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Assessing Global Trends in the Status, Causes, and Implications of Ageing Water Storage Infrastructure

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ABSTRACT

Water storage infrastructure, especially dams, have long been used to regulate variable river flow for purposes such as irrigation and hydroelectricity generation around the world. As large dams around the world age, operational costs and the risk of collapse increase, while overall efficiency declines. This paper provides an overview of global patterns in the ageing of large dams, using GIS in conjunction with the ICOLD database to provide a novel visual representation of these conditions. It also identifies major causes and consequences of ageing, such as sedimentation, maintenance, and ownership, and considers the impacts of each. The paper also explores the emerging trend of decommissioning dams that have become either unsafe or obsolete, and explores the motivations and barriers surrounding this practice.

Ageing dams are a critical yet frequently overlooked infrastructure issue faced by many countries around the world. As ever larger dams are designed to meet growing demand for water and electricity, it is important to learn from the lessons of the past and present to prepare for the future. This paper finds that while the age of a dam is a useful guideline as to its continued viability, each should be considered in its own context; the environmental conditions a dam faces and the maintenance that it receives are central in determining its safety and longevity.

Keywords: Large dams, Ageing, ICOLD, Infrastructure

I. INTRODUCTION

Freshwater is unevenly distributed around the world geographically: certain regions enjoy an abundance, while others face extreme scarcity. A temporal imbalance also exists, as floods are followed by low flow periods. For thousands of years, humans have sought to stabilize the flow of water upon which they depend through the construction of dams. These structures, while serving multiple functions, all follow the same basic principle: the impoundment of a waterway via the construction of a barrier. Upstream water levels consequently rise, forming an artificial reservoir, and in doing so alter the surrounding landscape (*USSD, 2010*). In the last century alone, thousands of large dams have been built around the world to regulate river flow for irrigation, hydropower, and flood control, with many performing multiple functions.

Dams are typically constructed using materials such as excavated earth and rocks, masonry, or concrete (*USSD, 2010*). Various designs exist, including embankment dams, arch dams, buttress dams, and gravity dams, among others. The type of dam depends on several context-specific factors, including geology, intended function, time of construction, and availability of materials (*USSD, 2015*). This paper focuses specifically on the subset of dams designated "large dams", which ICOLD (International Commission on Large Dams) defines 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, 2011*). ICOLD's current World Register comprises 59,071 large dams that satisfy these criteria, although this is not necessarily a complete list (*ICOLD, 2018*). Together, they store over

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16,200km^3, or approximately 16% of all surface water on Earth. The leading functions of these structures are, in order, irrigation, hydropower, water supply, flood control, and recreation (*ICOLD, 2018*).

Like all infrastructure, large dams are constructed with a design life, and as they age, they become more vulnerable to failure and more expensive to maintain. Thus, the ageing of these structures not only poses a threat to public safety, but also threatens potentially dramatic impacts for both the economy and the environment. Dam ageing is gradually emerging as a global development issue but has not yet been comprehensively assessed, a gap this paper aims to start addressing. It identifies key components of the issue of ageing water storage infrastructure, including contributing factors and consequences and discusses the costs and merits of potential interventions. It then provides a geographic overview of the state of large dams in various parts of the world, identifying overarching trends.

II. CAUSES AND IMPLICATIONS OF AGEING WATER STORAGE INFRASTRUCTURE

In much of the developed world, construction of dams, including large dams surged in the mid-20th century. This construction boom peaked in the 1960s/1970s, as seen in Figure 1, with only about 700 large dams existing worldwide prior to 1900 (*Wang et al., 2014*). In general, dams constructed between 1930-1970 have a design life of approximately 50-100 years (*Ho et al., 2017*). Consequently, a considerable number of large dams around the world have reached or are fast approaching the lower bound of their anticipated lifespan. However, it is crucial to recognize that not all dams age at an equal rate; two dams constructed in the same year could have very different effective lifespans, based on features of their respective contexts discussed below. Nonetheless, age remains the most widely available metric by which to compare these structures. Additionally, as dams age, there are several implications that must be considered.

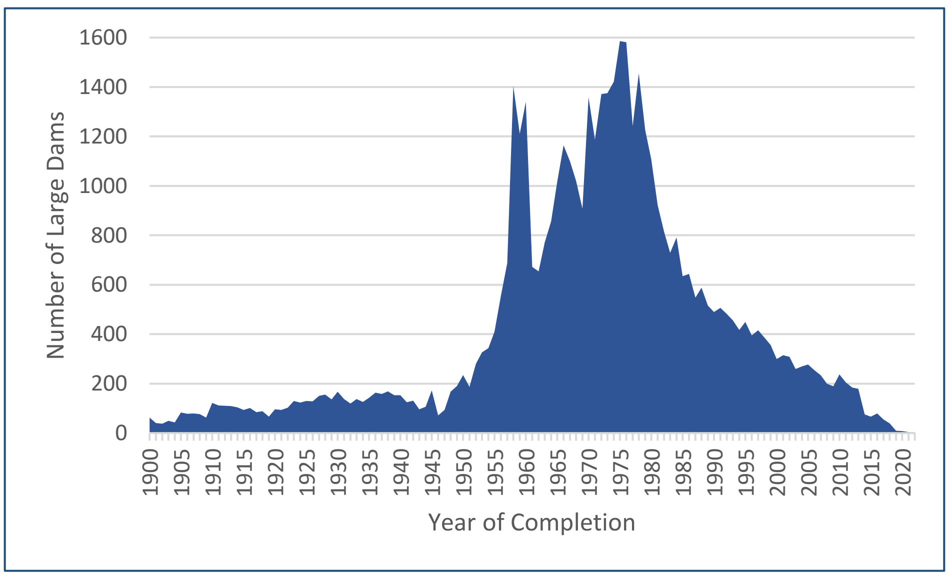

Figure 1. Construction of large dams since 1900 (Data Source: ICOLD Database)

i) PUBLIC SAFETY

Most large dams, even if structurally sound, are considered to be "high hazard" forms of infrastructure because the potential consequences of failure likely include the loss of human life (*USSD, 2015*), while also triggering forced displacement and the destruction of livelihoods. This was seen in the collapse of a saddle dam in Laos earlier this year, killing 40 and displacing over 6,500 others (*Olarn et al., 2018*). However, these figures pale in comparison to the effects of the Banqiao Dam failure in China in 1972 during a severe flood, resulting in the deaths of 171,000 people, the most of any dam failure in history (*Pappas, 2017*). Continued development downstream of dams also elevates the magnitude of the consequences of dam failure, which becomes more likely as dams age.

Dam failures, whether from seepage, overtopping, erosion, or structural failure, frequently result from poor design or construction, lack of maintenance, or operational mismanagement. (*FEMA*, *2017*). Regan (*2010*) found that a majority of public safety incidents occur in the first five years of a dam's operation, with earthen dams being the most susceptible to collapse, and gravity dams the least likely. While the number of incidents is small relative to the total number of dams, apart from initial failure, half of incidents occur on dams over 50 years old. In other words, apart from serious issues that are quickly made apparent, it is older dams that are more prone to failure.

ii) MAINTENANCE COSTS: A GROWING EXPENSE

As dams age, their upkeep generally becomes increasingly expensive. Maintaining dams requires not only regular inspection, but also repairs, which as an example leads the operating costs of hydropower dams to increase substantially after 25-35 years according a study of several hundred North American dams (*McCully*, *1996*). Maintenance is essential to longevity, and most dam failures are thought to have been preventable if they had been properly maintained and regularly inspected (*USSD*, *2010*). In some cases, particularly in the United States, rising maintenance costs have led privately owned dams to be abandoned, creating the risk of collapse without warning (*Alvi*, *2018*). Large dams pose an additional challenge, as interior deficiencies are more difficult to identify (*Wielman*, *2010*). That being said, it stands to reason that the costs of prevention through inspection and maintenance are immensely preferable to the costs of dam failure that could have conceivably been avoided.

iii) SEDIMENTATION: DECLINING EFFECTIVENESS

Dams not only impound the water in the rivers that they span, they also interrupt the downstream flow of sediment, leading it to collect in reservoirs. The storage capacity of dams subsequently declines over time as sediment accumulates, decreasing their effectiveness. Sumi et al. (*2004*) estimated total global annual reservoir capacity lost due to sedimentation to be $31km^3$, a rate that would see global capacity halved by 2100 if these rates persisted. It must also be noted that sedimentation rates vary widely according to factors such as elevation change and flow velocity, with distinct geographic trends (*Kondolf et al.*, *2014*). This in turn means that some dams are effectively ageing much more quickly than others. Sedimentation has been identified as a significant issue in several parts of the world, including Japan, Spain, the United States, and in the Nile River watershed (*Milligan*, 2013). More recently, some dams are designed with sediment bypasses, in an effort to minimize this impact (*Sumi et al.*, *2004*).

iv) DAM DECOMMISSIONING: BEYOND REPAIR

In some cases, the structural integrity of a dam becomes compromised to the point that it is simply too dangerous to remain standing, while in other situations its functional ability has become redundant. Under these circumstances, decommissioning, or removal of the dam can be the best option. Decommissioning is a relatively recent trend, as large numbers of dams begin to reach the end of their prescribed design life. Decommissioning is also increasingly supported by environmental groups, in an effort to restore river ecosystems, especially for sediment flow and fish migration (*USSD*, *2015*).

There are several decisions to be made when decommissioning a dam, the most important being whether to undertake a partial or complete removal (*USSD*, *2015*). In either case, decommissioning is typically an expensive and complicated procedure, often subject to lengthy regulatory approvals that can take years to resolve (*USSD*, *2010*). Many factors affect the cost of removal, but it is strongly correlated with dam height in particular (*Wielman*, *2010*). Dam removal can also be controversial, as the function it previously performed is lost, whether power generation or supporting irrigation (*Levesque & Yamazaki*, *2018*). In addition, the resulting rapid outflows of sediment that had been sequestered in the reservoir could prove detrimental to downstream waterways, ecosystems, and infrastructure such as bridges. At the same time, there has been promising evidence of a river's ability to "bounce back" relatively quickly following the removal of a dam (*Howard*, *2016; Access Science*, *2015*), yielding an overall positive environmental impact. As countries around the world grapple with the issue of ageing water storage infrastructure, decommissioning is therefore treated both as a priority and a last resort, depending on the value attributed to these environmental and economic impacts in different situations.

III. GLOBAL PATTERNS IN THE AGEING OF LARGE DAMS:

The world's large dams are heavily concentrated in just a handful of countries, as illustrated in Table 1. China and the United States together represent 56% of all large dams, while the top ten countries account for more than 80% of the global total. Recognizing the impacts of ageing dams for these countries is therefore especially critical.

Table 1. Large Dams by Country (*ICOLD, 2018)*

Country	Number of Large Dams
China	23 841
United States	9 265
India	5 100
Japan	3 118
Brazil	1 364
Korea (Rep. of)	1 338
Canada	1 169
South Africa	1 112
Spain	1 063
Albania	1 008
Turkey	974

The following sections briefly highlight the impacts of ageing large dams in various regions of the world. As seen in Figure 2 below, the median age of large dams is higher in much of Europe, as well as in the United States, between 50-100 years old. The United Kingdom has the earliest average date of completion, in 1910. Thus, dams in these countries are reaching and exceeding their design life. The average age in many other parts of the world is lower, reflecting the global dam-building boom in the 1970s. Ageing dams have therefore not yet posed such a pressing problem in these areas. Finally, it can be seen that dam-building has accelerated in parts of Asia and the Middle East in recent years. The more recent construction in these areas presents an opportunity to implement lessons learned in other parts of the world. It must be acknowledged, however, that this depiction represents only one dimension of the challenge posed by ageing large dams. Making policy decisions based solely on a national average is an oversimplification in that not only can two countries with the same average face very different situations, but also in that it fails to account for considerations discussed previously such as sedimentation rates or maintenance standards. Age should instead be viewed as useful proxy measure when evaluating the direct impacts of these other factors.

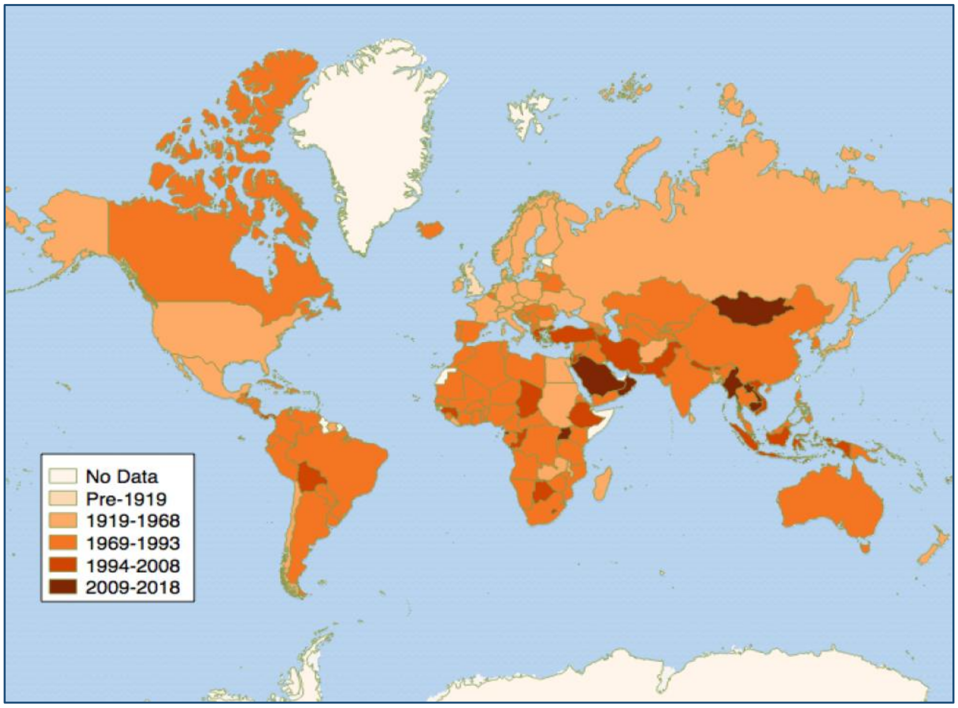

Figure 2. Average Age of Large Dams by Country

Regarding methodology, Figures 2-4 were developed using the ICOLD database. Any incomplete entries in the ICOLD database, specifically those dams lacking "Year of Completion" were omitted from analysis. A small number of dam entries listed expected completion dates beyond the present day, up to 2022, and were included in the analysis. Additionally, the ICOLD continental classification was adhered to, with the exception of Russia, Georgia, and Azerbaijan were included in Europe for the purposes of Figures 3 and 4. As Figure 3 indicates, the rate of construction of large dams has changed dramatically over the past century both on aggregate and in different parts of the world, reflecting the median national ages shown in Figure 2. The median was chosen as the measure of central tendency to minimize the influence of dramatic outliers; for example, dams that are more than 1500 years old. Figure 2 was created using QGIS 2.8 using a base map from the OpenLayers plugin.

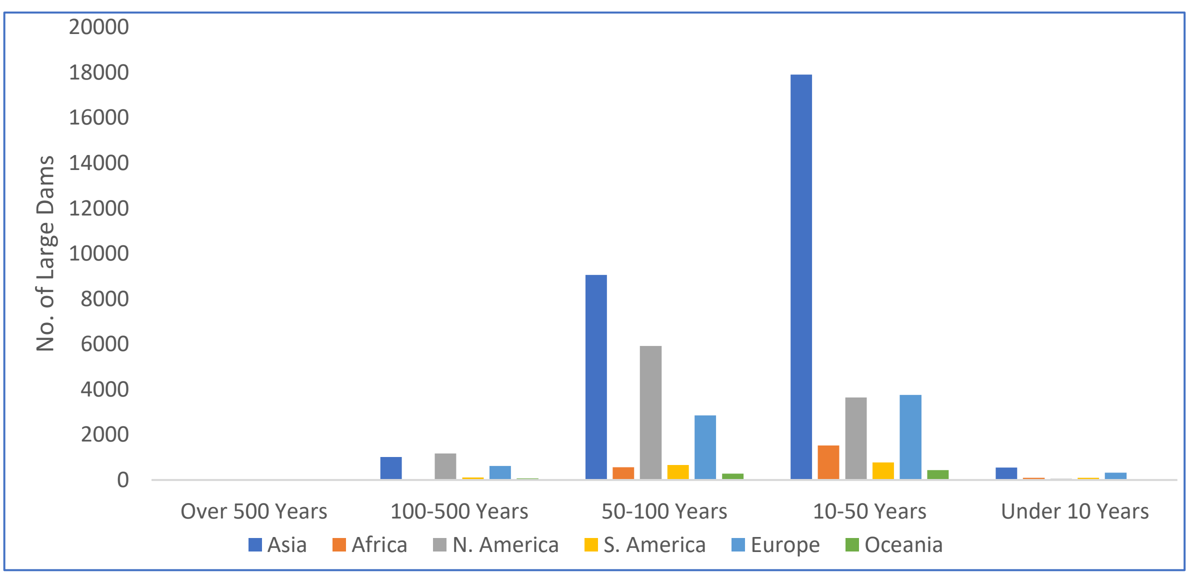

Figure 3. Age of Large Dams by Continent

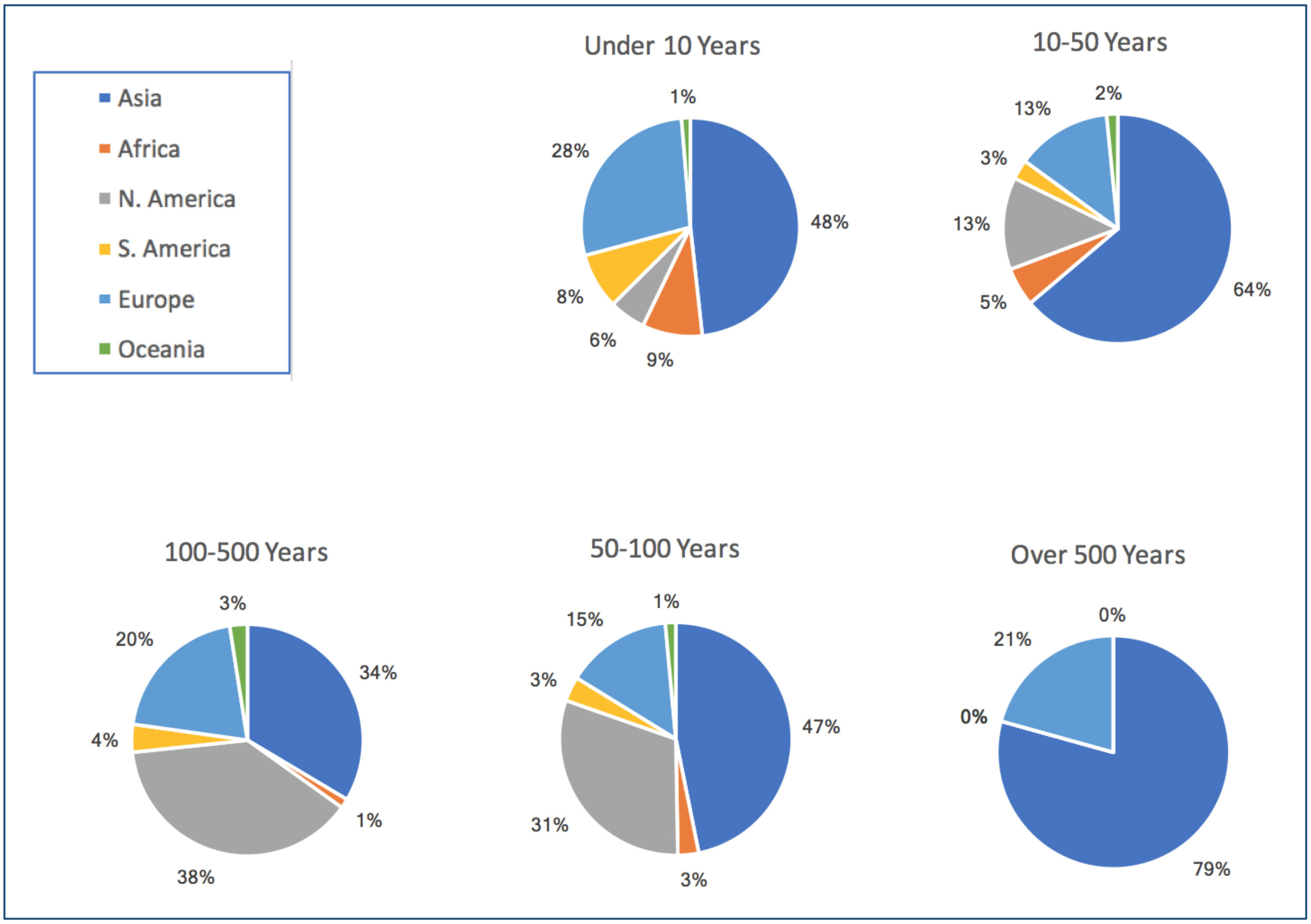

Figure 4. Regional Share of Large Dam Construction by Age

Figure 4, generated using information from the ICOLD database, further illustrates how the relative regional construction of large dams has varied over time. Of particular interest is the decline of the North American share, the corresponding surge in Asia in the past 50 years. The Figure also reveals an increasing relative share in both Africa and South America, while the resurgence in Europe is driven by Turkey and Eastern European nations; dam-building in Western Europe has almost stopped completely, with the notable exception of Spain. The following sections offer select highlights from each of these geographic regions.

i) NORTH AMERICA

Although Canada and Mexico are both among global leaders with regard to large dams (see Table 1), the problem of ageing water storage infrastructure is most prominent in the United States. Its more than 9,000 large dams are a small fraction of over 90,000 dams across the country, 70% of which will be over 50 years old by 2025 (*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, calling for an estimated $64 billion USD to adequately refurbish the nation's dams (*ASCE, 2017*). The burgeoning crisis was accentuated by the Oroville dam incident in California in February 2017, where the partial collapse of a spillway forced the evacuation of nearly 200,000 people. This 50-year-old dam, the highest in the United States at 235m, is critical to California's water supply and repairs are estimated at $500 million USD (*Vartabedian, 2018*). The incident has been blamed on human error, specifically inadequate inspection and maintenance (IFTR, 2018). In addition, a majority of dams in the United States are privately owned, yet no policy exists to direct funding for non-federal dams. This leaves owners fully responsible for the costs of upkeep (*Rowland & DeGood, 2017*), leading many dams to be left abandoned due to unmanageable costs (*Michigan, 2007*).

In combatting this issue, the USA has subsequently become a leader in dam decommissioning, with over 1,200 dams have been removed to date. That being said, these are primarily small and privately-owned rather than ICOLD-designated large dams (*Oldham, 2009*). One exception is the 64m-high Glines Canyon dam on the Elwha river, which was completely removed in 2014 to restore sediment outflow and rejuvenate fish populations (*Howard, 2016*). However, as is typical of most decommissioned hydropower dams, it had a relatively small hydropower capacity, while many others were no longer in service at the time of removal (*Oldham, 2009*).

ii) EUROPE

As in the United States, many European large dams already exceed the lower 50-year design life standard. In many parts of the continent, the construction of dams has effectively ceased, primarily because few waterways remain unimpeded. One notable exception is in Eastern Europe and Turkey, where the rate of dam building, particularly for hydroelectricity is among the highest in the world (*Zarfl et al., 2015*). There is also a growing call in Europe for the removal of dams and protection of remaining unimpeded waterways. In general, this is not motivated by a public safety concern, but is rather based on environmental grounds, as various groups urge the restoration of migratory routes for fish (*ERN, n.d.*).

One such case is the innovative partial removal of the Poutès Dam in France. Constructed during World War II, the 17m-high dam 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. Key changes include lowering the height of the dam to 4m, and constructing fish-ways to restore the salmon migration routes (*Xin, 2012*). Another innovation will allow sediment to periodically pass downstream. This work is to begin in 2019 and will cost approximately 10 million Euros (*ERN, n.d.*).

iii) ASIA

As Table 1 shows, each of China, India, Japan and the Republic of Korea are among the countries with the greatest number of large dams in the world. China alone represents almost 40% of the world's large dams, and also has some of the oldest. However, as of 1949, it had only 8 large dams, preceding a period of rapid growth that continues today (*Nilsson, 2009*). This means that most dams in China have not yet exceeded the 50-year age threshold, and the focus remains on continued construction, with projects such as the Three Gorges Dam on the Yangtze River. As mentioned previously strictly using age guidelines should be treated with caution, particularly as China has some of the highest sedimentation rates in the world, losing soil 57 times faster than it can be replaced (*Milligan, 2013*). This means that the dams are likely to decline in efficiency much more rapidly or will require significant maintenance investments to remain operational, although China has also proven innovative in sediment management (*Kondolf et al., 2014*).

Elsewhere in Asia, the current rate of dam construction in India is among the world's highest (*Zarfl et al., 2015*). In contrast, Japan and the Republic of Korea have limited opportunity for future water storage development, but 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 ageing water storage infrastructure, an emphasis has been placed on countering sedimentation that render the dams less effective (*Kantoush & Sumi, 2017*) to extend their design life and reduce downstream impacts.

vi) AFRICA

Dam building in Africa accelerated in the 1980s and 1990s, which means that ageing water storage infrastructure is not yet a widespread concern. Across the entire continent, Africa is home to approximately 2000 large dams, far fewer than other continents, with one-quarter of those in South Africa alone (*SANCOLD, 2018*). Nevertheless, this includes several notable structures, such as the Akosombo Dam in Ghana and Egypt's Aswan Dam. The continent as a whole has a high and increasing reliance on hydropower, but with significant untapped potential. Dam construction has increased in recent years in response to a rapidly growing population and demand for both energy and a secure water supply; the controversial Grand Ethiopian Renaissance Dam is indicative of this trend.

One instructive African example of ageing water storage infrastructure is the Kariba dam straddling the border between Zambia and Zimbabwe, forming the largest reservoir in the world by volume with a storage capacity of 180 km^3. A double curvature concrete dam, it stands 128m high and 579m wide across the Zambezi river. The dam was completed in 1959, and has fallen into dangerous condition, having begun to erode itself (*Leslie, 2016*). It is also located on a fault line, and could be damaged further by tectonic activity. Experts cautioned that the dam is at high risk of collapse if repairs are not made, and these repairs, valued at about 300 million USD, were scheduled to commence in 2016 (*World Bank, 2015*). The Kariba Dam supplies about half of Zambia's electricity, and the river basin is highly susceptible to severe floods and drought (*Leslie, 2016*). Such dependency, and the fact that failure could directly threaten approximately three million people makes removal extremely unlikely, despite the steep costs required to maintain it.

v) SOUTH AMERICA

Large dams are also somewhat younger in South America, and have not yet faced the same issue of widespread ageing seen in other regions. More than half of all large dams in South America are found in Brazil; however only a handful of dams have been present for more than 50 years. Today though, South America relies heavily on hydropower, and as countries across the continent seek to satisfy a growing energy demand, hundreds of large dams are planned or are currently under construction (Economist, 2016). There is, however, strong and coordinated public opposition to the underestimated negative impacts of these dams, including environmental impacts in the Amazon Basin and displacement of millions, especially Indigenous peoples (Economist, 2016).

iv) OCEANIA

There are more than 500 large dams in Australia, half of which are over 50 years old, and more than 50 have been in operation for more than a century (*ANCOLD, 2010*). As the driest inhabited continent with highly variable precipitation, there is a strong demand for water storage infrastructure, and Australia consequently has the world's highest per capita surface water storage capacity (*AWA, n.d.*). In addition to stabilizing water supply, dams are crucial for energy, as hydropower is responsible for over 65% of Australia's electricity generation (*AWA, n.d.*). Virtually all rivers in the more heavily populated south have already been dammed, leading construction to slow dramatically by the 1990s (*Gibbes, 2014*). More recently, attention is now turning to the relatively untouched northern river systems to redistribute water, although this has been met with strong resistance from Indigenous populations in the region (*Rayner, 2013*).

DISCUSSION:

The issue of ageing dams is clearly widespread, with especially significant consequences for large dams by virtue of their size and importance. The exact relationship between viability and longevity is imprecise; some dams remain sound and effective after several centuries, while others face serious threats to their structural integrity after only decades. Well-designed and properly maintained dams can easily operate for over 100 years (*Wielman, 2010*). Nevertheless, excluding failure in the initial years of operation, most incidents involve older dams.

Although some evidence suggests that embankment dams are the most susceptible to failure (*Regan, 2010; Mills, 2013*), this is difficult to confirm as they are also by far the oldest and most common (*ICOLD, 2018*). Other factors like sedimentation rates and maintenance are also highly influential for a dam's lifespan. Sedimentation is largely determined by a dam's geography, while ownership is an important aspect with regard to the latter, as it is challenging to ensure sufficient maintenance practices for privately-owned dams. This calls for an increased commitment to regular and thorough dam inspection. Doing so will require both financial and manpower resources, but has the potential to be a cost-saving preventative measure by avoiding the consequences of dam failure. A closer look could also identify dams not feasibly salvageable from an economic standpoint and are therefore candidates for removal.

All actions concerning large dams are associated with considerable expense, but costs vary greatly based on the specific conditions. This makes it difficult and perhaps unhelpful to attempt to perform a generalized cost-benefit analysis for ageing dams or decommissioning as a whole; some circumstances will call for one course of action, while others will suggest the opposite. For example, decommissioning is unlikely in economically crucial situations such as the Kariba dam. This likely explains why very few large dams have been fully removed, in contrast to smaller dams that do not offer the same scale of economic benefits. It is not necessarily the case that maintaining a dam is worthwhile simply because it has already been built; removing defunct dams promotes environmental restoration and removes unnecessary safety risks. Ultimately, value judgements will determine the fate of many of these structures.

Around the world, countries face the issue of ageing large dams and overall water storage development to varying degrees and under different conditions, yielding a mixture of solutions rather than a universal approach. Compounding this difficulty is that the ICOLD definition of large dams is for those above 15m, when today dams are being built larger than ever before, hundreds of metres high; it is challenging to generalize across such a range (*Poff & Hart, 2002*). In much of the developed world, dam construction has slowed and even reversed, due in part to the exhaustion of remaining undammed locations for their construction. There is also increasing awareness of the negative environmental impacts of dams, especially for fish species, a focal point of public advocacy for dam removal, as is sediment flow restoration. Furthermore, emerging alternative renewable clean energy sources such as solar and wind compete with hydropower (*Economist, 2016*). Simultaneously, the number of new and planned large dams is rapidly increasing in many other parts of the world, such as China, India, Brazil, and Eastern Europe (*Zarfl et al., 2015*). These regions have comparatively younger large dams on average, having belatedly joined the rush to harness the potential of hydropower. These countries will have to contend with ageing water storage infrastructure in the future, but have the advantage of being able to incorporate innovations that allow sediment flow and provide fishways, reducing the downstream impacts and extending the functional lifespan of the dams (*Purtill, 2012; Sumi et al., 2004*).

A final consideration moving forward is the complex effects of climate change on the longevity and impact of large dams. Changing precipitation patterns make the ability to ensure a stable water supply that much more valuable. At the same time, increasing frequency and severity of extreme weather events can overwhelm the dam's designed limits, or prematurely age the structure. In addition, increasing temperatures heighten rates of evapotranspiration, exacerbated by the larger reservoir surface areas. Emerging research also suggests that stagnant reservoirs are a large source of methane, a potent greenhouse gas, strengthening the case for decommissioning (*Gass, 2013*).

Moving forward, this remains a subject that has received relatively limited attention in the literature, leaving numerous opportunities for further research. In particular, more could be done to identify specific aging patterns with respect to dam height, reservoir size, function, and other key characteristics. In order to do so in a comprehensive manner, a priority must be to address the many gaps in the ICOLD database. In particular, several large dam profiles suffer from varying degrees of completeness, limiting their usefulness for analysis purposes.

CONCLUSION:

In conclusion, ageing water storage infrastructure poses a problem around the world, whether today or over the near future. Thousands of large dams around the world have or will soon exceed their 50-year design lifespan, and as a result appear set to incur greater maintenance costs while simultaneously declining in their effectiveness, and posing serious threats to the environment and human safety. These concerns, in addition to greater awareness of the negative environmental externalities of dams and their role on the global water cycle, has led to an increase in the decommissioning of dams, notably in the United States and Western Europe. However, the 50-year threshold is not a definitive measure, nor is there a common solution to the issue of ageing large dams. Ultimately, the longer a flaw is left undetected and consequently unresolved, the greater the costs will be to restore it. Therefore, improving dedicated observation of these vital structures is imperative in order to identify issues as quickly as possible before they worsen.

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