An Enhanced Inventory of Global Dams and Reservoirs And Their Contribution to Sea Level

by

Blake Allen Walter

B.S., Kansas State University, 2016

A THESIS

submitted in partial fulfillment of the requirements for the degree

MASTER OF ARTS

Department of Geography
College of Arts and Sciences

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2018

Approved by:

Major Professor
Dr. Jida Wang

Copyright

Abstract

In the 1950s-60s, the world was experiencing a dramatic increase in artificial water impoundments in an unprecedented effort to eliminate spatial and temporal variations in water accessibility. Dam construction has since decreased, but recently, efforts to supply water and power to a booming world population may once again spark another dam construction boom. Water supplies in some regions are already highly stressed in an effort to satisfy the ever-growing water demand for agriculture, industrial, and domestic uses. With nearly 30% of the world's population living in water-scarce regions, an improved understanding of total stored surface water has never been more needed. Yet, a complete and spatially-explicit, worldwide inventory of such storage capabilities is lacking. Using several open-source dam registries and high-resolution global lake mapping datasets extracted from thousands of Landsat images, we here aim to provide an updated and spatially-explicit inventory of dams and artificial reservoirs across the world.

The following research uses novel techniques to merge 5 authoritative, open-source dam registries into a single dam and reservoir dataset, which we deemed as the Global Dam and Reservoir Inventory (GDRI). In total, GDRI documents 89,500 dams and 83,767 reservoirs for a total capacity of 8,492km^3 and total surface area of 754,551km^2. Reservoirs account for approximately 2.5% of the Earth's terrestrial water. In other words, 1 unit of water for every 40 units has been artificially created. Further downscaling of the non-geocoded records provided by the International Commission of Large Dams (ICOLD) using similar geocoding methods allowed for the thorough use of all available ICOLD records. Additional capacity estimates from downscaled ICOLD records increased the GDRI capacity documentation to 8,603km^3 and surface area documentation to 859,271km^2. Compared to its counterpart, the Global Reservoir and Dam dataset (GRanD), GDRI increased the number of dams documented by 1204%, reservoirs by 1127%, total capacity by 37%, and total surface area by 68%.

Initial water impoundment from dam construction activities can lower sea level by permanently trapping water storage on land. Dam construction resulted in an equivalent sea level drop (SLD) of 23.4mm or 0.08mm/yr. Since the dam construction boom of the 1950s-1960s, yearly SLD increased to 0.27mm/yr. By considering the hydrological characteristics of dam location, in terms of endorheic and exorheic basins, we found that exclusion of endorheic located dams

decreases the overall effect on SLD by 5.47% or 1.28mm. Failure to consider the hydrologic characteristic of dam location can result in the overestimation of dam-induced SLD.

After the dam construction boom of the 1950s-1960s, the world has seen a decreasing trend in dam construction, but developing countries (China, Brazil, India) are still actively pursuing dam projects that are larger and more ambitious than ever before. We see less developed countries often lack the capabilities for dam construction possibly increasing stress on natural water supplies in those regions.

The datasets produced are by no means perfect. Overall, the described procedures should be considered a heuristic model, where fastidious quality assurance and automated procedures work to thoroughly eliminate many of the issues encountered with the dataset production, but errors may still exist. However, duplication between the contributing dam datasets, spatial limitations of the lake datasets, imperfect geocoding procedures, and inclusion of more dam datasets provide opportunity for future refinement and improvement of the datasets.

This research contributes vital information about anthropogenic water resources that incrementally enhances our knowledge of global hydrology and the interactions taking place between different water entities.

Table of Contents

List of Figures

List of Tables

Acknowledgements

Every good gift and every perfect gift is from above, coming down from the Father of lights with whom there is no variation or shadow due to change. – James 1:17

I want to first thank God for providing me with this wonderful opportunity to learn amongst scholars and friends; for instilling in me the patience, determination, and work ethic I needed. This whole experience has allowed me to cultivate lifelong friendships with fellow graduate students and faculty. I have been able to expand my knowledge of culture far beyond that which was North Central Kansas and make connections with friends from all over the world. For this, I want to thank my fellow graduate students and I am forever thankful.

The Department of Geography, here at Kansas State University, has helped me develop into the young professional that I desired to be when I accepted this position. I must thank the entire Department of Geography faculty and staff for preparing and teaching me in a way that set me apart from my peers.

To Dr. Jida Wang, thank you for being an overall outstanding teacher, mentor, and friend. I owe this entire work to your incredible support and expertise. I could always, no matter the problem, count on your help and advice. I want to thank you for challenging me and pushing me to solve problems that may have been beyond my knowledge. It was here, where I learned to problem solve and become self-sufficient. Thank you.

Lastly, I want to thank my family and my loving wife for the support throughout all my years of schooling. Nicholle, you have consistently been there for me, literally…we ride to school and eat lunch together every day. I can't tell you how much I will miss that! Thank you for keeping me grounded and focused, all while putting up with my shenanigans at the same time. I love you.

Chapter 1 - Introduction

1.1 Introduction

In the 1950s-60s, the world was experiencing a dramatic increase in artificial water impoundments in an unprecedented effort to eliminate spatial and temporal variations in water accessibility (Oki and Kanae 2006). Dam construction has since decreased, but recently, efforts to supply water and power to a booming world population may once again spark another dam construction boom. Dams have been constructed for centuries in order to provide water to regions experiencing highly variable water supplies. The United States alone has constructed nearly 84,000 dams in response to increased water demands from a growing population and economy (NID 2013). Artificial water impoundments, also known as reservoirs, are the direct result of dam construction. The resulting reservoir created from the backflow of water serves a variety of purposes including river transport, hydroelectricity, water supply, irrigation, flood control, and recreation (Baxter 1977).

1.1.1 Benefits of Dams and Reservoirs

Today, dams and reservoirs are an essential part of society and their role will continue to increase as population and economies increase. The United States Army Corps of Engineers (2016) reported 68,153,794 tons of cargo passing through the lower lock and dam of the Upper Mississippi River near St. Louis, Missouri. Compared to semi-truck transport, this amount of cargo shipped downriver by barges equates to an estimated cost savings of $3 billion. Without dams to regulate the seasonal flow downstream, river transport would not be possible year around. Hydroelectricity is seeing a resurgence in popularity. Strained electrical grids from growing populations coupled with policymakers pushing to combat climate change with renewable sources of energy, has resulted in 3,700 proposed dam projects which are expected to increase the global hydropower capabilities by 73% (Zarfl et al. 2015). One of the most important services provided by dams and reservoirs includes supplying a year around source for drinking water, household and industrial uses, and cropland irrigation to locals and the surrounding farmland. Considering that irrigation accounts for 85% of total human water use, which in turn produces nearly 40% of the world's crops, these services provided by dams and reservoirs are vital (Gleick 2003, Rosegrant, Ringler and Zhu 2009). Irrigation practices use a combination of renewable, above-ground water and non-renewable groundwater resources. Since 1960, total irrigation demands that rely on non-renewable water resources has nearly tripled to 20% (Wada, van Beek and Bierkens 2012). Groundwater is such a major contributor to food production that approximately 11% of international food trade is produced from non-renewable water resources (Dalin et al. 2017). Without irrigation practices, production of staple food crops could decrease as much as 60%, and production of grains, such as cereal could decrease as much as 20% (Siebert and Doll 2010). Some areas of the world, where renewable water is highly variable and often scarce, excessively pump non-renewable groundwater to supplement the water shortage needed for drinking and irrigation (Wada, Wisser and Bierkens 2014, Famiglietti et al. 2011, Russo and Lall 2017). This unsustainable dependence on groundwater could cause major depletions of the world's large aquifers, which could, in turn, shift global water dependence towards renewable reservoirs water supplies. Already there has been an enormous increase in irrigation that is dependent on water stored in reservoirs. Biemans et al. (2011) reported that irrigation from reservoirs increased from 18km^3/yr to 460km^3/yr over the 20th century. This trend will likely continue to increase as agriculture operations expand to feed the growing population.

The concern of water security continues to grow as water demands from the booming world population continue to escalate. Water availability is already a real threat to approximately 2.4 billion people who live in highly water-stressed areas (Oki and Kanae 2006). Even more startling, Vorosmarty et al. (2010) noted that roughly 80% of the world population's water security is highly threatened due to increasing anthropogenic demand and degrading environmental conditions. As the world population's need for water continues to increase, people progressively look towards these man-made water storages for relief. Yet, a complete, spatially-explicit, and quantitative understanding of global artificial water storage capabilities is entirely missing. Without this knowledge, water managers and policymakers have limited ability to effectively plan and budget for future water uses.

1.1.2 Environmental Impacts

Dams and reservoirs are both beneficial and highly necessary for many areas of the world, but their existence can greatly affect the surrounding environment and even alter local climate patterns (Carpenter, Stanley and Vander Zanden 2011, Degu et al. 2011). The introduction of a dam has major ecological implications on both upstream and downstream river segments. Nutrient and sediment transport, fish migration, and frequency of natural flood events become greatly reduced or completely prohibited with the introduction of a dam (Nilsson and Berggren 2000). Dams can efficiently trap up to 80% of incoming sediment from river inflow leading to severe downstream environmental consequences such as increased erosion, nutrient deprivation, and contribution to the loss of river delta formation (Vorosmarty et al. 2003). Riparian plant composition can even become highly modified within a regulated river system. Jansson, Nilsson and Renofalt (2000) found that non-floating seed dispersal was greatly reduced on dammed river systems versus free-flowing rivers systems. Studies conducted on large dams proposed for the Andean region revealed that sediment supplies to the Amazon Basin could be reduced up to 64%, seasonal flood stages altered up to 37% of peak flood height, and downstream annual fish yields reduced by 88% (Forsberg et al. 2017). Similarly, Gupta, Kao and Dai (2012) have shown that large dams constructed on major rivers in southeast Asia and India have caused at least a 75% reduction in annual average sediment load in the last 70 years.

When considering new dam construction, environmental impacts of dams are often overlooked or completely ignored, but Han, Kwak and Yoo (2008) emphasize the importance of analyzing the cost in economic benefits lost by dam-induced environmental change. For instance, the Three Gorges Dam is the world’s largest dam. With a height of 185m (607ft) and length of 2,335m (7,660ft), the dam created a reservoir approximately 600km (375mi) long with a capacity of 39.3km^3, enough water to generate 22,500mW of electricity (Britannica 2018). The creation of the controversial dam came with benefits of electricity production and flood control, but also with evident drawbacks as 1.3 million people would be displaced and expected environmental consequences would incur. However, the magnitude of these environmental impacts are now becoming clear as loss of fish habitat, severe erosion, toxic algae blooms, and degraded water quality are forcing Chinese officials to invest in a $26.45 billion, 10-year mitigation effort to help relieve some of these unexpected issues (Stone 2011).

Past and present consequences of dam construction have some calling for policymakers to carefully analyze and consider potential human, environmental, and economic impacts of dam construction (Latrubesse et al. 2017). To do this, a thorough understanding of where dams and reservoirs are currently located could help inform decision makers on the immediate and future upstream and downstream impacts, which can lead to more sustainable dam construction practices.

1.1.3 Economic & Social Impacts

By 2040, world electrical demand is anticipated to grow by more than 40% (IEA 2017). To supplement these energy needs in a sustainable manner, policymakers often default to hydropower as the answer. However, the cost of large dam projects is frequently underestimated. Analysis of past dam projects has shown that large hydropower projects built in every region of the world have suffered cost overruns with a mean cost overrun of 96% (Ansar et al. 2014). On average, this equates to cost overruns of $800,000 to $1.3 million per installed mW of energy. It is suggested that developing countries pursue smaller, alternative means to energy production such as wind and solar, which can have much lower cost overruns (under $250,000), and assume less environmental, social, and economic risk (Sovacool, Gilbert and Nugent 2014, Ansar et al. 2014). Without taking into consideration environmental and social effects, these economic cost overruns can be seen as a worthwhile investment over time. Awojobi and Jenkins (2015) found that 78% of the 58 hydropower projects analyzed experienced cost overruns, equivalent to a 27% increase in initial cost estimate when scaled to cost per megawatt of energy produced. However, over the life of the dams, a net economic present value of $913 billion has been generated due to the avoidance of fossil fuels for energy production.

Running costs, maintenance, and unforeseen issues over the life of the dam can place a financial burden on the agencies or governments in charge of dam operations. Sedimentation, one of the major drawbacks of dam construction, can decrease overall reservoir capacity, reduce water quality, and increase downstream hydraulic processes, specifically erosion (Rahmani et al. 2018). Reducing the amount of sedimentation is vital for the longevity of the reservoir. Sedimentation in Kansas has resulted in a 17% decrease in overall storage capacity for 26 federally managed dams (Rahmani et al. 2018). Efforts to reduce years of sedimentation, like dredging, are expensive with often only negligible improvements observed. In 2013, a $49 million dredging operation aimed at restoring 0.010km^3 (16% of the original capacity) of storage in John Redmond reservoir was proposed by the United States Army Corps of Engineers (USACE 2013). The marginal improvement in storage resulting from the proposed dredging operation makes it clear that dredging is not a realistic solution and alternative solutions must be considered. Certain solutions include a holistic approach in the planning phases that considers reducing sediment production in the upstream catchment, in the reservoir, and at the dam. Specifically, increasing vegetation both in the upstream catchment and within the reservoir, creating bypass tunnels for sediment flows downstream, sluicing, and drawdown flushing are a few alternative, cost-effective methods that have been proposed (Kondolf et al. 2014, Schleiss et al. 2016).

The subsequent flooding of the reservoir will inevitably disrupt and displace hundreds or thousands of indigenous people living in that valley. Displaced people will be provided a resettlement package that includes compensation for their land, new housing, and other losses accrued by displacement. Often, these displaced people have a hard time coping with the loss of their livelihood and emotional attachment to their native land (Ledec and Quintero 2003, Tilt, Braun and He 2009). The World Commission of Dams (2000) estimates that 40 to 80 million people have been displaced due to dam and reservoir construction.

1.1.4 Role in Sea Level

While the world population continues to manipulate the terrestrial hydrological cycle to satisfy increasing water demands, the earth's oceans are conversely experiencing a persistent rise in sea level. Global sea level rise (SLR) is one of the most prominent research topics within the scientific community. SLR estimations using altimetry data in the past two decades indicate an increase of 3.3 ± 0.4mm/yr^{-1} (Cazenave et al. 2014). N.R.C. (2012) extrapolated SLR estimates into the future using various model results and observations. The authors predict sea levels to rise 18-48cm by 2050 and 50-140cm by 2100. These SLR estimations are alarming considering that approximately 10% of the world's population live in regions less than 10m above sea level (McGranahan, Balk and Anderson 2007). Anthoff (2006) modeled coastal impacts with a projected SRL of 1m over the next century. He found that of all the land threatened by SLR, 25% of the threatened land occurs in North America, while the population in South (38%) and East Asia (34%) is affected the most. Contributions to SLR are primarily caused by two factors, both the result of climate change: 1). warming of the ocean's temperatures, and 2). melting of glaciers and ice sheets (Domingues et al. 2008, Jacob et al. 2012, Church 2011). However, Chao, Wu and Li (2008) and Wada et al. (2017) noted that the impoundment of terrestrial runoff in reservoirs retains water storage, which otherwise, would end up draining to the ocean, and thus partially counteracting the contributions of thermal expansion and melting of glaciers and ice sheets to SLR. The magnitude of this counteraction could be more accurately estimated with a better understanding of the distribution of dams and reservoirs.

1.2 Background

Water is an essential resource. Not only is water vital for basic human survival, water is necessary for plants and animals to survive, which in turn, provide the human race with a source of energy. The reliance upon water for survival by nearly every living organism reaffirms that water is one, if not *the* driver of life on Earth. Yet, our knowledge of global water availability is limited and largely incomplete (Lehner and Doll 2004, Lehner et al. 2011). Perhaps the reason for this deficiency in knowledge stems from the highly variable nature of water, both temporally and spatially (Oki and Kanae 2006). Since the earliest civilizations, humans have been attempting to suppress and control the spatial and temporal variability of water through the construction of dams and subsequent creation of large reservoirs. The earliest dams were thought to have been constructed for crop irrigation practices, flood control, and water supply. Over the course of a couple of centuries, the use of dams has expanded to include hydroelectricity and recreation (Chao et al. 2008, Baxter 1977). To date, the magnitude at which water is artificially impounded is unknown. Chao et al. (2008) noted that total reservoir capacity estimates are highly variable ranging from less than 4,000km^3 to 15,000km^3. Chao et al. concluded total water storage to be at 8,300km^3. Other well-known studies such as Lehner et al. (2011) estimated total reservoir storage capacity at 6,200km^3, while Vorosmarty et al. (2003) estimated 7,000km^3.

1.2.1 Dam and Reservoir Mapping

Several efforts have been made to compile existing dam and reservoir data in an attempt to develop a global dataset. However, many of the datasets are incomplete, restricted to a specific region, or limited to large reservoirs. Additionally, some of the dam datasets available lack spatial information that is vital when attempting to map dam location. One of the first global reservoir databases produced was the Global Lakes and Wetlands Database (GLWD). This database was compiled using several other datasets, including the Digital Chart of the World (ESRI), ArcWorld (ESRI), and Wetlands map of the World Conservation Monitoring Center (WCMC) (Lehner and Doll 2004). Mapped global lake, reservoir, and river area totaled 2.7 million km^2. However, they were only able to account for 654 large reservoirs worldwide. This dataset has been widely used, but is now considered insufficient and outdated due to improvements in available datasets and the development of new, more complete datasets. Following GLWD, Lehner et al. (2011) produced the Global Reservoir and Dam (GRanD) database. Primarily using dam records provided by

AQUASTAT (FAO 2016) and supplemental dam attribute information documented by ICOLD (ICOLD 2016), Lehner et al. mapped 6,862 dams and their associated reservoirs. This dataset is still widely used today and considered to be the most complete global reservoir datasets available. On a regional scale, Yang and Lu (2013) conducted an extensive lake segmentation and classification on the Yangtze River Basin in China. Using remote sensing, available online sources, and visual interpretation, they were able to delineate and classify 43,600 reservoirs and 42,700 natural lakes. Their results document over 7 times more reservoirs in China alone than Lehner et al. (2011) documented on a global scale. The sheer difference in the number of lakes documented by Yang and Lu (2013) to Lehner et al.'s (2011) global dataset is a testament to the improvements that need to be made in respect to global dam and reservoir datasets.

While there are several global lake datasets available (Verpoorter et al. 2014, Cael, Heathcote and Seekell 2017, Messager et al. 2016, Feng et al. 2016, Lehner and Doll 2004), a complete and exhaustive global reservoir/dam dataset is lacking. Many of these datasets are either limited to regional areas (Ran and Lu 2012, Yang and Lu 2013, Cai et al. 2016), or are highly incomplete at the global scale (Lehner and Doll 2004, Lehner et al. 2011). The scientific community would benefit greatly from the completion of a new and comprehensive dataset that encompasses the entire earth and a large majority of its reservoirs.

1.2.2 Global Sea Level Effects

Global SLR is a high priority topic in the scientific community. In the past two decades, Cazenave et al. (2014) estimated that sea levels have risen at approximately 3.3 ± 0.4mm/yr. Thermal expansion is the primary contributor to SLR accounting for approximately 1.5mm ± 0.4 mm/yr. or one-half of the total SLR (Church and White 2011, Domingues et al. 2008). Over time, the gradual rise in sea level is estimated to be 18-48 cm by 2050 and 50-140 cm by 2100 (Cooper et al. 2013). Extreme rises in sea level can have devastating effects on people living near coastal areas. Direct flooding by ocean tides or surges, indirect flooding, saltwater intrusion, and several other hazards could potentially affect 10% of the world’s population that currently resides in low-lying coastal areas (Cooper et al. 2013, McGranahan et al. 2007).

While melting glaciers and thermal expansion contribute to SLR, artificial water impoundment can actually counteract these contributions by causing sea level drop (SLD). Using 29,484 dam records reported in the ICOLD dataset, Chao et al. (2008) summed the reported reservoir capacity to determine the total nominal global reservoir capacity to be 8300km^3. By including a subsurface seepage rate equivalent to 5% of the reservoir's capacity along with the nominal above ground capacity, Chao et al. determined total artificial water capacity to be 10,800km^3, which contributed 30.00mm or 0.55mm/yr. to SLD. Using Gravity Recovery and Climate Experiment (GRACE) terrestrial water storage anomalies, Pokhrel et al. (2012) modeled artificial water impoundment capacities, and taking into account a realistic reservoir storage of 70% of 85% of the maximum capacity and a 5% water seepage rate, they estimated SLD contributions to be 21mm. Most recently, Wada et al. (2017) utilized an updated version of the ICOLD database of 48,064 records to find a combined capacity of 7,968 km^3. Using the same seepage rate (5%) as Chao et al., the total capacity for artificially stored water was found to be 10,416km^3 or equivalent to 28.9mm SLD.

The aforementioned studies help researchers understand that other contributors to global sea level rise may be of greater magnitude than previously thought due to the lag in sea level rise caused by artificial water impoundments. However, the estimates of the contribution to global SLD derived from these studies could be improved with the implementation of a more comprehensive dam and reservoir datasets that takes into account spatial location and small reservoirs.

1.3 Statement of Problem

Currently, a comprehensive database documenting the existence of dams and reservoirs, their spatial characteristics, and attribute information is lacking (Chao et al. 2008, Lehner et al. 2011). In response to this deficiency in knowledge, there have only been a few notable databases compiled that attempt to document the extent and distribution of dams and reservoirs. Most recently, Lehner et al. (2011) developed a high-resolution Global Reservoir and Dams (GRanD) database documenting 6,862 dams and their associated reservoirs. However, this dataset is incomplete and does not account for reservoirs smaller than 0.1km^3. The dataset is also limited by the completeness of the sourced dam datasets such as the International Commission on Large Dams World Register of Dams (ICOLD) database (ICOLD 2016), which is considered the most complete global dam registry. GRanD only accounts for the large dams around the world while failing to provide spatial extents and information of smaller dams. The lack of spatial information for small dams only allows researchers to provide rough estimates on the number of reservoirs smaller than 0.001km^2. The effect on SLD attributed by these undocumented small lakes could be considerable and should be considered in global analyses (Downing et al. 2006). Most studies have only extrapolated the number and capacity of small reservoirs during analysis (Chao et al. 2008, Lehner et al. 2011). These projections can vary greatly and severely underestimate the magnitude of contribution for small reservoirs.

Another aspect regarding the spatial locations of reservoirs that further complicate the accuracy of the aforementioned results is the exclusion of endorheic and exorheic lake classification. Lakes found within an endorheic watershed will not affect SLD. Instead, water found within endorheic watersheds will remain landlocked and; therefore, would not flow to the ocean. Without these important considerations, SLD estimates provided by Chao et al. (2008) and Wada et al. (2017) may have overestimated the cumulative effect of reservoirs on SLD.

The importance of enhancing global dam and artificial lake documentation is two-fold: 1) estimates of total water volume impounded can be more accurately derived, informing the scientific community of artificially stored water availability; 2) the contribution to global sea budget can more accurately be estimated with a more complete global reservoir database that accounts for small reservoirs and spatial location.

1.4 Research Objectives

The research conducted here has the following objectives and expectations:

1) Document and inventory the spatial extent and volume of dams and reservoirs on a global scale, while also retaining key attribute information. This research is estimated to produce a global dam and reservoir dataset that documents more dams and reservoirs, total surface area, and total volume than documented by the GRanD dataset (Lehner et al. 2011).

2) Construct the historical trajectory of the net contribution of artificial impoundment to global sea level while accounting for endorheic and exorheic basins. Dam-induced sea level effects are anticipated to be greater than those predicted by Chao et al. (2008).

1.5 Improvements to Current Research

Again, knowledge pertaining to our global water resources, especially the spatial locations of dams and reservoirs is lacking considerably. The GRanD and GLWD datasets are one of the only datasets available that attempt to spatially document dams and reservoirs on a global scale. The incompleteness of these datasets is evident when compared with existing, open-source dam registries. For instance, GRanD only documents 6,862 reservoirs worldwide while the most recent ICOLD contains 59,218 registered dam records. According to the 2013 National Inventory of Dams (NID 2013), the United States alone contains 74,097 dams. There is a clear shortfall in our ability to document our artificial water resources globally. By utilizing a new high-resolution global lake dataset (Sheng et al. 2015, Wang et al. 2015, Wang et al. 2016), NID dataset, ICOLD dataset, and several other dam/reservoir datasets, spatial documentation of artificial reservoirs could be vastly improved.

The major issue with the GLWD and GRanD datasets is the lack of small-to-medium sized reservoir documentation. The GRanD dataset, in particular, only documents lakes >10ha and extrapolates the number of small reservoirs present using models. These small reservoirs are estimated to outnumber large dams by tenfold, and with arid regions, such as areas in India and Africa, experiencing increases in small dam construction between 60% and 900%, it is important to document this integral part of the hydrologic cycle (Downing et al. 2006, Hughes and Mantel 2010, Carpenter et al. 2011). Since the release of the GRanD dataset, more comprehensive and complete dam datasets have become available, which can be used to improve the documentation of small-to-medium sized dams and reservoirs. The research conducted here integrates several current, open-source dam datasets into a single dam and reservoir dataset. Additionally, these new and improved datasets document small-to-medium reservoirs, which are often excluded from past datasets and could have a substantial impact on total capacity and SLD estimates.

As mentioned earlier, both Chao et al. (2008) and Wada et al. (2017) fail to consider the spatial locations of the dams with respect to their hydrologic basins when estimating water impoundments effect on SLD. A spatially explicit dataset allows for the consideration of this spatial phenomenon, which may reduce the overall effect of water impoundments on SLD. This consideration will not only provide more realistic SLD effects, but also demonstrate the importance of the confined endorheic hydrologic cycle in future estimates.

The datasets produced here have the ability to provide the scientific community as well as the society with vital information concerning artificially impounded water bodies and dams that have been overlooked for decades. With increased global coverage and documentation of artificial reservoirs, it is hoped that the results produced from this research will help water managers around the world budget stored water reserves with greater efficiency in order to preserve water supplies into the future. A better understanding of artificial water impoundments effects on sea level budget will aid in researchers reevaluating the magnitude of major contributors to SLD, such as thermal expansion of the oceans or the melting of the ice caps and glaciers.

The results are a step in answering some of the many water-related issues faced today. It is hoped that the findings produced in this research will result in a significant contribution to the scientific community and society as a whole.

Chapter 2 - Methods & Analysis

2.1 Data Acquisition

2.1.1 Dam Datasets

The creation of an exhaustive and spatially-explicit global dam dataset required several, authoritative dam datasets to ensure complete coverage around the world. A total of 5 datasets were used in this study (**Figure 2.6, Step 1**). Each dataset was carefully considered for accuracy and completeness and subsequently found to be the most comprehensive open-source datasets available. These datasets are primarily dam registries constructed on a volunteer basis by government entities and authorities. In total, these datasets provide attribute information to 155,712 dams, but spatial location to only 90,452 dams worldwide. Two of the 5 datasets used contained non-spatial dam records (**Table 2.1**).

One of the datasets lacking spatial information is the World Register of Dams (hereafter referred to as ICOLD), which is produced by the International Commission of Large Dams (ICOLD 2016; http://www.icold-cigb.org). ICOLD is considered to be the most “complete” global dataset, but only to the extent of contributions from willing countries and water authorities. This dataset documents 59,218 dams with a capacity greater than or equal to 1 x 10^{-6}km^3. While this dataset has been used extensively for hydrological research in the past (Chao et al. 2008, Wada et al. 2017), the potential of this dataset has been stunted by a lack of spatial coordinates for all dam records. The complete acquisition of spatial coordinates for the ICOLD dataset has not yet been successfully accomplished.

The second dataset with spatial information absent, the AquaSTAT dataset (hereafter referred to as FAO), only partially lacks spatial information. This global dataset is produced by the Food and Agricultural Organization (FAO 2016; http://www.fao.org/NR/WATER/aquastat/dams/index.stm) and contains records for 14,698 dams with capacities greater than 5 x 10^{-7}km^3. Of these, 8,656 dams have documented spatial coordinates. Spatial coordinates provided for these dams were determined at a 1:1,000,000 scale (precision = 10”) or 1:250,000 scale (precision = 2”) if able.

The largest dataset used for the study was the National Inventory of Dams (hereafter referred to as NID). This dataset has been produced by the United States Army Corps of Engineers since 1975 and documents a total of 74,096 dams collected from 68 federal and state registries in the United States (NID 2013; http://nid.usace.army.mil/cm_apex/f?p=838:12). Dams included in the dataset are either classified as potentially or highly hazardous, have a height equal to or exceeding 7.62m with a capacity greater than 1.85 x 10^{-5}km^3, or have a height equal to or exceeding 1.82m with a capacity greater than 6.1 x 10^{-5}km^3. NID alone accounts for nearly 75% of the dams documented worldwide.

The Global Reservoir and Dams (GRanD) dataset, created by Lehner et al. (2011), documents 6,862 dams and reservoirs collected from 11 different datasets. The dataset documents dams with a height exceeding 2m or capacity greater than 0.1km^3. This dataset remains the most comprehensive, single most authoritative global dam and reservoir dataset available, and contains spatial coordinates for both dams and reservoirs. These spatial coordinates were provided by contributing datasets and verified using various GIS techniques. This dataset has been extensively applied in hydrological research (Biemans et al. 2011, Zarfl et al. 2015, Wada et al. 2014, Strokal et al. 2016, Ziv et al. 2012).

Lastly, the smallest, dataset used to document reservoirs in Canada is the Canadian Register of Dams (hereafter referred to as CDA), which is created by the Canadian Dam Association (CDA 2016;http://geogratis.gc.ca/api/en/nrcan-rncan/ess-sst/0c78d7fe-100b-5937-b74e-7590a03a6244.html). This dataset is meant to supplement dam documentation in Canada and documents 838 dams at a scale of 1:1,000,000. Finer scales are available, but lack detailed attribute information needed for this study. The 1M CDA dataset was deemed the most suitable.

Table 2.1 Authoritative dam datasets and their spatial and non-spatial records.

Dataset	*Spatial Dam Records*	*Non-Spatial Dam Records*	*Total*
CDA	838	0	838
FAO	8,656	6,042	14,698
GRanD	6,862	0	6,862
ICOLD	0	59,218	59,218
NID	74,096	0	74,096
TOTAL:	90,452	65,260	155,712

Before implementing these datasets in the following procedures, each individual dataset was assessed for duplicated dam records that, if unaccounted for, could exaggerate global capacity estimates. These duplicated dams include dams that are spatially duplicated or dams that are spatially different, but document the same waterbody. While it is possible to have multiple dams existing on a single waterbody, many of these dams report the full capacity of the reservoir. For instance, a waterbody with 5 dams may have the capacity reported 5 different times; thus, reporting a capacity 5 times greater than what actually exists. CDA, ICOLD, and NID were all found to have duplicated dams (**Table 2.2**). An automated process allowed for the comparison, identification, and subsequent removal of duplicated dams within these datasets.

Table 2.2 Datasets total after duplicate identification and removal.

Dataset	*Raw Dam Totals*	*Identified Duplicates*	*Post-Processing Total*
CDA	838	288	550
ICOLD	59,218	1,341	57,877
NID	74,096	1641	72,455

2.1.2 Lake Datasets

To produce a global reservoir dataset using dam location as the sole reservoir identifier, it was necessary to obtain a global lake dataset, from which reservoir extents could be extracted. Thus, the circa 2015 Global Lake Inventory, co-developed by Dr. Jida Wang at Kansas State University and his collaborators at the University of California-Los Angeles, was used to provide a high-resolution coverage of water bodies (Sheng et al. 2015, Sheng et al. 2016, Wang et al. 2015, Wang et al. 2016). This dataset, containing approximately 9.5 million lakes, has been created using thousands of Landsat images to extract water body extents larger than 0.004km^3 (~4 Landsat pixels) around the global continental surface. Landsat images during "steady" climatic periods were selected in order to map the average seasonal extent for each water body (Lyons and Sheng 2018). This dataset has undergone rigorous quality control to assure a high level of accuracy and entirety of the dataset and methods. The full global lake mapping dataset has yet to be released to the public.

In conjunction with the 2015 Global Lake Inventory, the maximum surface water extent extracted from the Global Surface Water dataset, which is produced by the European Commission's Joint Research Center (JRC)(Pekel et al. 2016), was also used to supplement any water bodies potentially missing from the 2015 Global Lake Mapping. Pekel et al. (2016) used the entire Landsat 5, 7, and 8 archives of 3 million images to map the maximum water extents from 1984 to 2015. This high-resolution dataset maps water extents greater than 30m x 30m with less than a 1% false positive rate. While, Pekel's dataset may seem superior and the optimal choice for reservoir extraction, it is our goal to map "normal" reservoir extents. The maximum water extent does not provide realistic reservoir area, as most reservoirs are not kept at maximum capacity. It is this reason why the 2015 Global Lake Inventory will serve as the primary lake mapping dataset for reservoir extraction.

2.2 Dam Dataset Compilation

2.2.1 Dam Location Spatial Offset

All datasets, with exception of ICOLD and nearly half of the records in AquaSTAT, provided spatial coordinates for each dam record. However, spatial locations provided by the datasets are often not exact and spatially offset from the actual dam or reservoir location (**Figure 2.1**).

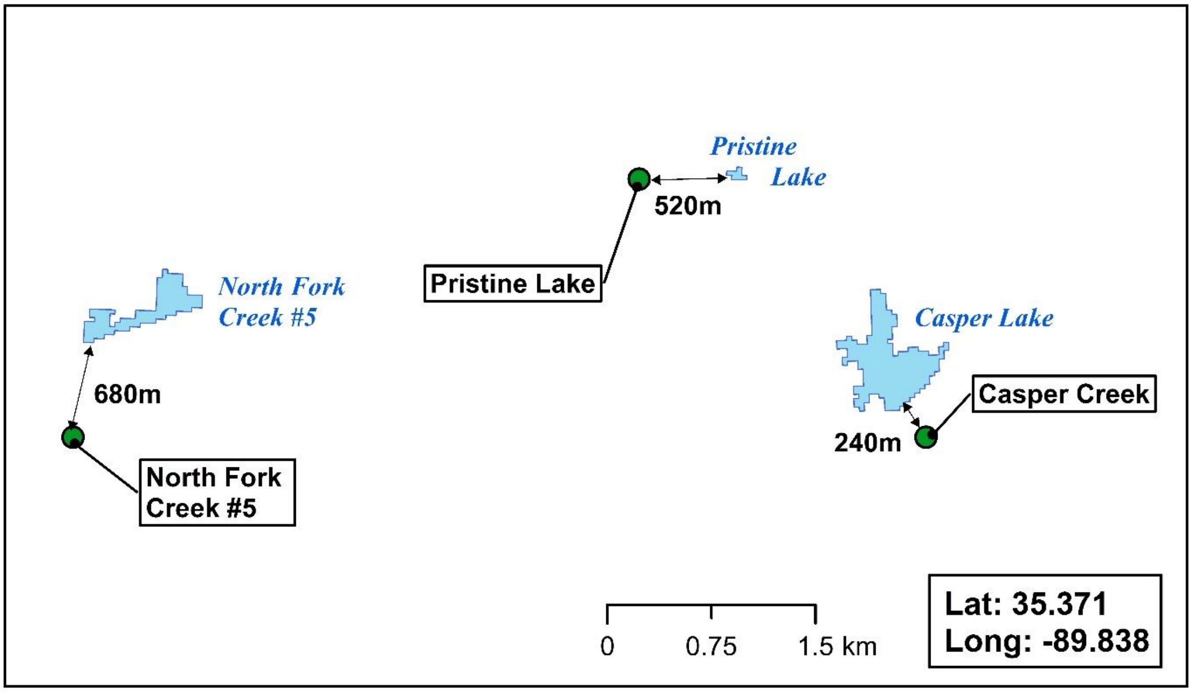


Figure 2.1 Example of spatial offset observed between registered dam points and mapped lake extents. Spatial offset can vary substantially.

In order to ensure the necessary GIS procedures needed to correctly associate the dam with its respective reservoir, a spatial tolerance of 1km was implemented. The tolerance was conservatively chosen based upon a random, visual assessment of dams exhibiting spatial offset.

It was concluded that a 1km tolerance was neither too small to effectively associate dams and reservoirs, nor too large to introduce substantial amounts of error. Therefore, this spatial tolerance is used in all GIS, geocoding, and manual inspection processes throughout the study to enhance the effectiveness of the novel procedures implemented.

2.2.2 Geocoding

Two main issues were encountered during the compilation and production of the global dam dataset. The most challenging issue originated from the lack of spatial coordinates, particularly in the ICOLD dataset. This issue presented a unique challenge of geocoding the dam locations based only upon the qualitative attributes provided. To overcome this issue, a novel geocoding tool was developed by integrating Google Maps Geocoding API and other ArcGIS functions in the Python environment (**Figure 2.6, Step 2**). This tool is able to automatically search specific attributes, or “keywords”, for each dam record and retrieve spatial coordinates. This approach resulted in 44,381 dam coordinates out of the 59,218 records provided by ICOLD. The major drawback to geocoding using keywords was an unknown number of erroneous spatial coordinates. In other words, geocoding the keywords for a particular dam may return a result that is located at the wrong dam, wrong country, or even in an area with no dams present. Because of the ambiguity of the resulting errors, several rounds of systematic, manual inspection were needed to ensure that all geocoded dam locations were valid and as accurate as possible.

The inspection process used dam attribute information, Global Lake Inventory extents, and high-resolution Google Earth images jointly, to validate the geocoded location. Specifically, each dam point was assumed to be associated with the largest water extent provided by the Global Lake Inventory. Then, attribute information (i.e. the name of the dam) for each dam record was cross-referenced to the name of that corresponding water body in the Google Earth Imagery, where it could be determined whether the dam was correctly geocoded. Due to the sheer size of the dataset and limitations of Google Earth, such as language ambiguity and incomplete documentation, it cannot be assumed that geocoded dam points are completely accurate. Therefore, a random accuracy assessment was conducted to validate the geocoding procedures (see **Section 4.2.1**). The novel geocoding techniques implemented here, coupled with an extensive, manual inspection produced 12,357 geocoded dam locations that can be considered correct.

As discussed earlier, the AquaSTAT dataset lacks spatial coordinates for less than half of the records. However, AquaSTAT was not geocoded due to substantial overlap with GRanD. Geocoding AquaSTAT would likely result in large amounts of duplicated data that would inevitably need to be removed later.

2.2.3 Dataset Aggregation

The second issue was the presence of duplicated or spatially associated dam records. The combination of regional and global datasets inevitably produced some overlapping results. In some cases, such as in GRanD and AquaSTAT, similar registries were used to build each dataset; and therefore, result in dam records that have identical coordinates (hereafter referred to as "duplicated"). In other cases, dam location may differ slightly, but is still within the 1km spatial tolerance of each other (hereafter referred to as "spatially associated"; **Figure 2.2**). Lastly, two dams may be distant, but remain in the extent of the same water body (hereafter referred to as "reservoir associated"; **Figure 2.3**). All of these scenarios must be resolved in order for the final dam dataset to exhibit mutual exclusiveness.

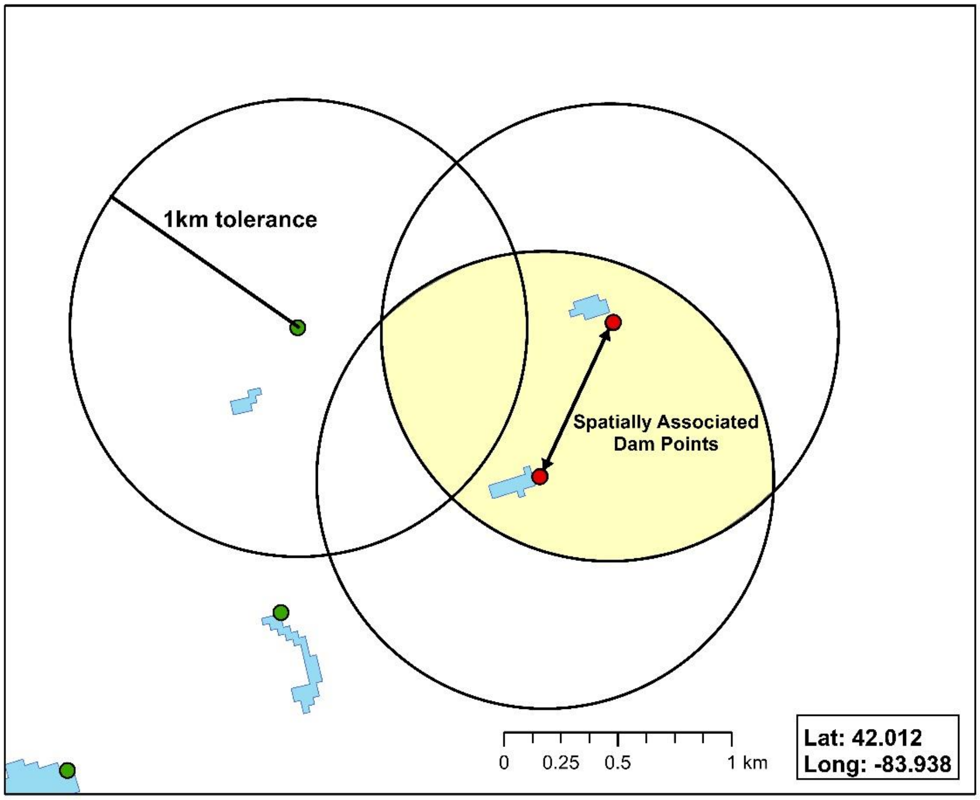


Figure 2.2 Example of a "spatially associated" scenario. Two or more dams lie within the intersected region of the 1km spatial tolerance.

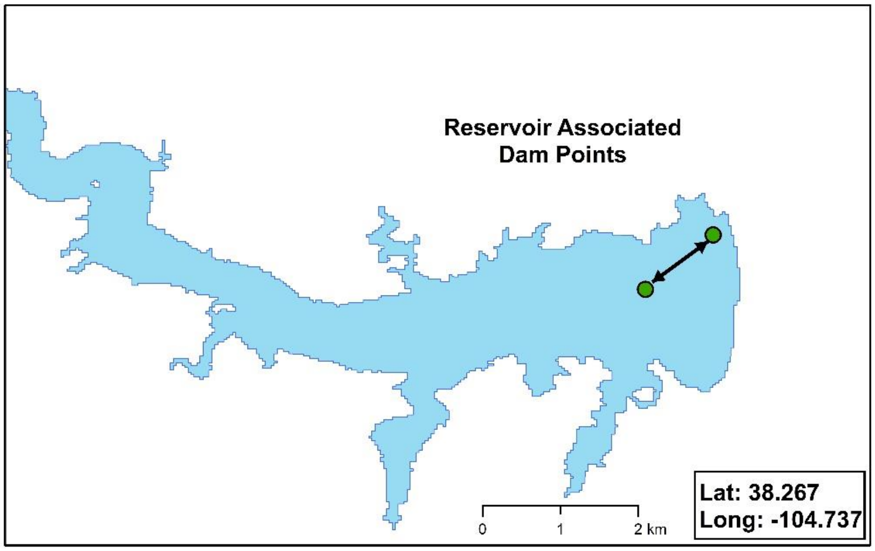


Figure 2.3 Example of a "reservoir associated". Two or more dams lie within the same lake extent.

Several GIS techniques executed with a custom Python tool were used to identify "problem" dams that were 1) duplicated, 2) reservoir associated, or 3) spatially associated (**Figure 2.6, Step 3**). Dams fitting these criteria were marked with unique identifiers. Because some overlapping dam records will certainly be removed in the end, a "hierarchy" must be established to determine which dataset takes precedence over another dataset. This hierarchy ranks datasets based upon the presumed authority, or thoroughness of the dataset, with 1, being the most authoritative, and 5, being the least authoritative. Since regional datasets are likely the most authoritative dataset available for that region, NID and CDA are assigned values of 1 and 2, respectively. Next, AquaSTAT and GRanD receive values of 3 and 4, respectively. And finally, the underlying uncertainty of geocoded dam location qualifies the ICOLD dataset as the least authoritative. It was also determined that dams originating from the same dataset that is spatially associated will not be deleted due to the higher likelihood that each dam documents a different water body. The novel script may not be perfectly robust, but it has identified many of the "problem" scenarios and conflicting situations. After identification of "problem" dams, the final dam dataset resulted in a total of 89,500 dams.

2.2.4 Downscaling of ICOLD

Not all ICOLD records were properly geocoded or retained in the final compiled dam dataset. Of the 59,216 ICOLD records, 49,749 records were not used in the final dam dataset. To fully utilize all ICOLD records and understand their spatial distribution, total global storage capacity, and effect on SLD, these "unused" records were spatially downscaled to a larger spatial scale (**Figure 2.6, Step 4**). Since our geocoding techniques were unable to extract the dam's exact spatial location, these dam records can be downscaled to the next finest administrative unit possible using geocoding methods similar to those described in **Section 2.2.2**. The original geocoding algorithm was modified to use provided spatial attributes such as nearest town, state/province, and country to downscale dam points to their administrative unit. After duplicates, reservoir associated dams, and natural "dam-raised" lakes were removed, these modified geocoding methods resulted in 48,335 downscaled ICOLD records.

2.3 Reservoir Dataset Extraction

2.3.1 Challenges

The newly compiled dam dataset now allows for the subsequent assignment of dams to their respective reservoirs, and the extraction of reservoirs from the 2015 Global Lake Inventory (**Figure 2.6, Step 3**). However, as discussed earlier, the spatial offset presented several additional challenges with dam and reservoir assignment. Assignment of dams and reservoir pairs operated based on a spatial tolerance of 1km. Within the 1km tolerance of each dam, reservoir assignment challenges instigated by the spatial offset are generally caused when, 1) there are more water bodies than dams or, 2) when there are more dams than water bodies. Because the water bodies lack attribute information that could link it to the correct dam, the challenge of dam and reservoir pairing arose. Again, novel procedures were developed to resolve this issue of dam and reservoir assignment. These procedures were founded on several assumptions deemed to be the most logical solutions.

2.3.2 Assignment Scenarios and Assumptions

A novel procedure was automated in the Python environment and applied to cope with the dam and reservoir assignment problems. The procedure consists of three different "rounds" of assignment, each operated on two assumptions described below.

The first assumption maintained that larger water bodies are more likely to be documented than smaller water bodies. This was frequently observed as dams documenting larger water bodies were consistently located on or very near the respective water body (**Figure 2.4**). Cross-referencing registry dam names with reservoir names generated by Google Earth confirmed this assumption to be accurate. Therefore, the first round of dam and reservoir assignment operated by assigning a dam to the largest water body within the 1km spatial tolerance.

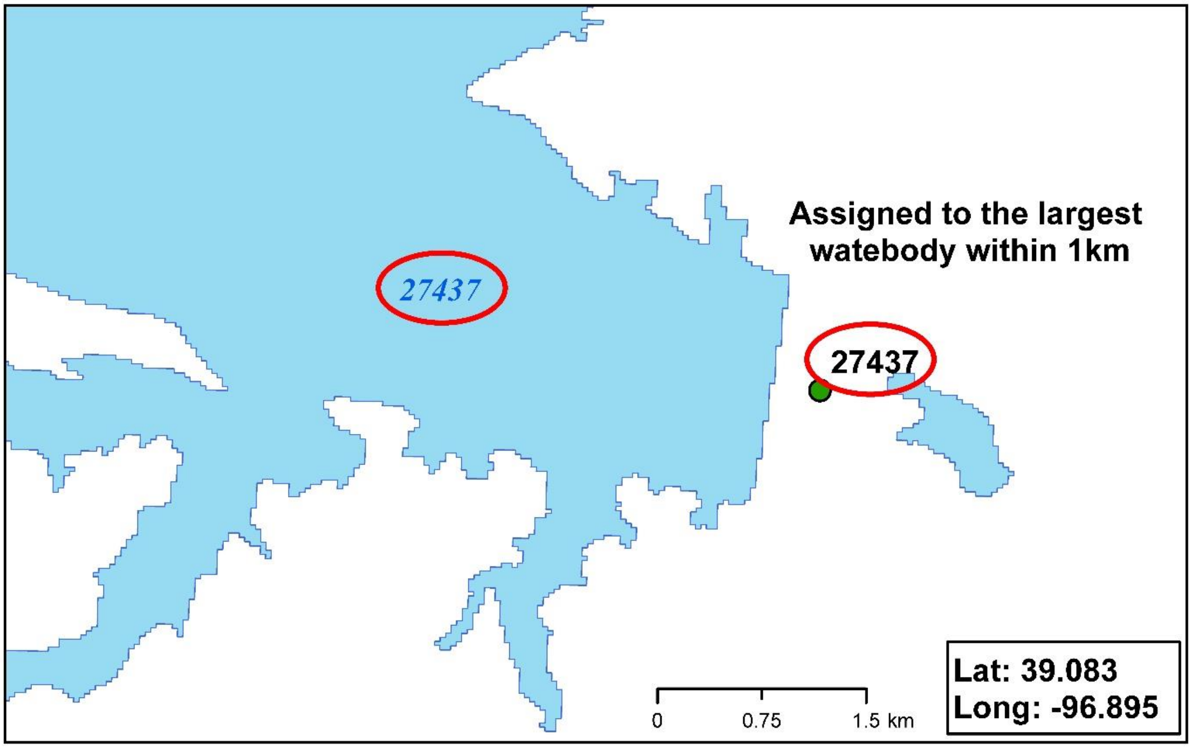


Figure 2.4 Example of Dam/Reservoir assignment. Dams are assigned to the closest, largest waterbody within the 1km spatial tolerance.

The second assumption was established on Tobler's First Law of Geography (Tobler 1970), where "everything is related to everything else, but near things are more related than distant things." Assignment is complicated for dams identified as "reservoir associated" or "spatially associated" (**Figure 2.5**). As a result, the second round of dam and reservoir assignment worked to assign the reservoir to the closest dam identified from a group of "associated" dams. A final, third round of assignment, established again on the Tobler's First Law of Geography, assigned remaining "unassigned" dams to the next closest water body. The last round of assigned aimed to eliminate the number of "orphan" dams or dams left unpaired to a reservoir.

The number of assignment issues is endless. Due to the sheer size of the dataset, it is simply not possible to think of and resolve each possible assignment issue. This novel procedure, founded on robust, logical assumptions, was employed here to maximize the results, while minimizing possible error. Although thorough, the procedure was unable to assign all dams to their respective reservoir. In total, 83,767 water bodies were designated as reservoirs.

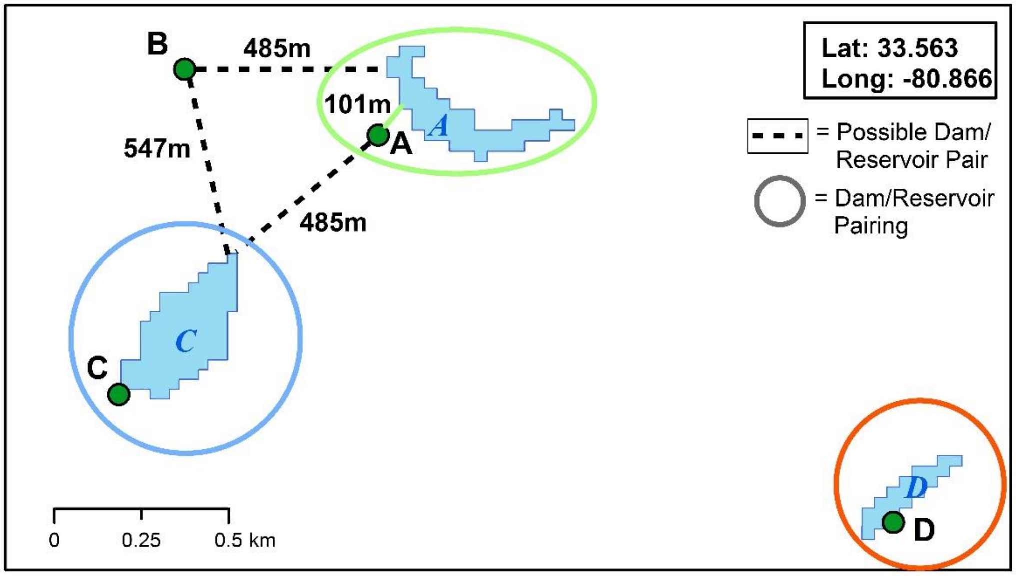


Figure 2.5 Example of a complicated dam/reservoir assignment scenario. Reservoir *A*/Dam A would pair as Dam A is the closest to Reservoir *A* within the 1km tolerance of Dam A. Dams/Reservoirs C & D pair by intersection with the water extent. Dam B is left unpaired.

2.3.3 Supplemental Reservoir Dataset

Limitations related to the spatial resolution of the 2015 Global Lake Inventory resulted in the omission of small or recently constructed reservoirs. This inventory is limited to perennial water bodies larger than 0.004km^3 or 4 Landsat pixels. To overcome this limitation, the JRC’s maximum surface water extent dataset (Pekel et al. 2016) was used. Similar to the assignment process described previously, this dataset was applied to assign the remaining dams to their respective reservoirs. This dataset was especially effective in capturing reservoirs created by dams located on river systems. These dams were considered to have an accompanying reservoir if a substantial backflow of water was evident in satellite imagery. Otherwise, river dams with no apparent reservoir were assumed to be non-storage based regulatory structures.

2.4 Impact to Sea Level

2.4.1 Reservoir Area and Capacity Estimation

The completeness of dam information for each record varies among the original registry sources. In order to develop a comprehensive understanding of how artificial reservoirs affected global surface water budgets, reservoir capacity and area information must be known. In our compiled dam dataset, approximately 800 records (< 1%) were missing capacities and 24,000 records (~27%) were missing areas. Therefore, dam records lacking area or capacity information were supplemented to better understand their hydrologic characteristics (**Figure 2.6, Step 6**).

Area information missing for assigned dam records can be easily supplemented using the corresponding reservoir area provided by the 2015 Global Lake Inventory.

Missing capacities can be estimated using empirical equations calibrated by Lehner et al. (2011). The volume estimation equations are as follows:

$$V = 0.678(A \cdot H)^{0.9229} \qquad 1)$$

$$V = 30.684 \cdot A^{0.9578} \qquad 2)$$

where *V* notates reservoir capacity or volume (in 10^6 m^3), *A* represents reservoir area (in km^2), and *H* represents dam height (in m). Equation 1 has a reported $R^2 = 0.92$ and equation 2 an $R^2 = 0.80$. For each record missing capacity information, capacity is estimated using equation 1 if dam height is documented, or equation 2 if dam height is unavailable.

The uncertainties of estimated reservoir capacities are quantified from the root mean square error (RMSE) of the applied empirical equations:

$$RMSE = \sqrt{\frac{(1-R^2)\cdot\sum(y- \bar{y}^2)}{n}} \qquad 3)$$

where R^2 is the reported good-of-fit for either equation, y any estimated capacity, $\bar{y}$ the average of all estimated capacities, and n the number of estimations.

In total, 560 dam capacities were estimated using the described technique. Specifically, 388 dam capacities were estimated using equation 1, while remaining 172 missing capacities were estimated with equation 2. Of the ~24,000 dam records missing area information, approximately 22,000 of these records were assigned area information based upon the assigned reservoir extent.

2.4.2 Sea Level Contributions

To fully understand the cumulative effects of artificial water storage on the sea level budget, all dams, including non-geocoded, downscaled ICOLD dams, were included. However, use of the downscaled ICOLD dams in this analysis requires special caution as to prevent overestimation of cumulative capacity caused by repeated dam documentation between the downscaled ICOLD and the other datasets. To minimize this issue, cumulative capacity for each enumeration unit (country) of the downscaled ICOLD was subtracted from the non-ICOLD cumulative capacity of the compiled dam dataset for the same enumeration unit. This difference, if positive, would then be considered as additional capacity documentation and added to the overall cumulative capacity of the unit. If negative, then it must be assumed that the compiled dam dataset has already efficiently documented the capacity of that enumeration unit.

Dam-induced change in sea level (mm) can be derived by dividing cumulative dam capacity to the area of the ocean (3.63×10^8 km^2). Yearly sea level impacts can be determined by summing capacities for every reservoir constructed in a given year. These yearly sea level impacts can then be summed to produce a total sea level impact for reservoirs constructed over a specific time period. The location of dams with respect to their specific hydrological basin must be considered in this analysis. Dams and any stored water located within endorheic basins will not contribute to sea level because all water entering an endorheic basin is topographically landlocked; and therefore, any accumulating artificial water storage occurring within an endorheic basin will not contribute to sea level changes. Thus, endorheic located dams should not be considered.

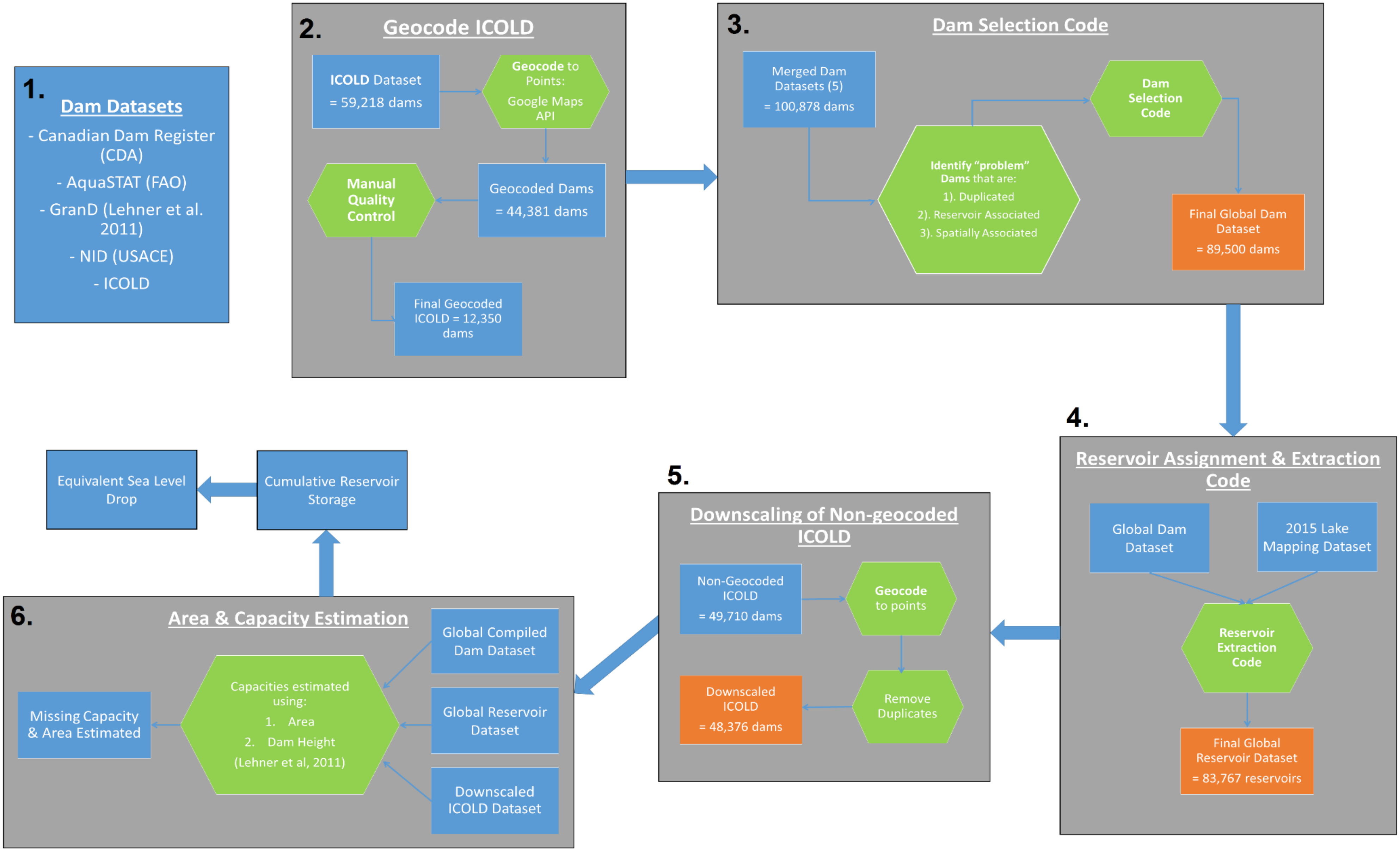


Figure 2.6 Schematic flow chart depicting a six-step procedure for GDRI development and analysis.

Chapter 3 - Results

The following chapter concentrates on addressing the objectives of this research. Data qualities and characteristics of the newly created datasets will be analyzed and comparatively assessed with GRanD. Contributions to sea level generated from GDRI will be reported. Further analysis that extends beyond the research objectives, such that which uses GDRI to understand temporal and spatial characteristics of dams across the world or discussion of dataset limitations will follow in Chapter 4.

3.1 Global Datasets

3.1.1 Dam Dataset

Novel geocoding, compilation, and quality assurance methods applied to 5 authoritative dam registries have resulted in the creation of the Global Dam and Reservoir Inventory (GDRI), which documents 89,500 dams worldwide (**Figure 3.4 (A)**). Reported and derived capacities for GDRI dams total 8,492 ± 280km^3. The dataset accounts for roughly 2.5% (754,551km^2) of the global terrestrial freshwater surface area.

Inclusion of original records in GDRI varied among the contributing datasets (**Table 3.1**). This can partially be attributed to the hierarchy ranking established during the compilation process. Dataset usage was highest with NID and ICOLD at 97.8% and 76.7%, respectively. GRanD record usage was the lowest (9.5%) due to duplication with the higher ranked FAO dataset. CDA and GRanD together only contributed 1.3% of all the records used, while NID, the largest dataset accounted for 81% of the dataset.

Table 3.1 Contribution of each dataset to the final GDRI dam dataset.

Dataset	*Spatial Dam Records*	*"Used" Dam Records*	*Usage Rate*	*% of Total*
CDA	838	550	65.6%	0.6%
FAO	8,656	6,375	73.6%	7.1%
GRanD	6,862	653	9.5%	0.7%
ICOLD	12,350	9,467	76.7%	10.6%
NID	74,096	72,455	97.8%	81.0%
TOTAL:	108,844	89,500	87.1%	100.0%

Reservoir capacities were estimated (see **Section 2.4.1**) for 560 records (0.63% of records), which total 306 ± 280km^3. Estimated capacities represent approximately 3.61% of the total GDRI capacity (**Table 3.2**). Of the 560 estimated capacities, ICOLD accounted for 211 records (37.6%), then followed by NID with 134 records (23.9%). The capacity derivation techniques used were able to estimate ~70% of the missing capacities leaving only 242 GDRI records that were not estimated due to the lack of area information.

Table 3.2 Capacity contribution of estimated capacities.

Registry Capacity	*Estimated Capacity*	*# of Dams*	*% Estimated*	
			of Total Capacity	*of Dam Count*
8,185.8	306.2	560	3.61%	0.63%

Downscaled ICOLD records were not included in the final GDRI dam dataset. Instead, these records were used to help attain a more thorough understanding of cumulative dam capacity and effect on sea level by conservatively applying their attributes to GDRI. Downscaled ICOLD records document a total capacity of 7,031km^3. Differentiation between GDRI and downscaled ICOLD capacities within respective hydrological basins (endorheic vs. exorheic) resulted in a net capacity contribution of 111km^3, a 1.3% increase to GDRI for a total capacity of 8,603km^3 (**Table 3.3**). All downscaled ICOLD contribution occurred in endorheic regions, where downscaled ICOLD records documented more dams than GDRI. Exorheic regions were already well-documented by non-ICOLD GDRI datasets resulting in no additional downscaled contribution. These additional estimates conservatively take into account potential corresponding documentation between downscaled ICOLD and the other datasets used in GDRI, so as to not “double-count” dam capacities already documented.

Table 3.3 Additional capacity documentation derived from downscaled ICOLD points by hydrological basin.

	Total Capacity (km^3)			
Basin	*GDRI*	*Downscaled ICOLD*	*% Increase*	*Total Continental Capacity*
Endorheic	464	111	23.9%	575
Exorheic	8,028	0	0.0%	8,028
Total Capacity:	8,492	111	8.4%	**8,603**

3.1.2 Reservoir Dataset

Use of GDRI dams and novel reservoir assignment techniques produces a reservoir dataset that documents 83,767 reservoirs with a total capacity of 7,128km^3 and total surface area of 427,343km^2 (**Figure 3.1** and **Figure 3.5 (A)**). Reservoir extraction was 93.6% successful in assigning GDRI dams to their respective reservoirs.

3.2 GRanD Comparison

One of the objectives of this research was to develop a new dam and reservoir inventory that documents more spatial locations and a greater capacity than that of GRanD (Lehner et al. 2011). Inarguably, we have done so by increasing the number of dams documented by 1,204%, total capacity by 37%, and total surface area by 68% (**Figure 3.1**; **Table 3.4**). It is undeniable that the majority of our dataset is made up of NID (U.S.) dams (81%), but even excluding the United States from both GDRI and GRanD datasets, GDRI still increased the number of dams documented by 231%, total capacity by 29%, and total surface area by 47%. A comparison between prominent countries/regions, again, reveal improvements made by GDRI to the number of dams, total capacity, and total surface area documented (**Table 3.5**). India is the one exception where GRanD documents more capacity than GDRI. This stems from capacity discrepancies and GRanDs inclusion of Farakka Barrage, a hydropower dam located on the Ganges River, that doesn’t create a traditional reservoir. GDRI documents Farakka Barrage, but does not report any storage attributes.

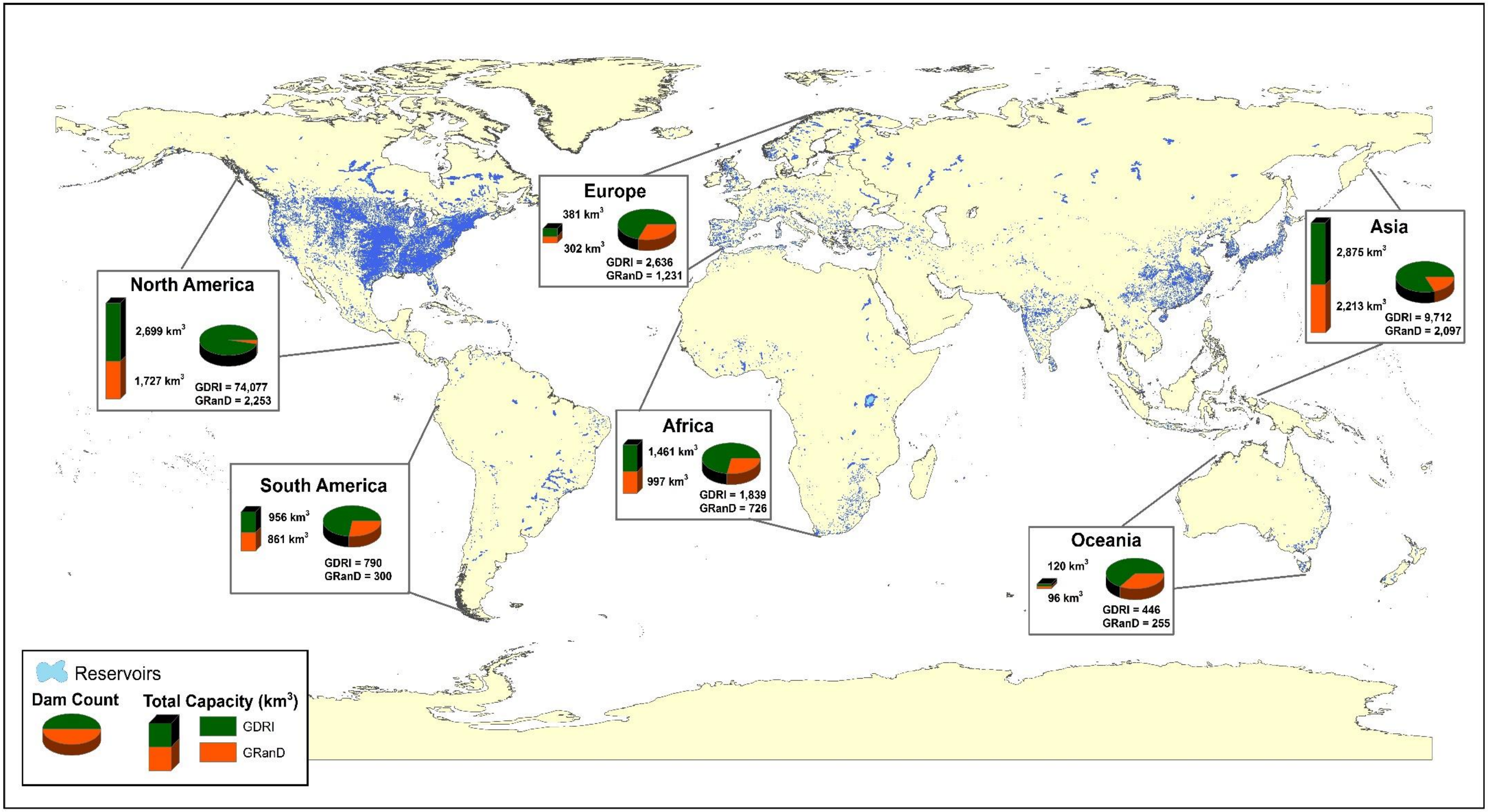


Figure 3.1 GDRI and GRanD comparison between dam count and total capacity. GDRI reservoirs shown in blue. Downscaled ICOLD contribution not included.

Table 3.4 Global and continental comparisons between GRanD and GDRI (without downscaled ICOLD contribution).

	Number of Dams			**Total Capacity (km^3)**			**Total Area (km^2)**		
Continent	*GDRI*	*GRanD*	*% Increase*	*GDRI*	*GRanD*	*% Increase*	*GDRI*	*GRanD*	*% Increase*
Africa	1,839	726	153%	1,461	997	47%	135,305	100,764	34%
Asia	9,712	2,097	363%	2,875	2,213	30%	235,591	132,189	78%
Europe	2,636	1,231	114%	381	302	26%	42,355	32,636	30%
North America	74,077	2,253	3188%	2,699	1,727	56%	279,100	143,417	95%
Oceania	446	255	75%	120	96	25%	7,000	4,910	43%
South America	790	300	163%	956	861	11%	55,200	36,530	51%
Global	89,500	6,862	1204%	8,492	6,196	37%	754,551	450,446	68%
Excluding US	16,439	4,970	231%	6,954	5,392	29%	583,247	392,429	49%

Table 3.5 Comparison between GRanD and GDRI (without downscaled ICOLD contribution for major countries and regions.

	Number of Dams			**Total Capacity (km^3)**			**Total Area (km^2)**		
Continent	*GDRI*	*GRanD*	*% Increase*	*GDRI*	*GRanD*	*% Increase*	*GDRI*	*GRanD*	*% Increase*
Brazil	264	178	48%	520	501	4%	28,803	22,816	26%
Canada	691	225	207%	1,335	829	61%	81,972	78,880	4%
China	5,433	767	608%	697	432	61%	22,495	13,294	69%
India	1,300	321	305%	250	262	-5%	33,054	10,527	214%
Russia	55	49	12%	895	812	10%	91,556	83,888	9%
South Africa	719	270	166%	43	31	39%	2,999	2,127	41%
Europe	2,629	1,228	114%	370	240	54%	39,626	30,562	30%

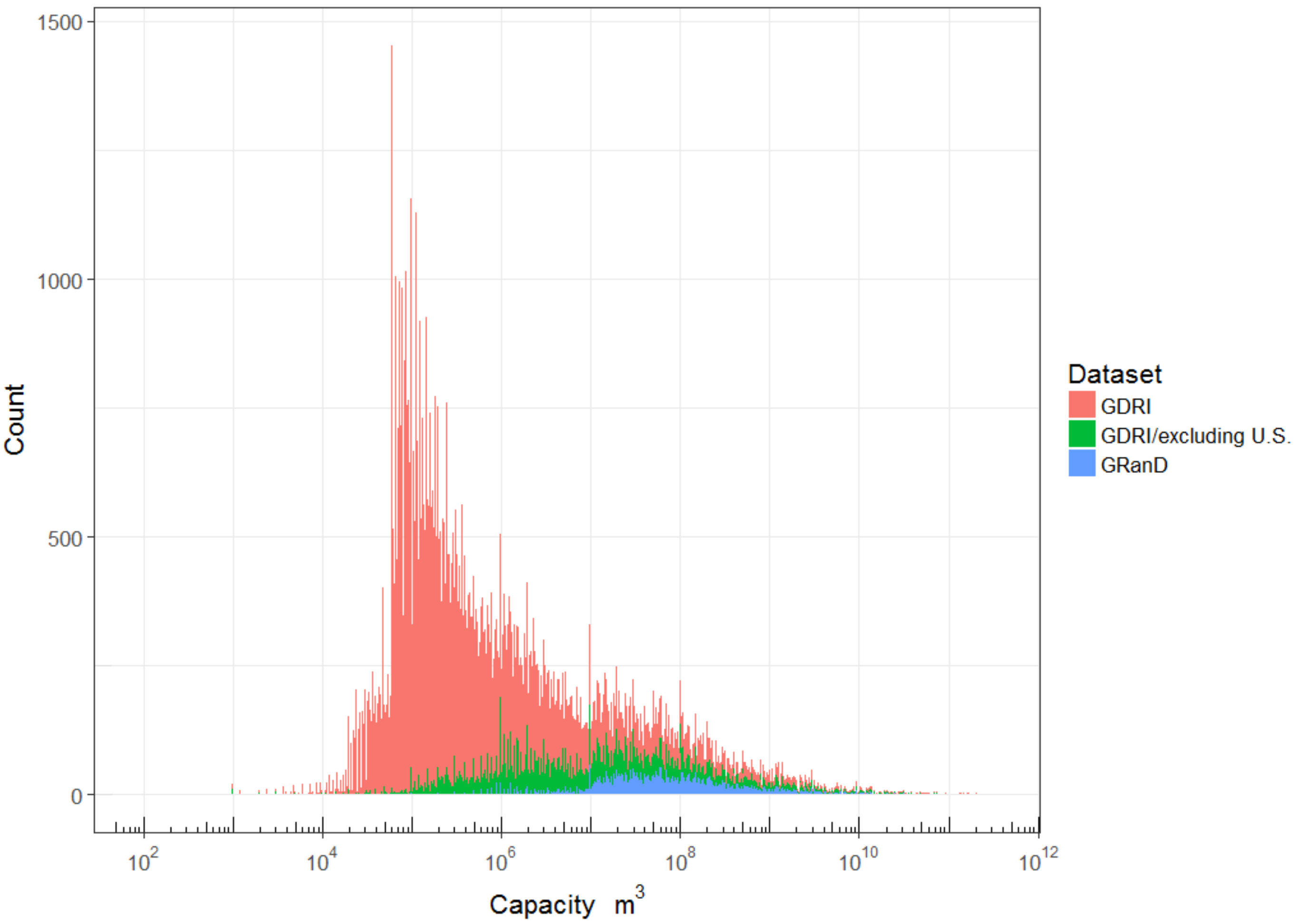


Figure 3.2 Distribution of dam capacities ($\log_{10}$) for GDRI and GRanD.

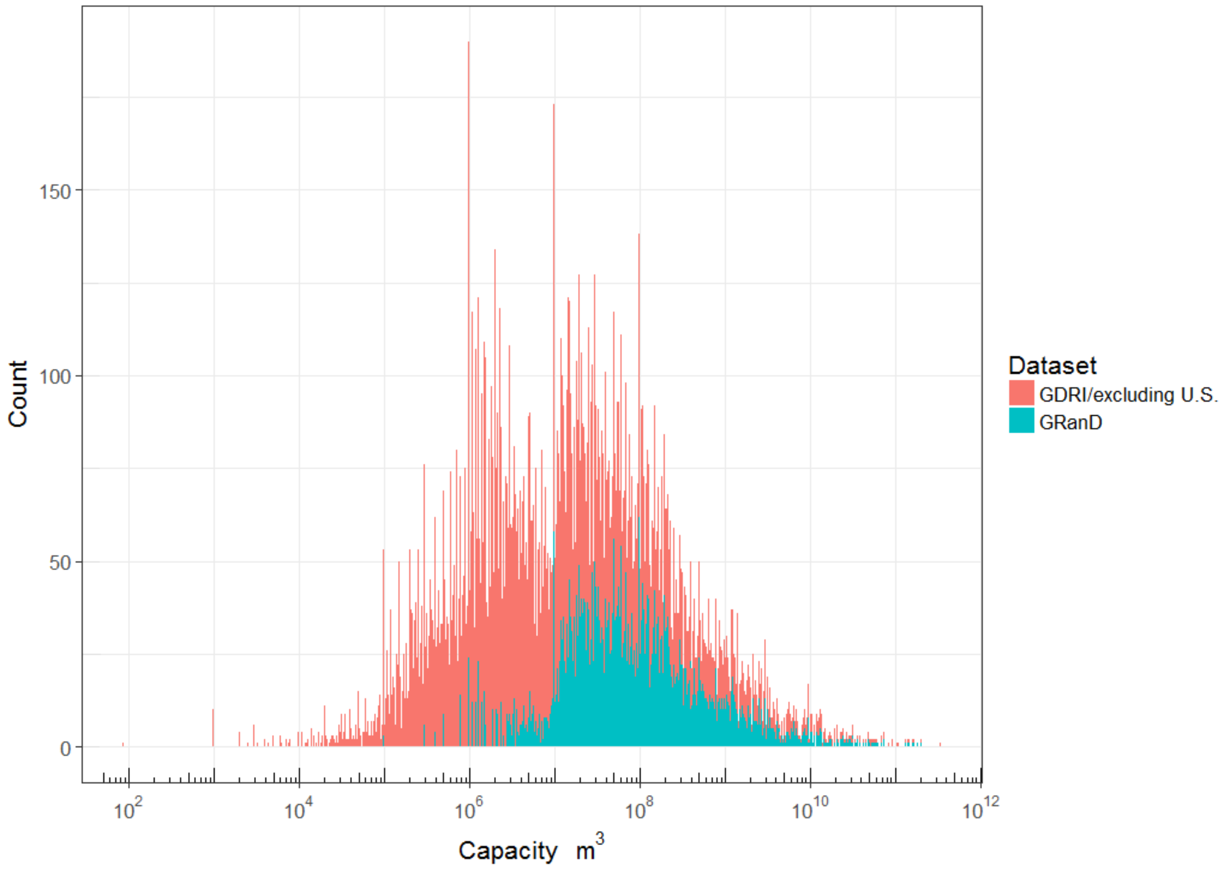


Figure 3.3 Distribution of dam capacities ($\log_{10}$) for GDRI (excluding U.S. dams) and GRanD.

Table 3.6 Mean and median capacity, area, and dam height reported by GDRI and GRanD

	GDRI		*GRanD*	
	Mean	*Median*	*Mean*	*Median*
Capacity (km^3)	0.095	0.0003	0.900	0.0638
Area (km^2)	8.600	0.0500	66.15	3.9000
Dam Height (m)	13.80	8.5344	45.50	36.000

GRanD effectively documents the majority of the large dams across the world, but fails to account for many of the thousands of small dams captured by GDRI (**Figure 3.2; Figure 3.3**). It is evident that GDRI more thoroughly documents the small dams not captured by GRanD. Average capacity reported by GDRI is nearly an order of magnitude less than that of GRanD, with V_{GDRI} = 0.095km^3 and V_{GRanD} = 0.900km^3 (**Table 3.6**). The shift in the distribution of documented capacities from larger dams to smaller dams is evident in dams with a capacity <0.01km^3. These dams comprise 87.7% of GDRI and only 10.93% of GRanD dams in number (**Table 3.7**).

Table 3.7 Continental comparison of GDRI and GRanD by capacity (*V*).

	Capacity (km^3)							Total
	$V \le 0.0001$	$0.0001 < V \le 0.001$	$0.001 < V \le 0.01$	$0.01 < V \le 0.1$	$0.1 < V \le 1$	$1 < V \le 10$	$V > 10$	
Africa								
GDRI (# of dams)	227	340	583	396	196	80	17	1,839
% of Total	12.34%	18.49%	31.70%	21.53%	10.66%	4.35%	0.92%	
GRanD (# of dams)	4	51	242	243	129	49	8	726
% of Total	0.55%	7.02%	33.33%	33.47%	17.77%	6.75%	1.10%	
% Increase	5575%	567%	141%	63%	52%	63%	113%	2
Asia								
GDRI	179	2,144	3,644	2,433	949	300	56	9,705
% of Total	1.84%	22.09%	37.55%	25.07%	9.78%	3.09%	0.58%	
GRanD	6	43	317	855	610	216	48	2,095
% of Total	0.29%	2.05%	15.13%	40.81%	29.12%	10.31%	2.29%	
% Increase	2883%	4886%	1050%	185%	56%	39%	17%	4
Europe								
GDRI	31	312	759	977	491	62	3	2,635
% of Total	1.18%	11.84%	28.80%	37.08%	18.63%	2.35%	0.11%	
GRanD	0	0	42	709	426	49	2	1,228
% of Total	0.00%	0.00%	3.42%	57.74%	34.69%	3.99%	0.16%	
% Increase	—	—	1707%	38%	15%	27%	50%	1
North America								
GDRI	20,982	38,028	10,738	2,873	1,113	310	35	74,079
% of Total	28.32%	51.33%	14.50%	3.88%	1.50%	0.42%	0.05%	
GRanD	0	0	3	1,273	737	211	25	2,249
% of Total	0.00%	0.00%	0.13%	56.60%	32.77%	9.38%	1.11%	
% Increase	—	—	357,833%	126%	51%	47%	40%	32
North America (≠ U.S.)								
GDRI	46	73	258	295	239	99	23	1,033
% of Total	4.45%	7.07%	24.98%	28.56%	23.14%	9.58%	2.23%	
GRanD	0	0	2	99	158	72	19	350
% of Total	0.00%	0.00%	0.57%	28.29%	45.14%	20.57%	5.43%	
% Increase	—	—	12,800%	198%	51%	38%	21%	2
Oceania								
GDRI	2	43	114	174	84	27	2	446
% of Total	0.45%	9.64%	25.56%	39.01%	18.83%	6.05%	0.45%	
GRanD	1	9	31	129	64	19	2	255
% of Total	0.39%	3.53%	12.16%	50.59%	25.10%	7.45%	0.78%	
% Increase	100%	378%	268%	35%	31%	42%	0%	1

	Capacity (km^3)							Total
	$V \le 0.0001$	$0.0001 < V \le 0.001$	$0.001 < V \le 0.01$	$0.01 < V \le 0.1$	$0.1 < V \le 1$	$1 < V \le 10$	$V > 10$	
South America								
GDRI	130	127	88	153	186	86	26	796
% of Total	16.33%	15.95%	11.06%	19.22%	23.37%	10.80%	3.27%	
GRanD	0	0	1	64	144	69	22	300
% of Total	0.00%	0.00%	0.33%	21.33%	48.00%	23.00%	7.33%	
% Increase	—	—	8700%	139%	29%	25%	18%	2
World								
GDRI	21,551	40,994	15,926	7,006	3,019	865	139	89,500
% of Total	24.08%	45.80%	17.79%	7.83%	3.37%	0.97%	0.16%	
GRanD	11	103	636	3,276	2,114	615	107	6,862
% of Total	0.16%	1.50%	9.27%	47.74%	30.81%	8.96%	1.56%	
% Increase	195,818%	39,700%	2404%	113%	43%	41%	30%	

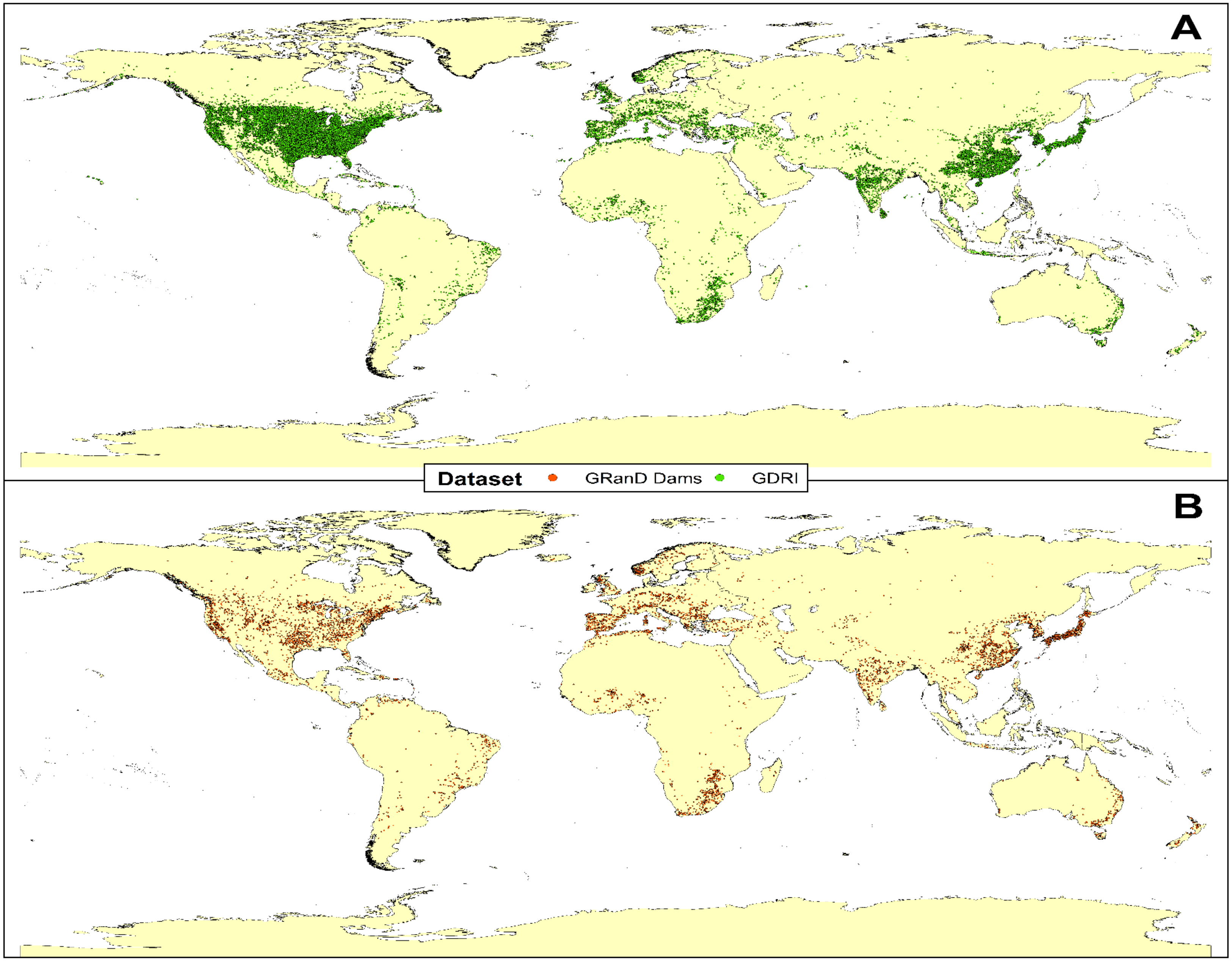


Figure 3.4 Dam dataset comparison between GRanD and GDRI.

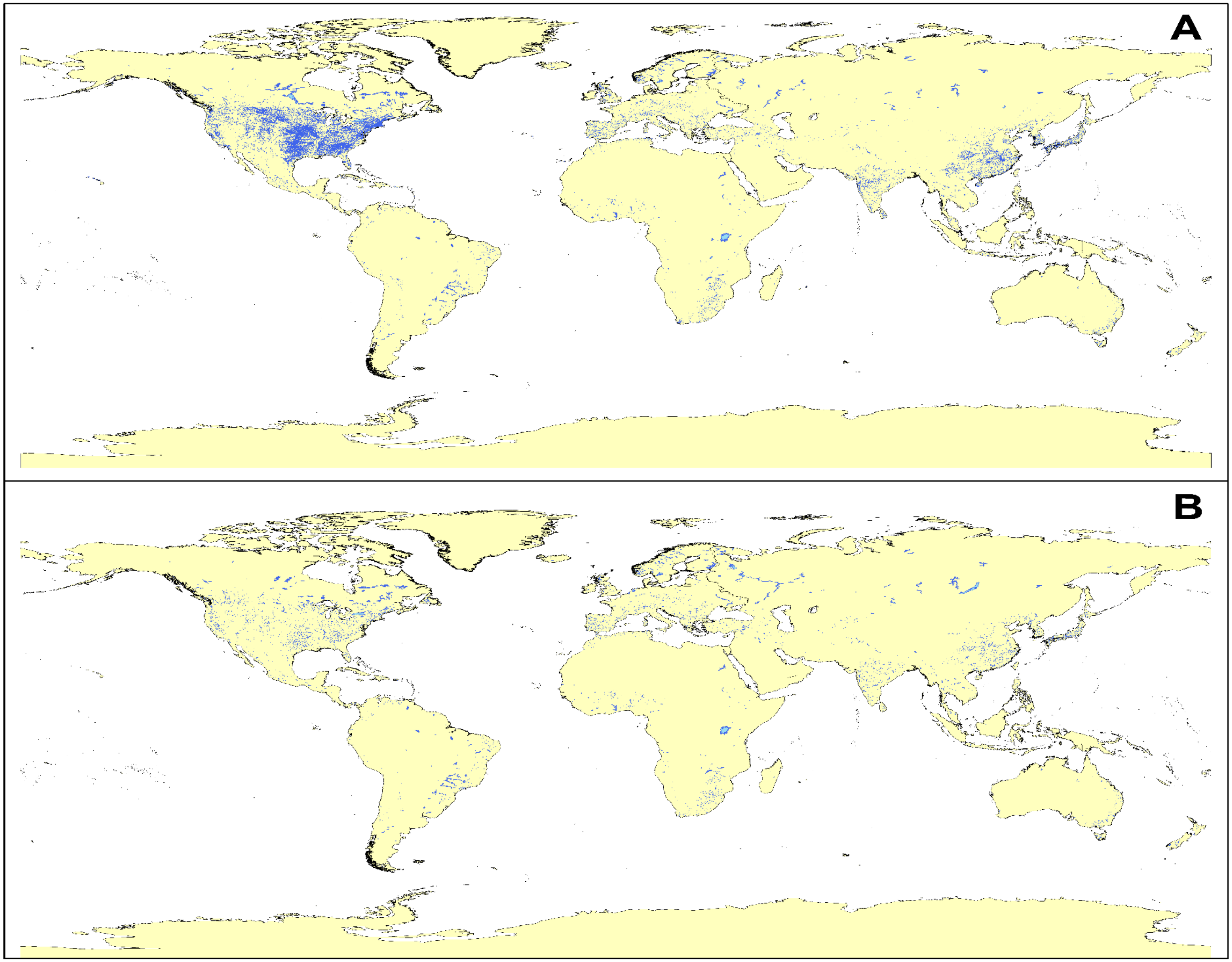


Figure 3.5 Reservoir dataset comparison between GRanD and GDRI.

3.3 Contribution to Sea Level

Endorheic regions, basins where surface water is land-locked preventing drainage to the ocean, occur in areas of the world largely impacted by arid or semiarid climates (Hammer 1986). In these regions, long-term water storage is vital for sustaining human life. Recent studies have revealed that endorheic basins and the saline lakes within are experiencing a drastic decline in water levels over the past two decades (Wurtsbaugh et al. 2017, Wang et al. 2018). Damming and diversion of upstream water supplies for irrigation or human consumption have been considered a factor in lake decline. Here, we see that dams may, in fact, play a role in saline lake decline within endorheic basins. While only 1.6% of the globally documented dams occur within endorheic regions, their total storage capacity accounts for 6.2% of the global dam capacity (**Figure 3.6**; **Table 3.8**). Furthermore, dams in endorheic basins have an average per dam capacity that is nearly 4 times greater than that of the dams located in exorheic regions (i.e., where surface runoff

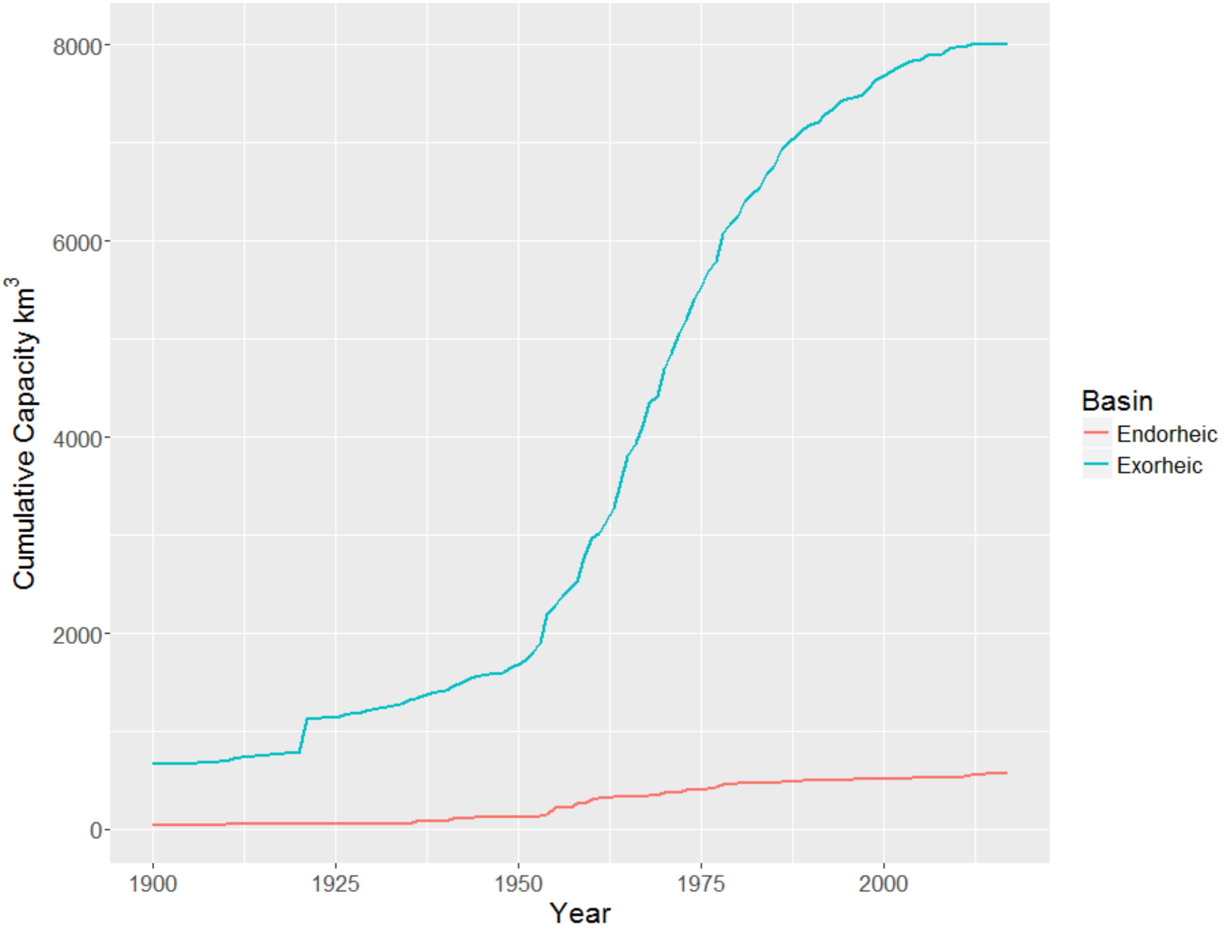


Figure 3.6 Cumulative capacity of endorheic and exorheic basins.

eventually reaches the ocean). It should also be noted that after 1975, endorheic dam construction rates have decreased at a slower rate than exorheic dam construction rates (**Table 3.9**). Coupled with a larger average per dam capacity, the slower reduction in dam construction indicates that the need for higher capacity, long-term water storage vessels in endorheic regions is still very prominent, even after the global dam construction boom of the 1950s and 1960s. However, in terms of capacity, dam construction in exorheic regions still outpace the amount of construction occurring within endorheic regions. As a percentage of total global capacity, capacity for endorheic located dams was at its highest during the 1950s and 1960s, but has been decreasing ever since (**Figure 3.7**). This trend can likely be attributed to artificial water storage reaching the hydrological and terrestrial limitations of endorheic basins, which represent only ~20% of the land surface area.

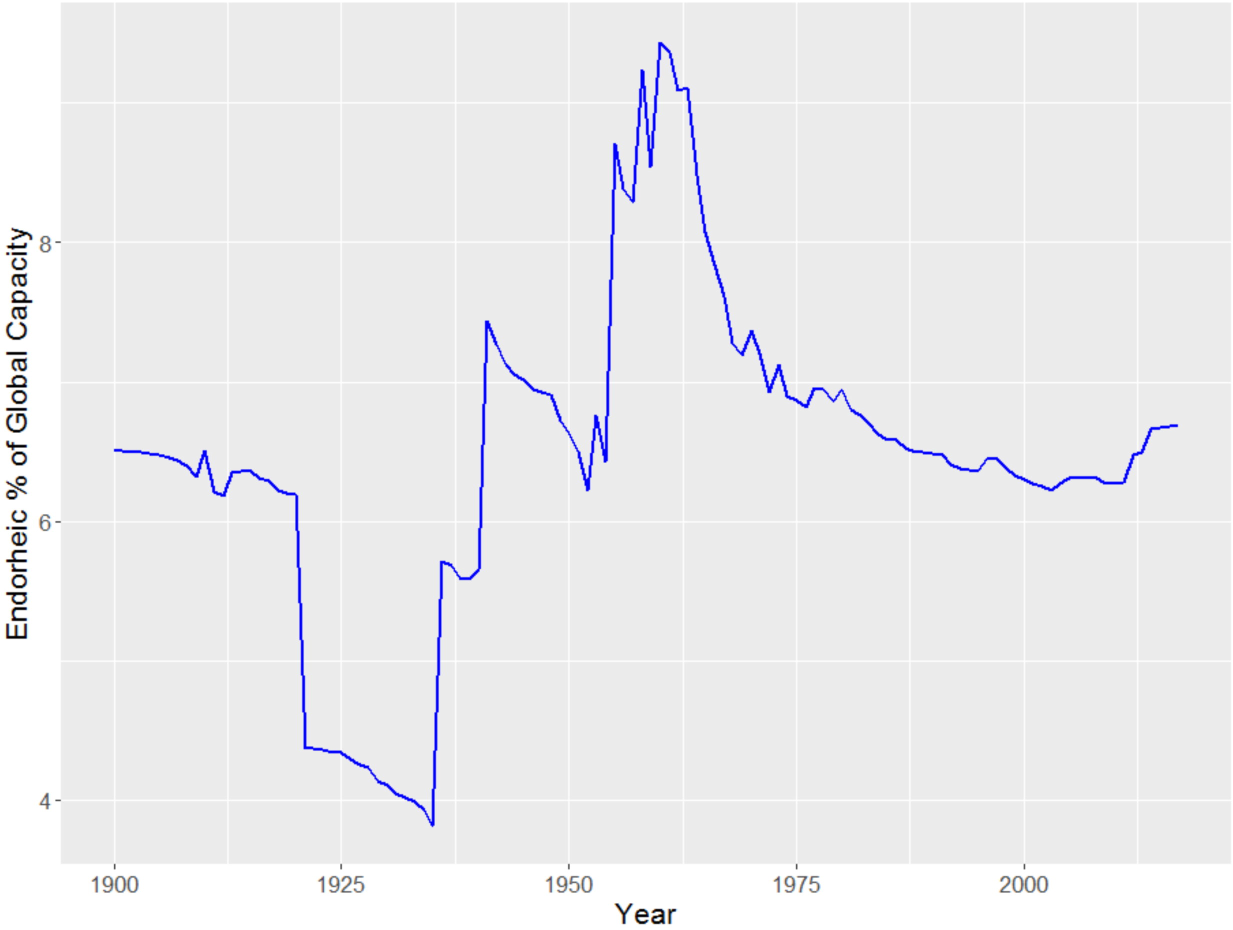


Figure 3.7 Capacity of endorheic located dam as a percentage of total global capacity.

Table 3.8 Characteristics of dams within endorheic basins

	Endorheic Basins	
# of Dams	1,462	1.6%
Area (km^2)	54,414	7.2%
Capacity (km^3)	575	6.2%
	Endorheic	*Exorheic*
Mean Dam Capacity (km^3)	0.39	0.10

Note: % indicates the value for dams in endorheic basins alone as a percentage of the value for all global dams (in endorheic and exorheic basins combined)

Table 3.9 Dam constructions within endorheic and exorheic basins.

	Pre-1900	*1900-1925*	*1925-1950*	*1950-1975*	*1975-2000*	*2000-Present*
Endorheic	124	153	215	450	380	140
% Increase	–	23.4%	40.5%	109.3%	**-15.6%**	**-63.2%**
Exorheic	4,884	5,125	9,630	44,700	19,870	3,829
% Increase	–	4.9%	87.9%	364.2%	**-55.5%**	**-80.7%**

The total amount of water reported to be impounded by GDRI dams, 8,603km^3, resulted in an equivalent sea level drop of 23.67mm, which is comparable to Chao et al. (2008) and Wada et al. (2017) who reported a SLD contribution of ~23mm (**Figure 3.8**). It is assumed here, that siltation of the reservoirs will not impact the reservoir's effect on SLD, because either silt or water stored by the reservoir affects SLD similarly (Chao et al. 2008). Over the documented years of dam construction (130 A.D. – 2017), reservoirs have affected SLD by approximately 0.08mm/yr. However, since the 1950's, when nearly 78% of the dams had been constructed, SLD was affected 0.27mm/yr.

Spatial location must be considered when estimating water impoundment effects on SLD. Dams located within endorheic basins will not contribute any effect to SLD and will actually suppress the magnitude of SLD effect enacted by water impoundments slightly. With this taken into consideration, we found that exclusion of endorheic located dams decreases the overall effect on SLD by 6.68% or 1.58mm (**Figure 3.9**).

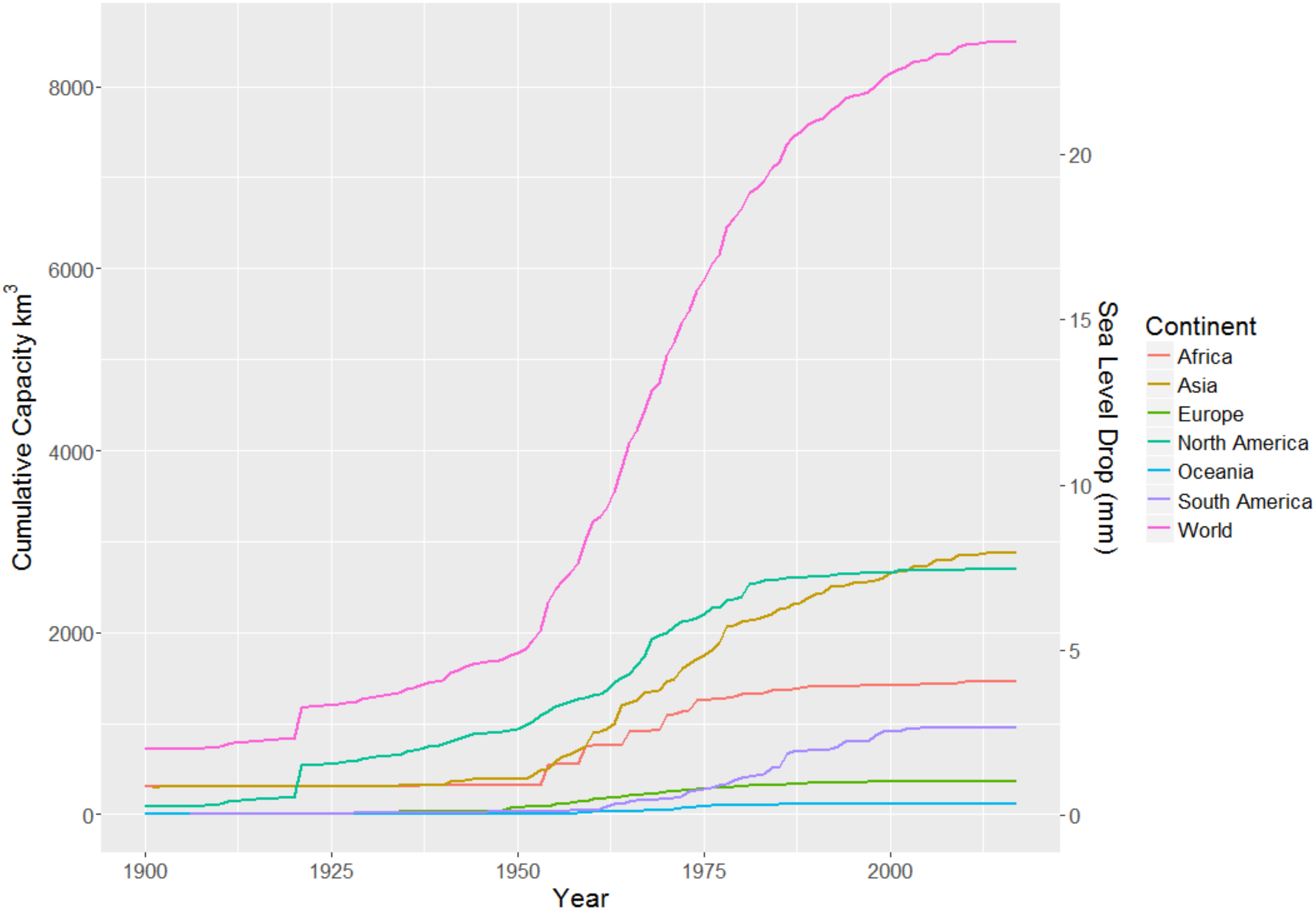


Figure 3.8 Cumulative capacity and SLD estimates by continent.

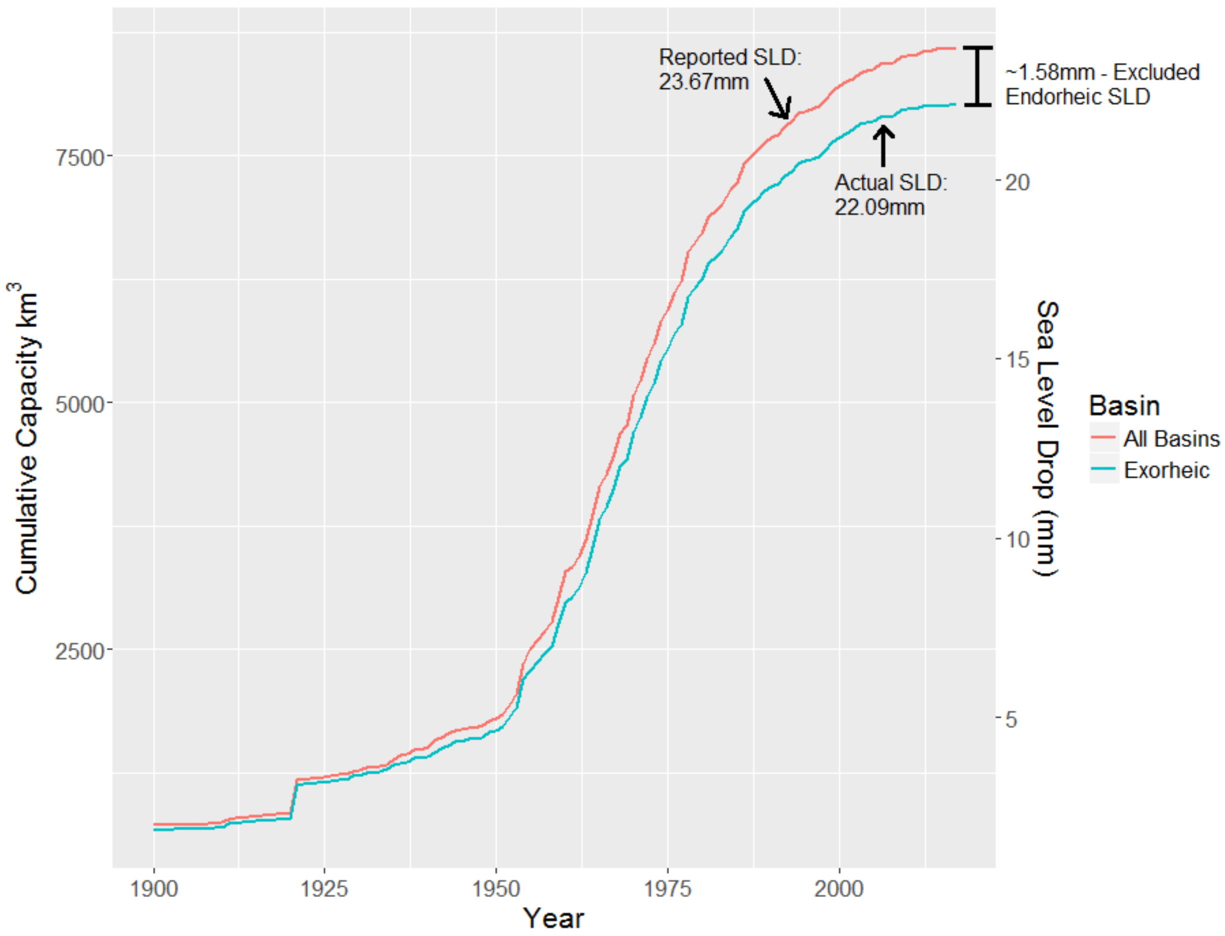


Figure 3.9 Influences of reservoir water impoundments on SLD

Chapter 4 - Discussion

4.1 Distribution of Dams and Dam Construction Trends

The expansiveness of GDRI can now provide better insight on the distribution of dams and stored water across the world. The United States, China, India, and Japan are the world leaders in dam construction comprising 90% of the documented global dams. Without the United States; China, India, and Japan still account for 48% of the dams, but only 13% of the total capacity. Despite having only 0.7% of the documented dams, Canada contains the most stored water by volume among all countries with 1,335km^3 (**Table A.1**). Egypt, Suriname, Zambia, and Russia exhibit the highest average capacity per dam (>16km^3/dam), but this estimate could be inflated due to limited dam documentation.

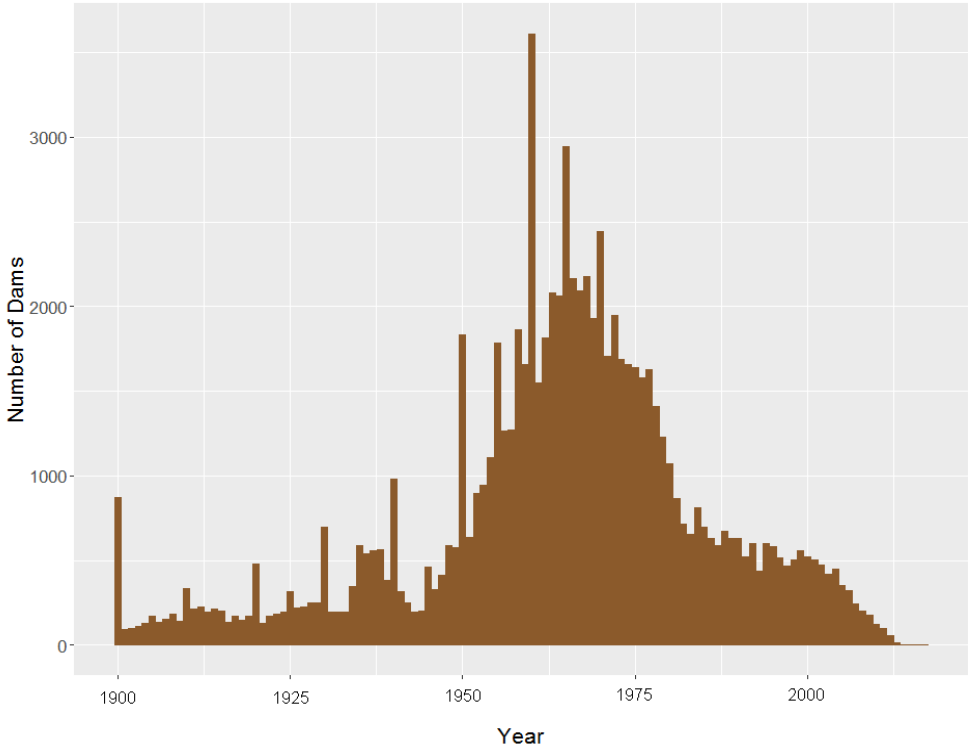


Figure 4.1 Global dam construction since 1900.

Overall, global dam construction peaked in the 1950s and 1960s and has been declining ever since (**Figure 4.1**). Nearly 78% of GDRI dams were constructed after 1950. The magnitude of dam construction varies greatly from country to country and is largely dependent upon the health of the economy and the overall development of the country. The Human Development Index (HDI), developed by the United Nations, utilizes several metrics such as a country's education standards, economy, and life expectancy to assess the overall development of a country (United Nations 2018). It is evident that highly developed countries have substantially more dams constructed than lesser developed countries (**Figure 4.2**). Even more, of the 106 countries classified as poorly developed (HDI classification = "Low"), only one country (Burkina Faso) has more than 50 dams (**Figure 4.6; Figure 4.7**). Lesser developed countries are often lacking the ability to construct dams desperately needed for agriculture and drinking water. However, it must be noted that some developing countries may now be experiencing an increase in dam construction compared to their more developed counterparts. For countries with more than 50 documented dams, Turkey and Algeria have the highest average year of dam construction at 1986 and 1974, respectively. Interestingly, Turkey and Algeria were classified as "moderately" developed 25 years ago, but are now considered to be "highly developed". The "developing" stage for these countries

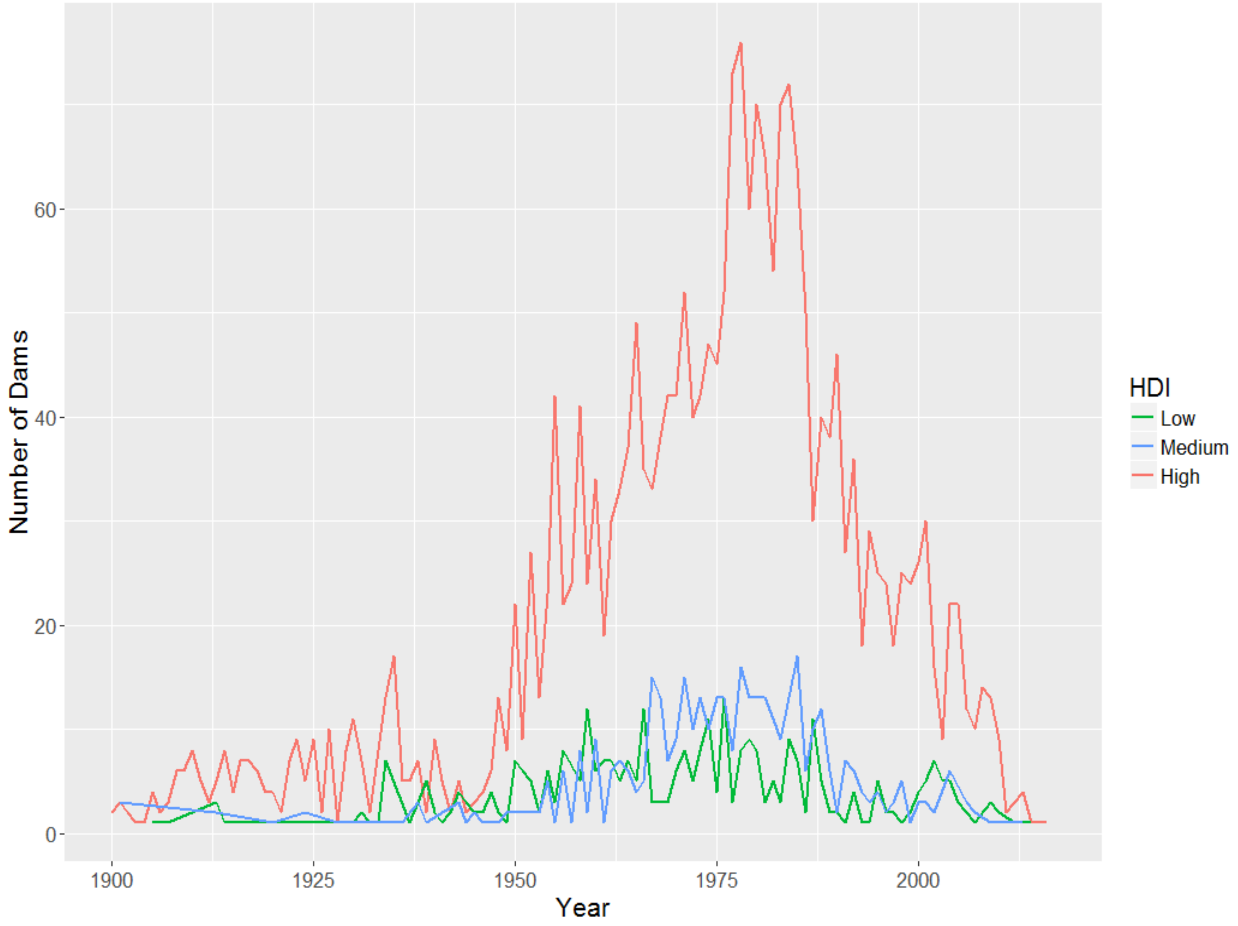


Figure 4.2 Global dam construction since 1900 by Human Development Index (HDI) classification. Countries classified as "Very Highly" developed are excluded for scaling purposes.

likely coincides with recent dam construction experienced by these countries. Globally, the average dam construction year, 1959, indicates that some developing countries are still experiencing a strong push for dam construction. On a continental scale, it is evident that some areas of the world have become stagnant in dam construction while others are continuing to increase their hydrological storage capabilities. Dam construction in Europe appears to have peaked in the 1960s; whereas, Africa saw a boom in dam construction around 1980, and South America is seeing a small spike in dam construction at the start of the 21st century (**Figure 4.3**). The high frequency in dam construction still occurring within Asia can largely be attributed to China's push for hydropower expansion (**Figure 4.4 & 4.5**)(Chang, Liu and Zhou 2010, Kong et al. 2015). In South America, Brazil is planning to more than double the number of hydropower operations in order to meet energy demands (Tundisi et al. 2014).

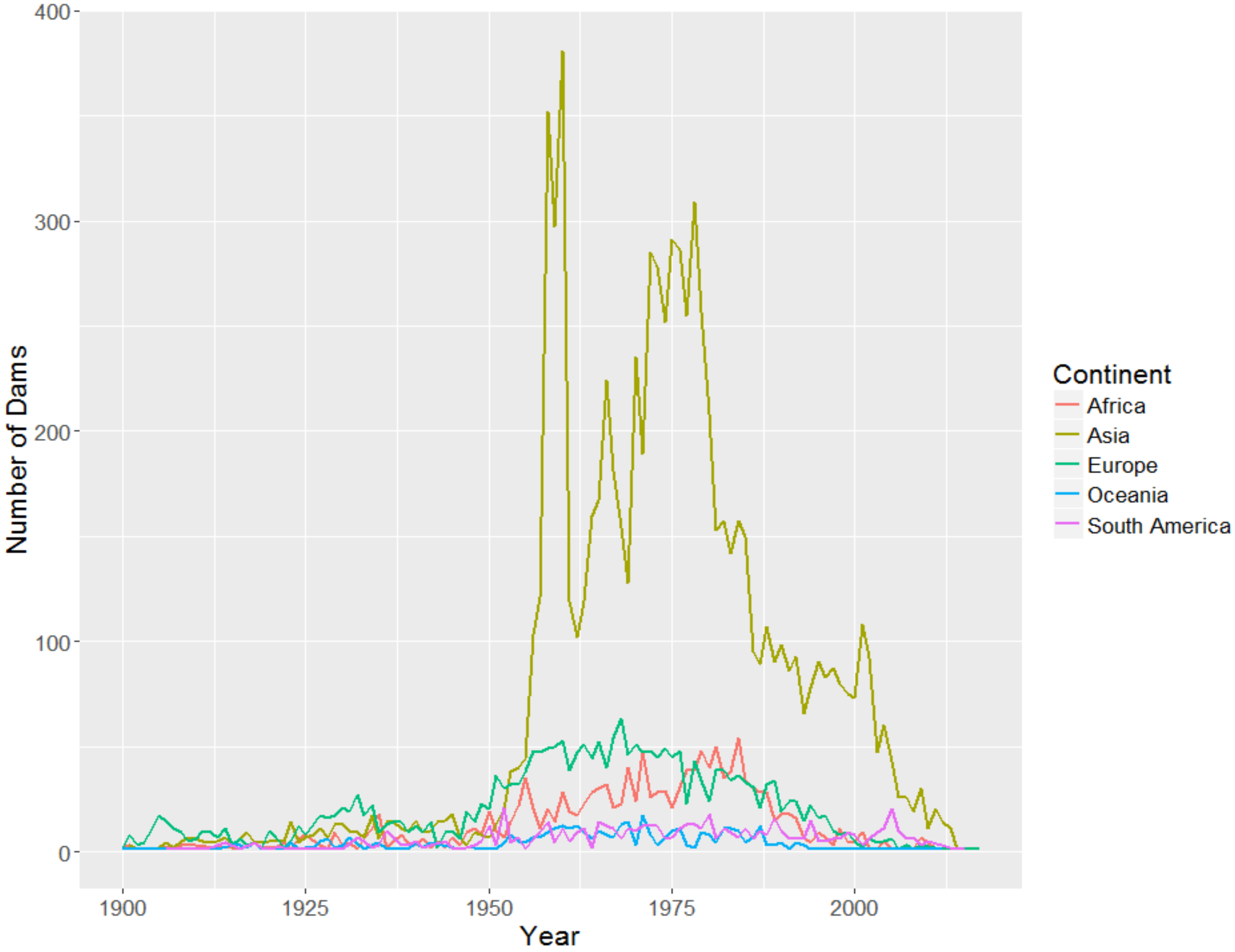
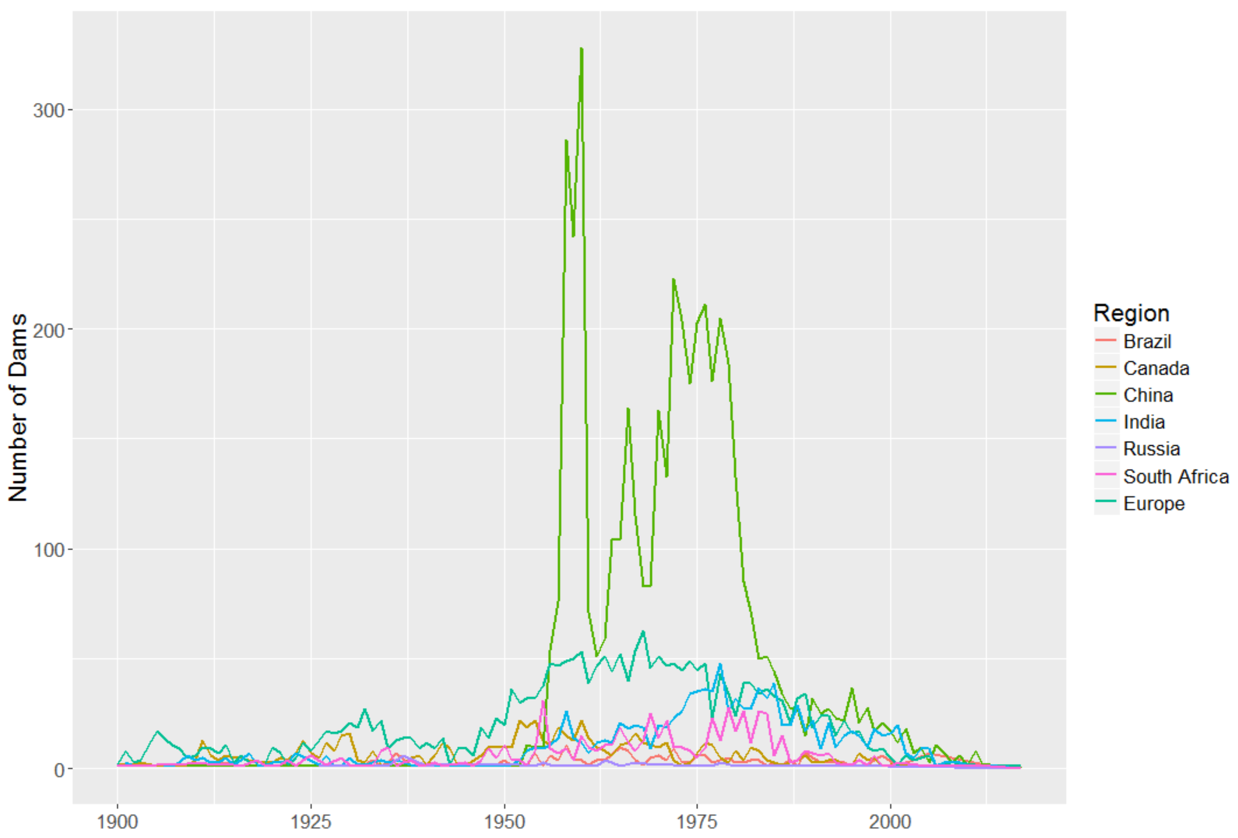


Figure 4.3 Dam construction since 1900 by continent.



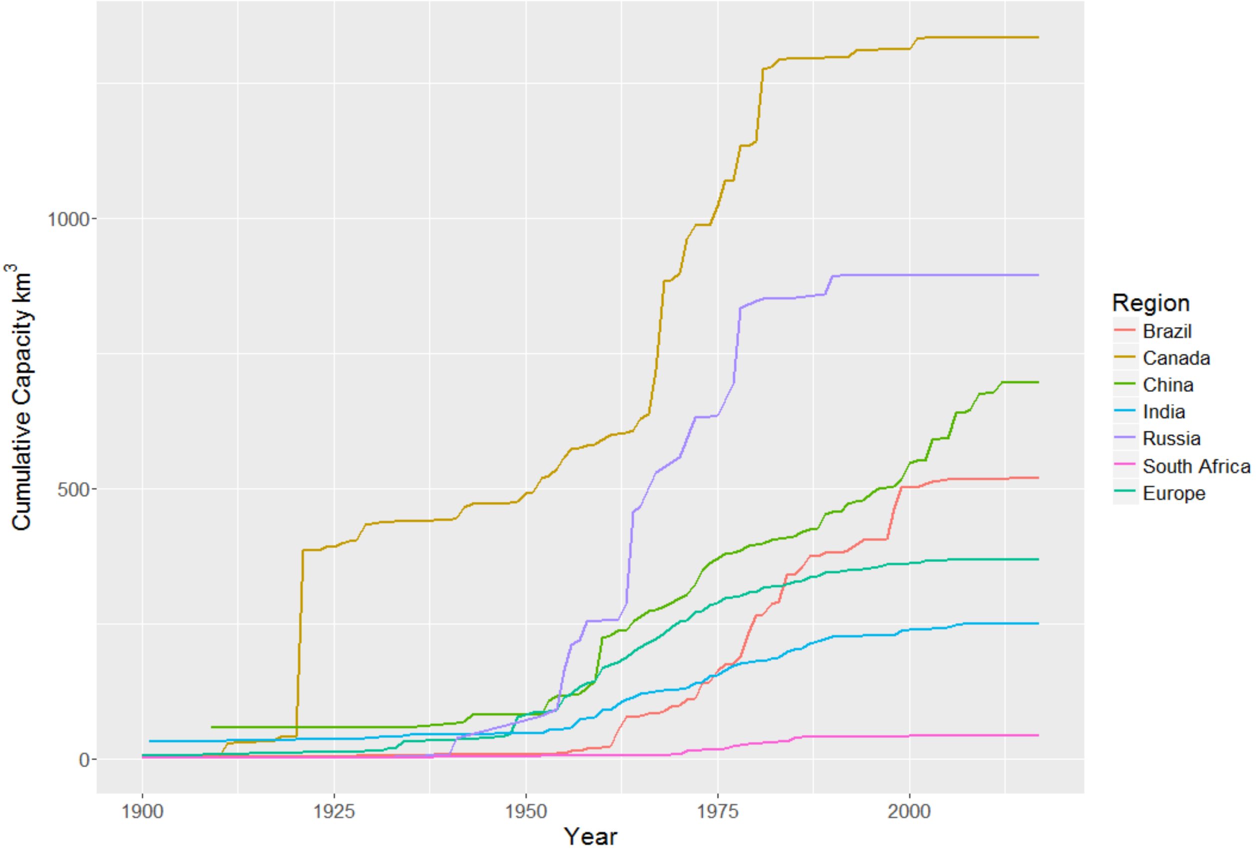


Figure 4.4 (top) Dam construction since 1900 by country/region. **Figure 4.5** (bottom) Cumulative capacity since 1900 by region/country.

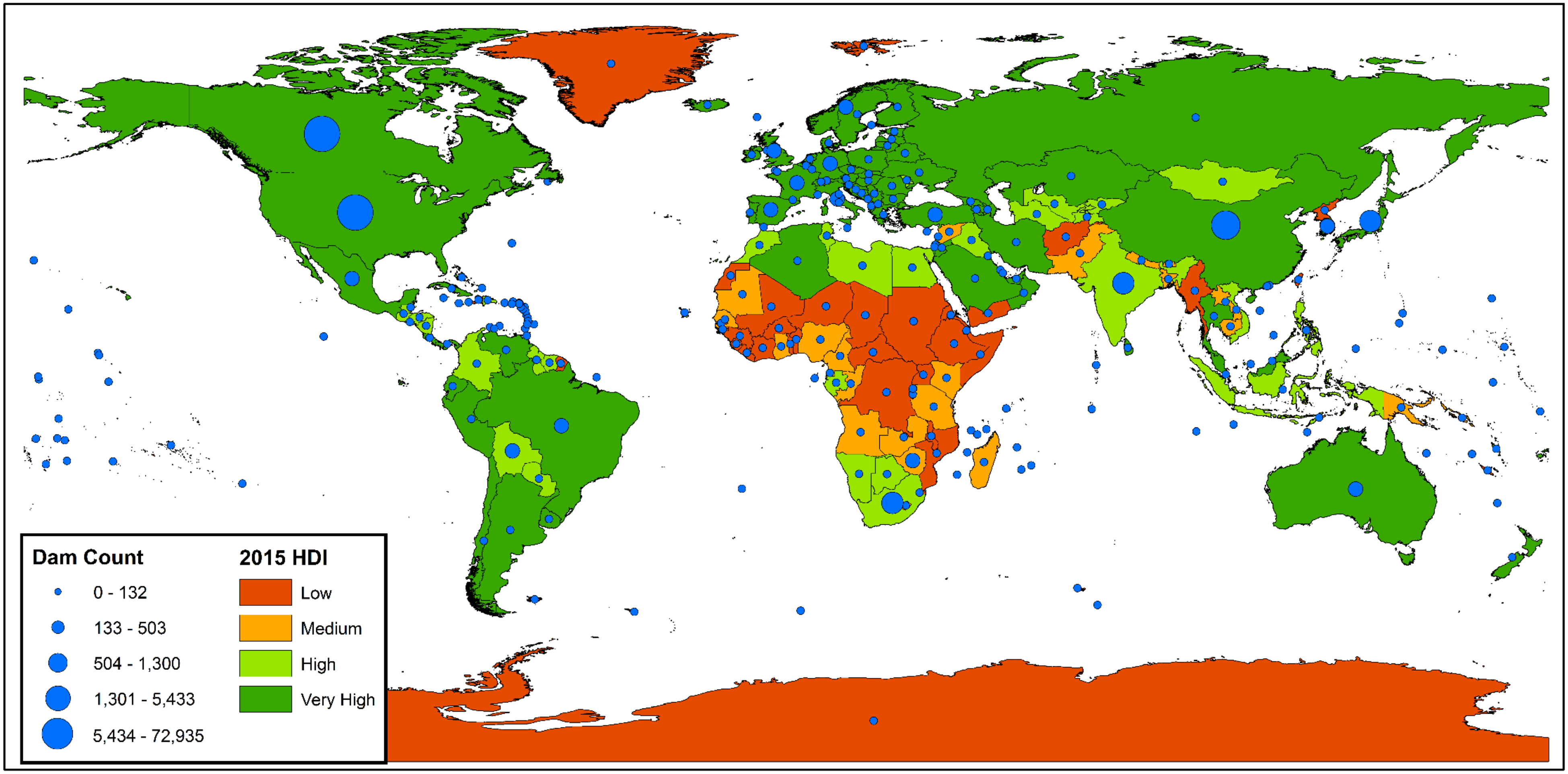


Figure 4.6 Dam number and HDI classification by country.

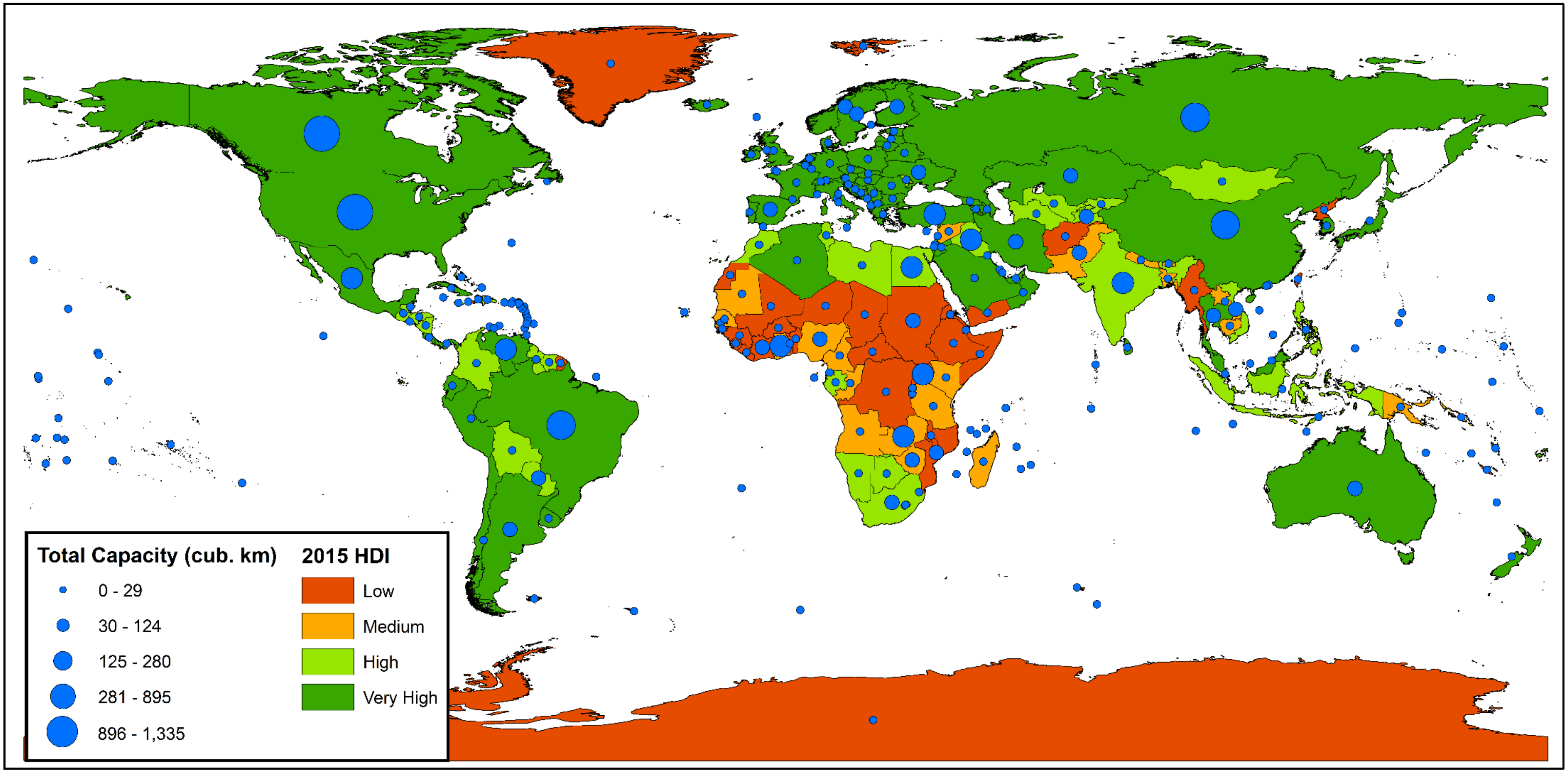


Figure 4.7 Total dam capacity (km^3) and HDI classification by country.

While overall global dam construction has decreased since the 1970s, the size, in terms of capacity, of the dam projects have continued to steadily increase. Each year, dam projects have increased an average of 0.002km^3 since 1900 (**Figure 4.8**). The increase has been even more significant since 1950 with dam capacity increasing at 0.006km^3 per year. The push for larger and larger dams to supplement the world's growing energy and water demands is evident. The push for the construction of mega dams recently has spawned enormous projects such as Three Gorges Dam (Stone 2011), Sardar Sarovar Dam (Gupta et al. 2012), and the Merowe Dam (McDonald, Bosshard and Brewer 2009) all of which have been completed. In 1950, globally, only 10 mega dams existed, but by 1995, 295 more mega-dams had been constructed (Raina 2012).

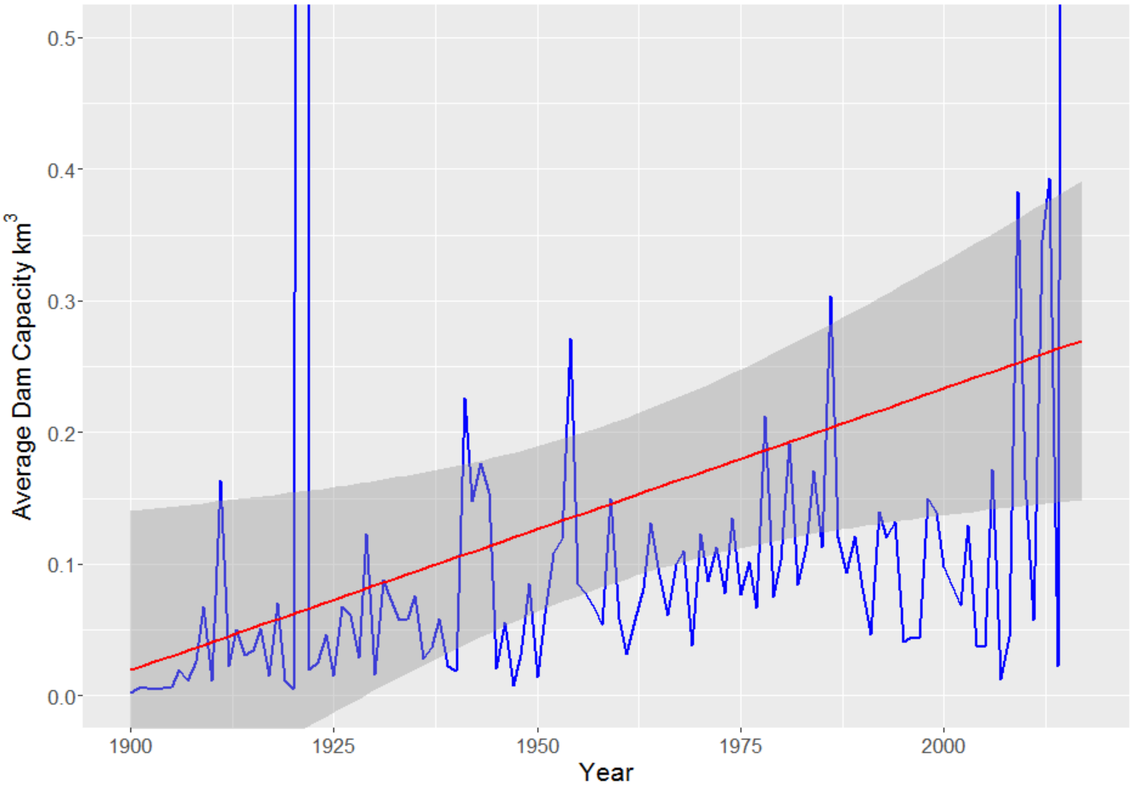


Figure 4.8 Average capacity for each dam constructed since 1900. (Adj. $R^2 = 0.038$, $p = 0.019$)

4.2 Dataset Limitations

The datasets produced are by no means perfect. Overall, the described procedures should be considered a heuristic model, where fastidious quality assurance and automated procedures work to thoroughly eliminate many of the issues encountered with the dataset production, but errors may still exist. For instance, duplication between the contributing dam datasets, spatial limitations of the lake datasets, imperfect geocoding procedures, and the inclusion of more dam datasets provide opportunity for future refinement and improvement of the datasets.

4.2.1 Geocoding Accuracy

Ensuring the accuracy of geocoded ICOLD records presented a great challenge. Even after several rounds of manual quality assurance, sources of error may still be present. Geocoding accuracy for the GDRI contributing ICOLD points was 94.6% accurate. Five hundred randomly sampled ICOLD dams were used to cross-reference the geocoded dam location and accompanying attribute information to Google Maps documentation. A dam was considered incorrect if attribute information indicated a different location (state, province, or country) or dam name than that provided by Google Maps. The validity of approximately 11% of the sampled dams remained inconclusive, as the dam was geocoded in the correct state, province, or country, but documentation in Google Maps (no reported name or language barriers) could neither confirm nor deny the validity of the dam. Thus, if geocoded to the correct administrative unit, we conservatively assumed these dams to be correctly geocoded. Dams with spatial coordinates provided by the other contributing authoritative datasets were assumed to be valid; and therefore, their corresponding location and attributes considered correct.

4.2.2 Dataset Accuracy

While we carefully considered the authoritativeness and completeness of the contributing datasets and assumed the provided spatial coordinates to be correct, it is important to evaluate the relative spatial accuracy in order to develop a thorough understanding of the datasets. Therefore, the success rate of dam and reservoir assignment can serve as a rough assessment for evaluating the spatial accuracy of the contributing dam datasets. By using the lake datasets as control features, accuracy for each dam can be determined if the dam is documenting a water body. Needless to say, the “accuracy” of the datasets could be adversely affected by spatial limitations in the lake datasets, but the lake datasets used are considered the most complete and spatially exhaustive datasets available. Spatial limitations of the lake dataset, where the dam’s reported reservoir area was less than the minimum lake area captured by the 2015 Global Lake Inventory dataset ($< 0.04km^2$), was found to cause only 28% of the unassigned dams (n = 5,733). Water bodies missed by the 2015 Global Lake Inventory were supplemented with the maximum surface water extent, extracted from the Global Surface Water dataset. It is therefore assumed the number of missing waterbodies > $0.04 km^2$ from either lake dataset to be minimal. Thus, the remaining unassigned dams can be attributed to erroneous spatial coordinates provided by the authoritative dam datasets themselves. With these assumptions, GRanD and ICOLD datasets were the most accurate with a 95% assignment rate; whereas, FAO and CDA were the least accurate with an 84% assignment rate (**Table 4.1**).

Table 4.1 Assignment success as a proxy for dataset accuracy.

Dataset	*# of Dams*	*# of Assigned Reservoirs*	*# of Unassigned Dams*	*Assignment Success (%)*
CDA	550	465	85	84.55%
FAO	6,375	5,409	966	84.85%
GRanD	653	626	27	95.87%
ICOLD	9,467	9,039	428	95.48%
NID	72,455	68,228	4,227	94.17%
Total:	89,500	83,767	5,733	93.59%

4.3 Future Improvements

Both GDRI datasets produced here have undergone thorough quality assurance using manual and automated techniques. Nevertheless, variation of both spatial accuracy and record completeness between the contributing dam datasets may result in some dam points being erroneously placed, duplicated, or documenting an already documented reservoir. Likewise, automated dam and reservoir assignment techniques were determined to be the most reliable and accurate methods, but errors will inevitably exist. For instance, some reservoirs may be incorrectly paired with their respective dam point or may not be a reservoir at all. The datasets produced here are in no way 100% accurate, but we believe that the quality assurance methods employed have worked to reduce the described errors as much as realistically possible.

One of the most challenging aspects of this research included the identification and resolution of errors. Some of these errors, such as record duplication or inaccurate spatial coordinates, existed within the dataset itself, but other errors, such as spatial duplication and reservoirs association, were introduced when using the datasets concurrently. These errors were handled accordingly, but undoubtedly some of these issues may still exist in the GDRI datasets. Further identification of potential errors, refinement, and quality assurance within and among the contributing datasets will improve the quality and accuracy of the data.

The novel geocoding techniques implemented resulted in a ~21% success rate in geocoding dams to their correct location. Using additional search criteria in the geocoding process may improve the results further. If time allows, manual adjustment of geocoded dams to their exact location using the provided dam attribute information and Google Maps documentation will undoubtedly improve the geocoded product. Dam name cross-referencing between downscaled ICOLD dams and other datasets would greatly improve the identification of "double-counted" reservoirs when attempting to supplement area and capacity estimates.

Lastly, assignment of dams to their respective reservoirs could be improved by considering more assignment scenarios, while also considering reservoir area. For instance, a comparison between the provided area values from the dam dataset to the area of the lake dataset's water extent may provide a more accurate pairing of dams and reservoirs. Additional assignment scenarios could possibly decrease the number of orphan dams. The proposed improvements would help perfect the current results, while adding marginal documentation. Vast improvements could be made by retrieving additional dam registries from local or regional governments.

Chapter 5 - Conclusions

5.1 Dataset Products

The research conducted here used novel techniques to merge 5 authoritative, open-source dam registries into a single dam and reservoir dataset, which we entitled as the Global Dam and Reservoir Inventory (GDRI). Using novel geocoding methods, we are the first to spatially document 12,350 (~21%) ICOLD records, which contributed 9,467 ICOLD records, or 794km^3, to the GDRI dam dataset. We prudently considered each dataset during the compilation process by implementing automated methods to identify and remove overlapping or duplicate records. GDRI is exceedingly more complete and spatially explicit than any comparable dataset available, including the Global Reservoir and Dams (GRanD) dataset. GDRI documents more dams and reservoirs, a greater total capacity, and total surface area than documented by GRanD. In total, GDRI documents 89,500 dams and 83,767 reservoirs for a total capacity of 8,492km^3 and total surface area of 754,551km^2. Compared to its counterpart, GRanD, GDRI increased the number of dams documented by 1204%, reservoirs by 1127%, total capacity by 37%, and total surface area by 68%. Further downscaling of the non-geocoded ICOLD records using similar geocoding methods allowed for the thorough use of all available ICOLD records. Additional capacity estimates from downscaled ICOLD records increased the GDRI capacity documentation to 8,603km^3 and surface area documentation to 859,271km^2.

Reservoirs account for approximately 2.5% of the Earth's terrestrial water. In other words, 1 unit of water for every 40 units has been artificially created. This number will only continue to increase for a number of reasons. First, demand for water and electricity will continue to drive the construction of dams. Secondly, groundwater pumping introduces more water into the hydrological cycle, which could end up in artificially constructed waterbodies.

5.2 Contribution to Sea Level

Initial water impoundment from dam construction activities can lower sea level by permanently trapping water storage on land. Contribution to sea level drop (SLD) was found to be 23.4mm since dam construction or 0.08mm/yr. Since the beginning of the dam boom in 1950, this yearly SLD contribution increases to 0.27mm/yr. These estimates liken to those of Chao et al. (2008) and Wada et al. (2017) who reported ~23mm in nominal SLD. By considering the hydrological characteristics of dam location, in terms of endorheic and exorheic basins, we found that exclusion of endorheic located dams decreases the overall effect on SLD by 5.47% or 1.28mm. Other studies investigating dam effects on SLD (Chao et al. 2008, Wada et al. 2017), fail to consider the hydrologic location of the dam, resulting in an overestimation of dam-induced SLD.

Yearly SLD has implications when considering the contributors to sea level rise (SLR). A yearly SLD of 0.27mm counteracts the positive contributors to SLR caused by the depletion of groundwater (Wada et al. 2016). Inclusion of reservoir groundwater seepage may even partially counteract other contributors to SLR, such as thermal expansion (Domingues et al. 2008) and melting of perennial ice (Reager et al. 2016).

5.3 Dam Trends

This dataset allows us to see patterns and trends in dam construction over time and how differences in economic and anthropogenic factors affect dam construction in different regions. Since the 1950s-1960s, the world has seen a decreasing trend in dam construction, but developing countries (China, Brazil, India) are still actively pursuing dam projects that are larger and more ambitious than ever before. We see less developed countries often lack the capabilities for dam construction possibly increasing stress on natural water supplies in those regions. However, as development increases, dam construction is likely to increase as well.

5.4 Contributions

This research contributes vital information about anthropogenic water resources that incrementally enhances our knowledge of global hydrology and the interactions taking place between different water entities. Specifically, these findings will expand our understanding of the spatial distribution of artificially impounded surface water and help quantify the amount of water readily available. This will inevitably lead to improved water budget management plans providing sustainable water supplies into the future.

Chapter 6 - References

Ansar, A., B. Flyvbjerg, A. Budzier & D. Lunn (2014) Should we build more large dams? The actual costs of hydropower megaproject development. Energy Policy, 69, 43-56.

Anthoff, D. N., R.J., Tol, R.S.J., Vafeidis, A.T. 2006. Global and regional exposure to large rises in sea-level- a sensitivity analysis. Tyndall Centre for climate change.

Awojobi, O. & G. P. Jenkins (2015) Were the hydro dams financed by the World Bank from 1976 to 2005 worthwhile? Energy Policy, 86, 222-232.

Baxter, R. M. (1977) Environmental Effects of Dams and Impoundments. Annual Review of Ecology and Systematics, 8, 255-283.

Biemans, H., I. Haddeland, P. Kabat, F. Ludwig, R. W. A. Hutjes, J. Heinke, W. von Bloh & D. Gerten (2011) Impact of reservoirs on river discharge and irrigation water supply during the 20th century. Water Resources Research, 47.

Britannica, E. o. E. 2018. Three Gorges Dam. In Encyclopaedia Britannica. Encyclopaedia Britannica, inc.

Cael, B. B., A. J. Heathcote & D. A. Seekell (2017) The volume and mean depth of Earth's lakes. Geophysical Research Letters, 44, 209-218.

Cai, X. B., L. Feng, X. J. Hou & X. L. Chen (2016) Remote Sensing of the Water Storage Dynamics of Large Lakes and Reservoirs in the Yangtze River Basin from 2000 to 2014. Scientific Reports, 6.

Carpenter, S. R., E. H. Stanley & M. J. Vander Zanden (2011) State of the World's Freshwater Ecosystems: Physical, Chemical, and Biological Changes. Annual Review of Environment and Resources, Vol 36, 36, 75-99.

Cazenave, A., H. B. Dieng, B. Meyssignac, K. von Schuckmann, B. Decharme & E. Berthier (2014) The rate of sea-level rise. Nature Climate Change, 4, 358-361.

CDA. 2016. Canvec 1M Manmade. ed. Canada: Canadian Dam Association.

Chang, X. L., X. H. Liu & W. Zhou (2010) Hydropower in China at present and its further development. Energy, 35, 4400-4406.

Chao, B. F., Y. H. Wu & Y. S. Li (2008) Impact of artificial reservoir water impoundment on global sea level. Science, 320, 212-214.

Church, J. A., J.M. Gregory, N.J. White, S.M. Platten, J.X. Mitrovica (2011) Understanding and projecting sea level change. Oceanography, 24, 130-143.

Church, J. A. & N. J. White (2011) Sea-Level Rise from the Late 19th to the Early 21st Century. Surveys in Geophysics, 32, 585-602.

Cooper, H. M., C. H. Fletcher, Q. Chen & M. M. Barbee (2013) Sea-level rise vulnerability mapping for adaptation decisions using LiDAR DEMs. Progress in Physical Geography, 37, 745-766.

Dalin, C., Y. Wada, T. Kastner & M. J. Puma (2017) Groundwater depletion embedded in international food trade. Nature, 543, 700-+.

Degu, A. M., F. Hossain, D. Niyogi, R. Pielke, J. M. Shepherd, N. Voisin & T. Chronis (2011) The influence of large dams on surrounding climate and precipitation patterns. Geophysical Research Letters, 38.

Domingues, C. M., J. A. Church, N. J. White, P. J. Gleckler, S. E. Wijffels, P. M. Barker & J. R. Dunn (2008) Improved estimates of upper-ocean warming and multi-decadal sea-level rise. Nature, 453, 1090-U6.

Downing, J. A., Y. T. Prairie, J. J. Cole, C. M. Duarte, L. J. Tranvik, R. G. Striegl, W. H. McDowell, P. Kortelainen, N. F. Caraco, J. M. Melack & J. J. Middelburg (2006) The global abundance and size distribution of lakes, ponds, and impoundments. Limnology and Oceanography, 51, 2388-2397.

Famiglietti, J. S., M. Lo, S. L. Ho, J. Bethune, K. J. Anderson, T. H. Syed, S. C. Swenson, C. R. de Linage & M. Rodell (2011) Satellites measure recent rates of groundwater depletion in California's Central Valley. Geophysical Research Letters, 38.

FAO. 2016. AQUASTAT Georeferenced Dam Database. Food and Agriculture Organization of the United Nations.

Feng, M., J. O. Sexton, S. Channan & J. R. Townshend (2016) A global, high-resolution (30-m) inland water body dataset for 2000: first results of a topographic-spectral classification algorithm. International Journal of Digital Earth, 9, 113-133.

Forsberg, B. R., J. M. Melack, T. Dunne, R. B. Barthem, M. Goulding, R. C. D. Paiva, M. V. Sorribas, U. L. Silva & S. Weisser (2017) The potential impact of new Andean dams on Amazon fluvial ecosystems. Plos One, 12.

Gleick, P. H. (2003) Water use. Annual Review of Environment and Resources, 28, 275-314.

Gupta, H., S. J. Kao & M. H. Dai (2012) The role of mega dams in reducing sediment fluxes: A case study of large Asian rivers. Journal of Hydrology, 464, 447-458.

Hammer, U. T. 1986. Saline lake ecosystems of the world. The Netherlands: Dr. W. Junk Publishers.

Han, S. Y., S. J. Kwak & S. H. Yoo (2008) Valuing environmental impacts of large dam construction in Korea: An application of choice experiments. Environmental Impact Assessment Review, 28, 256-266.

Hughes, D. A. & S. K. Mantel (2010) Estimating the uncertainty in simulating the impacts of small farm dams on streamflow regimes in South Africa. Hydrological Sciences Journal-Journal Des Sciences Hydrologiques, 55, 578-592.

ICOLD. 2016. World Register of Dams. ed. Paris: International Commission On Large Dams.

IEA. 2017. World Energy Outlook 2017: Executive Summary. France: International Energy Agency.

Jacob, T., J. Wahr, W. T. Pfeffer & S. Swenson (2012) Recent contributions of glaciers and ice caps to sea level rise. Nature, 482, 514-518.

Jansson, R., C. Nilsson & B. Renofalt (2000) Fragmentation of riparian floras in rivers with multiple dams. Ecology, 81, 899-903.

Kondolf, G. M., Y. X. Gao, G. W. Annandale, G. L. Morris, E. H. Jiang, J. H. Zhang, Y. T. Cao, P. Carling, K. D. Fu, Q. C. Guo, R. Hotchkiss, C. Peteuil, T. Sumi, H. W. Wang, Z. M. Wang, Z. L. Wei, B. S. Wu, C. P. Wu & C. T. Yang (2014) Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents. Earths Future, 2, 256-280.

Kong, Y. G., J. Wang, Z. G. Kong, F. R. Song, Z. Q. Liu & C. M. Wei (2015) Small hydropower in China: The survey and sustainable future. Renewable & Sustainable Energy Reviews, 48, 425-433.

Latrubesse, E. M., E. Y. Arima, T. Dunne, E. Park, V. R. Baker, F. M. d'Horta, C. Wight, F. Wittmann, J. Zuanon, P. A. Baker, C. C. Ribas, R. B. Norgaard, N. Filizola, A. Ansar, B. Flyvbjerg & J. C. Stevaux (2017) Damming the rivers of the Amazon basin. Nature, 546, 363-369.

Ledec, G. & J. D. Quintero. 2003. Good Dams and Bad Dams: Environmental Criteria for Site Selection of Hydroelectric Projects. ed. L. A. a. C. R. S. Development. The World Bank.

Lehner, B. & P. Doll (2004) Development and validation of a global database of lakes, reservoirs and wetlands. Journal of Hydrology, 296, 1-22.

Lehner, B., C. R. Liermann, C. Revenga, C. Vorosmarty, B. Fekete, P. Crouzet, P. Doll, M. Endejan, K. Frenken, J. Magome, C. Nilsson, J. C. Robertson, R. Rodel, N. Sindorf & D. Wisser (2011) High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. Frontiers in Ecology and the Environment, 9, 494-502.

Lyons, E. A. & Y. W. Sheng (2018) LakeTime: Automated Seasonal Scene Selection for Global Lake Mapping Using Landsat ETM+ and OLI. Remote Sensing, 10.

McDonald, K., P. Bosshard & N. Brewer (2009) Exporting dams: China's hydropower industry goes global. Journal of Environmental Management, 90, S294-S302.

McGranahan, G., D. Balk & B. Anderson (2007) The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. Environment and Urbanization, 19, 17-37.

Messager, M. L., B. Lehner, G. Grill, I. Nedeva & O. Schmitt (2016) Estimating the volume and age of water stored in global lakes using a geo-statistical approach. Nature Communications, 7.

National Research Council (U.S.). Committee on Sea Level Rise in California Oregon and Washington., National Research Council (U.S.). Board on Earth Sciences and Resources. & National Research Council (U.S.). Ocean Studies Board. 2012. Sea-level rise for the coasts of California, Oregon, and Washington : past, present, and future. Washington, D.C.: National Academies Press.

NID. 2013. National Inventory of Dams. ed. United States Army Corps of Engineers.

Nilsson, C. & K. Berggren (2000) Alterations of riparian ecosystems caused by river regulation. Bioscience, 50, 783-792.

Oki, T. & S. Kanae (2006) Global hydrological cycles and world water resources. Science, 313, 1068-1072.

Pekel, J. F., A. Cottam, N. Gorelick & A. S. Belward (2016) High-resolution mapping of global surface water and its long-term changes. Nature, 540, 418-+.

Pokhrel, Y. N., N. Hanasaki, P. J. F. Yeh, T. J. Yamada, S. Kanae & T. Oki (2012) Model estimates of sea-level change due to anthropogenic impacts on terrestrial water storage. Nature Geoscience, 5, 389-392.

Rahmani, V., J. H. Kastens, F. deNoyelles, M. E. Jakubauskas, E. A. Martinko, D. H. Huggins, C. Gnau, P. M. Liechti, S. W. Campbell, R. A. Callihan & A. J. Blackwood (2018) Examining Storage Capacity Loss and Sedimentation Rate of Large Reservoirs in the Central U.S. Great Plains. Water, 10.

Raina, V. 2012. Dam Building: Who's "Backward" - Subsistence Cultures or Modern "Development"? In The Wealth of the Commons: A World Beyond Market and State, eds. D. Bollier & S. Helfrich. Amherst, MA: Levellers Press.

Ran, L. S. & X. X. Lu (2012) Delineation of reservoirs using remote sensing and their storage estimate: an example of the Yellow River basin, China. Hydrological Processes, 26, 1215-1229.

Reager, J. T., A. S. Gardner, J. S. Famiglietti, D. N. Wiese, A. Eicker & M. H. Lo (2016) A decade of sea level rise slowed by climate-driven hydrology. Science, 351, 699-703.

Rosegrant, M. W., C. Ringler & T. J. Zhu (2009) Water for Agriculture: Maintaining Food Security under Growing Scarcity. Annual Review of Environment and Resources, 34, 205-222.

Russo, T. A. & U. Lall (2017) Depletion and response of deep groundwater to climate-induced pumping variability. Nature Geoscience, 10, 105-+.

Schleiss, A. J., M. J. Franca, C. Juez & G. De Cesare (2016) Reservoir sedimentation. Journal of Hydraulic Research, 54, 595-614.

Sheng, Y. W., C. G. Song, J. Wang, D. Garibay, J. Woods, E. A. Lyons & L. C. Smith. 2015. Automated quality assurance of quality control (QA/QC) in developing decadal global lake dynamic products using Landsat-7 and 8. In American Geophysical Union. San Franscisco, California.

Sheng, Y. W., C. Q. Song, J. D. Wang, E. A. Lyons, B. R. Knox, J. S. Cox & F. Gao (2016) Representative lake water extent mapping at continental scales using multi-temporal Landsat-8 imagery. Remote Sensing of Environment, 185, 129-141.

Siebert, S. & P. Doll (2010) Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation. Journal of Hydrology, 384, 198-217.

Sovacool, B. K., A. Gilbert & D. Nugent (2014) Risk, innovation, electricity infrastructure and construction cost overruns: Testing six hypotheses. Energy, 74, 906-917.

Stone, R. (2011) The Legacy of the Three Gorges Dam. Science, 333, 817-817.

Strokal, M., C. Kroeze, M. R. Wang, Z. H. Bai & L. Ma (2016) The MARINA model (Model to Assess River Inputs of Nutrients to seAs): Model description and results for China. Science of the Total Environment, 562, 869-888.

Tilt, B., Y. Braun & D. M. He (2009) Social impacts of large dam projects: A comparison of international case studies and implications for best practice. Journal of Environmental Management, 90, S249-S257.

Tobler, W. R. (1970) Computer Movie Simulating Urban Growth in Detroit Region. Economic Geography, 46, 234-240.

Tundisi, J. G., J. Goldemberg, T. Matsumura-Tundisi & A. C. F. Saraiva (2014) How many more dams in the Amazon? Energy Policy, 74, 703-708.

U.N. 2018. Human Development Index (HDI). United Nations Development Programme.

USACE. 2013. Water Supply Storage Reallocation John Redmond Dam and Reservoir, Kansas. Tulsa, OK: United States Army Corps of Engineers.

---. 2017. Upper Mississippi River Locks & Dams. ed. United States Army Corps of Engineers. St. Paul, MN.

Verpoorter, C., T. Kutser, D. A. Seekell & L. J. Tranvik (2014) A global inventory of lakes based on high-resolution satellite imagery. Geophysical Research Letters, 41, 6396-6402.

Vorosmarty, C. J., P. B. McIntyre, M. O. Gessner, D. Dudgeon, A. Prusevich, P. Green, S. Glidden, S. E. Bunn, C. A. Sullivan, C. R. Liermann & P. M. Davies (2010) Global threats to human water security and river biodiversity. Nature, 467, 555-561.

Vorosmarty, C. J., M. Meybeck, B. Fekete, K. Sharma, P. Green & J. P. M. Syvitski (2003) Anthropogenic sediment retention: major global impact from registered river impoundments. Global and Planetary Change, 39, 169-190.

Wada, Y., J. T. Reager, B. F. Chao, J. Wang, M. H. Lo, C. Q. Song, Y. W. Li & A. S. Gardner (2017) Recent Changes in Land Water Storage and its Contribution to Sea Level Variations. Surveys in Geophysics, 38, 131-152.

Wada, Y., L. P. H. van Beek & M. F. P. Bierkens (2012) Nonsustainable groundwater sustaining irrigation: A global assessment. Water Resources Research, 48.

Wada, Y., D. Wisser & M. F. P. Bierkens (2014) Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources. Earth System Dynamics, 5, 15-40.

Wada, Y., M. H. Lo, P. J. F. Yeh, J. T. Reager, J. S. Famiglietti, R. J. Wu & Y. H. Tseng (2016) Fate of water pumped from underground and contributions to sea-level rise. Nature Climate Change, 6, 777-+.

Wang, J., Y. W. Sheng, C. G. Song, T. Urano, P. J. Satori & S. J. Ford. 2015. A high-resolution global lake inventory with classified freshwater and saline types. In American Geophysical Union. San Francesco, California.

Wang, J., C. G. Song, J. T. Reager, F. Yao, J. S. Famiglietti, Y. W. Sheng, G. M. MacDonald, R. A. Marston & Y. Wada (2018) Recent global decline in endorheic basin water storage and its impact on sea level budget. Nature Geoscience, in revision.

Wang, J., T. Urano, C. Bailey, P. J. Satori, B. A. Walter, M. Ding, C. G. Song & Y. W. Sheng. 2016. Progress of global lake inventory: freshwater and saline lakes. In AAG Great Plains/Rocky Mountains Regional Division Fall Meeting. Colorado Springs, Colorado.

WCD. 2000. Dams and Development: A New Framework for Decision-Making. ed. W. C. o. Dams. London: World Commission on Dams.

Wurtsbaugh, W. A., C. Miller, S. E. Null, R. J. DeRose, P. Wilcock, M. Hahnenberger, F. Howe & J. Moore (2017) Decline of the world's saline lakes. Nature Geoscience, 10, 816-+.

Yang, X. K. & X. X. Lu (2013) Delineation of lakes and reservoirs in large river basins: An example of the Yangtze River Basin, China. Geomorphology, 190, 92-102.

Zarfl, C., A. E. Lumsdon, J. Berlekamp, L. Tydecks & K. Tockner (2015) A global boom in hydropower dam construction. Aquatic Sciences, 77, 161-170.

Ziv, G., E. Baran, S. Nam, I. Rodriguez-Iturbe & S. A. Levin (2012) Trading-off fish biodiversity, food security, and hydropower in the Mekong River Basin. Proceedings of the National Academy of Sciences of the United States of America, 109, 5609-5614.

Appendix A - Additional Information

Table A.1 List of Countries and their documented dams.

Country	*Continent*	*HDI Classification*	*Dam Count*	*Capacity* (km^3)	*Area* (km^2)
Canada	North America	Very High	598	1,334.55	174,188.94
United States	North America	Very High	72718	1,186.23	88,032.20
Russia	Europe	Very High	49	918.80	91,555.98
China	Asia	Very High	788	835.31	22,494.92
Brazil	South America	Very High	178	654.63	76,920.72
India	Asia	High	343	320.61	46,996.00
Egypt	Africa	High	11	280.02	12,217.56
Uganda	Africa	Low	15	225.00	73,849.00
Zambia	Africa	Medium	12	216.15	7,985.34
Iraq	Asia	High	18	202.34	6,690.05
Turkey	Asia	Very High	245	193.63	17,892.49
Venezuela	South America	Very High	35	170.31	6,145.36
Ghana	Africa	Medium	32	163.00	9,013.02
Mexico	North America	Very High	141	140.36	6,253.30
Ethiopia	Africa	Low	25	136.71	810.58
Mozambique	Africa	Low	17	124.22	5,492.60
Argentina	South America	Very High	42	123.84	3,579.22
Zimbabwe	Africa	Medium	172	105.40	3,477.38
Australia	Oceania	Very High	188	100.88	6,332.98
Iran	Asia	Very High	85	97.41	2,719.17
Kazakhstan	Asia	Very High	17	91.11	9,883.90
Malaysia	Asia	Very High	20	80.67	3,047.69
Thailand	Asia	Very High	48	79.18	5,391.44
Paraguay	South America	High	7	77.72	5,824.37
Pakistan	Asia	Medium	36	62.27	1,660.31
Spain	Europe	Very High	250	60.78	3,089.59
Nigeria	Africa	Medium	85	54.72	2,718.67
Finland	Europe	Very High	19	52.24	12,805.06
Ukraine	Europe	Very High	9	48.45	7,329.07
Cote d'Ivoire	Africa	Low	43	46.87	3,530.46
Vietnam	Asia	High	12	45.75	1,784.90
Norway	Europe	Very High	123	42.65	2,030.24
South Africa	Africa	High	552	42.57	4,312.79
Tajikistan	Asia	High	16	41.76	5,786.71
Sweden	Europe	Very High	51	39.89	8,809.16
Sudan	Africa	Low	17	38.12	3,587.71
North Korea	Asia	Low	37	37.16	1,300.23
Syria	Asia	Medium	6	25.97	1,495.79

Country	*Continent*	*HDI Classification*	*Dam Count*	*Capacity (km^3)*	*Area (km^2)*
Japan	Asia	Very High	543	24.93	1,696.38
Azerbaijan	Asia	Very High	20	24.25	1,128.91
Suriname	South America	High	1	24.00	1,600.00
Kyrgyzstan	Asia	High	8	23.40	545.30
Cameroon	Africa	Medium	22	23.20	1,912.87
Tanzania	Africa	Medium	18	22.51	660.12
Colombia	South America	High	37	20.23	692.03
Morocco	Africa	High	56	20.15	990.03
Indonesia	Asia	High	84	19.62	11,414.80
Burma	Asia	Low	20	18.01	782.36
New Zealand	Oceania	Very High	65	17.83	1,805.67
Uruguay	South America	Very High	4	17.35	1,515.38
Romania	Europe	Very High	79	17.25	1,827.45
South Korea	Asia	Very High	56	17.15	7,715.62
Laos	Asia	Medium	8	16.96	862.33
Mali	Africa	Low	11	15.79	1,337.00
Angola	Africa	Medium	24	14.93	758.93
Honduras	North America	High	10	14.89	529.55
France	Europe	Very High	113	14.83	1,216.35
Portugal	Europe	Very High	55	14.63	777.68
Italy	Europe	Very High	89	14.05	1,438.90
Chile	South America	Very High	10	14.02	1,165.57
Greece	Europe	Very High	19	13.70	488.98
Panama	North America	Very High	4	12.52	11,200.12
Kenya	Africa	Medium	25	11.25	309.62
Turkmenistan	Asia	High	17	11.05	1,244.47
Sri Lanka	Asia	Very High	63	10.16	463.68
Philippines	Asia	High	17	9.74	2,004.56
Algeria	Africa	Very High	55	9.58	2,778.51
Mongolia	Asia	High	0	9.58	267.33
Burkina Faso	Africa	Low	93	8.50	1,475.61
Bangladesh	Asia	Medium	2	8.27	777.15
Bulgaria	Europe	Very High	46	7.92	465.59
Ecuador	South America	Very High	4	7.48	295.34
United Kingdom	Europe	Very High	89	7.29	655.35
Uzbekistan	Asia	High	9	7.21	350.36
Netherlands	Europe	Very High	5	6.61	1,471.29
Congo (Democratic Republic of the)	Africa	Low	30	5.53	642.73
Peru	South America	Very High	10	5.16	383.99
Togo	Africa	Low	8	5.15	494.03
Iceland	Europe	Very High	6	5.11	470.91

Country	*Continent*	*HDI Classification*	*Dam Count*	*Capacity* (km^3)	*Area* (km^2)
Albania	Europe	Very High	5	5.11	258.50
Cuba	North America	Very High	1	5.11	244.37
Lesotho	Africa	Medium	8	4.78	122.94
Germany	Europe	Very High	60	4.35	405.58
Costa Rica	North America	Very High	14	4.34	176.32
Afghanistan	Asia	Low	4	4.27	115.88
Poland	Europe	Very High	29	4.18	530.79
Benin	Africa	Low	6	4.15	950.00
Bosnia and Herzegovina	Europe	Very High	11	3.83	140.57
Switzerland	Europe	Very High	36	3.80	103.30
El Salvador	North America	High	3	3.53	212.80
French Guiana	South America	Low	1	3.50	310.08
Czech Republic	Europe	Very High	35	3.45	272.13
Tunisia	Africa	High	49	3.40	363.20
Serbia	Europe	Very High	17	3.30	381.51
Georgia	Asia	Very High	12	3.17	13,579.78
Austria	Europe	Very High	22	2.93	249.07
Dominican Republic	North America	High	16	2.90	1,066.17
Taiwan	Asia	Low	5	2.71	46.24
Rwanda	Africa	Medium	5	2.48	2,392.21
Macedonia	Europe	Very High	9	2.34	57.33
Guinea	Africa	Low	20	2.10	117.93
Greenland	North America	Low	0	2.01	80.13
Slovakia	Europe	Very High	15	1.84	118.84
Moldova	Europe	High	2	1.78	144.50
Niger	Africa	Low	3	1.67	307.65
Saudi Arabia	Asia	Very High	2	1.47	7,624.68
Armenia	Asia	Very High	17	1.40	85.73
Belarus	Europe	Very High	1	1.34	64.11
Nicaragua	North America	High	1	1.25	54.00
Namibia	Africa	High	26	1.21	172.74
Bolivia	South America	High	279	1.20	5,244.90
Papua New Guinea	Oceania	Medium	2	1.14	44.99
Mauritania	Africa	Medium	3	1.05	636.39
Montenegro	Europe	Very High	3	1.05	24.86
Latvia	Europe	Very High	3	1.01	102.00
Central African Republic	Africa	Low	1	1.01	38.51
Ireland	Europe	Very High	4	0.99307	495.76
Croatia	Europe	Very High	8	0.98082	90.72
Botswana	Africa	High	13	0.96534	114.62
Cambodia	Asia	Medium	2	0.95500	41.45

Country	*Continent*	*HDI Classification*	*Dam Count*	*Capacity* (km^3)	*Area* (km^2)
Swaziland	Africa	Medium	11	0.91499	69.09
Puerto Rico	North America	Low	35	0.88686	38.85
Guyana	South America	High	4	0.80915	1,543.00
Hungary	Europe	Very High	5	0.65098	176.07
Lithuania	Europe	Very High	2	0.61710	92.15
Madagascar	Africa	Medium	12	0.61346	69.91
Congo	Africa	Medium	10	0.58400	0.04604
Hong Kong	Asia	Very High	0	0.56263	5.82
Liberia	Africa	Low	5	0.46820	32.34
Yemen	Asia	Low	30	0.46350	34.60
Guatemala	North America	High	3	0.46093	13.03
Sierra Leone	Africa	Low	8	0.45000	21.00
Gabon	Africa	High	4	0.44003	51.70
Senegal	Africa	Medium	1	0.39400	317.50
Jordan	Asia	Very High	9	0.38412	18.68
Libya	Africa	High	9	0.37210	43.48
Oman	Asia	Very High	7	0.34645	25.94
Lebanon	Asia	Very High	2	0.34568	6.05
Cyprus	Asia	Very High	4	0.33383	20.62
New Caledonia	Oceania	Low	0	0.31740	43.25
Slovenia	Europe	Very High	2	0.22274	33.75
Jamaica	North America	High	2	0.22000	38.00
Nepal	Asia	Medium	2	0.19737	28.60
Belgium	Europe	Very High	5	0.18047	12.58
Baker Island	Asia	Low	2	0.15428	38.30
Fiji	Oceania	Very High	0	0.15401	8.70
Belize	North America	High	0	0.12170	NA
Western Sahara	Africa	Low	0	0.11000	30.00
Mauritius	Africa	Very High	9	0.08740	12.91
Luxembourg	Europe	Very High	1	0.07920	5.15
Malawi	Africa	Low	10	0.07677	4.97
Singapore	Asia	Very High	2	0.07498	8.54
Trinidad and Tobago	South America	Very High	0	0.06570	4.31
Haiti	North America	Low	0	0.06200	3.00
United Arab Emirates	Asia	Very High	67	0.06144	17.21
Eritrea	Africa	Low	2	0.05811	0.54043
Burundi	Africa	Low	5	0.05707	1.91
Faroe Islands	Europe	Low	0	0.04495	4.14
Martinique	North America	Low	1	0.01580	0.85000
Bhutan	Asia	Medium	5	0.01342	0.72017
Guam	Oceania	Low	0	0.01172	0.55205

Country	*Continent*	*HDI Classification*	*Dam Count*	*Capacity (km^3)*	*Area (km^2)*
French Polynesia	Oceania	Low	0	0.00653	NA
Isle of Man	Europe	Low	0	0.00609	0.37129
Cape Verde	Africa	High	0	0.00575	NA
Antigua and Barbuda	North America	Very High	7	0.00487	30.71
Guadeloupe	North America	Low	0	0.00413	1.26
Mayotte	Africa	Low	0	0.00350	0.49000
Andorra	Europe	Very High	0	0.00289	0.15488
Saint Lucia	North America	High	1	0.00260	0.14125
Jersey	Europe	Low	0	0.00237	0.20486
Guernsey	Europe	Low	0	0.00109	0.06755
Seychelles	Africa	Very High	0	0.00102	0.01800
Israel	Asia	Very High	0	0.00067	0.92112
Reunion	Africa	Low	0	0.00052	0.14500
Grenada	North America	Very High	4	0.00002	NA

Notes:

1. Countries with no capacity reported not shown
2. Capacity estimates include additional downscaled ICOLD capacities
3. Dam count based on the GDRI dam dataset

Appendix B - Summary of Codes

Table B.1 List of codes used for dataset creation.

Code Name	Purpose	Description
Dam_Geocode.py	Geocoding	• Geocodes all ICOLD records based upon the provided attributes (dam name, reservoir name, nearest town, state/province, country) • Returns latitude and longitude coordinates for each record
DamCompilationCode.py	Dam Compilation	• Merges all 5 datasets together (CDA, FAO, GRanD, FAO, geocoded (validated) ICOLD, NID) • Identifies "problem" dams that are spatial duplicates, reservoir associated, and spatially associated dam points
DamSelection.py	Dam Compilation	• Selects identified "problem" dams based upon a hierarchy ranking and marks dams to keep/delete • Ranking (1-highest priority, 5-lowest priority): 1. NID 2. CDA 3. FAO 4. GRanD 5. ICOLD
LakeSelection.py	Reservoir Extraction	• Utilizes the compiled dam dataset and a near table to assign dam/reservoir pairs
ICOLD_Downscaling.py	Geocoding	• Downscales the non-geocoded ICOLD points using provided attributes (nearest town, state/province, country) • Returns latitude and longitude coordinates for each record
Area_Capacity_Estimation.py	Area/Capacity Estimation	• Utilizes area information from lake datasets and established equation from Lehner et al. (2011) to estimate area/capacity

Code Name	Purpose	Description
		- RMSE also calculated
Area_Capacity_Downscaling.py	Capacity Estimation	- Utilizes established equation from Lehner et al. (2011) to estimate capacity - RMSE also calculated