*Photo 1. Small dam in Xintai, Shandong Province, China (Credit: Dingfan Cui, 2022).*

# TITLE: Understanding the environmental processes when removing small dams

LWS 548 Major Project

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## EXECUTIVE SUMMARY

At the end of their life-cycle dams can be removed or rebuilt. Dam removal can be used to recover the ecosystem; avoid the dam failure and the loss of property and life. Many countries have promulgated policies for removing small dams and have begun to carry out small dam removals projects. Therefore, a comprehensive review of the challenges and benefit of small dam removal can be useful to wide range of managers. This report reviewed literature and provided case studies material to show what can be learned when contemplation dam removal. Dams have significant impacts on river ecosystem, causing changes in the hydrological regime, water quality and river channel morphology. Small dam removal can result in short-term problems (reservoir erosion, downstream sediment transport, and ecosystem disruption over minutes to months) and long-term responses (changes in overall watershed conditions over weeks to decades, including habitats improvement, environmental services restoration), which can be highly variable because of the different characteristics of dams and reservoirs. In many watersheds climate change can have positive or negative impacts on the aquatic ecosystem before or after dam removal. However, climate change will likely contribute to the creation of a different ecosystem that was present before the dam was built and the one that was created during the period of dam operations.

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## INTRODUCTION

Have you ever noticed how powerful the river is? A river can create electricity for the local village through the creation of small dam. Large dams have well-documented and quantifiable consequences, but small dams are often seen as socially and environmentally benign (Muller, Mantel & Hughes, 2010). However, many impacts on the ecosystem from small dams have been identified over time. As a result, expectations are high that the removal of small dams will rapidly restore the aquatic ecosystem. The aim of this project is to show what some of the challenges are, how fast river systems recover and what changes might occur after dams are removed.

Dams provide a wide range of benefits to human lives not only for electricity production but also for providing recreations opportunities in the reservoir of dams and for partially mitigations droughts. However, the impacts on environmental services can be profound. The main reason why many countries are carrying out dam removal projects is to avoid property and life loss due to potential dam failure as dams age.

China is the world leader in building dams, both large dams (> 150 m in height) and small concrete dams (< 100 m in height). The country has a history of dam construction: since 1950, 23,841 large dams and tens of thousands of small hydropower dams (installed capacity of less than 50,000 kilowatts) have been built (CSDMS, 2014). The Yangtze River basin, Asia's longest river, contains over 50,000 dams of various sizes (Gan, 2020, CSDMS, 2014). Small hydropower stations in the Yangtze basin once became the main source of electricity for villages in southern China as this was promoted as a "clean" energy source during 1980 to 2015 (Diao, 2021). The central government of China provided priority support to the small hydropower stations to solve the electricity scarcity in rural areas (Diao, 2021). With such strong support, private owners owned 80% of the 25,000 small hydropower stations in the Yangtze River Economic Belt, where most stations have less than 50,000 kilowatts installed capacity (Diao, 2021). However, the negative impacts of these dams and hydropower facilities have been investigated and reported in the literature, in China and the US (Bloomberg, 2021; Leslie, 2019). For example, 3514 reservoirs in China burst between 1951 to 2011, according to China's Ministry of Water Resources. One of the most severe accidents was when a torrential rain in August 1952 broke the Banqiao dam and 61 other dams, which killed 240,000 people (Bloomberg, 2021).

To respond to these events China's Ministry of Ecology and Environment and the National Development and Reform Commission in 1919 issued a policy outlining the small hydropower renovation and transformation plan (MEE & NDRC, 2019). This plan was expected to correct the ecological and environmental problems caused by small hydropower stations, protect and restore the river ecosystem, and promote the Yangtze River Economic Belt to embark on a new path of ecological priority with green development (MEE & NDRC, 2019). The Chinese government planned to demolish dams within the core or buffer zone of nature reserves, dams with no power generation since 2013, and those that had severely damage the ecological environment. Dams that seriously affected the safety for flood control were identifies (MEE & NDRC, 2019). Tens of thousands of dams were identified to be demolished across the country (MWR, NDRC, MEENEA, 2018). Within the Yangtze River Economic Belt alone, over 3,500 small dams (out of 25,000 small hydropower stations total), were removed by the end of 2020 (Wang, 2021). The public has generally been supportive of dam removal for the benefit of river ecosystem restoration (Xinhua, 2022).

The United States has the second largest number of dams in the world, with more than 91,000. The average age of the dams is 57-years and approximately 81% of dams are marked as having a high-hazard-potential (ASCE, 2021). Dam removal is increasingly regarded as a realistic option once the cost of keeping a dam in place is higher than the cost of removing it, especially in areas where the potential for river restoration is significant (Ryan Bellmore et al., 2017). Given the large quantity and age structure of dams in the United States and altering social norms, dam removal is anticipated to continue on an upward trajectory (Ryan Bellmore et al., 2017). The world's largest dam removal project is the Klamath Dam which was 52.73 meters high on the mainstem Klamath River in the USA by 2022 (Blumm & Illowsky, 2022). Therefore, all the dam removal cases presented in this report belong to the category of small dams.

The ecological interactions and effects on dam establishment and removal are complex. Dams affect the watershed dynamics in many ways: by controlling stream flow, increasing evaporation, altering groundwater flow, blocking fish migration, and others (Schreier, 2020)., The intention for removing dams is to mitigate some of their negative impacts, that altered the hydrological and ecosystem dynamics. For example, dam removal can increase fish migration in the short-term and restore the fish habitat in long-term (Stanley & Doyle, 2003). It is essential to have a thorough knowledge of the ecological repercussions (both positive and negative) of restoration activities and the time to restore since dam removal (Bednarek, 2001). The local community and inhabitants must thoroughly grasp the dam removal process.

The paper aims to summarize the environmental impacts of a small dam and assess the short- and long-term environmental impacts of small river dam removal, as well as the potential issues associated with climate change. In addition, the challenges, and opportunities of removing small dams at the end of their life cycle to improve the ecosystem services are reviewed. All the information provided by this paper would be beneficial for informing future dam removal planning, especially the Yangtze River Basin in China.

## METHODS

This report reviews the existing literature and shows two case studies to form a comprehensive understanding of small dam removal and the related environmental effects.

The first step is to introduce the basic knowledge related to "small dam establishment and removal,"; "hydrology and water quality effects before and after dam removal,"; and "climate change and dam,"; using these as the keywords to search the relative references. Since climate change needs considerable evidence to prove, many websites and news cited for indicating climate change effects. The second step is to better visualize the impacts of dam removal and show the recovery process after the dams being removed by providing two case studies from the United States.

This report aims to establish an overall understanding of small dam removal; therefore, all relative information is general. While another essential purpose is to generate recommendations for the existing small dams and dams' future, some suggestions and backgrounds are focused on the Yangtze River Basin in China.

## LITERATURE REVIEW

### Basic knowledge - Hydrological cycle & Dam

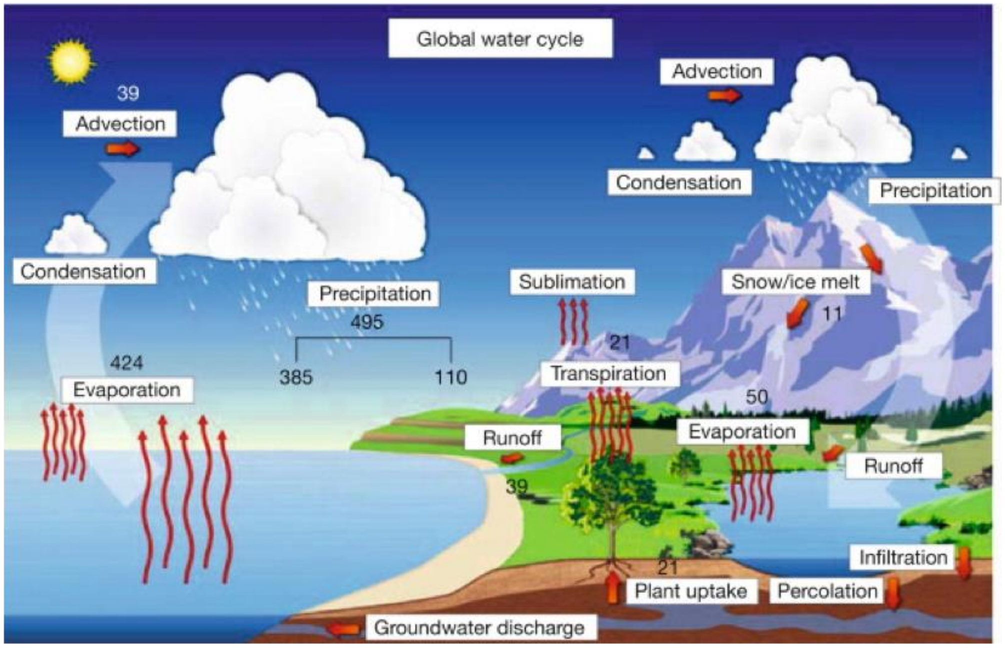


*Figure 1. Global water cycle, credit: the book "Hydrology" (Marshall, 2013).*

Dams have many benefits for human beings, such as water for drinking and industrial use, inland navigation, flood control, hydropower generation, irrigation, and recreation (Bhakra Beas Management Board, n.d.). However, Dam affects the river ecosystem by altering the hydrological cycle.

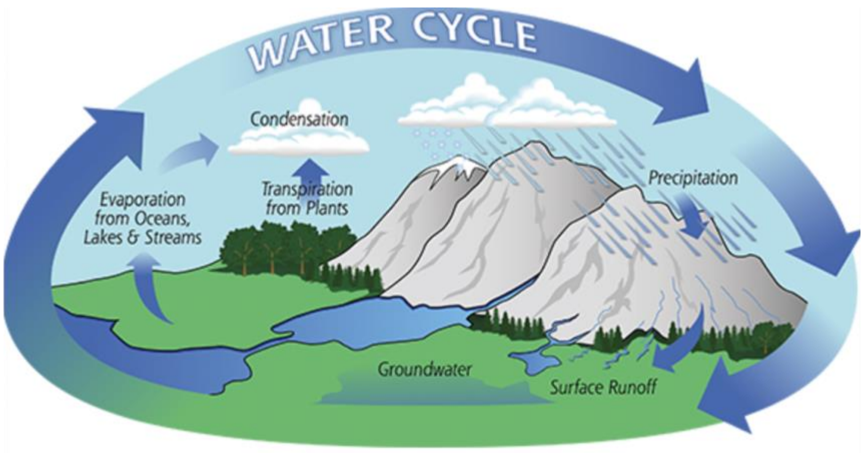


*Figure 2. The main processes in the water cycle, credit: NASA website (Cosner, C., n.d.).*

### Environmental concern on damming a river

*Table 1. Impacts of dam.*

| Hydrology Effects | Impact |
|---|---|
| **Controls stream flow** | • Shift the low flow regime<br>• Diminish peak flows<br>• Affect interannual flow variability<br>• Reduce sediment transport<br>• Created different habitat conditions |
| **Increases evaporation** | • Alter surrounding microclimates<br>• Affect natural temperature swings, ecosystems, and habitats<br>• Increase the moisture content<br>• Disrupt the natural rainfall patterns<br>• Result in more frequent and violent flooding |
| **Creates stagnant conditions downstream** | • Lead to warmer temperatures and lower dissolved oxygen levels<br>• Convert inorganic mercury to methylmercury<br>• Harm to reservoir fish consumers by bioaccumulate |
| **Disconnections and Diversions** | • Cause fragmentation of aquatic habitats<br>• Obstruct fish migration |
| **Water Quality Effects** | **Impact** |
| **Change thermal regimes** | • Aquatic bodies maintain higher temperatures than nature during the late summer and fall<br>• Cause huge temperature variations<br>• Harm to temperature-sensitive aquatic species |
| **Dissolved Oxygen stratification** | • Deoxygenation of deep reservoir water<br>• Diminish the total oxygen level of water bodies |
| **Cause eutrophication** | • Result in algae, phytoplankton, or floating macrophytes blooms<br>• P bonded to sediment particles instead of absorbing by biota |
| **Trap sediment** | • Alter habitat<br>• Reduction in the ratios of silicon to nitrogen |

### Hydrology Effects

**Dams control stream flow.** A dam normally holds water during heavy rain periods and releases it in a regulated manner to accomplish a specific purpose (McCartney & Kleinschroth, 2020). During the day, when societal demand for energy is highest, many hydroelectric dams discharge more water (Poff & Schmidt, 2016). Dams have a significant influence on hydrology because they may shift the low flow regime, diminish peak flows, and affect interannual flow variability (Mailhot, et al., 2018). Because of the varying daily pattern of water flows caused by hydropeaking, productive, downstream coastal ecosystems are generally harmed by repeated soaking and drying (Poff & Schmidt, 2016). The sudden drop in the peak water level can exposed the eggs of aquatic insects and fish or partially exposed rocks to the atmosphere that lead to mass mortality (Poff & Schmidt, 2016).

**Dam increases evaporation.** It increases the surface area of a body of water that is exposed to air and direct sunshine (Kohli & Frenken, 2015). Evaporation has an impact on the surrounding microclimates, affecting natural temperature swings, in the ecosystems, and habitats. Greater evaporation, for example, increases the moisture content of the air in the vicinity of a major dam, resulting in increased heavy rains (Hossain, Jeyachandran & Pielke, 2009). This can change the natural rainfall patterns in the surrounding areas, putting a strain on ecosystems and communities that rely on them. It also leads to higher storm surge rates, which can result in more frequent and violent flooding than the dam was built to withstand (Stahl, 2017).

**Dam creates stagnant conditions downstream.** Dams impound water and modify river flow, creating artificial habitat. These impoundments retain silt, resulting in stagnate conditions with warmer temperatures and lower dissolved oxygen levels than the rest of the river system (University of Massachusetts Amherst, 2017). Because of the stagnant water in reservoirs, inorganic mercury can be converted to methylmercury by the breakdown of organic materials from decaying plants. Methylmercury tends to bioaccumulate and induce harmful consequences in people and wildlife that consume reservoir fish (Greentumble, 2016). This happens mostly in the reservoir.

**Dam causes disconnections and diversions.** Dam acted as a barrier, blocking the river. It can cause fragmentation of aquatic habitats. Dams, even those with fish, can obstruct fish migration (Bidgood, 2013).

**Water Quality Effects**

**Dam changes thermal regimes.** The temperature of the surface water layers of the reservoir increases during the summer. During low electricity demand less water is released which results in increasing water temperatures in pools below the dam. One solution is to drawn the water into the turbine through a conduit at the reservoir's bottom, lowering the temperature of the water flowing downstream (John, J. E. A. 1971). The other mechanism is that the sluggish water flow and reservoirs with large surfaces absorb more solar energy (Riverkeeper, 2015). Thermal pollution refers to temperature fluctuations in water bodies, and aquatic species are temperature sensitive (Lyubimova et al., 2018). During the late summer and fall, aquatic bodies can maintain higher temperatures than is provided by nature (Riverkeeper, 2015). Temperature variations can affect the reproduction, metabolism, and growth rates of aquatic species, and even kill them (Parkinson et al., 2016). Evaporation in pools downstream of the dam can increase the concentrations of contaminants.

**Dam causes dissolved oxygen stratification.** Dam can cause oxygen stratification because the reservoir is calmer, and microorganisms' breakdown the organic sediments at the bottom, absorbing oxygen (Knight, J. 2015). The stratified structure of a reservoir from the top to the bottom, including supersaturated, undersaturated, and anoxic hypolimnion layers, is known as oxygen stratification (Knight, J. 2015). The anoxic condition is detrimental to aquatic life, and the suction and emission through the turbine can even diminish the total oxygen level of water bodies (Knight, J. 2015).

**Dam can cause eutrophication.** Increased nutrient concentrations, such as nitrogen and phosphorus, promote plant growth and can result in algal blooms (Glibert, P. M., 2017). Eutrophication and happen in the reservoir or in pools below the reservoir, depending on the nutrient source and quantity (Glibert, P. M., 2017). Decomposition of dead algae can deplete dissolved oxygen in water, resulting in an increase in ammonia, iron, manganese, and hydrogen sulphide concentrations. By increasing planktonic algae biomass, biodiversity will decline, and the color, taste, and aroma of water would be negatively influenced (Bunea et al., 2012). As a result, eutrophication can have an impact on both aquatic and terrestrial life. Furthermore, because of its relevance, phosphorus is frequently employed to assess eutrophication (Michigan State University, n.d.).

**Dam traps sediments.** As rivers reach the reservoirs, their velocity decreases and they lose their ability to carry sediments. Sand & gravelare usually deposited at the reservoir inflow, while the fine sediments settle to the bottom of the reservoir (Winton, Calamita & Wehrli, 2019). The most immediate effect of sediment depletion is an increase in erosion downstream of dams due to outflows, which causes channel incision, which can harm macroinvertebrates and fish habitats inside the channel (Kondolf, 1997). Meanwhile, sediment accumulation reduces the dam's water storage and hydropower production capacity and increases the potential dam failure by stressing the dam structure (Randle et al., 2017). Ecosystems like floodplains and deltas, which rely on sediments supplies and nutrients to sustain habitat quality and production, are affected by dams (Winton, Calamita & Wehrli, 2019). The reduction of sediments decreases the element silicon

(Si), contributing to the decrease in Si to nitrogen ratios with eutrophication (Turner et al., 1998). The alteration of this ratio can affect certain types of plankton. These shifts in the community have important implications for coastal and estuarine fish communities and the appearance of potentially dangerous algal blooms (Winton, Calamita & Wehrli, 2019). Moreover, the reservoirs can sequester phosphorus (P) by sedimentation. Sediment plays a critical role in the movement and destiny of P, which is mainly transported by rivers as particulate P (Zhou, Zhang & Lu, 2013). An assessment by Zhou, Zhang & Lu (2013) on a load of P affected by the Three Gorges Project in the middle and lower Yangtze River (MLY) highlighted that to the MLY, sediment load is reduced by 91%. Total P and particulate P loads for MLY were isolated at 77% and 83.5% per year, respectively, and 75% and 92%, respectively, in the dry season (Zhou, Zhang & Lu, 2013). Reservoir retention can significantly restrict P supply to downstream regions and the coastal zone, impacting regional nutrient constraint patterns, trophic conditions, food web dynamics (Maavara et al., 2015) and aquatic productivity.

### Environmental concern after removing dam

As with dam establishment, dam removal is also disruptive to the ecosystem. ***Figure 3*** shows a hypothetical river's response to dam removal in the short-term and long-term. The green line in ***Figure 3*** below shows the potential trajectory of river condition by dam removal. Following dam removal, the most significant alterations of the river conditions are flow, aquatic connectivity, and sediment transport (Foley et al., 2019). Short-term responses occur during dam deconstruction, and include reservoir erosion, downstream sediment transport, and ecosystem disruption over minutes to months (Foley et al., 2019). Long-term responses to dam removal include changes in overall watershed conditions over weeks to decades, including habitat establishment, recovery of natural sediment and flow regimes, riparian vegetation succession, and food web development (Foley et al., 2019). Based on the different characteristics of dams and reservoirs (e.g., size, removal strategy, and existing environmental situation), the timing and outcomes after dam removal can be different (Foley et al., 2019).

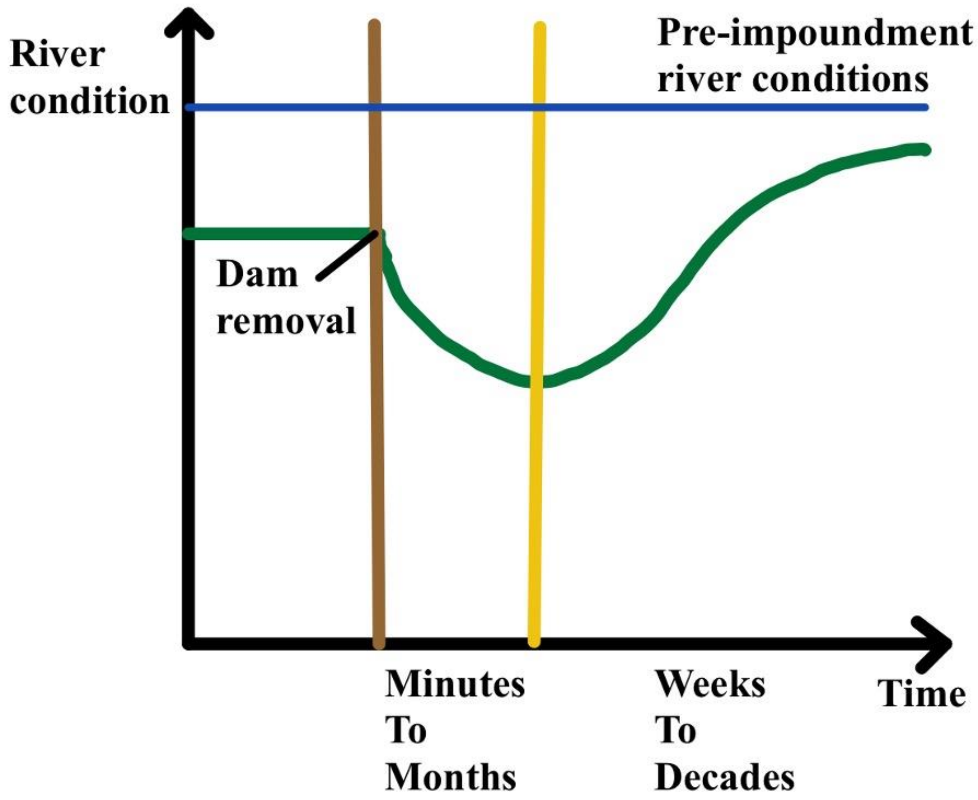


*Figure 3.Simplified diagram of River response to dam removal concept (Based on Foley et al., 2019).*

**Natural flow regimes can be restored after dam removal.** The first response following dam removal is the free flow that reconnects the river network; in the absence of physical obstruction of the river, the water is no longer released according to human needs, thus restoring the natural flow regime (Poff et al., 1997). van Oorschot et al. (2022) modeled the recovery times of natural flow regime restoration. They found that the recovery period is proportional to the river's capacity to return to undisturbed hydro-morphodynamic conditions, which varies amongst river systems.

**Dam removal can re-establish the aquatic food web from upstream to downstream.** Downstream stagnation conditions ease as the natural flow regime recovers, allowing the migration and movement of fish (Bednarek, 2001). Within a few weeks or months after low-head dams were removed in the midwestern and eastern United States, upstream fish migration became apparent, and within one to three years, up to 95% of all species discovered downstream of the dams were found upstream (Bellmore et al., 2019). Except invertebrates that actively move and passively drift downstream (Bellmore et al., 2019). These migrations enable nutrient and organic matter delivery between upstream to downstream, re-establishing aquatic and riparian food webs within months to years (Bellmore et al., 2019).

Dam removal contributes to maintaining fish habitat and stimulating spawning due to the return of seasonal flow dynamics and flooding (Bednarek, 2001). On Florida's Chipola River, following the Dead Lake dam removal, fluctuations in flow increased, followed by an increase of fish species diversity from 34 to 61 species after three years of dam removal (Hill, Long & Hardin, 1993). By restoring flows that inundate terrestrial regions, dam removal can reconnect riparian and aquatic ecosystems (Bednarek, 2001). The riparian regions will be inundated more frequently, resulting in improved riparian vegetation and some wetlands (Bednarek, 2001). Dam removal contributes to species richness with more complex food webs and organism movement, thus increasing the sustainability of the whole watershed ecosystem (Bellmore et al., 2019).

**Dam removal can return active sediment transport to a river.** For most dam removals, short-term downstream ecological responses (over days to years) are mostly attributable to reservoir sediment erosion, which accelerates the transit and deposition of sediment, nutrients, and organic matter downstream and temporarily increases river turbidity (Bellmore et al., 2019). Bednarek (2001) pointed out that fine silt is mobilized and redistributed from the slow-moving reservoir when a dam is demolished, revealing gravel, cobble, and boulders inside formerly impounded regions. The kind of deposits and the time required to remove the dam are the two main factors that determine the fate of the impounded sediment (Foley et al., 2017). Dam removal is generally intended to restore native fish's preferred habitat and increase local fish populations (Bednarek, 2001). However, dam removal increases sediment loads in the short term, harming reproductive habitats for various creatures, including fish and mussels (Bogan, 1993). In addition, invertebrate habitats and food supplies such as leaf packs might be smothered, rendering them inaccessible (Doeg and Koehn 1994). The increased sediment loads also increase the potential of flooding and aggrade the bed levels downstream (Vahedifard et al., 2021). Oliver and Grant (2017) pointed out that it takes months to a few years for most sediment stored in reservoirs to be evacuated after dam removal.

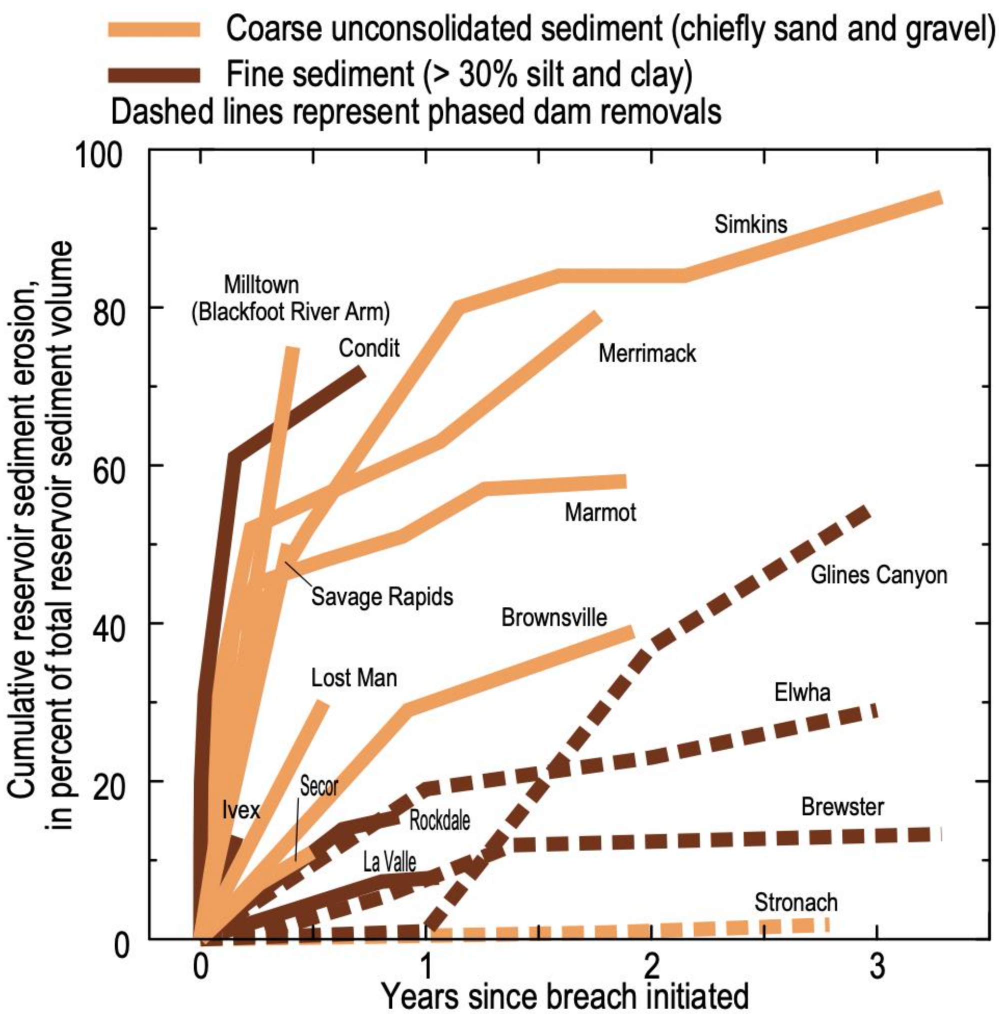


*Figure 4. The percentage of reservoir sediment eroded over time following dam removal, citing for university report (Foley et al., 2019).*

Impounded sediments may be contaminated and must be assessed and managed in any dam removal project. For instance, the 1973 dismantling of the Fort Edwards Dam on the Hudson River in New York led to the discharge of sediments polluted with PCBs (polychlorinated biphenyls) (Bednarek, 2001). Toxins produced upstream can easily settle out of the water column and concentrate in the fine sediments found in a slow-moving reservoir because of the large surface area (Bednarek, 2001). Contaminated sediments can also become entangled in algal mats or, in rare situations, adhere to algal cells and accumulate at higher trophic levels (Bednarek, 2001).

**Dam removal can restore the natural water temperature range of a river in the long-term.** According to modelled study of the Salling Dam on the AuSable River in Michigan, removing the dam will lower water temperatures by around 3° Celsius in the old impoundment and downstream, returning natural water temperatures to the river (Pawloski & Cook, 1993). Bartholow's prediction (2004) on the Klamath River showed that dam removal would erase the observed seasonal thermal signature delay at Iron Gate Dam, and temperatures throughout the upstream migration and spawning period would improve significantly without the impoundments. A slightly cooler trend in fall and winter and a warmer trend in spring and summer were shown upstream at Iron Gate Dam and Seiad Valley in ***Figure 5*** (Bartholow et al., 2004).

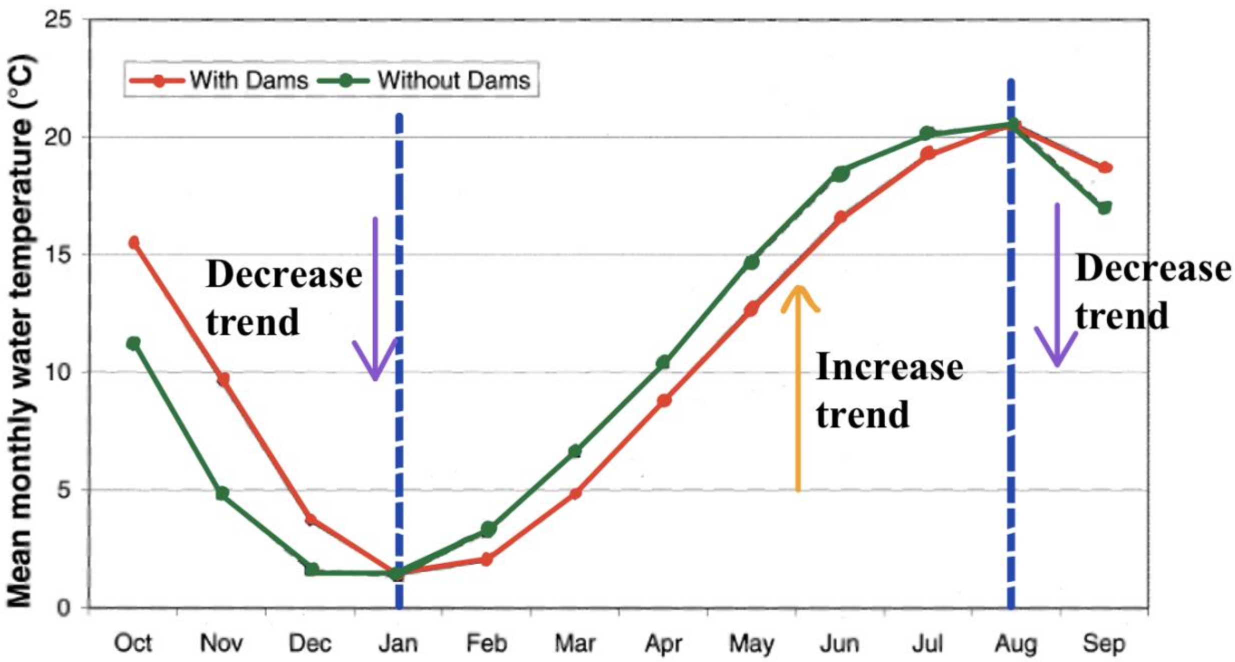


*Figure 5. Modified diagram from Averaged over a 40-year period at the Iron Gate Dam site, comparison of expected mean monthly water temperatures between the With Dams and Without Dams scenarios (Based on Bartholow et.al., 2004).*

However, dam removal has been shown to negatively affect water temperature and oxygen levels in the short-term (American Rivers, 2002). A quick reservoir disappearance causes short-term increases in velocity and pressure during removal, which raises the risk of gas-bubble disease in fish (Weitkamp & Katz 1980, Wik 1995). During a drawdown test on the Little Goose Dam in 1992, dissolved gas supersaturation rose, as did turbidity and reservoir fish and insect loss (Wik, 1995). Fortunately, these losses and alterations were only temporary, and they had little impact on the general population (Wik, 1995). Bednarek (2001) suggested that gradually removing water can avoid a sharp increase in velocity and lessen the possibility of supersaturation.

**Dam & Climate Change**

According to the assessment of flood and water scarcity risks under climate change to hydropower projects by Opperman et al. (2022), by 2050, 61 percent of the world's hydroelectric dams will be located in high- or extreme-risk basins of drought, flooding, or both. One in five existing hydroelectric dams will be located in areas with high flood risk due to climate change. Furthermore, falling water levels due to climate change leads to the decline of hydroelectricity production, which has already occurred in the southwestern US, southern Africa, and Brazil (Hirsheimer, 2022). For example, the United States is facing two serious issues, drought in the west and too much precipitation at once in the north (Grady & Dennis, 2022). The water level at Lake Powell has reached its lowest point since the lake was formed by damming the Colorado River in 1963 as a severe drought engulfs sections of the Western United States (Grady & Dennis, 2022). In contrast, the extreme precipitation in the Northeastern United States will increase the risk of flooding (Grady & Dennis, 2022). Therefore, climate change is an essential factor related to the dam that needs to be considered.

**Reservoirs emits greenhouse gases, that contributes to climate change.** Hydroelectric power is usually considered a “clean” energy, and even the World Bank is eager to promote hydro dams as a clean, climate-friendly, and cost-effective resource capable of alleviating global energy poverty (International Rivers, 2015). However, dam reservoirs emit greenhouse gases into the atmosphere, especially methane (CH4), due to anaerobic bacteria decomposing plant material on the reservoir bed (Rosa & Santos, 2000; Lima et al., 2007; 2008; Stahl, 2018). China's large dams emitted a total of 2.69 Tg (1 Tg=1 million tons) of CH4 per year to the atmosphere from the bootstrap analysis, which equates to 67.25 Tg carbon dioxide (CO2) in yearly greenhouse gases emissions (Lima et al., 2007; 2008; Hu & Cheng, 2013). Methane's greenhouse gas impact is 20 to 28 times greater than CO2 (AIDA, 2018). Furthermore, dams alter the flow, chemistry, sediment, and timing of the river dynamics, which dramatically changes floodplains and wetlands and can even destroy surrounding forests (Lima et al., 2007; 2008). Wetlands and forests are significant carbon sinks. Destroying them means the plants no longer absorb CO2; even the carbon they had absorbed would be released into the air via burning process (Stahl, 2018).

**Climate change has complicated impacts on dams.** Qin et al. (2022) used the Shared Socioeconomic Pathways scenarios to assess the climate change impacts on four aspects of critical dams in the Upper Yangtze River Basin during the 21st century. Firstly, inflow to dams is increasing across the basin, with high-flow variations being more noticeable than mean and low-flow changes and a diminishing gradient from upstream to downstream (Qin et al., 2022). Secondly, dams' regulating role is projected to enhance during the flood season and diminish during the dry season in future climate change scenarios (Qin et al., 2022). Thirdly, under future climates, most dams in the Upper Yangtze River Basin may expect a rise in hydropower output, an increase in assurance rate, and a significant increase in spilled water. However, a few dams in the catchment's downstream region are expected to go bankrupt shortly (Qin et al., 2022). While in drier climatic regions, there will be less water available for hydropower, such as Lake Powel, which has 1.074kilometer, only 10.058meter higher than the minimum power pool (Newburger, 2022). The hydropower production in existing dams will be much more variable due to extreme climate events. Fourthly, the probability of a severe flood surpassing the dam's design capacity, resulting in dam failure, would rise and should not be neglected under nonstationary future climate change circumstances (Qin et al., 2022).

**Climate change has an essential impact on the aquatic ecosystem, significantly affecting aquatic habitats.** Global warming is responsible for increased air temperature, which can directly warm the water, thus modifying species distribution and basic ecological processes (Poff, Brinson & Day, 2002). The situation can be multiplied with the dams; many sockeye salmons in Columbia River Basin in the U.S. are facing death (***Figure 6***) due to the hot temperature in the Columbia River and lower Snake River (Stefani, 2021). Salmon populations are severely declining, and the impact of climate change has made the situation more urgent (Mapes & Bernton, 2022). It is no coincidence that the salmon in the Klamath River in the U.S. face extinction in the near future, which can be earlier than four aging hydroelectric dams be removed (around 2023 or 2024) (Leslie, 2021). The primary purpose of many dam removal projects in the USA is restoring or recreating the salmon habitats, which can be difficult with the increasing temperature of the water body due to climate change. Fish species can be affected by the warmer temperature and tend to find other suitable habitat; thus, many species may move upstream, while some cool-adapted headwater species can be restricted by the geographic limitation (Poff, Brinson & Day, 2002). Water warming could be an important challenge preventing the success of the dam removal. Although demolition of dams can theoretically allow fish to migrate freely to find suitable habitats, in fact, due to the impact of climate change, suitable habitats have been reduced or disappeared, resulting in a decline in the number of fish populations or even extinction. This condition can also affect other aquatic organisms.

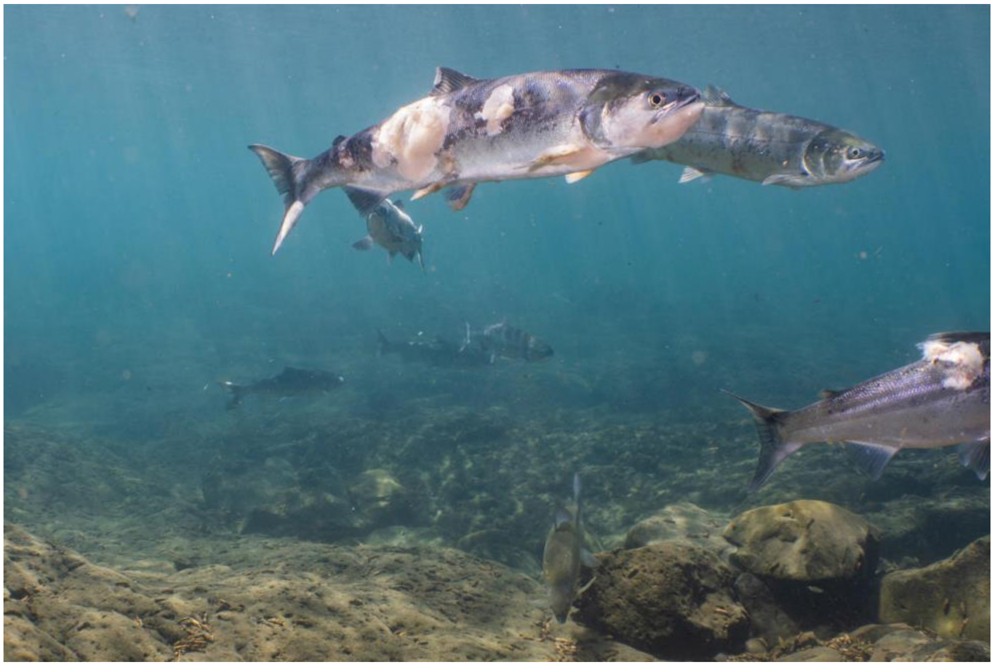
*Figure 6. Sockeye salmon are rotting to death in Columbia River's hot water, cite from the website. Credit: Columbia Riverkeeper (Stefani, 2021).*

**Dam removal cannot completely offset the impact of climate change, but dams can mitigate the harm of climate change to a certain extent.** Removing dams can result in a cooler temperature in free-flowing river, providing resiliency for these ecosystems to adapt to climate change. River water temperatures with a cooler baseline helps them to become more tolerant to rising temperatures (Erdenesanaa, 2021). Climate change brings more extreme precipitation and flooding, which can increase the risk of dam failure and necessitate more dam removals (Vahedifard et al., 2021). Unfortunately, dam removal data demonstrate that, while the physical response of the river and ecosystem is rather fast, the natural environment does not entirely recover to a pre-dammed state (Foley et al 2017). Under climate change trends, the recovery of the fish populations by dam removal is not always optimistic. According to the analysis in Kaoshan Stream (2016), even though dam removal appears to have reversed the salmon population loss, climate change-related variations in rainfall intensity represent a hazard to the salmon. Dam removal can create more suitable habitat, but the salmon population is expected to fall if typhoons grow more powerful than today (Battle et al., 2016).

Increased climatic variability will cause more extreme events (floods and droughts) to impact the watershed once the dam is removed. Dams, if properly constructed, can lessen flood occurrences and release water during droughts. For example, Japan frequently uses "Extreme Flood Control Operation" to deal with the water level of dams exceeding the maximum setting flood level that often occurs due to climate change (Nakamura & Shimatani, 2021). The total water transfer volume of the east and middle routes of the South-to-North Water Diversion Project in China has exceeded 50 billion cubic meters, which provides strong water resources support for optimizing the allocation of water resources, ensures the people's drinking water safety, and restores the ecological environment of rivers and lakes since January 7, 2022 (Zhu, 2022). While this project also increases the difficulties of the ecological environment restoration because it pumps the water continuously.

Climate change will also influence the ecosystem and rates of environmental services. It is unlikely that dam removal can recreate the ecosystem conditions that was present before the dams were built and those created during the operation of the dam. The impacts will be particularly challenging for those aquatic organisms that are less mobile. (e.g., some invertebrates). Predicting the type and rate of changes in the aquatic ecosystem as a result of climate change is very challenging and will require much more research.

**Small Dam Removal case studies**

**Case Study 1: ELWHA & GLINES CANYON DAMS, ELWHA RIVER, WASHINGTON, USA**


*Figure 7. Map of the Elwha River Basin, cited from website (Lohan, 2020A).*

## Background

The Elwha Dam (33m in height) and Glines Canyon Dam (64m in height) were built in the early 1900s to provide hydropower to power the growing settlement of Port Angeles and the Peninsula's regional expansion (U.S. Department of the Interior, 2021). The dams, on the other hand, blocked salmon migration upstream, disrupted the flow of sediment and wood downstream, and flooded the historic homelands and cultural sites of the Lower Elwha Klallam Tribe (Lohan, 2020A). They broke the web of ecological and cultural connections in the Elwha Valley.

## Dam Removal Process

In 1992, the Elwha River Ecosystem and Fisheries Restoration Act authored the restoration of dam removal project (U.S. Congress, 1992). After two decades of planning, the dam removal started on September 17, 2011. And finished after six months. Then the Glines Canyon Dam was removed in 2014 (U.S. Congress, 1992).


*Figure 8. The life process diagram of Elwha River's dams (Based on: SER, n.d; Lawson, 2016).*

## Dam Removal Outcomes

After removing the barriers on the Elwha River, the project's outcomes are fascinating.

*Table 2. Project Outcomes of Elwha Dam Removal and River Restoration (Based on: SER, n.d.).*

| Ecosystem | Environment | Biology | Socio-Economic & Community |
|---|---|---|---|
| Eliminate existing threats | Reinstate appropriate physical conditions | Achieve a desirable species composition | Cultural dimensions |
| Recover ecosystem functionality | Reestablish external exchanges with the surrounding landscape | Reinstate structural diversity | Recreational and commercial fishing |

- **Removing dam eliminate existing threats to the ecosystem.**

The river once again flows completely free from the headwaters down to the strait, creating and re-establishing a critical connectivity network for the surrounding landscape (Witze, 2014). It re-establishes external exchanges with the surrounding landscape. For example, with renewed sediment flow, sandy beaches are reappearing, and at nearshore, where the Elwha River meets the sea, habitat for rich shellfish beds is re-emerging (SER, n.d.).

- **The river's natural hydrology has been renewed, and the river ecosystem has begun to be restored.**

Dam removal renewed the free flow, which benefits fish to migrate. It has been recorded that 31 months after dam removal, all nine migratory fish (including steelhead, bull trout, cutthroat trout, lamprey, chinook, coho, sockeye, pink and chum salmon) crossed the previous Elwha Dam, and eight of the nine ascended via Glines Canyon within 60 months (Dunagan, 2022). River salmonids have renewed access to more than 70 river miles of pristine spawning habitat protected within the park (Lohan, 2020A). Dam removals impacted river ecosystem functionality and salmon-wildlife interactions. The life of a bird species called American dippers (Cinclus mexicanus) has been dramatically improved by accessing salmon and eating them (Lohan, 2020A). This evidence shows the functional recovery of the ecosystem.

- **Reestablish coastal habitats by releasing sediments**

Monitoring sediments conditions of the Elwha River through 15 sites before and after dam removal shown that it only took approximate two weeks for river transporting sediments down to the coastline (Lohan, 2020A). These heavy doses of sediment create new sandy areas that attract Dungeness crabs, shrimp and forage fish favored by salmon, birds and other marine life, instead of causing an ecological disaster (Lohan, 2020A).

Through this project, three key lessons were learned. The first one is that the ecosystem can be very resilient to these large-scale perturbations (SER, n.d.). Although removing dams resulted in new sediment flow and recreated the estuary, it provided new habitat for salmon and other species. The second is the project somewhat overlooked the riverine bird community (SER, n.d.). Dippers were studied while the other fishing-eating birds were not (Lohan, 2020A). The third one is a recommendation for the future dam removal project, which should aim to optimize the nearshore environment by letting the sediment come to the shore (SER, n.d.).

**Case Study 2: EDWARDS DAM, KENNEBEC RIVER, MAINE, USA**

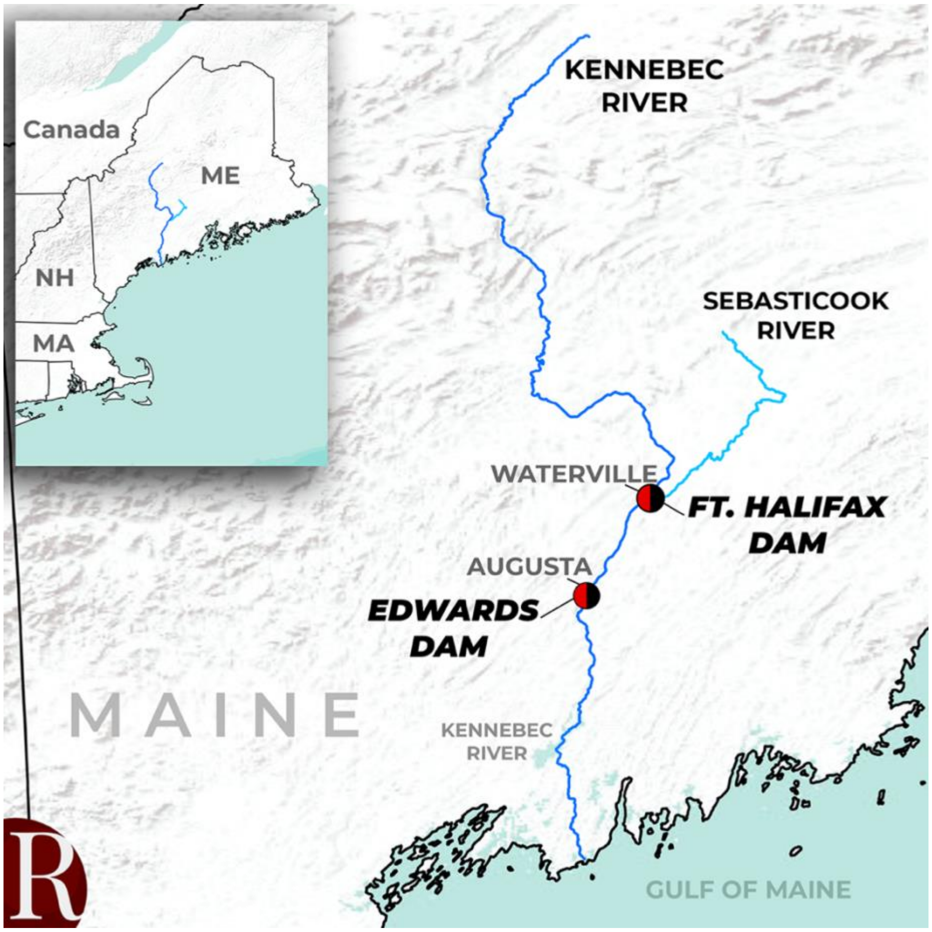


*Figure 9. Map of the Kennebec River Basin, cited from the website (Lohan, 2020B).*

## Background

The Edwards Dam (7.62m in height) was constructed in 1873 to provide hydropower to the surrounding areas with 3.5 MW capacity and facilitate easy navigation of upstream waters (Lawson, 2016; Graber, 2020). However, the dam gradually decreased fish populations and deteriorated the health of the Kennebec River (Graber, 2020).

## Dam Removal Process

The originally hydroelectric facility generated a small capacity, and by the middle of the 19th century, Edwards Dam was barely providing 0.1 percent of Maine's yearly electricity requirements (Graber, 2020). The "Kennebec Coalition," which was founded by American Rivers, the Natural Resources Council of Maine, the Atlantic Salmon Federation, and Trout Unlimited, successfully lobbied for the dismantling of Edwards Dam and the recovery of the Kennebec River (Graber, 2020). Due to the detrimental effects, the dam was having on the health of the river, the Federal Energy Regulatory Commission rejected the dam owner's request to renew his hydropower license in 1997; thus, the dam was removed when the license expired in 1999 (Graber, 2020).


*Figure 10. The life process diagram of Edwards Dam (Based on: Lawson, 2016; Graber, 2020).*

## Dam Removal Outcomes

Edwards Dam's removal brought many financial benefits through various recreational activities and generated many environmental benefits, such as improved water quality, reconnected the river with the ocean, and increased fish and vegetation (Lawson, 2016). The ecosystem in this watershed was recovered gradually.

*Table 3. Project Outcomes of Elwha Dam Removal and River Restoration (Based on: Graber, 2020; Lawson, 2016)*

| Ecosystem | Environment | Biology | Socio-Economic & Community |
|---|---|---|---|
| Reconnected the Kennebec River with the ocean | Improved water quality | Increased populations of migratory fish | Improved recreational activities |
| Recovered ecosystem functionality | | Increased vegetation cover in riverbanks | Commercial fisheries |

- **Dam removal improved water quality dramatically**

Water quality was improved from lower than the minimum water quality standard for Maine (Class C: lowest level to support all native fish) to Class B standard (unimpaired habitat for native fish) for just two months after Edwards Dam Removal (Lawson, 2016; Kennebec Coalition, 2000). A decade later, water quality categories have been raised, and mayflies and stoneflies, which were seldom observed in tests before to Edwards' departure, have grown considerably in quantity (Fahlund, 2021).

- **Dam removal reconnected the river with the ocean, recovering ecosystem functionality.**

Within hours of the dam's removal, the newly free-flowing Kennebec River appeared across riffles and past islands not seen since Thoreau and Hawthorne's days (Fahlund, 2021). Within a few weeks, vegetation began to sprout along the riverbanks, allaying worries that the reservoir's decline would result in a muddy, unattractive mess (Fahlund, 2021). A decade later, over two million alewives reappeared to the Kennebec, as well as striped bass, other native sea-run fish, Bald Eagles, and Osprey soar in the 17 miles restored habitat (Fahlund, 2021; Natural Resources Council of Maine, 2022). Sturgeon, striped bass, rainbow smelt, and other sea-run fish now have access to their former home (Lohan, 2021). For example, the population of Alewife returning to spawn increased from 78,000 in 1999 to 5.5 million in 2018 (Lohan, 2021). The free-flowing river has helped the entire web of creatures, from eagles to osprey to black bears (Fahlund, 2021; Natural Resources Council of Maine, 2022).

**Thinking of the future fate of the existing small dams**

By comparing the case studies of the United States and the dismantling policy of small hydropower dams by China, it is not hard to find that both aim to remove the dams reaching the end-of-life period or causing severe harm to the ecology. The future of dams faces the dilemma of building more dams to meet the growing demand for electricity and demolishing dams to satisfy the urgent need to repair the ecological environment. Except for hydropower, the dam has various functions like water supply, irrigation, and flood control; thus, removing all dams is unrealistic and unscientific. Ho et al. (2017) suggested that planning for the future of water, electricity, and food infrastructure requires taking into account the environmental and social effects of alternatives to dam services, such as hydropower (i.e., traditional fossil fuels, nuclear energy), or water supply (i.e., groundwater utilization, desalination, and water recycling). In order to balance water supplies and demands by dams, Ho et al. (2017) provided several options for aging or inadequate dams:

- Expand or retrofit dam capacity by adding the additional dam height or spillway capacity.
- Preserve or restore the old dam to the original design strength and capacity (need to consider the impact of climate change)

- Replace existing dams with smaller dams.
- Remove existing dams.

The final decision for the particular dam needs to consider cost, benefits, expected impacts, and adaptations for a long-time period, as well as the unpredictable factors from climate change (Ho et al., 2017). The Chinese government intended to demolish four types of dams, including dams within the core or buffer zone of nature reserves; dams that had no power generation since 2013; dams that had caused significant environmental harm; and dams that have been classified as risky dams that jeopardize flood control safety (MEE & NDRC, 2019). The "Classified rectification, one station, one policy" (three categories of withdrawal, retention, and rectification) considers various conditions, but the one-size-fits-all approach exists in implementation. For example, the hydropower stations of Changtan River, Cha'an, Chalin River, and Mulongtan in Zhangjiajie, Hunan were demolished after August 2019, but the reservoirs were still retained (Wang, 2021). The daily safety inspection and maintenance of the dam, the power supply of the flood gate, the exact scheduling of the reservoir, the timely replenishment of flood control materials, and other essential flood control operations have all been impacted by the absence of the hydropower plant (Wang, 2021). Furthermore, the definition of "serious environmental harm" is not defined. Many power plants, for instance, those are not located in the core area or buffer zone of nature reserves, have passed the environmental assessment certification and environmental protection approval and are even certified as "Small Green Hydropower" by the Ministry of Water Resources were forcibly dismantled due to "serious environmental harm" (Wang, 2021). Wang (2021) recommended three pieces of advice based on the "Opinions of the Party Central Committee and the State Council on Promoting High-quality Development of the Central Region in the New Era":

- The negative environmental effect of some power plants should be addressed in a integrated manner.
- Before removing the hydropower plant, the evaluation and demonstration of the system engineering should be done well.
- A timely compensation measure should be in place for small hydropower plants that must be removed.

Overall, small hydropower still plays an essential role in economic development and social stability. The future of the existing small dams should follow the three options of retention, rectification, and removal based on the conditions of the specific dam.

## CONCLUSIONS

Dam removal is the inevitable trend for existing small dams. Environmental degradation and climate change will likely accelerate the small dam removal process. Dam negatively impacts the river ecosystem by affecting the hydrology cycle, deteriorating water quality, and impacting aquatic habitats. Removing a dam can recover the flow, sediment regimes, watershed habitats, aquatic life, and vegetation in the short-term and long-term. Restoring the ecosystem to pre-dam conditions is unlikely due to climate change. Climate change brings opportunities and challenges to dam removal. It may reduce the life of dams or cause dam failure and create uncertainty about the success of the post-removal restoration. Successful dam removals can serve as a reminder that future dam removals must be tailored to local conditions. Before considering to remove a dam, people need to be aware of the possible challenges, constraints, and trade-offs between hydropower production, environmental concerns, aquatic productivity, and the effect of climate change.

## RECOMMENDATIONS

1. Changing the hydropower schedule can change the release of water from the dam, which can mitigate the environmental impact of existing dams
2. Removing dams is beneficial to improve the ecosystem functions and environmental services.
3. Establishing new ecosystems after dam removal will take different time periods and likely result in altered ecosystems, mainly due to climate change. Some watershed characteristics can theoretically affect the restoration period following dam removals, such as topography, stream order, sinuosity, vegetation, and sediment fractions.
4. Significant trade-offs exist between dam construction, maintenance, and removal impacts, exacerbated by climate change, power demand, and the occurrence of more extreme events.

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## APPENDIX

### Communication feature – Poster