Open Water Journal – Volume 7, Issue 1, Article 1

Exploring the Physical Attributes of 21st Century Large Dams: A Descriptive Study from Ecological and Sustainability Perspectives

Research Article

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Abstract

In response to growing energy needs and emerging water insecurity, countries around the world have resorted to building dams of unprecedented size. This dynamism emerged following a global consensus at the end of the 20th century that vowed to transform the large dam industry into one that was sustainable and ecologically sensitive. The consensus evolved due to years of popular anti-dam activism on a global scale and the emergence of new knowledge on various aspects of large dams. Although the number of large dams built has sustained its descending pattern that has initiated in the late 1970s, hundreds of dams with unprecedented size have emerged around the globe in the last twenty years. These dams have distinguished attributes. By descriptively examining ICOLD's World Register of Dams data, this study revealed that large dams of the 21st century are larger in size. They create expansive reservoirs with unprecedently large surface areas. Paradoxical to the size of their surface area, these reservoirs have limited storage capacity/volume and larger Surface-to-Volume Ratios. Such attributes come with far-reaching ecological and sustainability implications. The study concludes that large dams of the 21st century are incompatible with the environmental and sustainability-related standards/requirements of the contemporary ecological age. As such, these aspects of the 21st century large dams should be robustly scrutinized.

Keywords: Large Dams, 21st Century Large Dams, Ecological Costs, Sustainability Concerns

1.0 Introduction

By the end of the 20th century, a global consensus emerged to transform the large dam industry into one that was sustainable, inclusive (WCD 2000; IEA 2000), and participatory (Bandyopadhyay et al. 2002). Defined by the International Commission on Large Dams (ICOLD) as any dams with 15 meters or higher in height from its' foundation to the crest, or dams between 5 meters and 15 meters high impounding more than 3 million cubic meters of water (ICOLD 2011), large dams were becoming controversial by the end of the 20th century. In addition, the role of large dams in development was found as exaggerated (McCully 2001), and the objectivity of the claimed efficiency of large dams was considered prone to skepticism (Jairath 1990; Postel et al. 1996). It was recognized that large dams had inflicted severe, unacceptable, and unnecessary social and environmental costs (WCD 2000; Scudder 1996). Such costs in 75% of the cases were technically feasible and economically justifiable to mitigate (World Bank 1996; Dorcey et al. 1997). Accordingly, national energy policies were recommended to fully internalize hydropower projects' environmental and social costs (IEA 2000).

Furthermore, bringing necessary changes in the planning, designing, and operating of large dams was demanded (Dorcey et al. 1997). Even the need for non-structural and multidisciplinary interventions to improve water use efficiency was stressed (Gleick 1998; Postel 2000). A substantial reduction in the funding of large dam projects followed these changes (Nusser 2003). As such, it was predicted that the water resources management of the 21st century would depart from constructing massive infrastructures towards a “soft path” of relying on small-scale decentralized facilities (Gleick 2003).

However, this is not how the large dam industry subsequently transformed. Against the growing resistance and accumulating knowledge on the downsides of large dams, the proponents of these dams have continued to push for further investment in these giant infrastructure projects. They link large dams with a wide array of socio-economic, ecological, safety-related (e.g., floods), and even recreational benefits. The proponents argue that large dams are crucial for socio-economic development as they provide necessary inputs for economic growth, including electricity and water (Berga et al. 2006; Chen et al. 2016; Tortajada 2015).

By providing food and energy securities through expanding irrigation sources and energy grids, large dams are considered crucial for poverty alleviation (Duflo and Pande 2007; WB 2010; UN Water 2016). In addition, they are promoted as the primary source of renewable energy (Tortajada 2015). In general, large dam proponents argue that building more large dams is crucial crucial for satisfying the increasing global demand for energy to materialize the envisioned positive economic growth (Shi et al. 2019; Zarfl et al. 2014).

After a brief period of restrain, countries once again have started to rely on large dams to cope with their increasing energy needs and emerging water insecurities. Within the last two decades, dams with unprecedented size have emerged in different world regions, mainly in Global South. More specifically, ICOLD data reveals that among the top ten years with the greatest number of large dams (≥ 100 meters), seven of them are built within the 21st century (ICOLD 2019). (See Table 1).

Table 1: Top 20 Years with the Highest
Number of Large Dams ≥100m Completed per Year

#	Year	Frequency
1	2013	34
2	2011	29
3	2009	26
4	2012	25
5	1974	24
6	2001	23
7	2006	23
8	1976	20
9	2010	20
10	1964	19

Data Source: ICOLD’s World Dams Register

These observations suggest the need to systematically explore the nature and attributes of the 21st century large dams. Furthermore, in the contemporary ecological age, such an inquiry is crucial for understanding these dams' environmental and sustainability-related implications.

1.1 The trajectory of large dams in the 20th Century

Damming rivers has persisted as one of the primary water control and management practices for at least 5,000 years (Smith 1971). From the initial human civilizations in Egypt around six millennium BC (Van Loon 1992) and the early farming communities in Mesopotamia around the 3rd millennium BC (Ponting 2007) to the subsequent ancient civilizations elsewhere, dams had been utilized to manage, control, and preserve freshwater resources. This tradition has continued to medieval times and subsequently to modernity.

Unlike the ancient civilizations that, as pure agrarian societies, used dams mainly for domestic and irrigation purposes [Ponting 2007; Ohlsson 1995), modern societies have created a diverse need for dams, including, but not limited to, irrigation and generating power. Although it was only in the late 19th century that hydropower was pioneered, it soon became the principal reason for impounding rivers (Lehner B. et al. 2011).

The trajectory of large dams in the 20th century suggests that the industry's evolutionary process is not spontaneous. On the contrary, the large dam industry in the 20th century has been directly shaped and transformed by prominent political and economic events and processes. Such events include the Great Depression in the 1930s, World War II in the 1940s, the launch of the post-WW II economic growth agenda, the decolonization process, the global spread of rights activism in the 1980s, and the emergence of new security and development paradigms in the 90s.

By the start of the 20th century, only several hundred large dams existed in different parts of the world. More specifically, there were approximately 600 large dams in existence in 1900. Many of the oldest of these dams were constructed by Colonial powers in Asia and Africa (WCD 2000). In the 1930s, the Great Depression and the New Deal in the United States facilitated the “big dams” era in the country (Bureau of Reclamation 2016). In the 1940s, contributing to the dams building dynamism of 1930s, WWII further accelerated the building of large dams in the United States (Leroy and Hart 2002). By generating low-cost hydropower, dams gave American heavy and defense industries a comparative advantage in producing airplanes, tanks, and ships during WWII (Bureau of Reclamation 2016). Soon, the hydropower output in the U.S. tripled and reached 40% of electrical use (USDoE 2016). By 1950, large dams became symbols of power, pride, and vivid illustrations of dominating nature (Steinberg 1993; Khagram 2004). With these developments, the total number of large dams built within the first fifty years of the 20th century rose to 5,000, of which only 10 were dams 150 meters or higher (Khagram2004). Despite this boom, the heyday of large dams has yet to come.

Over 90% of large dams were built during the 2nd half of the 20th century (Khagram2004). In the 1950s and 60s, two interrelated political and economic processes have facilitated the dawn of the “golden era” of large dams; the launch of the economic development agenda and the decolonization. These processes gave large dams a new mandate; the tools of industrialization and economic growth. At the dawn of the decolonization era, large dams became a symbol of national pride for the newly independent countries in Africa and Asia (Biswas 2012; Biswas and Tortajada 2001).

These countries viewed dams as tools for converging their economic and developmental status with that of Western societies. To reach the desired state of modernity, these countries needed industrialization, and dams (by providing power) were deemed critical to move the wheels of their envisioned industries. The experience of the United States with building large dams during the Great Depression gave these countries all the reasons to consider large dams as symbols of state power (Hasenöhrl 2018), the “cathedrals of development,” and even used the building of dams as a nation-building practice (Biswas 2012; Biswas and Tortajada 2017).

Accordingly, the construction of large dams was placed at the core of the economic development paradigm. Even the U.S. promoted large dams among developing countries by conditioning its loans with the construction of large dams as critical for the green revolution (Shiva 2000). In addition, international organizations, including the World Bank and the United Nations, supported and provided loans to developing countries to build large dams (Khagram2004; Hasenöhrl 2018).

In the immediate post-WWII years, the counter-decolonization efforts by the colonial powers also promoted building large dams in the Global South. These powers used dams as tools for executing and maintaining their power in their respective soon-to-be ex-colonies in Africa and Asia (Hasenöhrl 2018). This was in addition to the exploitative practices of the colonial powers earlier in the century. They exploited the use of large dams to transform small-scale traditional peasant farms into irrigated large-scale, market-oriented agriculture of natural resources and the cultivation of cash crops (Kelly et al., 2017). For example, in the late 19th and early 20th centuries, the British firmly left their mark largely on the Nile, the Indus, and the Ganges basins (McCully 2001).

The combined result of these factors was unprecedented growth in the number of large dams in the 2nd half of the 20th century. By the end of the century, more than 45,000 large dams were erected on rivers in 140 countries (WCD 2000). Among these, 300 were dams with a height of 150 meters or higher (WCD 2000).

The development agenda in the post-WWII years authoritatively promoted large dams as essential and necessary investments for economic growth. This claim has remained unchallenged for many years. Although some environmentalists and nature activists opposed the American adventurism in building large dams in the 1950s, 60s, and 70s (See; Russell 1999; McPhee 1989), the fundamental global challenges to large dams started emerging by the late 1970s and systematically strengthen in the 1980s.

The institutionalization of norms in the fields of environment and human rights facilitated the start of a systematic public opposition to large dams (Khagram 2004). By 1980, the golden era of building large dams was coming to an end (Devine 1995). Eventually, since the 1990s, in the face of new knowledge, the efficiency, economics, and benefits (or otherwise) of large dams landed under serious and critical scrutiny (WCD 2000; Postel 1996; Postel 2000; Jairath 1990).

By the turn of the 21st century, the number of large dams completed per year has dropped to under 200, representing a 75% drop in the construction rate of large dams in less than two decades (Khagram 2004). Simultaneously, a global consensus has evolved to transform the large dam industry into one that was sustainable and efficient (WCD 2000; Postel 2000; Nusser 2003). The expectations were that the new century will be the century of small dams and that the heydays of building large dams have ended (Babbit 2002; McCully 2001). The prophecy somehow revealed itself, although it was short-lived. Sometime during the initial years of the 21st century, states have once again resorted to building large dams; this time, however, larger dams with unprecedented height. By analyzing the existing ICOLD data, this study reveals the changing physical attributes of 21st-century large dams.

2.0 Materials and Methods

This study is a descriptive comparative survey of large dams. It exclusively focuses on comparing the physical attributes of the contemporary (built since 2000) large dams with those built before the year 2000. The comparison is at exploring how the large dam industry has transformed in the age of sustainability.

The variables used for comparison include the height of dams, the surface area of the reservoirs in m^2, the storage capacity/volume of reservoirs in m^3, and the Surface-to-Volume Ratios the reservoirs. The study uses secondary data from the International Commission on Large Dams (ICOLD)'s World Register of Dams. This register is a comprehensive and extensive database that is updated periodically and includes descriptive information of all the existing large dams around the world. As of April of 2019, there are a total of 59,072 dams registered in the database (ICOLD 2019).

To contrast the magnitude of large dams built before and since the year 2000, the study initially reclassifies the large category of large dams into the following two sub-categories:

- Large dams < 100 meters high,

- Large dams ≥ 100 meters high.

In this stage, the study compared the following attributes of large dams in each of the two sub-categories built in a single decade from the 1930s up until 2020:

- Number of dams in each sub-category built per decade,
- Per decade average height of large dams built within a decade,
- Per decade average reservoirs' surface area size,
- Per decade average reservoirs' storage capacity/volume.

In the second stage, the study compared the average Surface-to-Volume Ratios (S2WR) of large dams (≥ 100 meters high) built before and since the year 2000. The high level of missing data of the relevant variables used for calculating the S2WR is why the study compared this ratio exclusively for the large dams (≥ 100 meters high).

3.0 Results

3.1 The Changing Face of Large Dams in the 21st Century

Analyzing the ICOLD's World Register of Dams data reveals that the number of large dams built has been in consistent decline since the 1970s (See Figure 1). It, however, is a misleading portrait of the industry, which is caused by the definition of large dams itself. The widely used classification of large dams is that of the ICOLD that defines large dams as those 15 meters or higher in height from its' foundation to the crest, or dams between 5 meters and 15 meters high impounding more than 3 million cubic meters of water (ICOLD 2011). The World Commission on Large Dams (WCD) also adopted this definition for its Dams and Development report (WCD 2000).

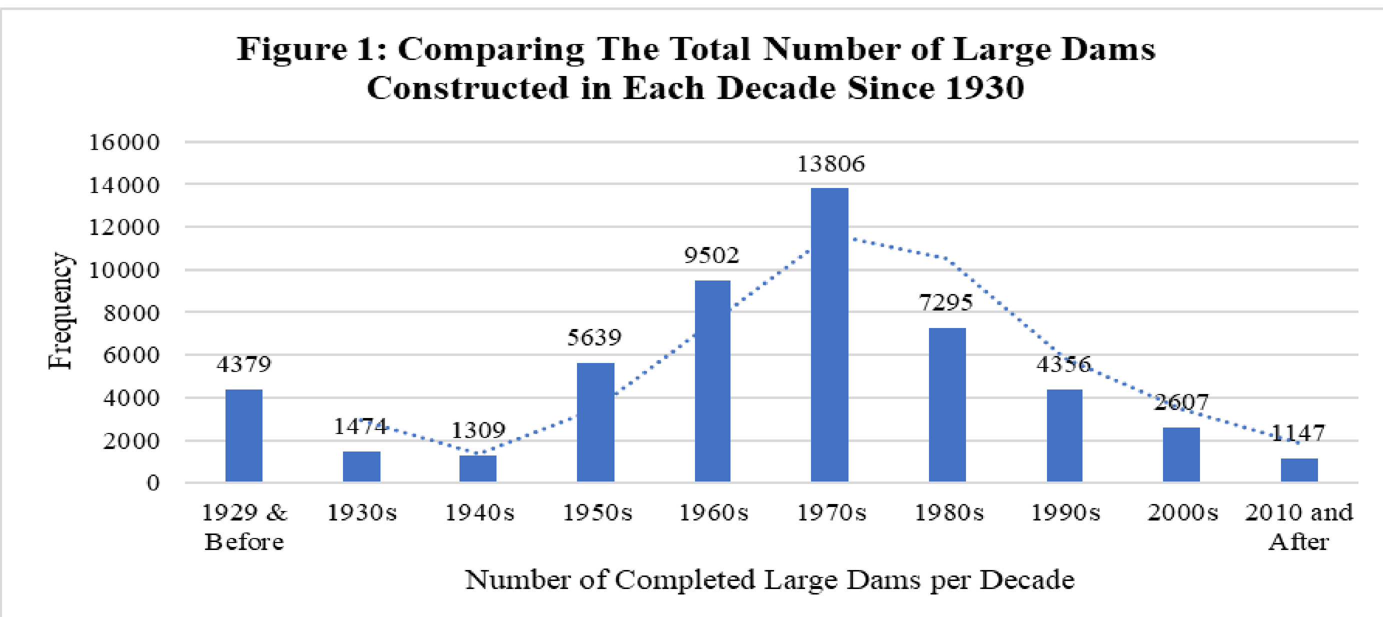
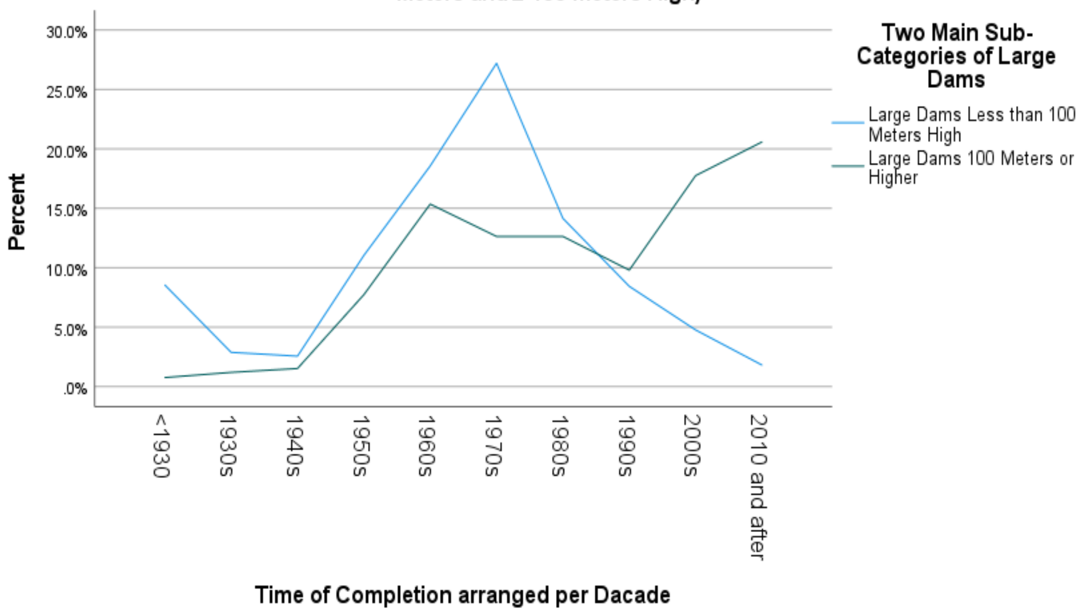


Figure 1. Comparing the Total Number of Large Dams Constructed in Each Decade Since 1930

In the backdrop of this broad definition lays a problematic face of dams of the 21st century. Re-classifying the broader category of "large dams" into two smaller sub-categories of 'large dams< 100 meters high' and 'large dams ≥ 100 meters high' reveals the obscured characteristics of contemporary large dams. Comparing the per decade percentages of each sub-category out of the total number of large dams built within the given decades provides more explanatory information regarding the changing face of large dams in the 21st century.

As indicated in Figure 2, the per decade percent distribution of large dams (< 100 meters in height) follows a declining pattern since the 1970s. This distribution pattern shows an opposite direction for the sub-category of large dams (≥ 100 meters high), mainly post-1990s. In the last at least twenty years, countries have significantly reduced building large dams that measure less than 100 meters high. However, simultaneously, they have been building dams that are exceedingly larger in all the corresponding attributes than those previously built.

Figure 2: Comparing the Per Decade Percent Distribution of the Two Sub-categories of Large Dams (< 100 Meters and ≥ 100 meters High)



The per decade percentage distribution of each sub-category is based on the total number of large dams built within given decade

3.2 Size of contemporary large dams

In the 21st century, countries are building more large dams (≥100 meters high) than ever before. By 2018, there were a total of 978 of these dams scattered around the world. Among these, over one-third (36% or 352 out of 978) have been constructed since the year 2000. These figures suggest that the main challenge with dams of the 21st century is their magnitude/size. As indicated in Figure 3, the number of large dams (≥100 meters high) built per decade since the 1920s peaked only in the last two decades (See Figure 3).

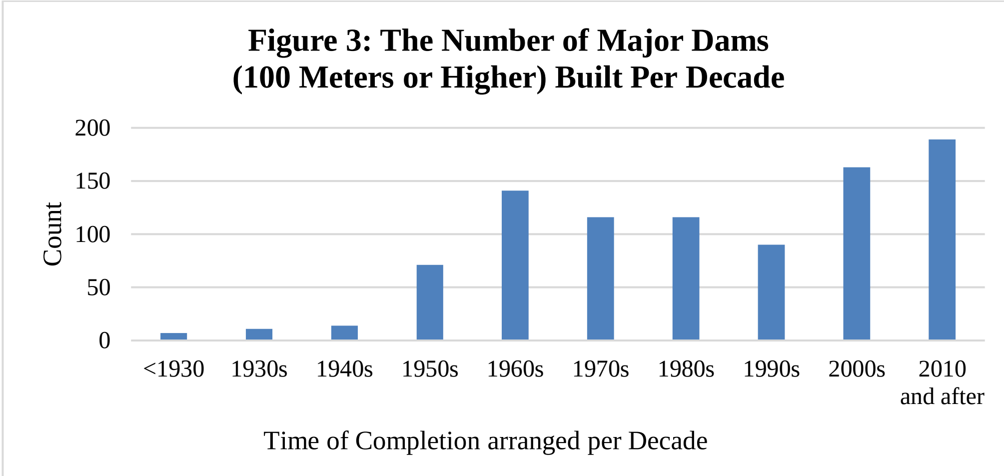


Figure 3. The Number of Major Dams (100 Meters or Higher) Built Per Decade.

Simply put, large dams (≥100 meters high) built since 2000 are both frequent and unprecedented in size. As an aggregate measure, the magnitude of these dams has caused a sharp increase in the per decade average height of all large dams built within the corresponding decade. As indicated in Figure 4, the average mean height of all large dams followed a steady pattern swinging between 25 and 30 meters high until the end of the 20th century. This average took on a drastic increase since the year 2000, and it peaked to over 60 meters average height in the second decade of this century.

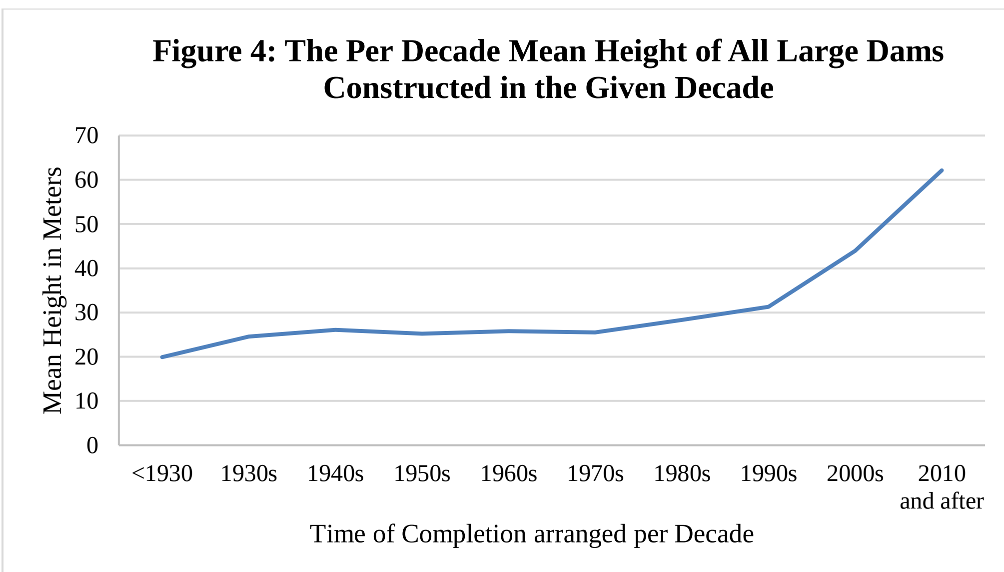


Figure 4. The Per Decade Mean Height of All Large Dams Constructed in the Given Decade.

Statistically, two potential factors caused this increase. First is the consistent decline in the number of large dams built (decrease in the denominator), and secondly, a dramatic increase in the number of large dams (≥100 meters high) built. As the number of large dams built has been consistently declining since the 1970s, the weight of this factor may not play a critical role in the drastic increase of the per decade average height observed only in the last two decades. The increase in the number of large dams (≥100 meters high) built seems to play a critical role.

The magnitude of the 352 large dams (≥100 meters high) built since the year 2000 is significant in causing a drastic shift in the central tendency-related values, mainly mean and the percentile points, of all the total large dams built within the correspondent period. The 21st century large dams, on average, are 49.1 meters high, while this number is 25.9 meters for dams built before the year 2000. Similarly, the 1st, 2nd, and 3rd percentile points of the dams built since 2000 are 24, 38, and 64, respectively. These numbers are 16, 20, and 30 meters for large dams built before 2000 (See Table 2).

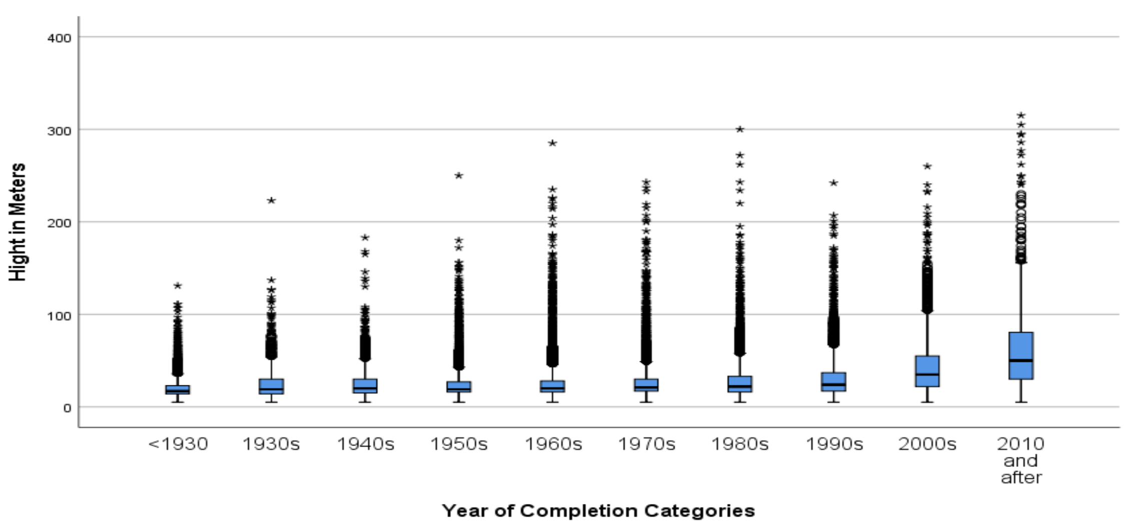
Table 2. Comparing Central Tendency Attributes (in meters) of Large Dams built Before and Since 2000

Statistics	Large Dams built since 2000	Large Dams built before 2000
Mean Height	49.41	25.97
25 Percentile	24.00	16.00
50 Percentile	38.00	20.00
75 Percentile	64.00	30.00
Missing	101	356
Total	47760	3754

Source: ICOLD’s World Dams Register

These descriptions depict that it is not a few outliers and gargantuan dams that skewed the mean. On the contrary, dams of the 21st century are so tall and large in magnitude that they caused an unprecedented increase in the central tendency attributes of the overall large dams built during this period (See Boxplot 1).

Boxplot 1:Boxplot Statistics for the Height of Large Dams



These descriptions suggest that large dams of the 21st century are, on average larger in size. They are strategically designed to be larger in order to grab more water from the rivers. This leads us to examine the surface area and the capacity of the reservoirs that these dams have created.

3.3 Reservoir surface area of contemporary large dams

Comparing the average surface area of large dams built before and since the year 2000 shows a stark contrast. In general, as an aggregate measure, the mean surface area of reservoirs of tens of large dams built before the year 2000 is 23,533,300 m^2, while this number for the number of large dams built since 2000 is 30,699,080 m^2. This shows that the average surface area of reservoirs of the large dams built since 2000 is 30% more than that of the dams built earlier. Statistically, these averages cannot assess individuum in a population. The numbers, however, reveal a general comparison between the nature of the contemporary large dams with those built earlier. This study, to render this comparison more proportionate in terms of time, also looked at the per decade average surface area of large dams built within the corresponding decade.

As indicated in Figure 5, the average reservoirs' surface area shows a rapid and unprecedented spike in the last two decades. This means that large dams built since the year 2000 created expansive reservoirs. Preferably, dams impound the flow of rivers in spots that are naturally narrowed down by valleys at both sides to serve as sidewalls. Looking at the surface areas of contemporary large dams indicates that these dams are built larger to embank wider valleys. This results in the creation of expansive reservoirs. Does this mean that these dams are more efficient environmentally and economically in terms of their capacities? However, the subsequent crucial inquiry is to look at the capacity/volume of these expansive reservoirs.

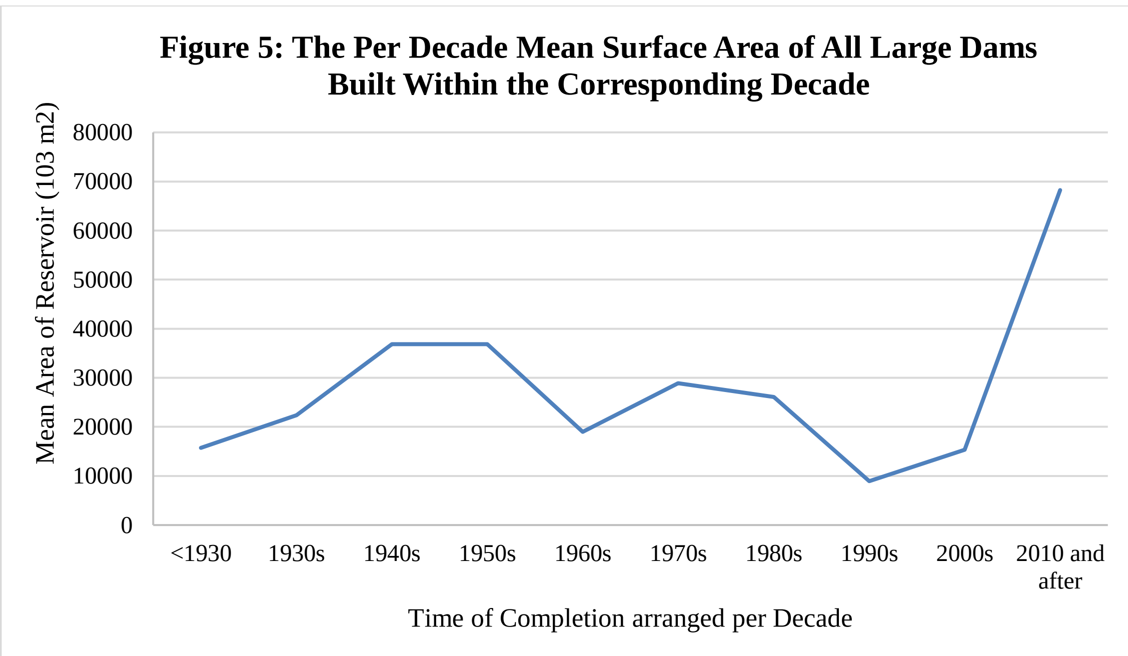


Figure 5. The Per Decade Mean Surface Area of All Large Dams Built Within the Corresponding Decade.

3.4 Volume/capacity of the contemporary large dams' reservoirs

Building higher dams to impound rivers for creating reservoirs with larger surface areas is not the entire story of contemporary large dams. A puzzling aspect of these dams is the challenged volume/capacity of the contemporary dams' reservoirs.

Despite being the tallest and creating more expansive reservoirs, large dams of the 21st century cannot create reservoirs with capacities/volumes compatible with their size. The average capacity of large dams built in the last two decades compared with that of large dams built before the year 2000 is slightly greater (382,169,840 m^3 vs. 316,642,360 m^3). However, a closer look at the data suggests that, on average, the highest reservoir capacity was of dams built in the 1960s and 70s (see Figure 6).

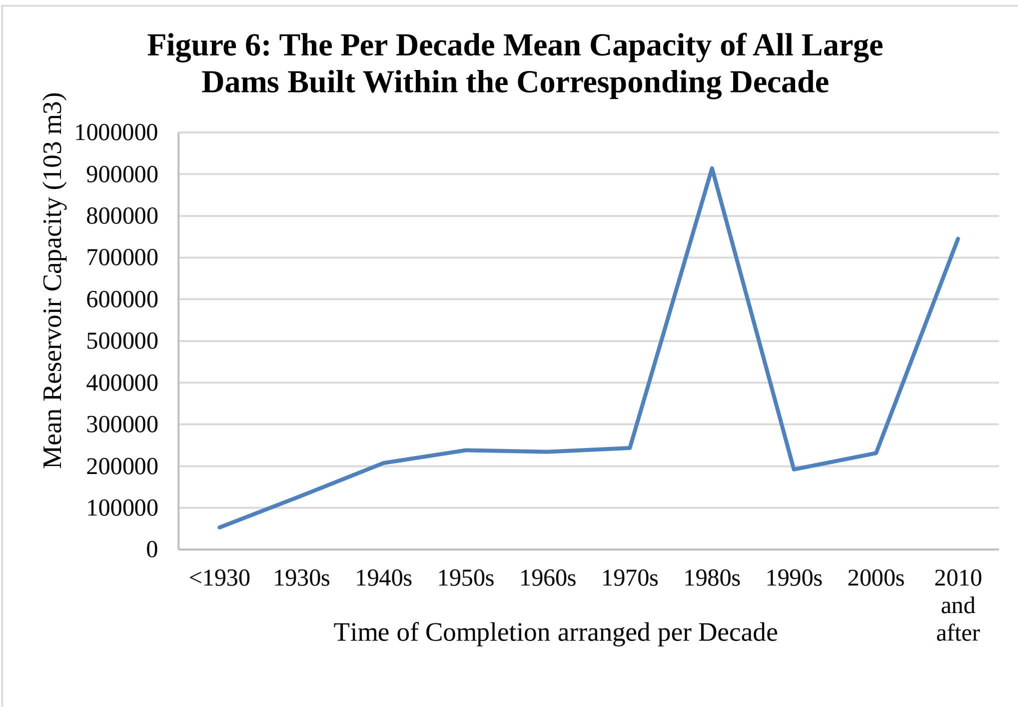


Figure 6. The Per Decade Mean Capacity of All Large Dams Built Within the Corresponding Decade.

The reservoirs created by the large dams of the 21st century, on average, do not have the highest capacity. Although these dams effectively embank rivers and create expansive artificial bodies of water, the area above these dams does not have the natural capacity to store large volumes of river water. This is puzzling, and it leads us to inquire about the approximate efficiency of the reservoirs created by contemporary large dams that measure 100 meters or more in height.

3.5 Surface Area-to-Volume Ratio of large dams (≥100 meters high)

The Surface-to-Volume Ratio represents the reservoirs' surface area (in square meters) per their unit volume (in cubic meters). To understand the attributes of contemporary dams, it is crucial to contrast the Surface Area-to Volume Ratio of large dams (≥100 meters high) built both before and after 2000. As indicated in Table 1, the average Surface Area-to-Volume Ratio for the overall category of large dams (≥100 meters high) ever built is 0.33. A stark contrast is observable if this ratio is calculated separately for large dams (≥100 meters high) built before and after the year 2000. For those dams built before 2000, this ratio is 0.22 smaller than the total average of 0.33. However, for the large dams (≥100 meters high) of the 21st century, this ratio is unproportionately much larger with a value of 0.77 (See Table 3).

Table 3. Mean Surface Area per Volume Ratio for Large Dams (≥ 100 Meters High) built Before and Since 2000

Statistics	Large Dams (≥100 m high) built since 2000	Large Dams (≥100 m high) built before 2000	All Large Dams (≥100 m high)
Mean	0.77	0.22	0.33
Median	0.028	0.028	0.027
St. Dev	4.47	2.17	2.80
Range	35.1	39.6	39.6
Valid	140	491	651
Missing	212	75	327
Total	352	566	978

Source: ICOLD's World Dams Register

To be more specific and proportionate in terms of time, it would be interesting to determine the changing pattern of this ratio per decade. As seen in Figure 7, the Surface-to-Volume Ratio of major dams constructed since 2000 is the highest. This shows that while these dams create expansive reservoir areas, they do not have much capacity/volume for storing water. It means that the large dams (≥100 meters high) of the 21st century, unlike those built before 2000, create much wider areas with limited depth for storing a cubic meter of freshwater. A plausible explanation for such inefficiency (larger surface area with limited storage capacity) is the saturation and exploitation of sites naturally suitable for building dams (See discussion).

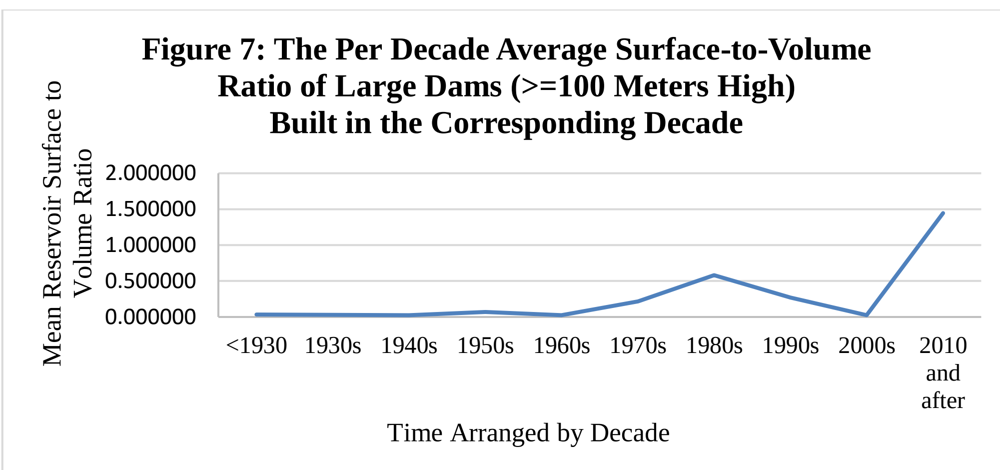


Figure 7. The Per Decade Average Surface-to-Volume Ratio of Major Dams (>=100 Meters High) Built in the Corresponding Decade

Keeping in mind the prevailing water crisis worldwide, the rationale behind the emergence of large dams (≥100 meters high) is puzzling. While the availability and distribution of freshwater sources are rapidly changing, the size and capacity of large dams (≥100 meters high) and their numbers are increasing. This is the new face of dams in the 21st century; larger structures on depleting and volatile rivers impounding shallow reservoirs. It suggests that the problems with large dams of the 21st are different from those of the previous century and must be studied independently.

4.0 Discussion

Building large dams—a loose definition that incorporates any dam measuring either 15 meters or more in height or dams between 5 meters and 15 meters high impounding more than 3 million cubic meters of water (ICOLD 2011)—has continuously been declining since the late 1970s. Paradoxical to this is the unprecedented rise in the number of dams with a height of 100 meters or higher. In the last twenty years, while hundreds of large dams (≥100 meters high) have been built in countries across the developing world, hundreds more are under construction. These countries justify building such dams to satisfy their increasing energy needs and to mitigate their emerging water insecurities.

However, in addition to rendering draining financial costs [36], building dams with such magnitude come with human and ecological costs. Such costs outweigh the claimed benefits of large dams (Namy 2010). As contemporary large dams are unprecedented in their size and in creating expansive reservoirs, the varied costs they inflict must be explicitly and independently evaluated.

Generally, the size of dams is one of the primary predictors of their ecological costs (Egre and Milewski 2002; Poff and Hart 2002; Hart et al. 2002). The larger the dam, the more dramatic and more severe the environmental effects are (Baxter 1977). As such, the enormous height of contemporary large dams increases the magnitude of their ecological ramifications. Most importantly, in the current ecological age, states are constructing larger dams without considering their sustainability in terms of the prevailing conditions of the Anthropocene.

The sustainability of the dams and reservoirs in the classic utilitarian understanding is measured by the life expectancy of the reservoir, which is calculated based on the rate of sedimentation (Graf et al. 2010; Morris and Fan 1998). By this standard, the larger the reservoir, the longer the life expectancy in terms of reservoir storage capacity, and hence the more sustainable the reservoir will be. Such is an approach that does not consider the prevailing challenges of the contemporary ecological age. In general, the current way of governing and managing freshwater [including building dams] is becoming obsolete in relation to humanity's social and environmental challenges in the upcoming 50 years (Rockstrom et al., 2014).

In addition, as the large dams of the 21st century have different attributes from those previously built, the conventional approaches for reservoir optimization in terms of sustainability purposes must be reconsidered for these projects. In the age of environmental shocks, the sustainability of large dams has a direct link to ecological factors. These include, but not limited to, the health of the river's ecosystem (Nusser 2003; Covich 1993; Ligon et al. 1995; Collier et al. 1996) and the emission of greenhouse gases (Maeck et al. 2014; Wik et al. 2016; Stanley et al. 2016; Li and Zhang 2014; Vincent et al. 2000).

The unprecedented size of contemporary large dams needs to be considered as a determinant of their ecological sustainability (or otherwise). On the contrary, the main criteria used to classify the size of these dams is arbitrary, and it lacks incorporating the potential risks and safety considerations associated with the prevailing climate changes. Such arbitration has two limitations. First, it fails to reflect the variation in the size of the dams, and secondly, it conceals the different uses and ramifications of the different sizes of dams, including their ecological effects (Poff and Hart 2002).

As mentioned earlier, the dam's size has direct relations with the magnitude of its potential ecological and environmental impacts (Egre and Milewski 2002; Poff and Hart 2002). One such impact is the potential range of ecological disturbances to the aquatic ecosystem (ASCE 1997). Large dams have negative impacts that impair rivers' health and natural flow and disrupt the biophysical regimes of the river, such as the natural flow variation and sedimentation regimes (Petts 1984).

The size of the dam along with the operation type affects the Hydrolytic Residence Time (HRT)—the ratio of the storage volume (m^3) of the reservoir to its flow-through rate (m^3 per year) (Poff and Hart 2002). By creating vast reservoirs, large dams store more water for more extended periods. The seasonal inflows and the variability of inflow to larger storing bodies/reservoirs cause the stratification of water, which is one of the main determinants of the HRT of a reservoir (Rueda et al. 2006). Though the height/size of the dam alone is unlikely to predict the HRT meaningfully, it in combination with the type of dam's operation affects this rate, thereby inflicting severe costs on the biophysical regimes of the river (Morris and Fan 1998; Kalff 2002; Oud 2002).

As this study depicted, one of the main distinguishing attributes of contemporary large dams—those built since the year 2000— is the expansive surface area of their reservoirs. The exploitation of suitable dam sites was one of the main reasons for the decline in dam projects after the 1970s [Khagram 2004; Oud 2002]. As such, we can infer that new large dams are most likely built on terrains that require more human intervention and investment to control the flow of water effectively. These dams impound rivers at wider points and hence, create expansive reservoirs. Accordingly, with the emergence of new dams, the reservoir surface areas will likely increase substantially in the coming decades (Zarfl et al., 2015).

Generally, reservoirs with large surface areas cause the most severe environmental impacts and the most controversy (Egre and Milewski 2002). One such controversy is the emission of greenhouse gases (GHGs) from the surface of reservoirs. Unlike previous understandings, the surface area of reservoirs is not GHG neutral. On the contrary, through their surface area, reservoirs emit GHG (Maeck et al. 2014; Wik et al. 2016; Stanley et al. 2016; Li and Zhang 2014), including methane, CO2, and N2O (Maeck et al. 2014; Demarty and Bastien 2011; Li et al. 2015).

Recent findings suggest an estimated 25% more methane emissions by reservoirs than previously estimated (Deemer et al. 2016). The same study confirmed that the overwhelming majority (80% over the last 100 years and 90% over the last 20 years) of the radiative forcing from reservoir water surfaces is methane emission. In addition, tropical reservoirs contribute 64% of total CH4 emissions, and boreal and temperate reservoirs, respectively, contribute 27% and 9% of the total emissions (Li and Zhang 2014).

The surface area of reservoirs is a crucial determinant of high-level GHG emissions from reservoirs (Fearnside and Pueyo 2012; Galy-Lacaux et al. 1999). Though the exact figures of global reservoir surface area do not exist, there are some estimates. The common understanding is, the wider the surface area, the more GHG emissions. By this rule, the large dams of the 21st century have created reservoirs with larger surface areas that flood more organic carbon and potentially emit more greenhouse gases.

The third distinguishing characteristic of contemporary large dams with ecological implications is their larger Surface-to-Volume Ratio (S2VR). Technically, the ratio is both economically and ecologically significant. Economically, the ratio is vital for calculating both the cost of building dams and their productivity (McJannet et al. 2008). The smaller the ratio, the more efficient the dam is in storing more water and occupying a limited area.

Environmentally, in addition to compromising the biodiversity of a wider area, the larger S2VR of contemporary large dams (≥100 meters high) has significant implications for evaporation and potential emissions. The rate of evaporation of water from a reservoir is directly related to the size of its surface area that exposes more water to the atmosphere. Therefore, the larger this surface, the greater the evaporation rate. Accordingly, a percentage reduction in the surface area can cause an equal percentage point reduction in the evaporation volume of the water (McJannet et al. 2008).

In total, evaporation from reservoirs causes a 5% loss of the total river flows, which is more than industrial and domestic water consumption combined (Shiklomanov 2000). More evaporation in already shallow reservoirs further reduces the volume of water and hence causes a reduction in water release (Graf 1999). Technically, the productivity and efficiency of dams can be increased by preventing more evaporation by increasing the depth and reducing the surface areas of reservoirs (McJannet et al. 2008).

The second ecological ramification of the contemporary reservoirs with large S2VR is related to more GHG emissions. Larger ratios mean more emissions of greenhouse gases per kWh than reservoirs with smaller ratios—reservoirs built in canyons that flood smaller areas (Louis et al. 2000; Rudd et al. 1993). Accordingly, the depth of the reservoirs is one of the main variables used for setting the hydraulic habitat goals for a reservoir (Henriette and Smith 2008), which reduces the ebullition-based emission of methane (McGinnis et al. 2006; West et al. 2015). On the other hand, studies suggest that less hydrostatic pressure can stimulate the drawdown pathway of GHG emissions (Ligon et al. 1995). However, the shallow structures of the reservoirs created by contemporary major dams indicate less hydrostatic pressure.

5.0 Conclusions

At the end of the 20th century, countries had a choice to either rely on large dams or adopt new alternative approaches to satisfy their energy and water-related wants and needs. The first approach is justified and founded on the utilitarian logic of economic development, while the alternative path is based on the logic of sustainability. From this debate, a global consensus emerged that advocated for transforming the large dam industry into one that was both sustainable and inclusive through the diversion of large projects, towards a focus on small initiatives. However, after two decades, it became clear that this is not what happened. Unlike the expectations, the large dam industry did not cease to exist in the 21st century but rather re-emerged with a new face. In the 21st century, countries, mainly in the Southern Hemisphere, have chosen to follow the "hard path" laid out and paved by the developed countries in the Northern Hemisphere during the 19th and 20th centuries. In addition to those that have already been built, thousands of new large dams have been planned or are already under construction throughout the developing world.

These countries have resorted to building large dams of unprecedented magnitude (≥100 meters high). These dams are unprecedented in size/height. It is due to the heavy-duty function that these dams perform. Such function includes embanking rivers in flat terrain, thereby creating expansive and shallow reservoirs with wider surface areas, limited capacity/volume, and larger Surface-to-Volume Ratios. These attributes, which are specific to large dams built in the first two decades of the 21st century, have ecological and sustainability-related significance.

While countries have primarily been driven by the utilitarian logic of building large dams, they have simultaneously ignored the consideration of the severe environmental and ecological costs associated with such endeavors. In the Anthropocene age, it is imperative to scrutinize the environmental and ecological ramifications of contemporary large dams to re-evaluate their sustainability and efficiency.

Acknowledgements

This work was part of my Ph.D. dissertation that the Graduate School-Newark of Rutgers University partially funded under its Dissertation Fellowship program.

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