Development of Hydropower and the Environmental Impacts of Hydroelectric Dam Construction in China

Shingwun Sun[1*]

[1]The Hill School, 860 Beech Street, Pottstown PA 19464, USA

Abstract—The need to mitigate climate change and reduce carbon emissions has resulted in an increasing demand for the transition from fossil fuels to renewable sources of energy. Hydropower, in particular, has emerged as a prominent and extensively developed source of renewable energy in recent decades. This specific renewable energy harnesses the kinetic energy of falling or fast-flowing water to generate electricity. Despite being a dependable, adaptable, and cost-effective energy source, previous studies have highlighted the detrimental ecological effects of hydropower, ranging from altered land use to the disruption of natural habitats in the vicinity of dams. The main purpose of this study is two-fold. First, the change of renewable energy, particularly hydropower, is evaluated from 2000 to 2020 in China and globally, highlighting the leading role of hydropower in renewable energy generation. Second, this study aims to investigate the environmental influences of large hydroelectric dam construction and perform a case study of the Three Gorges Dam in China. The Pearson's linear correlation analysis was utilized to identify the association between hydropower and climate, and biodiversity, individually. Although dam construction can boost hydroelectricity generation, it can also have adverse effects on the regional climate and result in substantial depletion of biodiversity. This study will shed light on potentially reliable strategies to optimize the advantages of hydropower and minimize the negative environmental impacts of large-scale dam construction.

1. Introduction

Global warming has been indisputable over the last century due to the impact of human activities, and model projections indicate that it may rise by 1.1 to 5.4 °C by 2100, depending on various greenhouse gas emission scenarios[1]. This increase in surface temperature has resulted in numerous adverse effects, including rising sea levels and melting glaciers that cause flooding and droughts, changes in precipitation patterns leading to extreme weather events, and negative impacts on agriculture and biodiversity[2]. These effects threaten the health and stability of ecosystems and communities that rely on them for their livelihoods. As people begin to recognize the detrimental repercussions of global warming, there is a wave of desire for alternative energy sources, particularly the “renewable”. Even prior to the acceptance of global warming as a reality in the post-modern era, fossil fuels were nearly widely considered as highly “dirty” fuels responsible for several forms of terrible pollution, including acid rain. In contrast, nonconventional energy sources, particularly the renewable energy sources, have enjoyed a “clean” reputation vis-à-vis environmental repercussion[3].

There are numerous renewable energy sources, with hydropower being one of the most notable[4]. Hydroelectric energy is usually produced by dams and hydropower plants situated near reservoirs and rivers. Reservoir hydropower plants utilize water stored in a reservoir, whereas run-of-river hydropower plants harvest electricity from the river's natural flow[5]. A typical hydroelectric power plant consists of three parts: an electric plant that generates power, a dam that can control water flow by opening and closing, and a reservoir that stores water. Water from the reservoir runs through an intake and exerts pressure on the turbine blades, causing them to rotate. To produce electricity, the turbine spins a generator. The amount of electricity produced, which depends on the water flow rate and the distance the water falls, can be transmitted over long-distance power lines to power homes, factories, and businesses. As reported by the International Energy Agency, hydropower contributed 16.1% to global electricity generation in 2019, and it was expected to remain a significant source of electricity worldwide in the future[6]. The construction of hydroelectric dams, however, has the potential to kill or disrupt animals and other natural resources. Hydroelectric dams can adversely affect wildlife, environment, and biodiversity by disrupting the migration patterns of species like salmon and reducing the levels of dissolved oxygen in the water[7]. While hydropower is often recognized as a clean and renewable energy source, the negative impacts of large hydroelectric dams on climate, the environment,

*erick.sun.us@outlook.com

and biodiversity are frequently overlooked. These impacts have serious consequences for the health and stability of ecosystems and communities that depend on them for their sustenance. To mitigate their adverse effects, it is crucial that environmental evaluations are conducted before undertaking dam construction projects.

Taking the world's largest dam – the Three Gorges Dam (TGD) – as a typical case, this study will address the two-sided impact of large-scale dam construction on climate and biodiversity. On the one hand, the evolution of renewable energy generation (particularly the hydropower) in the past decades will be examined in China and globally, along with the change of surface temperature, precipitation, and carbon emission. Given the significant effects of dam construction on the local environment, on the other hand, this study will investigate how TGD construction influences ecosystem, including the loss of habitat for many species and the disruption of natural migration patterns. Through an examination of the TGD's impact on biodiversity, this study aims to offer insights into the broader implications of dam construction on the natural world and develop sustainable strategies for mitigating negative impacts in the future.

2. Materials and Methods

2.1. Three Gorges Dam

Situated on the Yangtze River in central China (Fig. 1), the Three Gorges Project is the largest hydroelectric power station in the world with over 22,500 megawatts of installed capacity. Located in the Hubei province, the region experiences a subtropical climate characterized by hot and humid summers and cool and dry winters[8]. Construction of the Three Gorges Dam began in 1994 and was completed in 2012 with the goal of preventing flooding in the Yangtze River basin and generating electricity. The dam spans over 2,300 meters in length and rises 185 meters high, resulting in the relocation of more than 1.3 million people. In a densely populated region with over 60 million inhabitants, the relocation of many individuals has also had notable effects on the local economy and way of life; meanwhile, the dam has positive effects on the region's economy by increasing electricity production and improving transportation along the Yangtze River[9].

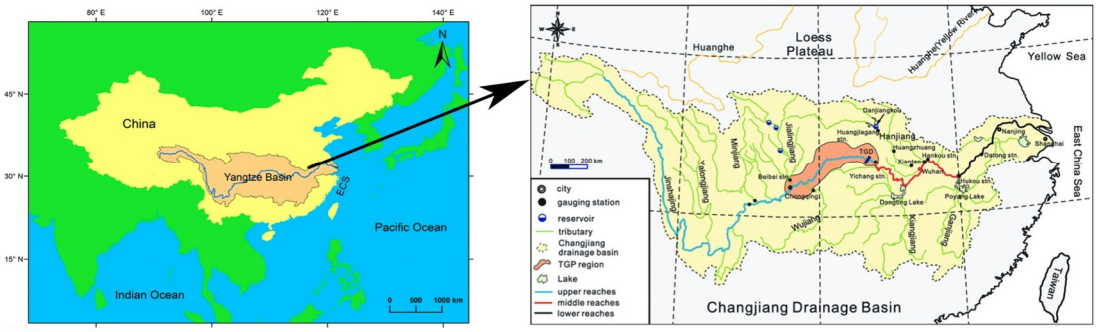

Fig. 1. The location and geography of the Three Gorges Dam, located in the Yangtze Basin. Adapted from Yang et al. [10].

2.2. Data

The global annual mean data of GDP, surface temperature anomalies, carbon emissions, renewable energy data in China were obtained from https://ourworldindata.org/. Using 2°x2° degree GPCC precipitation data from NOAA Physical Sciences Laboratory (2000-2020)[11], we estimate annual mean precipitation anomalies in China and the TGD region. Biodiversity data over the TGD area include the Yangtze Finless Porpoise, Carp Egg and Larvae[12], and Acipenser_sinensis[13]. The data set used in this study can be accessed via https://doi.org/10.5281/zenodo.7820466.

2.3. Method

The Pearson's Linear Correlation (PLC) is a statistical technique used to assess the strength and direction of a linear association between two variables. In this context, it is employed to investigate potential connections between hydropower and alterations in renewable energy, climate, and biodiversity. The PLC formula is as follows:

$$r = \sum(x_i - \bar{x})(y_i - \bar{y}) / \sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}, \quad (1)$$

where x_i and y_i are two time series, $\bar{x}$ and $\bar{y}$ are the arithmetic mean, respectively. r is correlation coefficient, ranging from -1 to 1.

The *student t-test* is additionally utilized to evaluate the significance of the PLC outcomes. This test relies on the t-statistic, derived from the means, standard deviations, and sample sizes of the compared groups.

3. Results and Discussion

3.1. Hydropower's Development in Recent Decades

The evolution of renewable energy has been a long and ongoing process, with various forms of renewable energy being developed and utilized over time. Fig. 2 show the change of different types of renewable energy generation (i.e., solar, wind, and hydropower) in the world and China from 2000 to 2020. As seen in both panels, hydropower serves as a leading renewable energy type, generating over 4200TWh of electricity globally and over 900TWh in China in 2020. Back in history, the first hydroelectric power plant was built in 1882 in Appleton, Wisconsin, using a water turbine to generate electricity. This early plant was relatively small, but it paved the

way for the development of larger hydroelectric power plants in the following decades. As technology improved and demand for electricity grew, hydroelectric power plants became increasingly common. In the early 20th century, large hydroelectric dams were built, such as the Hoover Dam in the United States and the Aswan Dam in Egypt[13]. These dams not only generated electricity, but also provided other benefits such as irrigation and flood control. Hydroelectricity has continued to evolve over the years, with the development of new technologies and innovations, as you may see in Fig. 2.

The evolution of hydroelectricity highlights its environmental and economic advantages. As hydroelectric power plants emit neither greenhouse gases nor air pollutants, they offer a clean, sustainable energy source. Utilizing hydroelectricity can also lessen fossil fuel dependence, thus mitigating climate change. However, controversies arise from the construction of large dams, which can adversely impact the environment and local communities through habitat loss for fish and wildlife, as well as displacement of affected residents.

Consequently, the establishment of hydroelectric power plants is now more frequently subjected to environmental regulations and impact evaluations. Despite the challenges, hydroelectricity continues to be a crucial renewable energy source, capable of meeting a substantial share of global electricity demands. In summary, hydroelectricity's evolution has significantly contributed to renewable energy development by providing a clean and dependable electricity source. Although the development of hydroelectric power plants faces challenges and controversy, the advantages of this renewable energy form render it vital in the worldwide shift towards a sustainable energy future.

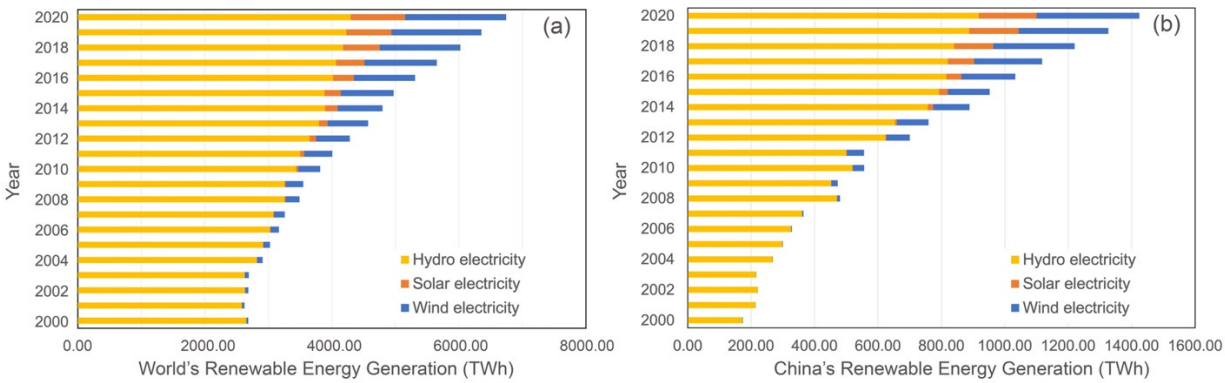

Fig. 2. Change in renewable energy generation (a) in the world and (b) in China from 2000 to 2020.

3.2. The impact of large hydroelectric construction on regional climate

The construction of large hydroelectric dams has sparked controversy due to their considerable effects on regional climate, including altering local water cycles. Dams can interfere with rivers' natural flows, impacting the quantity and timing of water accessible downstream for purposes like irrigation. Water levels and other hydrological processes may undergo changes due to dam construction, influencing regional climate in various ways, such as modifying evapotranspiration and precipitation patterns[14]. Furthermore, these changes may result in altered vegetation and land use, which can subsequently impact local weather patterns and temperatures. Reservoirs formed by hydroelectric dams can emit considerable amounts of greenhouse gases like methane and carbon dioxide, thus influencing regional and global climate in the long term.

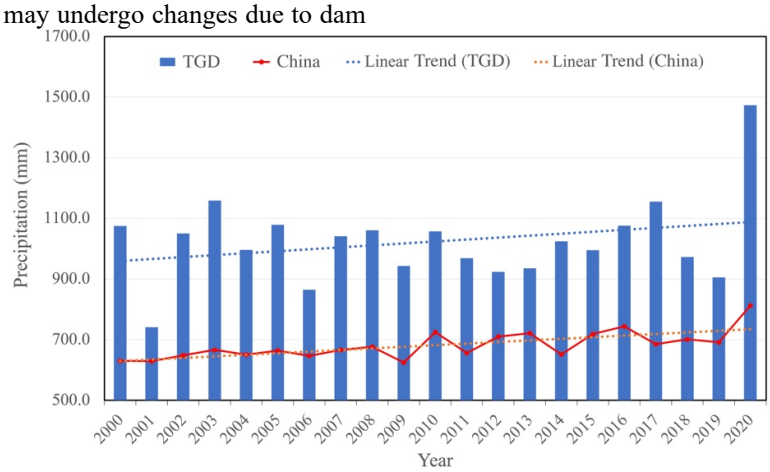

Fig. 3. Annual mean precipitation in China and the TGD area between 2000 and 2020.

Fig. 3 shows annual mean precipitation in China and the TGD area during the past two decades, illustrating the potential impact of hydropower and large hydroelectric construction on regional climate. The TGD region displays considerable variability, experiencing significant annual precipitation fluctuations, while China exhibits relatively stable precipitation levels. The minimum annual mean precipitation was 740.9 mm in

2001, while the maximum reached 1473.4 mm in 2020. Larger variability is detected over the second decade (2010-2019) than the first decade (2000-2009) in the TGD area, which further demonstrates the role of dam construction on regional evaporation and precipitation. Dam construction in the TGD region may contribute to increased rainfall, though other factors could also affect higher annual mean precipitation. One such factor is the "Meiyu season," a heavy rainfall period in the Yangtze River basin due to the monsoon, causing increased summer precipitation.

3.3. The impact of large hydroelectric construction on biodiversity

The construction and operation of substantial hydroelectric infrastructures, particularly large-scale dams, can profoundly influence biodiversity. These endeavors may modify natural habitats and disrupt water flow, engendering alterations in species composition and abundance within impacted regions. An examination of pertinent literature revealed that massive hydroelectric dams could precipitate the loss of as much as 80% of fish species in affected river systems[15]. Moreover, the transformation of natural habitats may result in the displacement of diverse species, subsequently causing population declines.

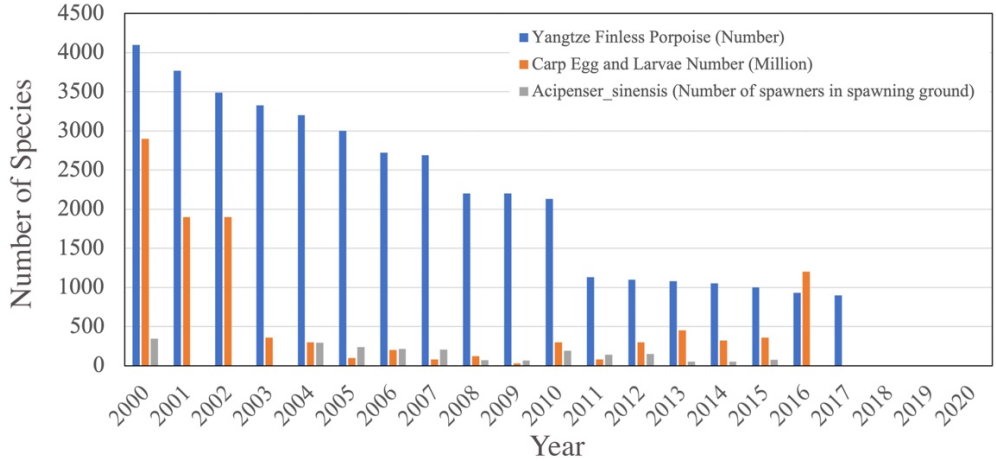

Fig. 4. Changes of biodiversity in the TDG area. Three typical species over the TGD area are selected to indicate biodiversity change.

As shown in Fig. 4, three typical species in the TGD region, namely, the Yangtze Finless Porpoise, Carp Egg and Larvae, and Acipenser_sinensis, generally show a decreasing trend over the construction period of the TGD project. Except for Carp Egg and Larvae, the Yangtze Finless Porpoise and Acipenser_sinensis continue to decline after the accomplishment of the TGD project till 2017, given the latest available data, suggesting the remarkable, negative influences of large dam construction on biodiversity. It is worth emphasizing that these detrimental effects are not transient but may persistently contribute to the diminishing populations of wild species.

Table 1. Correlation between hydropower, precipitation, and biodiversity indicators. * indicates that the correlation is significant at 95% confidence level based on the student-t test.

Correlation	Hydropower	Annual Mean Precipitation	Yangtze Finless Porpoise	Carp Egg and Larvae Number	Acipenser _sinensis
Hydropower	1.00	0.26	-0.95*	-0.37	-0.84*
Annual Mean Precipitation	0.26	1.00	-0.08	-0.05	0.29
Yangtze Finless Porpoise	-0.95*	-0.08	1.00	0.52*	0.84*
Carp Egg and Larvae Number	-0.37	-0.05	0.52*	1.00	0.54*
Acipenser_sinensis	-0.84*	0.29	0.84	0.54	1.00

Additionally, the interrelation among hydropower, annual mean precipitation, and biodiversity is investigated using PLC analysis, followed by the student's t-test for significance. Table 1 reveals a marginally positive correlation coefficient between hydropower and annual mean precipitation, hinting at the potential influence of dam construction on river flow, evaporation, and precipitation. Importantly, a robust negative correlation is observed between hydropower and three species in the TGD region. This lends credence to the argument that the large-scale TGD project may, at least in part, contribute to biodiversity loss in the Yangtze River basin.

4. Conclusion

This study highlights the dominant role of hydropower in global renewable energy development, while also

examining the negative environmental impacts of large dam construction, using the TGD as a case study. The study shows an increase in hydroelectricity production over the past two decades, but also identifies a decline in local species populations, indicating the detrimental effects of large dam construction on the ecosystem.

The construction of hydropower dams has significant impacts on renewable energy production, water resources, and economic development. However, maximizing the socioeconomic benefits of dam construction while minimizing its drawbacks is a complex challenge. This study uncovers the critical role of hydropower in optimizing the energy structure as the world shifts towards renewable energy. It also emphasizes the negative impacts of dam construction on regional climate and ecosystem, contradicting the argument that it improves livelihoods and ecosystem services. The study calls for more comprehensive environmental evaluations and policy interventions to address the impacts on biodiversity, climate, land use, and human activities before scheduling dam construction.

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