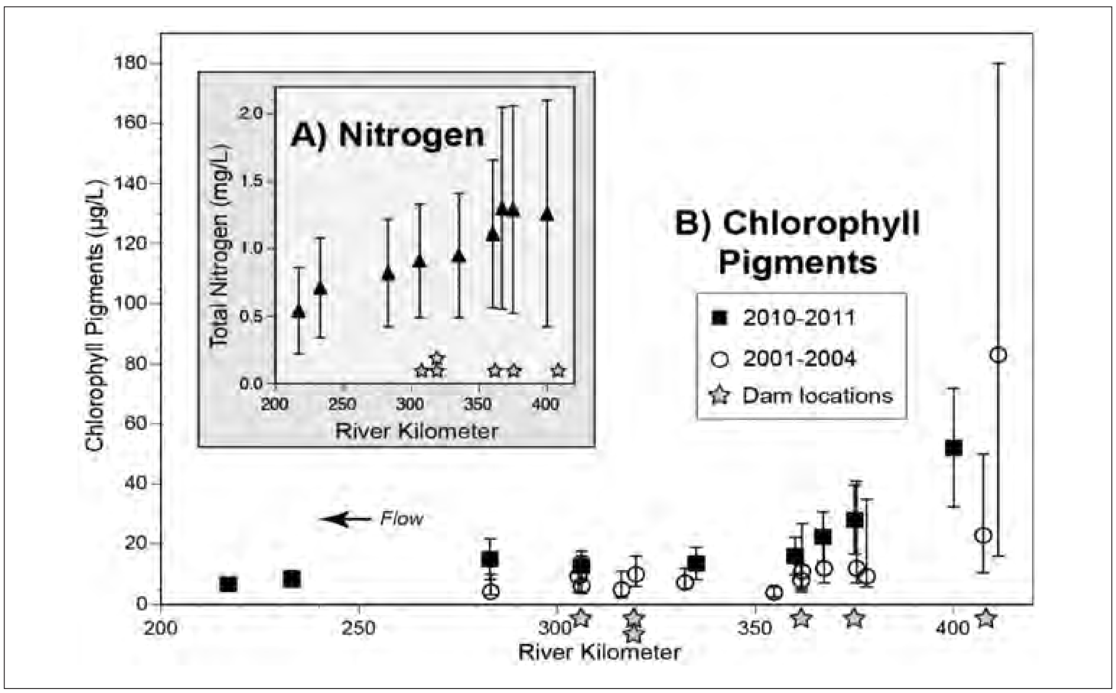

Figure 10. Water quality in the Klamath River (Oregon and California) between river kilometers 200 and 420. Stars mark dam locations: Link River (upstream), Keno, J.C. Boyle, Copco Nos. 1 & 2, and Iron Gate (downstream). A) Total nitrogen concentrations in 2010-2011 (data from Oliver *et al.* (2014)). B) Concentrations of chlorophyll pigments measured from 2001 to 2004 (data from Kann and Asarian (2006)) and in 2010-2011 (data from Oliver *et al.* (2014)).

4.5. Elwha and Glines Canyon Dams, Elwha River (Washington)

Unlike the Klamath River Hydroelectric Project dams built far upriver, the recently demolished Elwha and Glines Canyon hydroelectric dams were located close to the coast, on the Elwha River in the state of Washington. Built in 1911, 7 km upstream from the river's mouth at the Juan de Fuca Strait, the concrete Elwha dam was 33 m high (Figure 11A). The taller, arcuate Glines Canyon dam stood at 64 m, constructed 14 km farther upstream in 1927. Privately built for electricity generation with a combined capacity of 28 MW, the dams offered little flood control or water supply benefit (Randle *et al.*, 2015; Warrick *et al.*, 2015). The dams lacked fish ladders and effectively blocked anadromous fish runs. The U.S. Congress approved the purchase and demolition of the dams in 1992, recognizing that most of the river's watershed (as well as the Glines Canyon dam itself) was located in Olympic National Park. Due to persistent controversy, the actual removal was delayed for another two decades (East *et al.*, 2015; Nijhuis, 2014; Randle *et al.*, 2015).

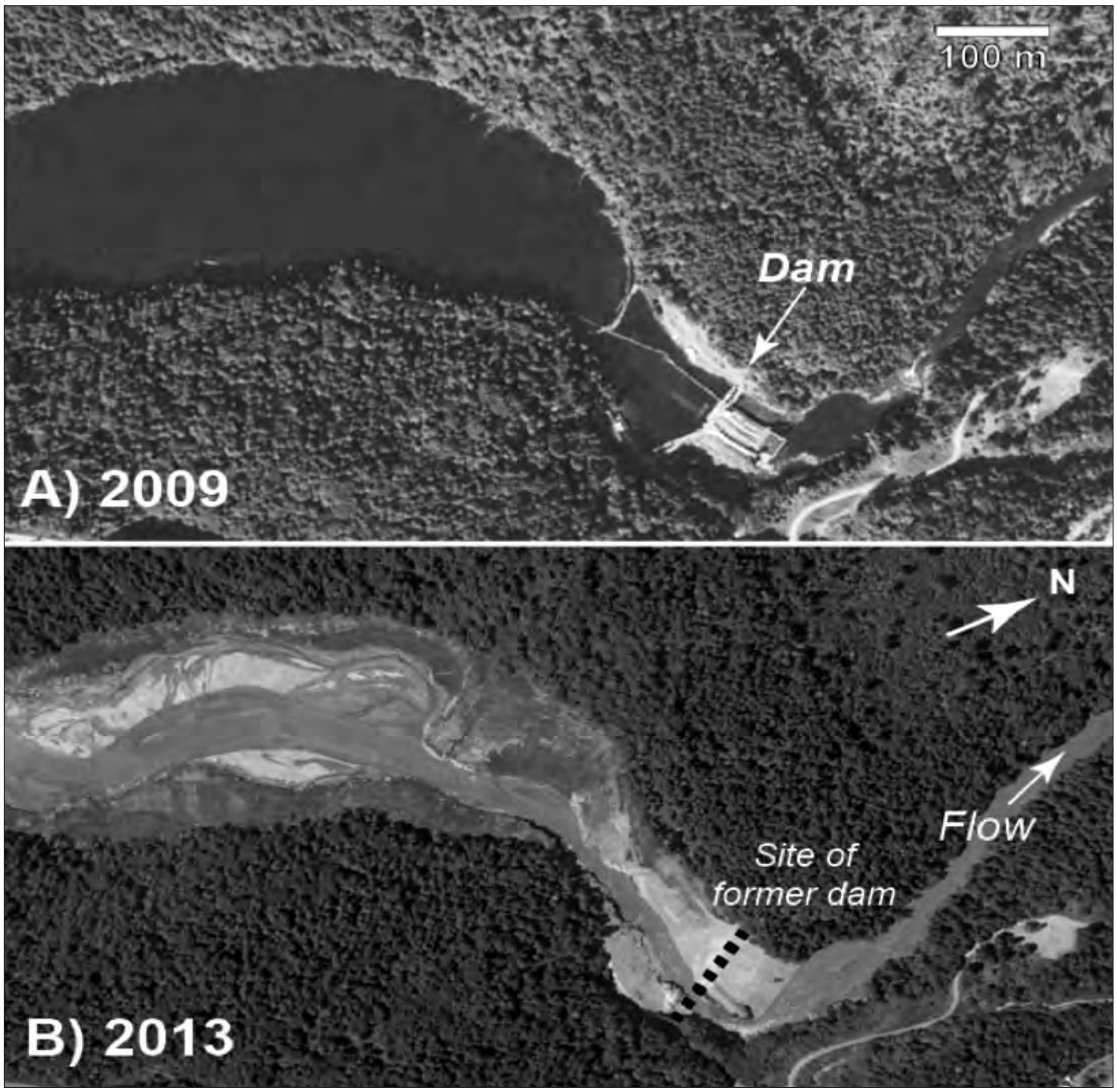

Figure 11. Sequence of aerial images of the Elwha dam site, Elwha River (Washington state). Map imagery: Google Earth, U.S. Department of Agriculture Farm Service Agency. A) View in the year 2009, with dam in place. B) View in 2013, after removal of dam.

With the dams collectively impounding an estimated 21 million m^3 of sediment, about half of which was fine-grained, there was concern that increased turbidity during dam removal would be detrimental to fish downstream. After extensive sediment studies and modeling, environmental managers decided to drain the reservoirs gradually to minimize the impact. (In the forested parkland of the drainage basin, industrial contaminants were not an issue.) Beginning in 2011, the concrete walls of the dams were notched incrementally, 3 to 5 m at a time, with pauses in between to permit dispersal of sediment. Within thirteen months, both reservoirs were completely drained. The demolition of the smaller Elwha dam was completed first. The river channel reestablished itself on the south side of the dam site and a system of smaller braided channels and terraces occupied the exposed sediments on the reservoir margins (Figure 11B). By 2014, both dams were completely removed and about half of the impounded sediment was mobilized, aggrading the river bed by a meter. An estimated 90% of the sediment was transported to the coast, prograding the delta and nourishing the local beaches (Dean, 2015; East *et al.*, 2015; Magirl *et al.*, 2015; Nijhuis, 2014; Randle *et al.*, 2015; Warrick *et al.*, 2015). The carefully planned, executed, and monitored dam removal project was the largest in the United States thus far. It demonstrated the value of lessons learned from prior experience, including the importance of several key factors: the watershed hydrology; hydraulic height of the impoundment; the sediment's grain size distribution, cohesiveness, thickness, and accumulated volume relative to annual input; and the need for gradual staging in the draining and demolition processes (Randle *et al.*, 2015).

4.6. Milltown Dam, Clark Fork and Blackfoot Rivers (Montana)

In the historic mining regions of the western United States, dams impounded tailings and ore milling waste, leaving a legacy of environmental contamination (James, 2005). Beginning in the 1860's and continuing for over a century, the headwaters of Montana's Clark Fork River were the scene of major copper mining and smelting activities, termed by some "the richest hill on Earth". This resulted in high concentrations of heavy metals in the river sediments, extending some 200 km downstream to Milltown, where an 8 m high hydroelectric dam was built in 1908 at the confluence with the Blackfoot River (Figure 12A). Arsenic detected in Milltown water supply wells in 1981 was an early indicator of the severity of the problem. The reservoir ultimately formed part of the Milltown Reservoir Sediments/Clark Fork River Superfund Site, one of the nation's largest (Axtmann and Luoma, 1991; Robbins, 2008; USEPA, 2011; 2013). Episodic winter ice jams mobilized contaminated reservoir sediments, heightening concern (Moore and Landrigan, 1999; Tuthill *et al.*, 2009) and work began in 2005 on the Milltown "Remediation, Restoration, and Redevelopment" project (USEPA, 2011).

As was done with the Elwha River dams (Section 4.5), the Milltown reservoir was first slowly drained (Figure 11B) prior to dam removal (Robbins, 2008; USEPA, 2011). While in the Montana case, the concern was contamination rather than turbidity, prudence and experience dictated a similarly patient approach. During reservoir draw-down, some increases in heavy metal concentrations were noted downstream (Plathe *et al.*, 2013). A temporary diversionary channel was established on the northern margin of the Clark River floodplain, permitting the dewatering of the contaminated sediments on the south side. A total of approximately 2 million m^3 of sediment were removed by railcar for supervised disposal offsite during 2007-2009 and the dam was demolished (Figure 11C). A sinuous, natural-appearing stream channel was reestablished through the remediated floodplain, the diversion closed, and a new state park was created on the reclaimed land (Figure 11D). Through the cooperation of federal and state governmental agencies, the local community, and the responsible parties, the project was brought to a successful conclusion (Clark-Fork-Coalition, 2015; DOJMT, 2015; USEPA, 2011; 2013)

Historic Western mining interests were closely linked to Eastern manufacturing. The Anaconda Copper Mining Company of Montana, accountable for much of the Clark Fork River pollution, acquired Connecticut's American Brass Company in a major early 20th century corporate merger (NY Times, 1922). Thus the former dam on the Naugatuck River of Connecticut (Section 4.3) was coincidently named "Anaconda". Anaconda Copper's corporate successor, the petroleum company Atlantic Richfield (ARCO, now part of BP) inherited extensive financial responsibility for the Clark Fork remediation under Superfund regulations (DOJMT, 2015; Robbins, 2008; USEPA, 2011).

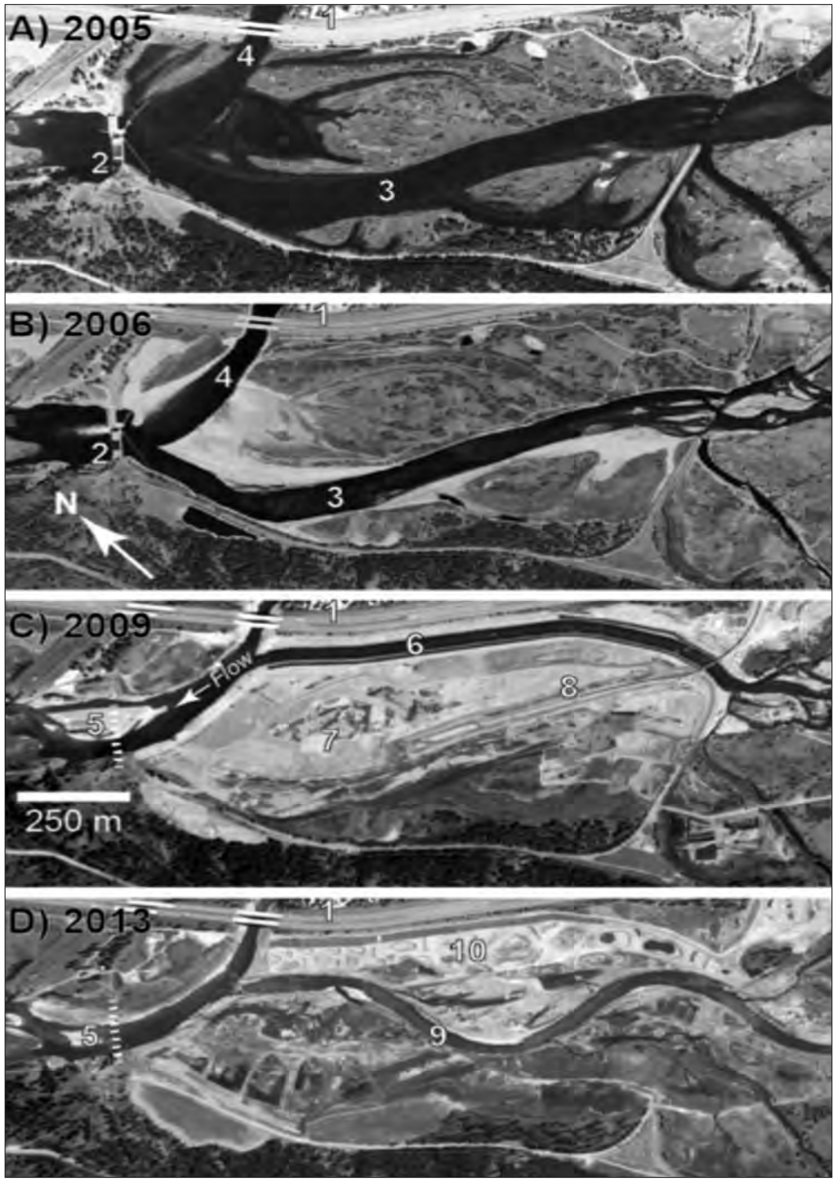

Figure 12. Sequence of aerial images of the Milltown dam site, confluence of the Clark Fork and Blackfoot Rivers (Montana). Map imagery: Google Earth, U.S. Department of Agriculture Farm Service Agency. A) View in the year 2005, with dam in place. B) In 2006 after the gradual draining of the reservoir. C) In 2009 after removal of dam and creation of a diversion channel to permit removal of contaminated reservoir sediment. D) In 2013 showing the restored, natural-appearing Clark River channel after completion of contaminated sediment removal. Key to indicated features: 1) municipality of Milltown, 2) Milltown dam, 3) reservoir behind dam (Clark Fork River), 4) reservoir behind dam (Blackfoot River), 5) former dam site, 6) temporary Clark River channel during floodplain sediment removal, 7) sediment removal activities in Clark River floodplain, 8) temporary railroad for sediment removal, 9) restored "natural" Clark River channel, 10) landscaping for the new state park.

5. CONCLUSIONS

Dam removal decisions should ideally be made after a thorough cost-benefit analysis. If dam obsolescence, structural safety, harm to fisheries, and reservoir eutrophication are among the primary concerns, decommissioning would likely be favored. On the other hand, dams provide considerable benefits including water storage for agricultural and urban consumption, renewable electricity generation, support of navigational canal systems, flood control, and lakes for recreation. Because of these competing factors and interests, dam removal decision-making in the United States is often fraught with controversy. Best practice indicates that all stakeholders should be heard as the merits of dam removal are debated.

If a dam is to be decommissioned, environmental managers should first conduct careful ecological, geomorphological, and sedimentological studies to minimize the possibility of unintended negative consequences. Chief among these is the release of contaminated reservoir sediments, which if present, should first be dredged for proper disposal. Recent experience has shown that dams should be demolished in gradual stages after first draining the reservoir, to reduce turbidity downstream during the procedure. Environmental managers should evaluate dams in the context of the full watershed; selective removal of a few dams in a river system may improve fish migration and stream connectivity while preserving water storage and hydroelectric benefits. There remains a paucity of dam removal documentation to aid decision makers; researchers should be encouraged to continue to close this knowledge gap. The extent to which reservoirs are either sources of greenhouse gases or carbon sinks also merits further study. The lessons being currently learned in the United States about the decommissioning of old dams should inform policy makers in other parts of the world where large dam construction is still ongoing.

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