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Ageing Water Storage Infrastructure: An Emerging Global Risk

Duminda Perera, Vladimir Smakhtin, Spencer Williams, Taylor North, Allen Curry

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Ageing Water Storage Infrastructure: An Emerging Global Risk

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EXECUTIVE SUMMARY

The Report provides an overview of the current state of knowledge on the ageing of large dams –an emerging global development issue as tens of thousands of existing large dams have reached or exceeded an "alert" age threshold of 50 years, and many others will soon approach 100 years. These aged structures incur rapidly rising maintenance needs and costs while simultaneously declining their effectiveness and posing potential threats to human safety and the environment.

The Report analyzes large dam construction trends across major geographical regions and primary dam functions, such as water supply, irrigation, flood control, hydropower, and recreation. Analysis of existing global datasets indicates that despite plans in some regions and countries to build more water storage dams, particularly for hydropower generation, there will not be another "dam revolution" to match the scale of the high-intensity dam construction experienced in the early to middle, 20th century. At the same time, many of the large dams constructed then are aging, and hence we are already experiencing a "mass ageing" of water storage infrastructure.

The Report further explores the emerging practice of decommissioning ageing dams, which can be removal or re-operation, to address issues of ensuring public safety, escalating maintenance costs, reservoir sedimentation, and restoration of a natural river ecosystem. Decommissioning becomes the option if economic and practical limitations prevent a dam from being upgraded or if its original use has become obsolete. The cost of dam removal is estimated to be an order of magnitude less than that of repairing.

The Report also gives an overview of dam decommissioning's socio-economic impacts, including those on local livelihoods, heritage, property value, recreation, and aesthetics. Notably, the nature of these impacts varies significantly between low- and high-income countries.

The Report shows that while dam decommissioning is a relatively recent phenomenon, it is gaining pace in the USA and Europe, where many dams are older. However, it is primarily small dams that have been removed to date, and the decommissioning of large dams is still in its infancy, with only a few known cases in the last decade.

A few case studies of ageing and decommissioned large dams illustrate the complexity and length of the process that is often necessary to orchestrate the dam removal safely. Even removing a small dam requires years (often decades), continuous expert and public involvement, and lengthy regulatory reviews. With the mass ageing of dams well underway, it is important to develop a framework of protocols that will guide and accelerate the process of dam removal.

Overall, the Report aims to attract global attention to the creeping issue of ageing water storage infrastructure and stimulate international efforts to deal with this emerging water risk. This Report's primary target audiences are governments and their partners responsible for planning and implementing water infrastructure development and management, emphasizing adaptation to a changing climate and sustainable development.

Keywords: *dams, large dams, dam ageing, dam decommissioning, dam re-operation, dam removal, dam failure, reservoirs, sedimentation, public safety, river restoration, water storage, water infrastructure.*

INTRODUCTION

Water storage infrastructure, particularly large dams in the last 100 years, has traditionally been used to regulate river flow worldwide. "Large dams" are defined by International Commission on Large Dams (ICOLD) as having a "*height of 15 metres or greater from lowest foundation to crest, or a dam between 5 metres and 15 metres impounding more than 3 million cubic metres*". ICOLD's current World Register of Dams (WRD) comprises over 58,700 large dams that satisfy these criteria, although this list may be incomplete (ICOLD WRD, 2020). Together, these dams can store approximately between 7,000 and 8,300 km³ (Vörösmarty et al., 2003; Chao et al., 2008, Zhou et al., 2015), or approximately 16% of all global annual river discharge, ~ 40,000 km³yr-1 (Hanasaki et al., 2006).

Dams exist in various designs and types that depend on several context-specific factors, including geology, reservoir storage capacity, intended dam function(s), availability of materials, and funds (USSD, 2015). The main functions of dams are, in descending order of their numbers: irrigation, hydropower, water supply, flood control, and recreation (ICOLD WRD, 2020). Some 30-40% of the world's irrigated land that contributes nearly 40% of the world's agricultural production relies on dams (WCD, 2000; Shah and Kumar, 2008). Also, the water supply to most urban and industrial regions of the world is ensured by large dams (Vörösmarty et al., 2003). By 2050, the estimated global population will be close to 10 billion (United Nations, 2017), and most of it will be located downstream of water reservoirs contained by dams (Ferre et al., 2014) that were built primarily in the 20th century.

Every infrastructure has a design life; hence infrastructure ageing is a normal process. The same applies to water storage dams of any size. "*Ageing can be defined as the deterioration process that occurs more than five years after the beginning of the operation phase so that deterioration occurring before that time is attributed to inadequacy of design, construction or operation…*" (Zamarrón-Mieza et al., 2017).

Some sources indicate that an average life expectancy of a dam is 50 years (Quinn, 2000; Mission, 2012) and that dams constructed between 1930 and 1970 (when most of the existing large dams were built) have a design life of approximately 50-100 years (Mahmood, 1987; Ho et al., 2017). Others suggest the service life of well-designed, well-constructed, and well-maintained and monitored dams can easily reach 100 years, while some dam elements (gates, motors) may need to be replaced after 30 to 50 years (Wieland and Mueller, 2009). According to Wan-Wendner (2018), all modern dams must meet safety regulations that typically model and examine scenarios of failure up to 100 years. In this Report, and similarly to Wan-Wendner (2018), an arbitrary age of 50 years is used as the point when "*a human-built, large concrete structure such as a dam that controls water would most probably begin to express signs of aging*."

These ageing signs may include increasing cases of dam failures, progressively increasing costs of dam repair and maintenance, increasing reservoir sedimentation, and loss of a dam's functionality and effectiveness. These manifestations are strongly interconnected. Therefore, age per se is not a decisive variable for action. Two dams constructed in the same year could have very different current status and effective lifespans based on their respective parameters and contexts. Yet, age is the simplest "macro" metric by which dams can be characterised and compared, in the context of their diminishing effectiveness, increasing risks, and impacts for the economy and the environment – in time. Ageing also increases the vulnerability of a dam to changing climate (Giuliani et al., 2016; Ehsani et al., 2017) due to exposure to more frequent and extreme floods and/or increasing evaporation from the reservoir that can lead to accelerated loss of its function (Zhao and Gao, 2018).

Many large dams worldwide have reached or are approaching the lower bound (50 years) of their anticipated lifespan. North America and Asia together hold ~ 16,000 large dams in the range of 50-100 years old and ~2,300 large dams over 100 years old (ICOLD WRD, 2020). In the USA, the average age of all the 90,580 dams (of all sizes) is 56 years (ASCE, 2017), and over 85% of them are reaching the end of their life expectancy in 2020 (Cho, 2011; Hansen et al., 2019). In China, over 30,000 dams are considered ageing (Yang et al., 2011). In India, over 1,115 large dams will be at ~50 years mark by 2025. Over 4,250 large dams would pass 50-years of age, with 64 large dams being 150 years old at 2050 (Harsha, 2019).

Overall, dam ageing appears to be gradually emerging as a development issue faced by many countries. Yet, it has not been comprehensively assessed globally or accounted for in future water storage infrastructure planning.

GLOBAL DATASETS ON DAM CHARACTERISTICS

The World Register of Dams (WRD), initiated in 1958 and maintained by ICOLD ever since includes ~58,700 records and is widely recognised as the most comprehensive global data source on large dams (www.icold-cigb.org). It contains details on *large* dams' height, length, capacity, function, and several other dam-related facts but does not include dams' coordinates. ICOLD has over 100 member countries and collects data through the ICOLD National Committees, but WRD also includes dams in non-member countries (ICOLD WRD, 2020). The data are made available at a fee.

Several other *global* databases on dams currently coexist; they differ in detail, theme, accessibility, and underlying data sources. The Global Dam Watch (GDW) platform is a useful entry point to at least three such databases (www.globaldamwatch.org) - GRanD, GOODD, and FHReD.

The Global Reservoir and Dam (GRanD) database was developed to provide a geographically referenced database of reservoirs for the scientific community. It has been a collaborative international effort and is presently managed by McGill University, Canada. The database contains 7,320 records on *large* dams defined as those with an excess capacity of 0.1 km³. This capacity is significantly larger than that of the ICOLD's capacity cut-off point of 3 million m³ (0.003 km³), which may partially explain the limited number of records in GRanD database compared to ICOLD WRD. The total water storage capacity of dams listed in GRanD is over 6,800 km³ (Lehner et al., 2011).

The Global Georeferenced Database of Dams (GOODD) is available through the GDW platform includes over 38,000 georeferenced entries. It is an open access data repository that contains details on *large to medium* dams and hosted by King's College London, UK (Mulligan et al., 2009). The definition of large and medium dams in GOODD is not entirely clear.

The third GDW database- Future Hydropower Reservoirs and Dams (FHReD) - focuses on *hydropower generation's planned reservoirs*. It contains some 3,700 records for, exclusively, hydropower dams with a capacity above 1 MW collected from various sources, including peer-reviewed literature, publicly available databases, and non-governmental organizations. The database is managed by the Eberhard Karls University of Tübingen, Germany (Zarfl et al., 2014). The database does not include dam height or storage capacity details, hence not directly comparable with the first two above in the context of dam size. However, considering hydropower capacity numbers only, the database lists some 160 dams with a capacity of over 1000 MW [which may be (arbitrary) seen as "large"]. Some 210 records with the capacity in the range between 100 and 1000 MW (which may be perceived as "medium"). Close to two-thirds and one-third of all records are dams with the capacities of 100 to 10 MW, and under 10 MW respectively. In the context of the above, at the very least, the dams in the last category (under 10 MW) may be seen as "small." Most of the dams listed in FHReD are in the planning stage, and only a few are under construction.

These three databases together present freely accessible georeferenced global information on dams. The GDW platform also provides links (where possible) or leads to almost 20 other external databases, including the global ones - ICOLD WRD and AQUASTAT (maintained by FAO) - and several national/regional dam databases.

Many features of the above databases are overlapping. On the other hand, the categorization of global dams by size differ between databases depending on the definition of "size" adopted. The level of detail for dam records, the sources and ways of data collection, and overall completeness of records vary as well. To improve the dam data collection and maintenance in the future, it would be beneficial, and in principle possible, to merge all these databases into a single online portal, adopting one approach and thresholds for differentiating the data by dam size categories (e.g., extra-large, large, medium, small). Access to such a database could differ for different users – i.e., free or for a minimal fee – to recover database maintenance cost.

At present, the ICOLD WRD remains the most extensive data archive so far and was used in this synthesis. Incomplete entries in the ICOLD WRD database were omitted, while the entries listed with expected completion dates up to 2020 were included in the analyses that follow as "existing" dams.

GLOBAL TRENDS IN LARGE DAM CONSTRUCTION AND AGEING

As shown in Figures 1 and 2, large dams' construction surged in the mid-20th century and peaked in the 1960s/70s, especially in Asia, Europe, and North America, while in Africa, the peak has occurred lately in the 1980s. The numbers of newly constructed large dams after that continuously and progressively declined. Most of the world's large dams are now concentrated in a few countries (Table 1). China leads the list with 23,841 dams, and the USA keeps the second position; together with these two counties host ~56% of all large dams, while the top 25 countries listed in Table 1 account for more than ~93% of the global total of large dams. Japan and the UK's average age of large dams is over 100 years, implying that the majority of dams in these countries were constructed before and in the early 20th century.

Figure 3 further illustrates how the regional construction of large dams varied over time. Of particular interest is the decline of the North American share and the corresponding surge in Asia in the past 50 years. The Figure also reveals an increasing relative share in Africa and South America, while Turkey and Eastern Europe drive the resurgence in this region; dam-building in Western Europe has almost stopped, with the exception of Spain.

As Figures 1-3 indicate, the construction of large dams has changed dramatically over the decades between 1900 and 2000 both globally and regionally. The median age of dams by country is shown in Figure 4. The median age was chosen as the measure of central tendency to minimise outliers' influence (for example, several large dams that are over five centuries old can be found in the Czech Republic and Japan). The median age of large dams is higher across much of Europe and North America, between 50 and 100 (Figure 4). The median age in other parts of the world is somewhat lower, reflecting the global dam-building boom in the 1970s. Therefore, ageing dams have not yet posed such a pressing problem in these areas but can be expected to - in the near future. It is evident that most of the world's large dams are located in Asia. China, India, Japan, and the Republic of Korea possess 55% of all large dams recorded in the ICOLD WRD database, and of these, a majority will reach the 50-year threshold in the coming years (Figure 3). The same will happen in Africa, South America, and Eastern Europe in the future. The

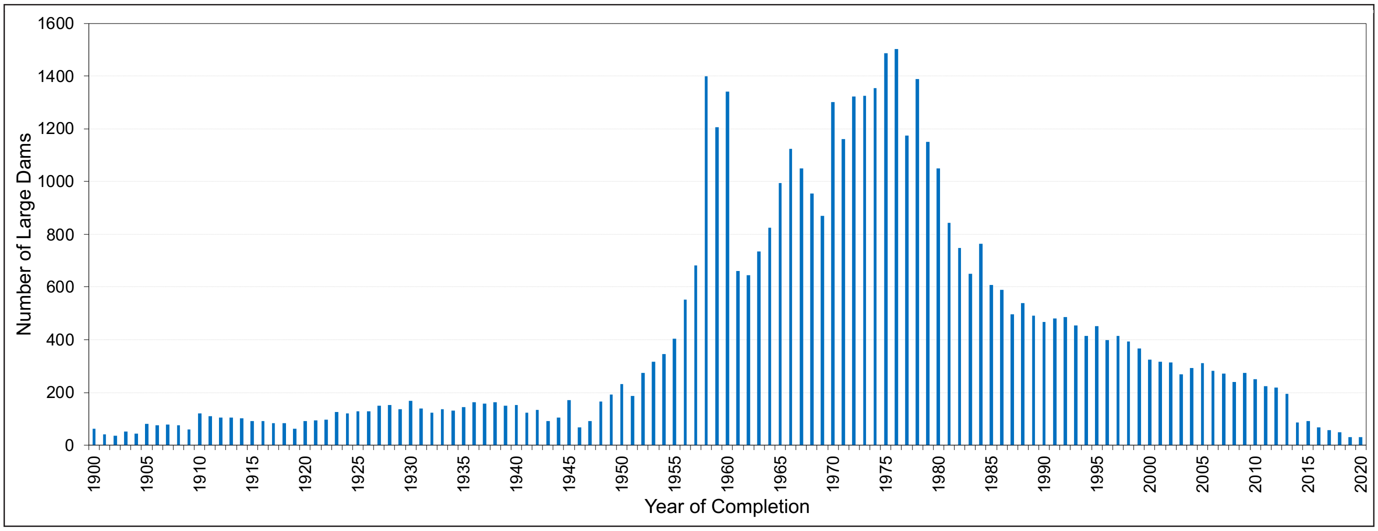

Figure 1. Annual construction of large dams globally since 1900 (Data source: ICOLD WRD, 2020)

trends illustrated in Figures 1 and 2 suggest that while large dam construction continues in some regions, the global dam construction rate has dropped dramatically in the last four decades and continues to decline.

Considering the clear decreasing trend in large dams' construction globally from the later part of the 20th century till the present, it is unlikely that it will be turned around in the next decades, regardless of some national plans to boost hydropower production. This statement can further be supported by the fact that only a small part of the planned dams registered in the FHReD database may be seen as large, that most of them are in the *planning* rather than the actual construction stage takes years to plan and implement dam projects. The already mentioned declining rate of large dam construction is partly because the best locations for such dams globally have been progressively diminishing as nearly 50% of global river volume is already fragmented or regulated by dams (Grill et al., 2015). Additionally, with the strong concerns regarding the environmental and social impacts of dams, and large dams in particular, as well as emerging ideas and practices on the alternative types of water storage, nature-based solutions, and alternative types of energy production (WWAP, 2018), it may be anticipated that new dam construction will continue only slowly in the

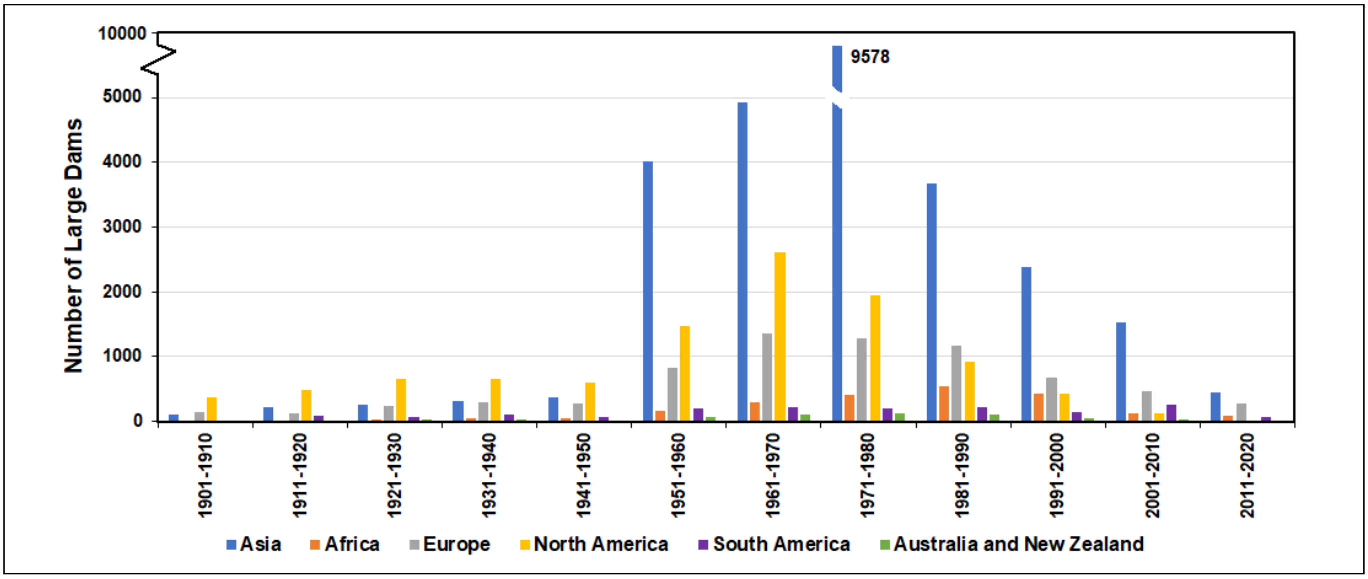

Figure 2. Decadal large dam construction in main geopolitical regions since 1900 (Data source: ICOLD WDR, 2020)

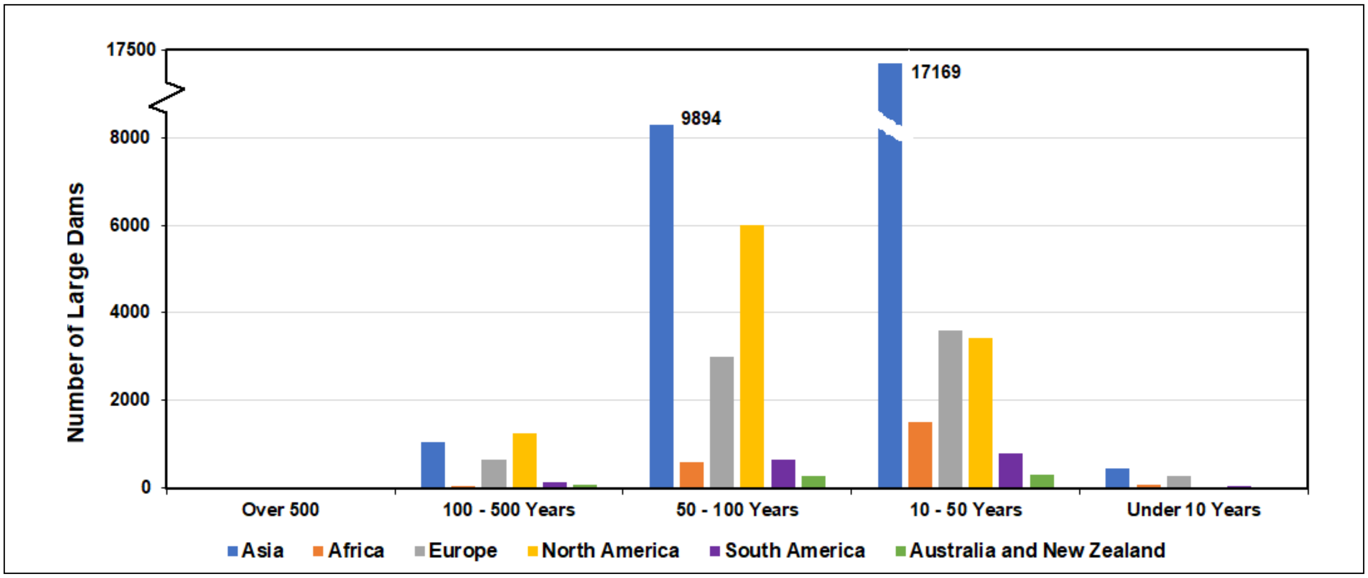

Figure 3. Age of large dams by main geopolitical regions (Data source: ICOLD WRD, 2020)

Table 1. Large dams by country[1]

Country	Number of Large Dams	Average Height (m)	Average Capacity (10^6 m^3)	Average Age (years)	Median Age (years)
China	23,841	26	38	46	51
USA	9,263	21	114	65	57
India	4,407	24	80	42	41
Japan	3,130	33	8	111	65
Brazil	1,365	26	655	51	50
South Korea	1,338	24	13	43	42
South Africa	1,266	23	26	45	43
Canada*	1,156	21	*	55	51
Mexico	1,079	30	165	61	52
Spain	1,064	39	70	56	52
Turkey	965	46	209	23	23
France	720	29	24	60	53
Iran	594	41	109	20	19
UK	580	23	13	106	111
Australia	567	31	170	57	49
Italy	541	42	27	67	65
Germany	371	26	12	70	53
Norway	347	30	163	56	53
Albania	308	27	19	44	44
Zimbabwe	256	25	36	36	31
Romania	241	32	43	42	42
Portugal	234	35	62	38	32
Austria	232	34	13	44	43
Thailand	220	25	376	35	36
Sweden	190	26	328	63	60

[1] ICOLD WRD, 2020

*The average dam capacity for Canada cannot be accurately estimated from ICOLD WRD.

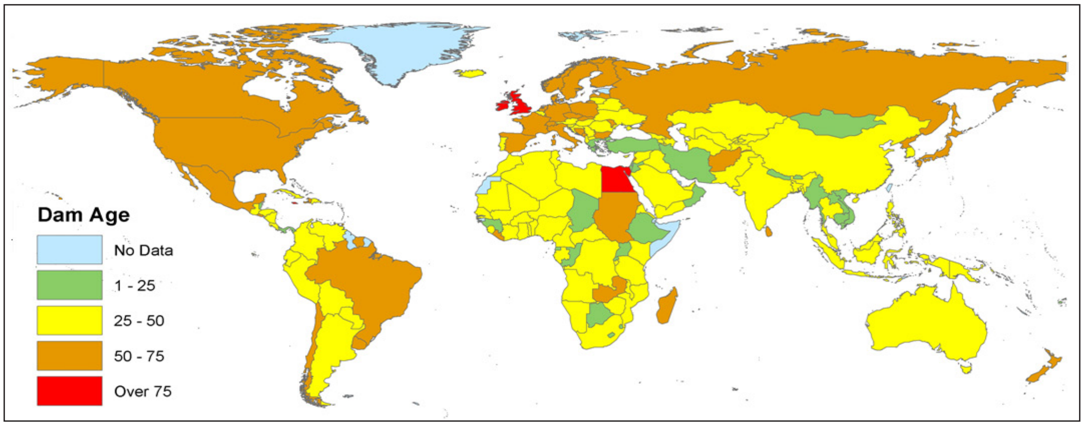

Figure 4. The median age of large dams by country (Data source: ICOLD WRD, 2020)

decades to come, and that additions to total global storage through such construction in the future will be relatively small.

Overall, it means that we are very unlikely to witness another "dam revolution," let alone "large dam revolution," which is occasionally predicted to occur (Cole et al., 2014; Zarfl et al., 2014). At the same time, numerous large dams already constructed in the world will be inevitable ageing. Hence, the world will have to face this new challenge, which is progressively more "trending."

OVERVIEW OF DAM AGEING BY REGION AND DAM FUNCTION

Sub-sections below summarise some details and examples of dam ageing by major geographical regions/continents of the world, with a primary aim to examine the issue of ageing in the context of dam *functions*. Some 33,128 of the dams in the ICOLD WRD have entries for function (only these records were analyzed here). In many cases, dams serve multiple functions, as shown in Table 2. These uses are listed in the ICOLD WRD in order of priority. For the analysis below, dams were counted based on the primary function listed. The most commonly identified function of large dams is irrigation, followed by hydropower, water supply, and flood control, respectively. A few functional categories that generally have the least number of dams (fish farming, navigation, etc.) have been lumped here under the category "Other."

Africa

Dam building in Africa accelerated in the 1980s and 1990s, which means that ageing water storage infrastructure is still not a pressing concern. Africa has far fewer large dams than other continents, approximately 2000, with one-quarter of South Africa alone (SANCOLD, 2020). Nevertheless, this includes several notable structures, such as the Akosombo Dam in Ghana, Kariba Dam in Zambia and Zimbabwe, and Egypt's Aswan Dam. The continent as a whole has a high and increasing reliance on hydropower. Dam construction has risen in recent years in response to a rapidly growing population and demand for both energy and a secure water supply (Yildiz et al., 2016); the Grand Ethiopian Renaissance Dam is indicative of this trend. The majority of large dams in Africa are primarily for irrigation, and for all dam functions, the average age is less than 50 years (Figure 5).

Asia

As Table 1 shows, China, India, Japan, and South Korea are among the most significant number of large dams globally. China alone hosts almost 40% of the world's large dams; (most) are approaching the 50-year age threshold. The focus remains on continued construction, with projects such as the Three Gorges Dam on the Yangtze River. Elsewhere in Asia, India's current dam construction rate is among the world's highest (Zarfl et al., 2014). In contrast, Japan and South Korea have limited opportunities for future surface water storage development. Still, in both countries, dams are widely used to maintain a reliable water supply amid highly variable seasonal flow (Kim et al., 2016). As the two countries face the issue of ageing water storage infrastructure, an emphasis has been placed on countering sedimentation that renders the dams less effective (Kantoush and Sumi, 2017) to extend their design life and reduce downstream impacts. Figure 5 demonstrates that large dams'

Table 2. Large dams by function (Data Source: ICOLD WRD, 2020)

Primary Function	Sole Use	Multiple Use	Total
Irrigation	12,250	3,925	16,175
Hydropower	5,099	1,212	6,311
Water Supply	2,965	1,432	4,397
Flood Control	1,893	1,678	3,571
Recreation	835	267	1,102
Others *(Fish Farming, Navigation, Tailings, etc.)*	1,269	303	1,572
Total	**24,311**	**8,817**	**33,128**

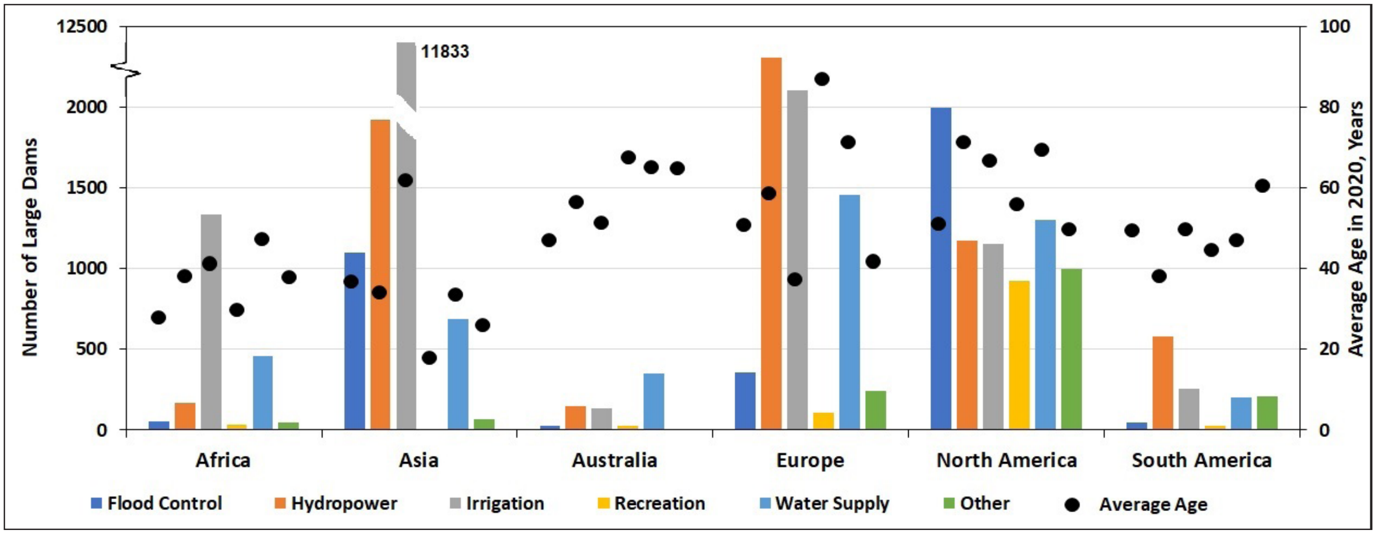

Figure 5. Large dam numbers (bars) and average age (circles) in primary geographic regions by function (Data source: ICOLD WRD, 2020)

average age in Asia is less than 50 years in nearly all categories, except for irrigation. However, irrigation is by far the most common function of large dams in Asia, suggesting that ageing water storage infrastructure does indeed pose a current and increasing challenge.

Australia

Of the more than 650 large dams in Australia, half are over 50 years old, and more than 50 have been in operation for more than a century (ANCOLD, 2010). Water storage infrastructure is crucial in the driest inhabited continent with highly variable precipitation, and Australia consequently has the world's highest per capita surface water storage (AWA, 2010). In addition to stabilizing the water supply, dams are crucial for irrigation and energy, as hydropower is responsible for over 65% of Australia's electricity generation (AWA, 2010). Water supply dams- the most numerous - are the oldest in Australia (Figure 5), together with recreational dams, which constitute only a small proportion of dams. Virtually all rivers in the more heavily populated South have been dammed, leading construction to slow dramatically by the 1990s (Gibbes et al., 2014). Attention has currently turned to the relatively untouched northern river systems (Clarence, Richmond, and Tweed) to redistribute water southward, which has been met with strong resistance from Indigenous populations in the region (Rayner, 2013).

Europe

Many large European dams are ageing, and across every category, the average age is near or above the 50-year threshold (Figure 5). Europe is unusual in that dams for irrigation are on average among the youngest, whereas in many other parts of the world, they are the oldest. The United Kingdom has most of the older dams with an age of over 100-years, with an average age of 106 years. About 10% of large European dams recorded in ICOLD WRD are over 100 years old. In many parts of Europe, dams' construction has virtually ceased, primarily because few waterways remain unimpeded. Notable exceptions are Eastern Europe and Turkey, where the rate of construction, particularly for hydropower dams, is among the world's highest (Zarfl et al., 2014). There is also a growing call in Europe to remove dams and protect remaining unimpeded waterways. In general, this is not motivated by a public safety concern but is based on environmental grounds, as various groups urge the restoration of migratory routes for fish (ERN, 2017).

North America

Canada, Mexico, and the USA are among the global leaders in large dam numbers (Table 1) but ageing water storage infrastructure is most prominent in the USA. It has >90,000 registered dams, of which >9,000 are large dams. Approximately 80% of all dams are >50 years old as of 2020 (Bellmore et al., 2016; ASCE, 2017). The American Society of Civil Engineers` (ASCE) Infrastructure Report Card has repeatedly assigned the country a "D" grade ("Poor/At Risk") for the dangerous state of its dams, citing the need for an estimated USD 64 billion to adequately refurbish the nation's dams (ASCE, 2017). This emerging issue was accentuated by the Oroville dam incident in California in February 2017, where the partial collapse of a spillway forced the evacuation of 200,000 people. This 50-year-old dam, the highest in the USA at 235 m, is critical to California's water supply, and repairs are estimated at USD 500 million (Vartabedian, 2018). The incident has been blamed on human error, specifically inadequate inspection and maintenance (IFTR, 2018). Most dams in the USA are privately owned, and this leaves owners fully responsible for the costs of upkeep (Rowland and DeGood, 2017), leading many dams to be left abandoned due to unmanageable costs (Michigan River Partnership, 2007). More than half of all the large dams in Canada are over 50 years old (ICOLD WRD, 2020). The Mactaquac Hydropower dam (New Brunswick) is the first large Canadian dam to face ageing and needs to address the decommissioning issue (Curry et al., 2020). North American dams' most common function is flood control, while the oldest dams, on average, are those used for hydropower. However, in nearly all functional categories, large dams' average age in North America exceeds 50 years (Figure 5).

South America

In South America, large dams have not yet faced the same issue of widespread ageing seen in other regions, although the average age in some functional categories is close to 50 years (Figure 5). More than half of all large dams are found in Brazil, although only a handful are over 50 years old. South America relies heavily on hydropower, with hydropower dams dominating over other functional categories. Also, hundreds of large dams are planned or currently under construction as countries seek to satisfy growing energy demand (Gerlak, 2019). There is, however, strong and coordinated public opposition to the negative impacts of these dams, including environmental impacts in the Amazon Basin and displacement of Indigenous people (Gerlak, 2019).

DAM DECOMMISSIONING: REASONS, IMPACTS, AND TRENDS

Dam decommissioning may include several scenarios or options, including i) retaining a dam but using it for a different purpose with or without modification [this is also often referred to as "re-operation (USSD, 2015; Owusu et al., 2020)]"; ii) partially removing the dam; or iii) fully removing the dam (The State of Victoria, 2016; Curry et al. 2020). In the context of this Report, dam decommissioning is understood primarily as full or partial dam *removal*. Dam re-operation may also be seen as a form of decommissioning in some cases, whereas dam repairs and upgrades that are done to maintain the same dam function or increase the safety of operations are not considered: they are seen as forms of regular dam maintenance. The life of a dam should include dam construction, the "beginning" and dam decommissioning, the "end" as equally important components of the overall process of a water storage infrastructure development (dam maintenance/repair/rehabilitation would be the "middle" life). Consequently, both construction of a new dam and its later decommissioning must consider various positive and negative economic, social, and environmental impacts.

As countries worldwide start to grapple with ageing water storage infrastructure, decommissioning may be seen both as a priority and the last resort depending on the value attributed to various impacts and considerations for each dam in its particular situation. There are, however, at least four primary and interconnected arguments in favor of decommissioning of ageing dams – public safety, growing maintenance costs, progressing reservoir sedimentation, and environmental restoration.

Public safety: increasing risk

Dams, and large dams in particular, even if structurally sound, are considered to be "high hazard" forms of infrastructure because of the potential loss of human life that would be a consequence of failure (USSD, 2015), in addition to triggering forced displacement and the destruction of livelihoods. Development downstream of dams is persistent and thus elevates the magnitude of the consequences of dam failure. Dam failures, whether from excessive seepage (piping), cracking,

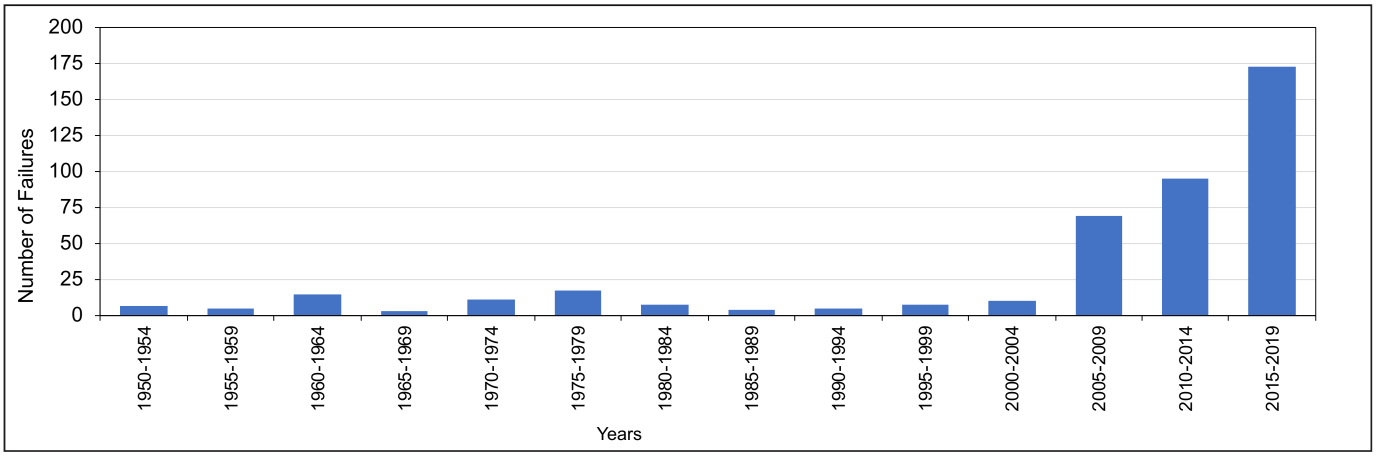

Figure 6. A time series of recorded dam failure accidents from 1950 to 2019.
Data sources: http://self.gutenberg.org/articles/list_of_dam_failures; https://en.wikipedia.org/wiki/Dam_failure; https://damsafety.org/Incidents

overtopping, or structural failure, are frequently the result of poor design or construction, lack of maintenance, or operational mismanagement (FEMA, 2019; https://damsafety.org/dam-failures). While Regan (2010) found that many public safety incidents occur in the first five years of a dam's operation, a considerable number of failures have also occurred in dams over 50 years old (Foster et al., 2000; Zhang et al., 2009). Older dams combined with poor maintenance represent a higher risk to public safety, particularly for downstream areas. Overall, the risks associated with large dams are "low probability and high consequence" (Bowles et al., 1999). Therefore, the challenge is to reduce the probability of avoiding the potential consequences; this requires an effort to conduct risk assessments for ageing dams.

Well-documented cases of failure of dams that were between 50 and 100 years old include Panjshir Valley Dam (Afghanistan, 2018), Ivanovo Dam (Bulgaria, 2012), Situ Gintung Dam (Indonesia, 2009), Kantale Dam (Sri Lanka, 1986), Kelly Barnes Dam (the USA, 1977) and others (Cooper and Gleeson, 2012; Zimmermann, 2019; USBR, 2015, Jayathilaka and Munasinghe, 2014; Associated Press, 2018). These cases have resulted in 10 to 200 fatalities and multi-million USD economic damages.

Figure 6 shows the sequence of recorded dam failure accidents over the last 70 years, irrespective of the size and dam capacity. The graph demonstrates the increase in such accidents from the beginning of the 21st century when many of these dams have reached and/or exceeded the beginning of the end of their design life. Flooding, seepage/internal erosion, deterioration, and structural instability have commonly mentioned as the failure mechanisms. At the same time, there are quite distinct differences between regions/countries masked in Figure 6. For example, an analysis of recorded USA's dam failures (https://damsafety.org/Incidents) suggests that over 75% of these occurred after 50 years of age, yet most of the Chinese dam failures were found to occur during the first years of exploitation (He et al., 2008). Overall, not all dam failures can be attributed to ageing without more detailed data of failures across all ages and failure triggers. Regardless, the commonly cited triggers of failures, i.e., structural flaws, extreme floods and overtopping, landslides, internal erosion, and maloperation, are more likely in older dams because ageing increases the vulnerability of a dam to such triggers.

Climate change considerations may accelerate a dam's ageing process and, thus, decisions about decommissioning. Extreme weather events, especially floods, are expected to become more severe and frequent with the changing climate. Consequently, these events increase the threat to aging large dams designed using historical hydrological data (Payne et al., 2004; Choi et al., 2020). The increasing frequency and severity of such events can overwhelm the reservoir's and dam's design limits and undermine dam safety which was established for a different (and stationary) climatic situation (Fluixá Sanmartín et al., 2018).

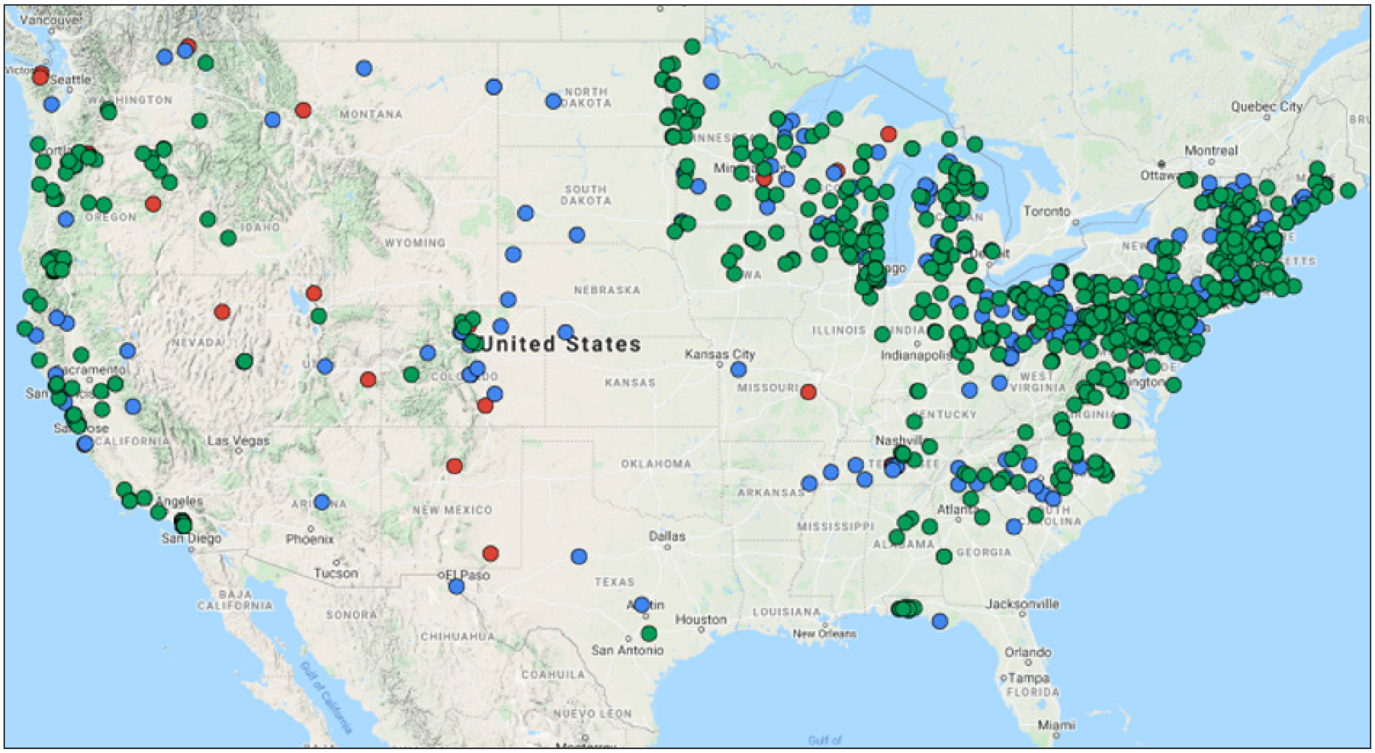

Figure 7. Location of dams removed in the USA in 1970-2019. Data source: www.AmericanRivers.org/Dams. Red circles – large dams (height >15 m); blue circles – medium-sized dams (height between 5 to 15 m); green circles – small dams (height <5 m).

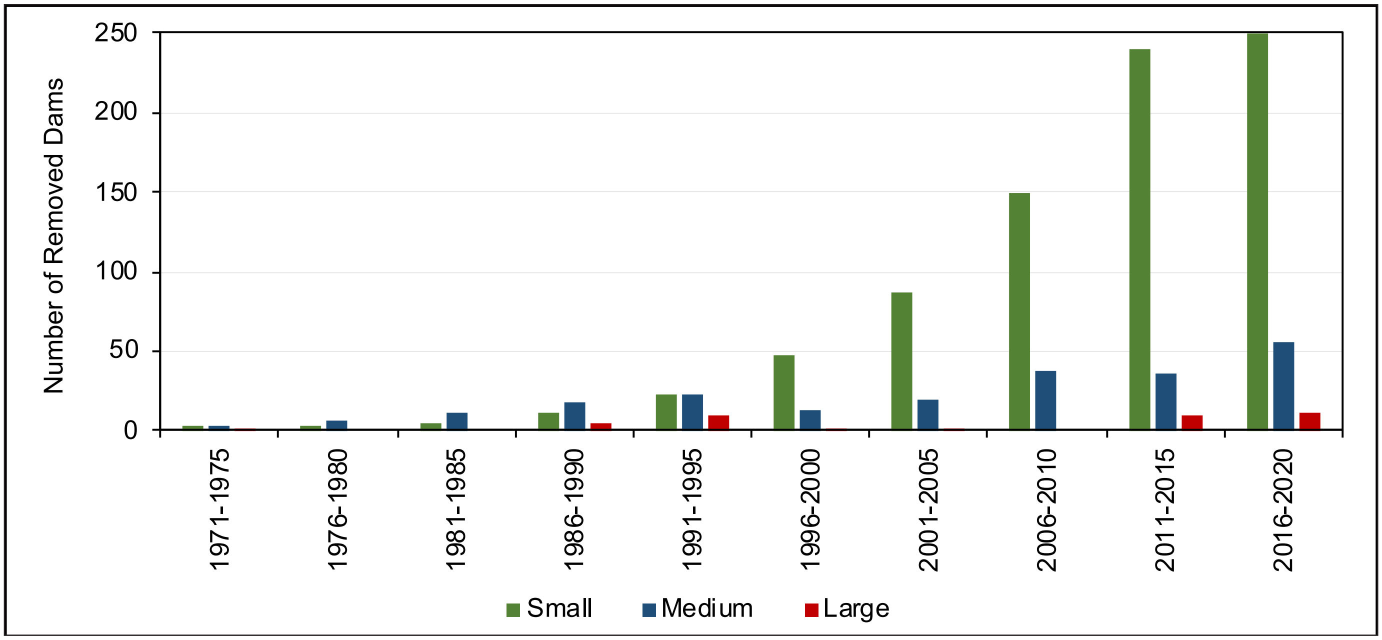

Figure 8. Dam removal in the USA since 1970 Data source: www.AmericanRivers.org/Dams. Red bars – large dams (height >15m); blue bars – medium-sized dams (height between 5m to 15m); green bars – small dams (height <5m).

Maintenance: rising expense

Their upkeep to sustain safety and dam function(s) is generally increasingly expensive as dams age. Maintaining dams requires regular inspection and repairs, which can substantially increase hydropower dams' operating costs by the age of 25-35 years (e.g., McCully, 1996). Maintenance and associated costs are imperative for public safety and sustaining longevity. Most dam failures are thought to have been preventable if they had been adequately maintained and regularly inspected (USSD, 2010). In some cases, rising maintenance costs have led privately-owned dams to be abandoned in the USA, creating the risk of failure and, more disastrously, collapse without warning (Alvi, 2018). Ownership is an important factor for dam maintenance and particularly challenging for privately-owned dams (Ho et al., 2017). Large dams create the issue of scale, e.g., internal structural deficiencies can be difficult to identify (Wieland, 2010). The costs of prevention through inspection and maintenance are, of course, immensely preferable to the costs of dam failure that could have been avoided. As the cost of maintenance and repair escalate with ageing infrastructure, these costs can be 10-30 times more expensive than dam removal (Headwaters Economics, 2016; Grabowski et al., 2018; Graham, 2019; Massachusetts Government, 2019).

Sedimentation: declining effectiveness of the function

Dams not only impound the water in rivers, but they also interrupt the dynamic, downstream transport of sediment, leading it to its accumulation in reservoirs. Sedimentation is determined mainly by a dam's geography and upstream basin conditions and processes. Sedimentation rates are critical for a dam's life expectancy, and the storage capacity of dams subsequently declines over time as sediment accumulates. Some sources estimate that at current reservoir sedimentation rates, the existing global reservoir storage capacity could be nearly ***halved*** by 2100 (Sumi et al., 2004). Sedimentation rates vary widely according to the river basin's geologic and physical condition (Kondolf et al., 2014). Consequently, some dams are "ageing" much more quickly than others due to sedimentation alone. Dealing with the sedimentation is a significant component of the high dam maintenance cost, as sedimentation can lead to the accelerated end of the dam's life. Regions/countries such as China, Europe, USA, Nile River basin, and Japan- – to mention a few - are experiencing significant impacts and incur high costs to overcome the problem (Wang and Hu, 2009; Milligan, 2013; Kondolf et al., 2014; Albayrak et al., 2019; Hydro Review, 2020;).

Environment: restoring or redesigning natural environments

Just as the construction of a dam has a transformative effect on the surrounding landscape, so does the dam's removal. The primary and most direct impact is the release of reservoir water and sediments, which may alter the downstream sediment budgets, change river geomorphology, and bring contaminants to downstream ecosystems (Warrick et al., 2015). However, when the more natural sediment flux along the river is reestablished, aquatic habitats and ecosystems are restored as well (Grant and Lewis, 2014). Dams also disrupt river connectivity, often creating significant negative impacts for fishes and ecosystems (e.g., Barbarossa et al., 2020). Restoring riverine connectivity by dam decommissioning is increasingly championed by science, environmental groups, and regulators (USSD, 2015; Magilligan et al., 2017; Roy et al., 2018; Birnie-Gauvin et al., 2020). There is evidence that river ecosystems may quickly return to pre-dam conditions (Access Science, 2015; Foley et al., 2017). However, the "new" post-dam ecosystem will not necessarily be the same as the pre-dam ecosystem (Bellmore et al., 2016).

Societal impacts of dam decommissioning

A dam removal/re-operation will have various societal impacts, such as ***changes in the local economy***. Fisheries, agriculture, tourism, and hydropower will be affected by dam removal and, in turn, impact employment opportunities and livelihoods. Rivers are rarely dammed for the sole purpose of fishery creation, and in most cases, damming a river result in losses of riverine fisheries (Jackson and Marmulla, 2001). Dam removal can increase fishery yields (Witze, 2014; Mapes, 2016; Ohno, 2019) that are important for local populations. The agricultural sector may benefit from or be inhibited by dam removal. For low-income, developing nations in the global South, dams and irrigation systems can play a critical role in alleviating poverty; hence, dam removal could have detrimental consequences to local livelihoods. Alternately, dam removal may turn out to be beneficial for people who previously relied on the reservoir footprint for agricultural lands such as pastoral societies or subsistence farming (Adams, 2000). Dam removal may stimulate the local economy by increasing tourism (Whitelaw and MacMullan, 2002; Ohno, 2019), but reservoirs can also attract tourists, e.g., swimming, fishing, and boating, which may be lost if the dam is removed. Hydropower generation can be significantly affected if a dam is removed. In developed economies where access to electricity is nearly universal, removing obsolete hydropower dams may have a limited impact on local societies (Baish et al., 2002; Germaine and Lespez, 2017). In contrast, in developing economies where people lack access to electricity for their homes and workplaces, a hydropower dam removal may have far-reaching negative consequences and, thus, not be a viable option to address ageing infrastructure.

Dam removal may impact the ***cultural history and heritage*** of a particular region. Dams that no longer serve their original purpose may still hold value to residents because of their longstanding history and ties to long-past industries, as examples from UK (Kotval and Mullin, 2009) or Sweden (Lejon et al., 2009) suggest. To maintain the historical and cultural integrity of dam locations post-removal, the dam's history may be commemorated (Goddard-Bowman, 2014). Conversely, dam removals may provide an opportunity for a return of previously impacted services provided by the free-flowing, pre-dam river, such as the renewal of sacred land and provisioning to ceremonial observances, e.g., fish and plants for indigenous communities (Guarino, 2013; White, 2016).

A common fear of dam removal in the developed world is its impact on ***property value***. Some sources indicate that lakefront (reservoir) properties are more valuable on the housing market than riverfront properties (Nicholls and Crompton, 2017), while others show the opposite (Provencher et al., 2008). While the literature to date is scant, there are many essential aspects of property value to be considered during decommissioning, such as the value of added land once the reservoir is removed, change in tax rates, and property buyout options (e.g., https://www.nbpower.com/en/about-us/projects/mactaquac-project/resources/).

Although dams are rarely built or removed solely to improve ***recreational activities***, the latter is highly valued by the public (Wyrick et al., 2009). Therefore, dam removal should account for the potential losses or gains in recreational value. Born et al., (1998) found that loss of recreation was one of the main perceived deterrents of dam removal, and yet arguments in favor of dam removal also cite an increase in recreation (see also https://www.nbpower.com/en/about-us/projects/mactaquac-project/resources/). This dichotomy of opinion demonstrates the importance of engaging local communities in decisions regarding recreation post-decommissioning.

When considering dam removal, scientists and policymakers prioritise safety and economics while residents prioritise recreation and ***aesthetics*** (Wyrick et al., 2009). The local community is a key stakeholder in dam removal projects, and the potential loss of aesthetics also needs consideration even though aesthetics can be subjective and a polarizing topic (Jørgensen and Renöfält, 2013). There is also a misconception that removing a dam will negatively alter the scenery by leaving a muddy and unsightly reservoir footprint (Sarakinos and Johnson, 2002). This is true immediately after the dam removal and reservoir drawdown (Lejon et al., 2009). However, this newly exposed zone can quickly evolve to increase wildlife and water quality, and in urban areas - the creation of green space and riverfront revitalization (Baish et al., 2002).

As can be seen from the above, the extent of dam removal impacts may vary based on geography and socio-economic conditions. In developed nations where water availability is reliable, many ageing dams have been rendered obsolete. Their removal may be the ideal choice to manage ageing infrastructure because of the cost-benefit and the positive ecological impacts of regaining a free-flowing river. However, dams may be critical infrastructure for low-income countries to provide clean water and sanitation, irrigate crops for improved livelihoods and poverty alleviation, and provide a reliable, clean energy source. In these cases, dam removal may not be a viable option. Thus, implementing one-size-fits-all criteria to assess and prioritise dam removal projects in the global context is at least useless and at most - dangerous. Dam removal should go through the same Environmental Impact Assessment and safeguard procedures that are required at the stage of dam construction.

Emerging trends

Dam decommissioning is not particularly new, and yet it is still a relatively recent phenomenon. The decommissioning scale globally remains somewhat uncertain, but several regional databases are emerging that are consolidating data (www.AmericanRivers.org/Dams; https://damremoval.eu/dam-removal-map-europe/).

The USA is the dam decommissioning leader with some 1,275 dams removed in 21 states over the last 30 years, and 80 dams removed in 2017 alone. The USA database begins with records from 1912. By categorizing these records into "large" (higher than 15 m, as per ICOLD definition), medium (height between 15 and 5 m), and small (height less than 5 m) dams, the pattern of dam decommissioning in the USA can be examined and mapped (Figure 7). The height was used in this Report as the key categorization variable because reservoir capacity was not always available in the USA database. All incomplete records (e.g., those without coordinates) were ignored, and only records from 1970 till the present were considered (as there were few removal cases before that). It can be seen from Figure 7 that only a few large dams were removed over the last 50 years. Most of the dams removed were small (<5 m height) and privately-owned (Oldham, 2009).

Figure 8 shows the growth of dam removal in the USA over time. Again, it is evident that small and medium dams dominate the removal arena, with most occurring since 2000. Removal of large dams is still in its infancy with just a few cases, but it includes the recent and most extensive dam removal worldwide to date (Elwha River dams – see next section)

CASE STUDIES OF DAM AGEING AND DECOMMISSIONING

The decommissioning of ageing dams is becoming progressively more common in some regions around the world. Many examples of decommissioning cases can be found, e.g., https://damremoval.eu/case-studies/ that features almost 40 case studies of dam removal in Europe; however, most are small dams. There are a few reports on large dam decommissioning, either entirely removed or under consideration.

The Glines Canyon and Elwha dams, Elwha River, Washington, USA. Age: ~ 110 years.

In 2011, the Elwha and Glines Canyon River dams` removal represented the largest dam removals in the US history. An estimated removal cost was almost USD 325 million. The dams had little remaining value as a power supplier; removal added safety and cultural benefits to the Lower Elwha Klallam Tribe (Headwaters Economics, 2016) and restored the river's ecosystem services for all. The Elwha River once hosted a thriving, diverse ecosystem crucial to the Lower Elwha Klallam Tribe's livelihood. As the logging industry brought economic development to the northwestern USA, two large hydroelectric dams were constructed

Figure 9. Glines Canyon Dam on the Elwha River during the dam removal process. Photo credit: USGS, Source: https://www.usgs.gov/center-news/new-report-synthesizes-us-dam-removal-studies

on the river in the early 1900s. The 64 m Glines Canyon Dam with a 50 million m³ capacity and the slightly smaller Elwha Dam was an important electricity source for the region for much of the 20th century. However, they provided no fish passage or environmental flows to support socially significant salmon, trout, and lamprey. Initial advocacy for both these dams' decommissioning began in the 1980s, gaining approval in 2004, but the removal process itself did not commence until 2011 (Nijhuis, 2014). The Glines Canyon dam removal followed a complex four-phase strategy, which allowed for the gradual removal of the dam using temporary spillways (National Park Service, 2015; Figure 9).

Similarly, the Elwha dam removal took place in phases, including the construction of temporary cofferdams allowing water to be pumped out to remove the fill material behind the dam (National Park Service, 2019). The removal of the Glines Canyon Dam was completed in 2014, marking the ecosystem's restoration, including the highly regarded salmon. The Elwha River case demonstrates the potential for positive impacts of dam removal for both the environment and the indigenous people for whom the river plays a vital role. However, it also illustrates the complexity and lengthy process that is often necessary to secure support and safely orchestrate the removal of such an extensive infrastructure. It is important to note certain favorable conditions that influenced this process. The Elwha River location in a national park itself contributed to its removal, and the removal increased tourism and recreational opportunities (Headwaters Economics, 2016). To date, the Glines Canyon dam remains the largest dam removal project in the world (Nijhuis, 2014).

The Poutès Dam, Allier river, France. Age 78 years

The Poutès Dam in France can be seen as a case of innovative partial removal. Constructed during World War II, the 17m-high and 2.4 million m³ dam capacity has produced hydroelectricity for well over 50 years (Xin, 2012). The removal was principally motivated by a desire to protect the endangered Atlantic salmon; no public safety concerns were reported. Fundamental changes include lowering the dam's height to 4 m and constructing fish-ways to restore the salmon migration routes (Xin, 2012). Another innovation will allow sediment to pass downstream periodically. This work started in 2019 and will cost approximately 10 million Euros (ERN, 2017; Figure 10).

Mactaquac Dam, Saint John River, New Brunswick Canada: Age ~50 years.

The Mactaquac Hydroelectric Generation Stations is a large dam - 55 m high, 16,282 m³ capacity, and over 1 km long (Curry et al., 2020) with a capacity of 670 MW (19% of the province of New Brunswick's total energy generating capacity). The dam and station were commissioned in 1968 and had an estimated design life of 100 years. Yet, a concrete expansion problem has pushed forward the end of the service life by nearly 40 years. A decision is required for the dam's future state, and four options have been considered: i) repowering—including building a new powerhouse and associated structure; ii) rebuilding—which would retain the reservoir with no power generation; iii) removal and river restoration (Figure 11); and iv) refurbishment (renewal)—known as "Life Achievement," which is an attempt to continue operations within the current footprint of the dam beyond 2030.

Consistent with large dam decommissioning to date, the estimated cost of the dam's removal was a fraction of the estimate to rebuild or refurbish the dam. An overarching science framework was developed to inform and support decision-making for the dam's review process (Curry et al., 2020). The plan revolved around three pillars: i) assessing engineering solutions for a build or remove option, ii) engaging the public using multiple conversation pathways, and iii) developing a science framework to support science solutions which will minimise the impacts on the aquatic environment under the removal/renewal options. The framework is currently being implemented; hence Mactaquac can be seen as the "living case" with a potential for removal eventually. The framework creates a solid foundation to ensure a successful, extensive dam review process and streamline a review process into a 10-year time frame, which is significantly shorter than experiences to date for comprehensive dam reviews, renewals, and removals.

Figure 10. The Poutès dam before (2015) and after partial removal in 2021 (photomontage). Photo credit © EDF Hydro

Figure 11: The Mactaquac Hydroelectric Generating Station Dam (actual current view- *top*) and the options considered for its renewal/removal: Repowering (construction of the new powerhouse and other components – *bottom left*); Maintaining the dam as a water control structure without power generation – *bottom middle*, and Removing the dam to ensure a free-flowing river - *bottom right* Credit and Source: New Brunswick Power 2013; https://www.nbpower.com/en/about-us/projects/mactaquac-project/resources/

Mullaperiyar Dam, Periyar River, Kerala, India. Age: 125 years

The Mullaperiyar Dam (Figure 12) is a gravity dam of 53.6 m in height and a reservoir capacity of 443 million m³. It impounds the Periyaru River in Kerala State, downstream to Tamil Nadu state, India. It was built in 1895 by the British government to provide irrigation and eventually began to generate power in 1959 (Chowdhury, 2013; Thatheyus et al., 2013). At the time of construction, the dam had an intended lifespan of 50 years (Chowdhury, 2013). Still, in service over a century later, the dam shows significant structural flaws and may be at risk of failure. The dam is located in a seismically active area. A minor earthquake caused cracks in the dam in 1979 (Rao, 2018), and in 2011, more cracks appeared

Figure 12 Mullaperiyar Dam, Periyar River. Photo credit: Mathrubhumi Media - www.mathrubhumi.com Kerala, India. Source: https://english.mathrubhumi.com/topics/Tag/Mullaperiyar%20Dam

in the dam due to seismic activity (Thatheyus et al., 2013). Leaks and leaching are also concerning, as the methods and materials used during construction are considered outdated compared to current building standards. In response to these structural issues, dam decommissioning has been considered. However, a conflict between Kerala and Tamil Nadu States started to grow regarding the best way to manage this ageing infrastructure (Thatheyus et al., 2013). Although the dam is located in Kerala, it is operated by the upstream state of Tamil Nadu. Kerala residents are afraid of a dam collapse and argue that the reservoir level must be lowered until the dam is fixed.

Meanwhile, Tamil Nadu residents want to maintain the water levels at capacity (Rao, 2018). In 2009, Kerala requested a new dam to be built, but Tamil Nadu opposed the idea. Currently, the decision of how to manage the ageing Mullaperiyar dam is hotly debated and working through the court system. A dam failure risk would be catastrophic: nearly 3.5 million people will be affected (Chowdhury, 2013).

Kariba Dam, Zambezi River, Zimbabwe, and Zambia. Age: 60 years.

The Kariba Dam (Figure 13) is a concrete arch dam 128 m in height that impounds the Zambezi River between Zimbabwe and Zambia. As of 2015, it was the largest man-made reservoir in the world, impounding 181 km³ of water (World Bank, 2015). During the construction, about 15,000 individuals were relocated from the reservoir footprint (Scudder and Habarad, 1991). The dam was completed in 1960 to cover the electricity demand of the Zambezi river basin region (Bertoni et al., 2019). About 35% of the basin's hydroelectric capacity originates at the Kariba dam, making it an essential source of energy for the region (Bertoni et al., 2019). The total capacity of the Kariba hydropower station is 1830 MW (World Bank, 2015). In 2015, the South African Institute for Risk Management identified that the Kariba dam needed urgent repairs after the dam's floodgates eroded a plunge pool at the dam's base, very close to its foundation (Liu, 2017). Erosion can potentially weaken the dam's foundation and could lead to its collapse (Leslie, 2016).

Additionally, repairing the spillway was deemed necessary to maintain the dam's stability (World Bank, 2015). A failure of the Kariba dam would be catastrophic and would also cause the collapse of downstream Cahora Bassa dam (Leslie, 2016). This would impact over three million individuals, and the population's electricity needs would no longer be met (Leslie, 2016). In 2014, almost USD 300 million was loaned to repair the Kariba dam (Leslie, 2016). Repair is expected to be completed by 2023 (World Bank, 2015). Dams like Kariba will likely continue to operate much longer with recurring investments into repairs despite the advanced age of 60 years by now, as they may be simply too large, risky, and costly to remove.

Figure 13. Kariba dam. Sources: Shuttestock (top) and Wikimedia Commons (bottom).

Arase Dam, Kuma River, Kumamoto Prefecture, Japan. ~56 years

The Arase Dam in Kumamoto Prefecture, Japan, was the first dam removed (Figure 14) at the continuous residents' pressure due to its socio-economic and environmental impacts. This 25 m high and 210.8 m wide dam (Hoyano, 2004; Young and Ishiga, 2014) was built in 1954 with a total storage capacity of 10 million m³, primarily for hydropower generation with a maximum output of 18.2 MW. (Tanabe, 2014). Regardless of its electricity production, the Arase Dam received continuous complaints from the Sakamoto village community due to its post-construction extreme impacts, including severe floods and consequent sludge accumulation, fewer sweet fish in the river. Further, it caused severe ecosystem damage to the estuary in the Yatsushiro Sea, reducing seaweed growth and lowering fish harvest (Tanabe, 2014). In 2010, Kumamoto Prefectural Government decided on removing the dam after considering the community

Figure 14. Arase Dam site before removal (top) and after removal in 2014 (bottom). Photo credit and source: Kumamoto Prefectural Government, Japan.

concerns. A year after the removal, a significant improvement in the river ecosystem was observed, including sand bars' reformation, the increased population of small crabs, shells, and fish habitats (Young and Ishiga, 2014).

CONCLUSIONS

Ageing water storage infrastructure slowly grows into a significant global development issue. Thousands of large dams built in the middle of the previous century have already or will soon exceed the age of 50 years – a lower bound of dam design lifespans - and many are approaching 100 years. As a result, they will incur more significant maintenance costs while simultaneously declining in effective functionality and posing threats to the environment and human safety. To effectively deal with this emerging problem, it will be important to develop frameworks to understand decommissioning processes and outcomes. This depends on accurate data, understanding of the factors and impacts of dam ageing in the local context, and establishing relevant policies sooner rather than later.

Several global-scale databases are identifying existing and planned dams. Many features of these databases are overlapping, but each has deficiencies with mixed levels of details. It would be beneficial to merge these databases into one online portal, adopting one approach and thresholds for differentiating the data by dam characteristics such as size and functions. Access to such a database would ideally be free for everyone but certainly should remain open or low cost to low-income, developing regions.

Analyses indicate that while large dam construction continues in some regions, the global construction rate has dropped dramatically in the last four decades and continues to decline. Therefore, it is unlikely that this trend will be turned around in the next decades, regardless of some national plans to boost hydropower production. Besides, only a small part of the planned dams may be seen as large; most of them are currently in the *planning* stage rather than the actual *construction* stage. It takes years to design and implement a dam project. Dams are declining to favor several factors such as strong concerns about dams' environmental and social impacts and emerging ideas for alternative types of water storage, nature-based solutions, and alternative energy sources. It appears that new dam construction globally will continue at a slow pace in the decades to come, and thus an addition to total global water storage behind dams in the future will be relatively small. Overall, we are very unlikely to witness another "dam revolution" and particularly a "large dam revolution," which is occasionally predicted to occur. At the same time, numerous aging large dams already exist worldwide. Hence, the world will have to face this new challenge, which is progressively increasing.

There is a notable decline in the North American share of large dams and the corresponding surge in Asia in the past 50 years. In most of western Europe, the construction of dams has effectively ceased. The age of large dams in Africa, South America, and Asia is generally less than 50 years, with some older dams for irrigation in Asia. However, irrigation is the most common function of large dams in Asia, and hence ageing water storage infrastructure in this region poses an increasing challenge. In North America, the ageing water storage infrastructure problem is most prominent in the USA, where 80% of all dams are already over 50 years old in 2020. This applies to nearly all functional categories of dams in the region.

As they age, a dam's structural integrity or functional ability most often becomes sub-optimal. Such issues lead to questions of dam decommissioning, its removal, or re-operationalization. There are several arguments in favor of decommissioning ageing dams, including protection of public safety, growing maintenance costs, progressing sedimentation of the reservoir, and environmental restoration. Decommissioning will also have various positive and negative economic, social, and ecological impacts to be considered. The nature of the implications and feasibility of dam removal will differ between low-income and high-income countries. Therefore, assessing dam removal in a local and regional social, economic, and geographic context is critical to protect the broader, sustainable development objectives for a region.

Whether a dam is to be removed, partially or entirely, decommissioning is much less costly than repairing or rebuilding. Overall, dam decommissioning should be seen as equally important as dam building in the overall planning process on water storage infrastructure developments.

Decommissioning dams is a relatively recent phenomenon. The scale of decommissioning varies globally and regionally; for example, it has become quite common in the USA and Europe. The dams removed are, however, primarily of smaller size. Removal of large dams is still in its infancy, although a few cases have been recorded mostly in the last ten years.

Case studies of dams' ageing and decommissioning illustrate the complexity and lengthy process necessary to secure support and safely orchestrate a dam removal. Even removing a medium-size dam requires years (sometimes decades), continuous experts, and public involvement and is often subject to lengthy regulatory approvals. It is essential to develop protocols and policies that will guide and speed up dam removal. Delaying the removal of certain aged dam structures could lead to catastrophic consequences with millions of people and their economies affected. Simultaneously, the magnitude of some large dam removal projects is merely prohibitive, and they will likely continue to operate much longer with recurring investments into repairs despite their advancing age.

Ultimately, value judgments will determine the fate of many of these large water storage structures. It is not an easy process, and thus distilling lessons from and sharing dam decommissioning experiences should be a common global goal. Lack of such knowledge and lack of its reflection in relevant regional/national policies/practices may progressively and adversely affect the ability to manage water storage infrastructure properly as it is ageing.

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REFERENCES

Access Science Editors. (2015). Effects of dam removal. Access Science. https://doi.org/10.1036/1097-8542.BR0617151

Adams, A. (2000). A Grassroots View of Senegal River Development Agencies: OMVS, SAED | International Rivers. (n.d.). Www.Irn.Org. Retrieved October 23, 2020, from http://www.irn.org/files/en/africa/grassroots-view-senegal-river-development-agencies-omvs-saed.html

Albayrak, I., Müller-Hagmann, M., & Boes, RM. (2019). Efficiency evaluation of Swiss sediment bypass tunnels. In Proceedings of the 3rd International Workshop on Sediment Bypass Tunnels, pp. 239-245. National Taiwan University, Taiwan.

Alvi, I.A. (2018) Dam incidents and failures can fundamentally be attributed to human factors. | Lessons Learned | ASDSO Lessons Learned. (n.d.). Damfailures.Org. Retrieved October 24, 2020, from http://damfailures.org/lessons-learned/dam-incidents-and-failures-can-

ANCOLD (Australian National Committee on Large Dams). (2010). Register of Large Dams in Australia. Accessed July 14, 2020 at https://www.ancold.org.au/?page_id=24

ASCE (American Society of Civil Engineers). (2017). 2017 Infrastructure Report Card. Accessed July 15, 2020 at https://www.infrastructurereportcard.org/cat-item/dams/

Associated Press. (2018). Dam burst inundates villages, leaves at least ten dead. CBSNews. Available from: https://www.cbsnews.com/news/dam-burst-afghanistan-panjshir-valley-villages-flooded-homes-destroyed-deaths/

Australian Water Association (AWA). (2010). Large Dams Fact Sheet. Accessed July 14, 2018 at http://www.awa.asn.au/AWA_MBRR/Publications/Fact_Sheets/Large_Dams_Fact_Sheet/AWA_MBRR/Publications/Fact_Sheets/Large_Dams_Factsheet.aspx?hkey=bb65d83c-f3fe-4812-8433-d21a110daeae

Baish, S. K., David, S. D., & Graf, W. L. (2002). The Complex Decision making Process for Removing Dams. Environment: Science and Policy for Sustainable Development, 44(4), 20–31. https://doi.org/10.1080/00139150209605779

Barbarossa, V., Schmitt, R. J. P., Huijbregts, M. A. J., Zarfl, C., King, H., & Schipper, A. M. (2020). Impacts of current and future large dams on the geographic range connectivity of freshwater fish worldwide. Proceedings of the National Academy of Sciences, 201912776. https://doi.org/10.1073/pnas.1912776117

Bellmore, J.R, Duda, J. J., Craig, L. S., Greene, S. L., Torgersen, C. E., Collins, M. J., & Vittum, K. (2016). Status and trends of dam removal research in the United States. Wiley Interdisciplinary Reviews: Water, 4(2), e1164. https://doi.org/10.1002/wat2.1164

Bertoni, F., Castelletti, A., Giuliani, M., & Reed, P. M. (2019). Discovering Dependencies, Trade-Offs, and Robustness in Joint Dam Design and Operation: An Ex-Post Assessment of the Kariba Dam. Earth's Future, 7(12), 1367–1390. https://doi.org/10.1029/2019ef001235

Birnie-Gauvin, K., Nielsen, J., Frandsen, S. B., Olsen, H.-M., & Aarestrup, K. (2020). Catchment-scale effects of river fragmentation: A case study on restoring connectivity. Journal of Environmental Management, 264, 110408. https://doi.org/10.1016/j.jenvman.2020.110408

Born, S. M., Genskow, K. D., Filbert, T. L., Hernandez-Mora, N., Keefer, M. L., & White, K. A. (1998). Socio-economic and Institutional Dimensions of Dam Removals: The Wisconsin Experience. Environmental Management, 22(3), 359–370. https://doi.org/10.1007/s002679900111

Bowles, D.S., Anderson, L. R., Glover, T. F., and Chauhan, S., (1999). Understanding and Managing the Risks of Aging Dams: Principles and Case Studies, in the Nineteenth USCOLD Annual Meeting and Lecture, Atlanta, GA, May 16-21, 1999.

Chao, B. F., Wu, Y. H., & Li, Y. S. (2008). Impact of Artificial Reservoir Water Impoundment on Global Sea Level. Science, 320(5873), 212–214. https://doi.org/10.1126/science.1154580

Cho, R. (2011). Removing Dams and Restoring Rivers. Columbia Water Center – Newsletter, Earth Institute, Colombia University, https://blogs.ei.columbia.edu/2011/08/29/removing-dams-and-restoring-rivers/

Choi, J.-H., Jun, C., Liu, P., Kim, J.-S., & Moon, Y.-I. (2020). Resolving Emerging Issues with Aging Dams under Climate Change Projections. Journal of Water Resources Planning and Management, 146(5), 04020025. https://doi.org/10.1061/(asce)wr.1943-5452.0001204

Chowdhury, A. R. (2013). Decommissioning dams in India: a comparative assessment of Mullaperiyar and other cases. Development in Practice, 23(2), 292–298. https://doi.org/10.1080/09614524.2013.772563

Cole, M. A., Elliott, R. J. R., & Strobl, E. (2014). Climate Change, Hydro-Dependency, and the African Dam Boom. World Development, 60, 84–98. https://doi.org/10.1016/j.worlddev.2014.03.016

Cooper, B., & Gleeson, J. (2012). Dams Safety Committee Annual Report 2011/2012 [Review of Dams Safety Committee Annual Report 2011/2012]. In http://www.damsafety.nsw.gov.au (p. 65). NSW Dams Safety Committee. https://www.parliament.nsw.gov.au/tp/files/57787/Dams%20Safety%20Committee%20Annual%20Report%202011-2012.pdf

Curry, R. A., Yamazaki, G., Linnansaari, T., Monk, W., Samways, K. M., Dolson, R., Munkittrick, K. R., & Bielecki, A. (2020). Large dam renewals and removals—Part 1: Building a science framework to support a decision-making process. River Research and Applications, 36(8), 1460–1471. https://doi.org/10.1002/rra.3680

Ehsani, N., Vörösmarty, C. J., Fekete, B. M., & Stakhiv, E. Z. (2017). Reservoir operations under climate change: Storage capacity options to mitigate risk. Journal of Hydrology, 555, 435–446. https://doi.org/10.1016/j.jhydrol.2017.09.008

ERN (European Rivers Network). (2017). Poutès dam. European Rivers Network. https://www.ern.org/en/poutes-barrage/

FEMA (Federal Emergency Management Agency). (2019). Types of Dams and Failure Modes. Retrieved October 23, 2020, from https://www.fema.gov/types-dams-and-failure-modes

Ferre, L.E., McCormick, B., Thomas, D.S.K. (2014). Potential for use of social vulnerability assessments to aid decision making for the Colorado dam safety branch. In Association of State Dam Safety Officials Annual Conference (Vol. 2, Issue 664e684). Dam Saf. 2014 (2), 664e684.

Fluixá-Sanmartín, J., Altarejos-García, L., Morales-Torres, A., & Escuder-Bueno, I. (2018). Review article: Climate change impacts on dam safety. Natural Hazards and Earth System Sciences, 18(9), 2471–2488. https://doi.org/10.5194/nhess-18-2471-2018

Foley, M. M., Bellmore, J. R., O'Connor, J. E., Duda, J. J., East, A. E., Grant, G. E., Anderson, C. W., Bountry, J. A., Collins, M. J., Connolly, P. J., Craig, L. S., Evans, J. E., Greene, S. L., Magilligan, F. J., Magirl, C. S., Major, J. J., Pess, G. R., Randle, T. J., Shafroth, P. B., … Wilcox, A. C. (2017). Dam removal: Listening in. Water Resources Research, 53(7), 5229–5246. https://doi.org/10.1002/2017wr020457

Foster, M., Fell, R., & Spannagle, M. (2000). The statistics of embankment dam failures and accidents. Canadian Geotechnical Journal, 37(5), 1000–1024. https://doi.org/10.1139/t00-030

Gerlak, A. K., Saguier, M., Mills-Novoa, M., Fearnside, P. M., & Albrecht, T. R. (2019). Dams, Chinese investments, and EIAs: A race to the bottom in South America? Ambio, 49(1), 156–164. https://doi.org/10.1007/s13280-018-01145-y

Germaine, M.-A. & Lespez, L. (2017). The Failure of the Largest Project to Dismantle Hydroelectric Dams in Europe? (Sélune River, France, 2009-2017). Water Alternatives, 10(3), 655–676.

Gibbes, B., Quiggin, J., & Larsen, J. (2014). Dam hard: water storage is a historic headache for Australia. The Conversation. Retrieved October 23, 2020, from https://theconversation.com/dam-hard-water-storage-is-a-historic-headache-for-australia-33397

Giuliani, M., Anghileri, D., Castelletti, A., Vu, P. N., & Soncini-Sessa, R. (2016). Large storage operations under climate change: expanding uncertainties and evolving tradeoffs. Environmental Research Letters, 11(3), 035009. https://doi.org/10.1088/1748-9326/11/3/035009

Goddard-Bowman, R. (2014). Something old is something new: The role of heritage preservation in economic development. Papers in Canadian Economic Development, 9(0), 96. https://doi.org/10.15353/pced.v9i0.23

Grabowski, Z. J., Chang, H., & Granek, E. F. (2018). Fracturing dams, fractured data: Empirical trends and characteristics of existing and removed dams in the United States. River Research and Applications, 34(6), 526–537. https://doi.org/10.1002/rra.3283

Graham, J. (2019). GSS Engineering Consultants Ltd, Cost Comparison of Dam Repair/Rebuild vs Decommissioning + Before & After Pics. http://www.ontarioriversalliance.ca/wp-content/uploads/2019/06/Summary-of-Dam-Removal-Costs-GSS-Engineering-Consultants-Ltd.-7.pdf.

Grant, G. E., & Lewis, S. L. (2014). The Remains of the Dam: What Have We Learned from 15 Years of US Dam Removals? Engineering Geology for Society and Territory - Volume 3, 31–35. https://doi.org/10.1007/978-3-319-09054-2_7

Grill, G., Lehner, B., Lumsdon, A. E., MacDonald, G. K., Zarfl, C., & Liermann, C. R. (2015). An index-based framework for assessing patterns and trends in river fragmentation and flow regulation by global dams at multiple scales. Environmental Research Letters, 10(1). https://iopscience.iop.org/article/10.1088/1748-9326/10/1/015001/meta.

Guarino, J. (2013). Tribal advocacy and the art of dam removal: The Lower Elwha Klallam and the Elwha dams. American Indian Law Journal, 2(1), 114–145.

Hanasaki, N., Kanae, S., & Oki, T. (2006). A reservoir operation scheme for global river routing models. Journal of Hydrology, 327(1–2), 22–41. https://doi.org/10.1016/j.jhydrol.2005.11.011

Hansen, H. H., Forzono, E., Grams, A., Ohlman, L., Ruskamp, C., Pegg, M. A., & Pope, K. L. (2019). Exit here: strategies for dealing with aging dams and reservoirs. Aquatic Sciences, 82(1). https://doi.org/10.1007/s00027-019-0679-3

Harsha, J., (2019). Ageing Large Dams and Future Water Crisis [Review of Ageing Large Dams and Future Water Crisis]. Economic & Political Weekly, 26–27, 37–42.

He, X.Y., Wang, Z.Y., Huang, J.C. (2008). Temporal and spatial distribution of dam failure events in China. International Journal of Sediment Research, 23, 398-405

Headwater Economics. (2016). Dam Removal: Case Studies on the Fiscal, Economic, Social, and Environmental Benefits of Dam Removal, http://headwaterseconomics.org/economic-development/local-studies/dam-removal-case-studies

Ho, M., Lall, U., Allaire, M., Devineni, N., Kwon, H. H., Pal, I., Raff, D., & Wegner, D. (2017). The future role of dams in the United States of America. Water Resources Research, 53(2), 982–998. https://doi.org/10.1002/2016wr019905

Hoyano, H. (2004). The Struggle over the Arase Dam: Japan's First Dam Removal Begins. The Asia-Pacific Journal - Japan Focus, 2(8), 1–4. Retrieved August 6, 2004, from https://apjjf.org/-Hoyano-Hatsuko/2074/article.html

Hydro Review, (2020). Your Dedicated Source of Hydropower News. (n.d.). Hydro Review. https://www.hydroreview.com/2017/02/22/dealing-with-sediment-effects-on-dams-and-hydropower-generation/

ICOLD WRD (International Commission on Large Dams World Register of Dams). (2020). World Register of Dams: General Synthesis. Accessed October 01, 2020 at https://www.icold-cigb.org/GB/world_register/general_synthesis.asp

IFTR (Independent Forensic Team Report). (2018). Independent forensic team report final 01/05/18. Issue. Retrieved October 13, 2020, from http://issuu.com/asdso/docs/independent_forensic_team_report_fi?e=16355058/57087615

Jackson, D. C., & Marmulla G. (2001). The influence of dams on river fisheries. FAO Fisheries Technical Paper 419 (2001): 1-44. Available from:
http://www.friendsofmerrymeetingbay.org/cybrary/pages/20010000_UN_FAO_Dams,%20fish%20and%20fisheries.pdf#page=6

Jayathilaka, S., & Munasinghe, A. (2014). Dam Safety to Ensure the Public Safety. Dam Safety and Water Resources Planning Bulletin. Columbo: Sri Lanka.

Jørgensen, D., & Renöfält, B. M. (2013). Damned If You Do, Dammed If You Don't: Debates on Dam Removal in the Swedish Media. Ecology and Society, 18(1). https://doi.org/10.5751/es-05364-180118

Kantoush, S.A. & Sumi, T. (2017). The ageing of Japan's dams: Innovative technologies for improving dams water and sediment management. in River Sedimentation. Wieprecht et al. (Eds). 2017. Taylor & Francis Group, London. ISBN 978-1-138-02945-3.

Kim, B.S., Chang, I.J., Sung, J.H., & Han, H.J. (2016). Projection in Future Drought Hazard of South Korea Based on RCP Climate Change Scenario 8.5 Using SPEI. Advances in Meteorology. https://doi.org/10.1155/2016/4148710

Kondolf, G. M., Gao, Y., Annandale, G. W., Morris, G. L., Jiang, E., Zhang, J., Cao, Y., Carling, P., Fu, K., Guo, Q., Hotchkiss, R., Peteuil, C., Sumi, T., Wang, H.-W., Wang, Z., Wei, Z., Wu, B., Wu, C., & Yang, C. T. (2014). Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents. Earth's Future, 2(5), 256–280. https://doi.org/10.1002/2013ef000184

Kotval, Z., & Mullin, J. (2009). The Revitalization of New England's Small Town Mills: Breathing New Life into Old Places. Local Economy. 55. Retrieved from https://scholarworks.umass.edu/larp_faculty_pubs/55

Lehner, B., Liermann, C. R., Revenga, C., Vörösmarty, C., Fekete, B., Crouzet, P., Döll, P., Endejan, M., Frenken, K., Magome, J., Nilsson, C., Robertson, J. C., Rödel, R., Sindorf, N., & Wisser, D. (2011). High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. Frontiers in Ecology and the Environment, 9(9), 494–502. https://doi.org/10.1890/100125

Lejon, A. G. C., Renöfält, B. M., & Nilsson, C. (2009). Conflicts Associated with Dam Removal in Sweden. Ecology and Society, 14(2). https://www.jstor.org/stable/26268322

Leslie, J. (2016). "One of Africa's Largest Dams is Falling Apart". The New Yorker. Accessed July 22, 2020 at https://www.newyorker.com/tech/elements/one-of-africas-biggest-dams-is-falling-apart

Liu, A. (2017). New Design of Dams on Zambezi River. Proceedings of the 2017 5th International Conference on Machinery, Materials and Computing Technology (ICMMCT 2017). https://doi.org/10.2991/icmmct-17.2017.102
Magilligan, F. J., Sneddon, C. S., & Fox, C. A. (2017). The Social, Historical, and Institutional Contingencies of Dam Removal. Environmental Management, 59(6), 982–994. https://doi.org/10.1007/s00267-017-0835-2

Mahmood, K. (1987). Reservoir sedimentation: impact, extent, and mitigation. The World Bank. https://documents.worldbank.org/en/publication/documents-reports/documentdetail/888541468762328736/reservoir-sedimentation-impact-extent-and-mitigation
Mapes, L.V. (2016). Elwha: Roaring back to life. (2011). The Seattle Times. http://projects.seattletimes.com/2016/elwha/

Massachusetts Government, USA. (2019). Economic Benefits from Aquatic Ecological Restoration Projects in Massachusetts, https://www.mass.gov/doc/economic-benefits-from-aquatic-ecological-restoration-projects-in-massachusetts-summary-of/download

McCully, P. (1996). Getting Old: Dam Aging and Decommissioning. International Rivers. Accessed July 8, 2018 at https://www.internationalrivers.org/getting-old-dam-aging-and-decommissioning

Michigan river Partnership. (2007). The Growing Crisis of Aging Dams: Policy Considerations and Recommendations for Michigan Policy Makers. PSC. https://publicsectorconsultants.com/2007/04/01/the-growing-crisis-of-aging-dams-policy-considerations-and-recommendations-for-michigan-policy-makers/

Milligan, B. (2013). Massively Redistributed in Space and Time. Free Association Design. https://freeassociationdesign.wordpress.com/2013/09/02/massively-

Mission. (2012) Clean Water. (n.d.). Web.Mit.Edu. Retrieved November 21, 2020, from http://web.mit.edu/12.000/www/m2012/finalwebsite/problem/dams.shtml

Mulligan, M., Saenz-Cruz, L., van Soesbergen, A., Smith, V.T., & Zurita, L., (2009). Global dams database and geowiki. Version 1. http://geodata.policysupport.org/dams. Version 1

National Park Service. (2015). "Removal of the Glines Canyon Dam". Accessed at https://www.nps.gov/olym/learn/nature/removal-of-the-glines-canyon-dam.htm

National Park Service. (2019). Dam Removal. Accessed at https://www.nps.gov/olym/learn/nature/dam-removal.htm
Nicholls, S., & Crompton, J. L. (2017). The effect of rivers, streams, and canals on property values. River Research and Applications, 33(9), 1377–1386. https://doi.org/10.1002/rra.3197

Nijhuis, M. (2014). World's Largest Dam Removal Unleashes US River After Century of Electric Production. (2014, August 27). National Geographic News. https://www.nationalgeographic.com/news/2014/8/140826-elwha-river-dam-removal-salmon-science-olympic/

Ohno, T. (2019). Contextual Factors Affecting the Modes of Interaction in Governance: The Case of Dam Removal in Japan. Interactive Approaches to Water Governance in Asia, 55–76. https://doi.org/10.1007/978-981-13-2399-7_3

Oldham, K. (2009). Decommissioning dams - costs and trends - International Water Power. (n.d.). Www.Waterpowermagazine.Com. Retrieved October 14, 2020, from https://www.waterpowermagazine.com/features/featuredecommissioning-dams-costs-and-trends

Owusu, A. G., Mul, M., van der Zaag, P., & Slinger, J. (2020). Re-operating dams for environmental flows: From recommendation to practice. River Research and Applications. https://doi.org/10.1002/rra.3624

Payne, J. T., Wood, A. W., Hamlet, A. F., Palmer, R. N., & Lettenmaier, D. P. (2004). Mitigating the Effects of Climate Change on the Water Resources of the Columbia River Basin. Climatic Change, 62(1–3), 233–256. https://doi.org/10.1023/b:clim.0000013694.18154.d6

Provencher, B., Sarakinos, H., & Meyer, T. (2008). Does Small Dam Removal Affect Local Property Values? An Empirical Analysis. Contemporary Economic Policy, 26(2), 187–197. https://doi.org/10.1111/j.1465-7287.2008.00107.x

Quinn, E. M. (2000). Dam removal: a tool for restoring riverine ecosystems. https://conservancy.umn.edu/bitstream/handle/11299/59446/1/5.1.Quinn.pdf.

Rao, S. (2018). Explainer: Why Kerala and Tamil Nadu have fought for decades over the Mullaperiyar dam. Scroll.In. Retrieved October 18, 2020, from https://scroll.in/article/864687/explainer-why-kerala-and-tamil-nadu-have-fought-for-decades-over-the-mullaperiyar-dam

Rayner, T. (2013). Dam it all? River futures in northern Australia. The Conversation. Retrieved October 12, 2020, from https://theconversation.com/dam-it-all-river-futures-in-northern-australia-17131

Regan, P.J. (2010). Dams & Civil Structures: An Examination of Dam Failures vs. Age of Dams. Hydro Review. Accessed July 10, 2018 at https://www.hydroworld.com/articles/hr/print/volume-29/issue- 4/articles/dams--civil-structures.html

Rowland, J., & DeGood, K. (2017). What the Oroville Dam Disaster Says About America's Aging Infrastructure. (n.d.). Fortune. Retrieved October 17, 2020, from https://fortune.com/2017/02/18/oroville-dam-%20california-flood/

Roy, S. G., Uchida, E., de Souza, S. P., Blachly, B., Fox, E., Gardner, K., Gold, A. J., Jansujwicz, J., Klein, S., McGreavy, B., Mo, W., Smith, S. M. C., Vogler, E., Wilson, K., Zydlewski, J., & Hart, D. (2018). A multiscale approach to balance trade-offs among dam infrastructure, river restoration, and cost. Proceedings of the National Academy of Sciences, 115(47), 12069–12074. https://doi.org/10.1073/pnas.1807437115

SANCOLD (South African Register of Large Dams). (2020). Accessed July 17, 2020 at http://www.sancold.org.za/index.php/about-dams/register-of-large-dams

Sarakinos, H. & Johnson, S. E. (2002). Social Perspectives on Dam Removal [Review of Social Perspectives on Dam Removal]. In, W. L. Graf (Ed.), Dam Removal Research (Issue 9717592-4-3, pp. 40–54). The H. John Heinz III Center for Science, Economics and the Environment. http://www.riversimulator.org/Resources/NGO/DamResearchFullReport.pdf

Scudder, T., & Habarad, J. (1991). Local Responses to Involuntary Relocation and Development in the Zambian portion of the Middle Zambezi Valley. Migrants in Agricultural Development, 178–205. https://doi.org/10.1007/978-1-349-11830-4_12

Shah, Z., & Kumar, M. D. (2008). In the Midst of the Large Dam Controversy: Objectives, Criteria for Assessing Large Water Storages in the Developing World. Water Resources Management, 22(12), 1799–1824. https://doi.org/10.1007/s11269-008-9254-8

Sumi, T., Okano, M., & Takata, Y. (2004). Reservoir Sediment Management with Bypass Tunnels in Japan [Review of Reservoir Sediment Management with Bypass Tunnels in Japan]. In Proceedings of the Ninth International Symposium on River Sedimentation (pp. 1036–1043). https://www.researchgate.net/publication/228511069_Reservoir_sedimentation_management_with_bypass_tunnels_in_Japan

Tanabe, N. (2014). Arase Dam: Japan's First Dam Removal Project Underway-JFS Japan for Sustainability. (n.d.). JFS Japan for Sustainability. JFS Newsletter No.147, Retrieved October 24, 2020, from https://www.japanfs.org/en/news/archives/news_id035105.html

Thatheyus, A., Dhanaseeli, D. P. , & Vanitha, P. (2013). Inter - State Dispute over Water and Safety in India: The Mullaperiyar Dam, a Historical Perspective. American Journal of Water Resources, 1(2), 10-19. DOI: 10.12691/ajwr-1-2-2

The State of Victoria. (2016). Decommissioning dams, A guide for dam owners (pp. 1–40) [Review of Decommissioning dams, A guide for dam owners]. The State of Victoria Department of Environment, Land, Water and Planning. https://www.water.vic.gov.au/__data/assets/pdf_file/0018/54243/Decommissioning-dams-A-guide-for-dam-owners.pdf

The World Bank. (2015). The Kariba Dam Rehabilitation Project: Fact Sheet. The World Bank. Available from: https://www.worldbank.org/en/region/afr/brief/the-kariba-dam-rehabilitation-project-fact-sheet.

United Nations. (2017). World population projected to reach 9.8 billion in 2050, and 11.2 billion in 2100 | UN DESA | United Nations Department of Economic and Social Affairs. UN DESA | United Nations Department of Economic and Social Affairs. https://www.un.org/development/desa/en/news/population/world-population-prospects-2017.html
USBR (United States Bureau of Reclamation). (2015) Dam failure and flood event case history compilation. RECM – Reclamation Consequence Estimating Methodology. Available from: https://www.usbr.gov/ssle/damsafety/documents/RCEM-CaseHistories2015.pdf.

USSD (United States Society on Dams). (2010). The Aging of Embankment Dams. United States Society on Dams. Accessed June 30, 2018 at https://www.ussdams.org/wp-content/uploads/2016/05/aging.pdf

USSD (United States Society on Dams). (2015). Guidelines for Dam Decommissioning Process. Accessed June 30, 2018 at https://www.ussdams.org/wp-content/uploads/2016/05/15Decommissioning.pdf

Vartabedian, R. (2018). Human error played a role in Oroville Dam spillway failure, report finds. Los Angeles Times. Accessed July 17, 2020 at https://www.sandiegouniontribune.com/news/california/la-me-oroville-investigation-report-20180105-story.html?00000168-c155-df9b-adfc-cb55faa70000-p=40

Vörösmarty, C. J., Meybeck, M., Fekete, B., Sharma, K., Green, P., & Syvitski, J. P. M. (2003). Anthropogenic sediment retention: major global impact from registered river impoundments. Global and Planetary Change, 39(1–2), 169–190. https://doi.org/10.1016/s0921-8181(03)00023-7

Wang, Z., & Hu, C. (2009). Strategies for managing reservoir sedimentation. International Journal of Sediment Research, 24(4), 369–384. https://doi.org/10.1016/s1001-6279(10)60011-x

Wan-Wendner, R. (2018). Aging concrete structures: a review of mechanics and concepts. Die Bodenkultur, 69, 175-199. doi: 10.2478/boku-2018-0015

Warrick, J. A., Bountry, J. A., East, A. E., Magirl, C. S., Randle, T. J., Gelfenbaum, G., Ritchie, A. C., Pess, G. R., Leung, V., & Duda, J. J. (2015). Large-scale dam removal on the Elwha River, Washington, USA: Source-to-sink sediment budget and synthesis. Geomorphology, 246, 729–750. https://doi.org/10.1016/j.geomorph.2015.01.010

White, A. (2016). Mactaquac dam to be kept going until 2068, NB Power says | CBC News. (n.d.). CBC. Retrieved October 24, 2020, from https://www.cbc.ca/news/canada/new-brunswick/mactaquac-nbpower-dam-future-option-1.3903621

Whitelaw, E., & MacMullan, E. (2002). A framework for estimating the costs and benefits of dam removal. BioScience, 52:724–730. https://doi.org/10.1641/0006-3568(2002)052[0724:AFFETC]2.0.CO;2

Wieland, M., & Mueller, R. (2009). Dam safety, emergency action plans, and water alarm systems, International. Journal of Water Power and Dam Construction, 34-38,

Wieland, M. (2010). Life-span of storage dams. International Water Power and Dam Construction International Water Power. (n.d.). Www.Waterpowermagazine.Com. http://www.waterpowermagazine.com

Witze, A. (2014). Dam demolition lets the Elwha River run free. (2014, December 30). Science News. https://www.sciencenews.org/article/dam-demolition-lets-elwha-river-run-free

WCD (World Commission on Dams). (2000). Dams and Development. A New Framework for Decision-making. The Report of the World Commission on Dams. Earthscan Publications: London.

WWAP (United Nations World Water Assessment Programme)/UN-Water. (2017), Fact 6: Hydropower | United Nations Educational, Scientific and Cultural Organization. (n.d.). Www.Unesco.Org. Retrieved October 23, 2020, from http://www.unesco.org/new/en/natural-sciences/environment/water/wwap/facts-and-figures/all-facts-wwdr3/fact-6-hydropower/

WWAP (United Nations World Water Assessment Programme)/UN-Water. (2018). The United Nations World Water Development Report 2018: Nature-Based Solutions for Water. Paris, UNESCO.

Wyrick, J. R., Rischman, B. A., Burke, C. A., McGee, C., & Williams, C. (2009). Using hydraulic modeling to address social impacts of small dam removals in southern New Jersey. Journal of Environmental Management, 90, S270–S278. https://doi.org/10.1016/j.jenvman.2008.07.027

Xin, G. (2012). French Dam Removal Opens Way for Atlantic Salmon. International Rivers. Accessed July 24 at https://www.internationalrivers.org/resources/french-dam-removal-opens-way-for-atlantic-salmon-

Yang, M., Qian, X., Zhang, Y., Sheng, J., Shen, D., & Ge, Y. (2011). Spatial Multicriteria Decision Analysis of Flood Risks in Aging-Dam Management in China: A Framework and Case Study. International Journal of Environmental Research and Public Health, 8(5), 1368–1387. https://doi.org/10.3390/ijerph8051368

Yildiz, D., Yildiz, D., & Gunes, M. S. (2016). Africa in Motion: Why the rush to build Grand Renaissance and Inga 3 Dams in Africa? IARJSET, 3(9), 1–6. https://doi.org/10.17148/iarjset.2016.3901

Young, S. M., & Ishiga, H. (2014). Environmental change of the fluvial-estuary system in relation to Arase Dam removal of the Yatsushiro tidal flat, SW Kyushu, Japan. Environmental Earth Sciences, 72(7), 2301–2314. https://doi.org/10.1007/s12665-014-3139-3

Zimmermann, F. B. (2019) Brazil's Latest Dam Disaster: Human Loss and Environmental Degradation. Australian Institute of International Affairs. Available from: http://www.internationalaffairs.org.au/australianoutlook/brazil-dam-disaster/

Zarfl, C., Lumsdon, A. E., Berlekamp, J., Tydecks, L., & Tockner, K. (2014). A global boom in hydropower dam construction. Aquatic Sciences, 77(1), 161–170. https://doi.org/10.1007/s00027-014-0377-0

Zhang, L. M., Xu, Y., & Jia, J. S. (2009). Analysis of earth dam failures: A database approach. Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards, 3(3), 184–189. https://doi.org/10.1080/17499510902831759

Zhao, G., & Gao, H. (2018). Automatic Correction of Contaminated Images for Assessment of Reservoir Surface Area Dynamics. Geophysical Research Letters. https://doi.org/10.1029/2018gl078343

Zhou, T., Nijssen, B., Gao, H., & Lettenmaier, D. P. (2015). The Contribution of Reservoirs to Global Land Surface Water Storage Variations. Journal of Hydrometeorology, 17(1), 309–325. https://doi.org/10.1175/jhm-d-15-0002.1

Zamarrón-Mieza, I., Yepes, V., & Moreno-Jiménez, J. M. (2017). A systematic review of application of multi-criteria decision analysis for aging-dam management. Journal of Cleaner Production, 147, 217–230. https://doi.org/10.1016/j.jclepro.2017.01.092

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