Research in Ecology
https://ojs.bilpublishing.com/index.php/re

ARTICLE

Effects of Mountain Rivers Cascade Hydropower Stations on Water Ecosystems

Mengtian Sun[1,2] Kai Huang[1,3] Jinhua Shao[1,3,4*] Weixiong Wu[1,3] Xinyue Liang[1,3]

1. Guangxi Key Laboratory of Water Engineering Materials and Structures, Nanning, Guangxi, 530023, China
2. College of Hydrology and Water Resources, Hohai University, Nanjing, Jiangsu, 210098, China
3. Guangxi Hydraulic Research Institute, Nanning, Guangxi, 530023, China
4. Research Centre on Ecological Sciences, Jiangxi Agricultural University, Nanchang, Guangxi, 533045, China

ARTICLE INFO

Article history
Received: 22 December 2021
Accepted: 18 January 2022
Published: 16 February 2022

Keywords:
Mountain rivers
Cascade hydropower stations
Development and operations
Ecological flow
Water ecosystems
Effects and countermeasures

ABSTRACT

China is rich in hydropower resources, and mountain rivers have abundant water resources and huge development potential, which have a profound impact on the pattern of water resources allocation in China. As the main way of water resources and hydropower development, the construction of cascade hydropower stations, while meeting the requirements of water resources utilization for social development, has also brought adverse effects on river ecosystems. Therefore, the impact of the construction of cascade hydropower stations on mountainous river ecosystems, where the minimum ecological flow of rivers must be ensured and reviewed. In addition, this paper proposed the deficiencies and outlooks for cascade hydropower stations based on previous research results.

1. Introduction

China is rich in water energy resources, with an annual river runoff of about 2.8 trillion m^3, accounting for 5% of the world's total runoff and ranking sixth in the world [1]. In recent years, the current situation of energy supply and demand in China has become increasingly severe, and hydropower energy as a clean and renewable energy source has been vigorously developed by the country, and hydropower development is also the main form of contemporary development and utilization of hydropower resources [2]. As of 2019, China has built 98112 various types of reservoirs with a total capacity of 898.3 billion m^3, of which there are 774 large

*Corresponding Author:
Jinhua Shao,
Guangxi Key Laboratory of Water Engineering Materials and Structures, Nanning, Guangxi, 530023, China; Guangxi Hydraulic Research Institute, Nanning, Guangxi, 530023, China; Research Centre on Ecological Sciences, Jiangxi Agricultural University, Nanchang, Guangxi, 533045, China;
Email: jinhua20211103@outlook.com; shaojinhwa@163.com

DOI: https://doi.org/10.30564/re.v4i1.4259

reservoirs with a total capacity of 715 billion m^3; 3978 medium-sized reservoirs with a total capacity of 112.7 billion m^3 [3].

As an important constituent type of rivers in China, mountain rivers possess abundant water resources and huge development potential, which have a profound impact on the pattern of water resources allocation in China. Mountain river areas are often relatively closed, less socio-economically developed, with fragile ecosystems and complex geological formations [4]. Cascade development of mountain rivers refers to the placement of a series of stepped water hubs on mountain rivers in order to fully exploit the hydroenergy resources of mountain rivers [5]. The construction of large scale cascade hydropower stations on mountain rivers has greatly contributed to the allocation and management of local water resources and promoted local economic development, but it has also brought about a huge impact on the local mountain rivers and ecosystems. Moreover with the fact that cascade hydropower development has a watershed impact, which brings about a series of group, systematic and cumulative impacts in the watershed [6], makes the impact of cascade power stations on rivers much greater than that of single hydropower project [7]. In recent years, the construction of cascade power stations in mountain rivers has produced adverse effects on mountain river ecosystems. Therefore, it is far-reaching to study the effects of cascade power station construction on mountain river ecosystems, to comprehensively understand the adverse effects on the ecological environment and take certain preventive management measures against them. Based on these results, this paper summarizes the impact of the construction of cascade hydropower stations on mountain river ecosystems and some preventive management measures, and proposes directions that still need to be further explored to provide some references for the continued study of the impact of cascade power plant construction on mountain rivers. As shown in Figure 1, people build cascade hydropower stations in mountain rivers. Figure 2 introduces the framework of this paper.

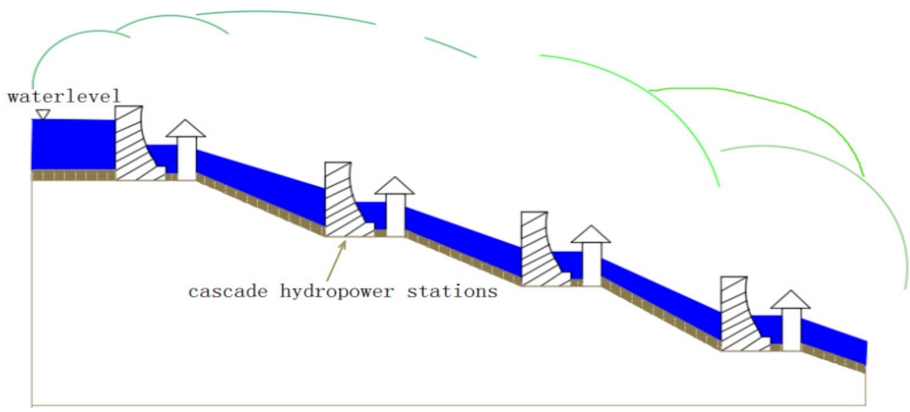

Figure 1. The cascade hydropower stations

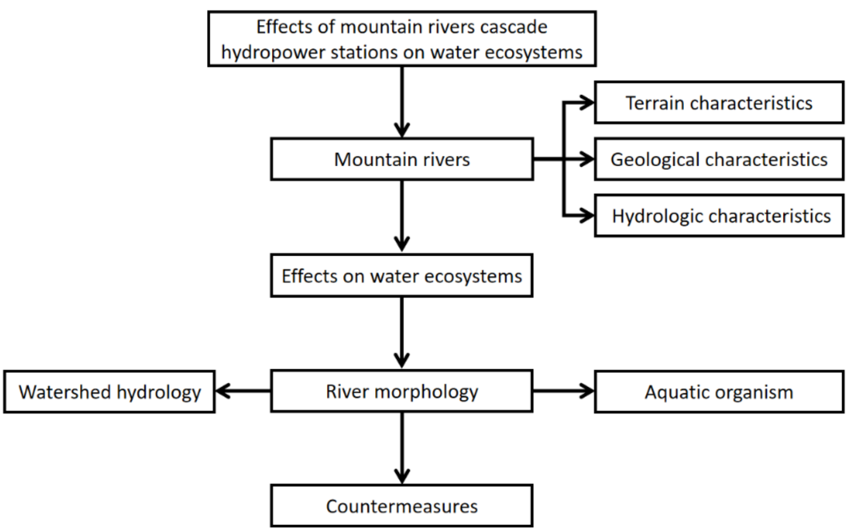

Figure 2. the framework of this paper

2. Mountain Rivers

The interaction between the hydrological processes of mountain rivers and the mountain ecosystems on both sides of the river are complex, which must be studied as a complete ecosystem. The equilibrium and stability of this ecosystem is formed over a long period of time. With the construction of water hubs, especially the construction of cascade hydropower stations of the watershed, the equilibrium of this system is disrupted, causing drastic changes to form a new equilibrium in a short period of time. The new ecosystem may cause changes in the river water environment, leading to a reduction in the range of species resource habitats, regulation of resource allocation, etc., which in turn affects the health of the entire ecosystem and its ability to develop sustainably.

2.1 The Concepts of Mountain Rivers

Literally, mountain rivers are rivers that originate from and are located in mountainous areas. This concept has been interpreted differently in different disciplines. Lewin J [8] considered mountain rivers as rivers with coarse bed material and slopes greater than 1% with plunging deep channel morphology. James C considered mountain rivers as rivers with beds composed of coarse-grained bed sand, with slopes between 0.5% and 5% of the river bottom and water depths less than 10 times the bed sand grain size. Qian Ning et al. included alluvial cones and pebbly rivers formed in ice-water depositional plains in the category of mountain rivers [9]. Zhang Guangke described the characteristics of watercourse branching ratio, branching capacity, watercourse level, and width-to-depth ratio of mountain rivers based on the analysis of river characteristics, and pointed out that the branching ratio of watercourses in mountain rivers is usually 3-4, and the branching capacity is a constant close to 4. Generally, the width-to-depth ratio tends to a constant after the watercourse level is 12 [10]. Wang Xiekang et al. argued that to describe or study mountain rivers and their characteristics, they should be based on mountainous region or mountainous watersheds, combined with their own unique substrate conditions and the hydrological characteristics of rivers, and it is unreasonable to ignore any aspect to define them [11].

2.2 The Characteristics of Mountain Rivers

2.2.1 Terrain Characteristics

The basic river types of mountain rivers are canyons and wide valley sections, which are influenced by the topography, geology and lithology along the course of the river. Both of them usually occur in close proximity to each other. The canyon section usually has a narrow valley body. The water cuts the valley bottom deeper and the valley slope is steep. Some banks are even accompanied by bare high mountains and octopus wall, the valley trough is deep, and the difference in river width between flood level and mid-water level is not significant. The wide valley section usually has an open valley body, a wide and shallow river bed, the water cuts the valley bottom shallower, the banks are accompanied by cascades, and the river is accompanied by side beaches and river core islands, and the difference in flood level, mid-water level and the difference between flood level, mid-water level and dry water level is relatively significant.

The longitudinal section of the river in the mountainous area is steep at the top and slow at the bottom, with sudden high and low, uneven, cascade-like and gradually sloping downstream. The small undulating river bottom results in very uneven water depths along the river, ranging from a few meters to tens of meters in deep water, but usually less than 1 meter in shallow water.

There are rock spouts and rocks entering in the banks of mountain rivers, so the river's shoreline is very irregular, especially for dry rivers, which have narrow channels, with wide and narrow river surfaces, many chokepoints, sharp bends and narrow channels.

2.2.2 Geological Characteristics

The main composition of the bed of mountain rivers is bedrock and pebbles, and the grain size of pebbles is usually coarse, and some thicker cover of pebbles and gravels also exists. That is, mountain rivers are mainly stony riverbeds, but also have a definite pebble bed. Stony riverbeds are more stable and siltation is not obvious, but suffered from long-term undercutting and lateral erosion by water flow, the riverbeds will have a certain degree of shape change. Local river sections are subject to landslides, landslides and outbreaks of flash floods in streams and gullies, which can produce intense and frequent deformation. The pebble bed is subjected to long-term transport and friction by water flow, and there is a clear phenomenon of siltation change, with a smooth surface and no angularity. However, the pebbles are large in size and weight, so the riverbed is also relatively stable.

2.2.3 Hydrologic Characteristics

During the flood season, the main runoff source of mountain rivers is rainfall, while the major method is groundwater recharge in dry season. In the season of heavy rainfall, the water level is higher and the flow is larger. However, in the season of less rainfall, the water level and flow are more stable and the flow is smaller, meaning a more steady dry period. Due to the narrow riverbed and large slope, heavy rainfall can quickly converge into the main stream with a rapid water flow, leading to the rise of water level and the surge of flow , but also can discharge the flood and drop the water level quickly. Therefore, mountain rivers have obvious phenomenon of storm rise and fall, and the variation of water level and flow is also significant.

3. Effects on Water Ecosystems

The development of hydropower cascades plays as a large driving role in the natural ecosystem and can cause drastic changes in various ecological elements, the complexity of the mountain rivers' own ecosystem as well as the instability of ecological elements. With the cumulative effects of the cascaded power stations, the impact on the ecosystem will be greater. The development of hydropower cascades will undoubtedly produce strong disturbances and adverse effects on the watershed ecosystems, which in turn will cause transformation in river morphology, watershed hydrology, local destruction of vegetation, soil erosion, animal infestation, and threats to fish survival and reproduction [12].

3.1 Watershed Hydrology

3.1.1 Water Temperature

Water temperature is one of the most important factors in analyzing the impact of watershed cascade power plant development on the water environment. To a certain extent, water temperature can change the physical, chemical and biological properties of water bodies, influencing the material cycle and energy flow of water bodies, as well as the development, metabolism, growth structure and population distribution of organisms in water bodies. Reservoir water temperature observation has been carried out in China since the mid-1950s, and in the 1960s reservoir water temperature observation was gradually carried out in large and medium-sized reservoirs [13]. At present, the methods of predicting reservoir water temperature distribution at home and abroad mainly include empirical formula method, numerical analysis method, and analogy method [14,15]. Zhu Bofang [16] proposed the empirical formula method, and on the basis of statistical analysis of the measured water temperature, the formula for calculating the intra-annual variation, average annual temperature, annual variation, and phase difference of reservoir water temperature was proposed. And the analogy method is to use the measured water temperature information of constructed reservoirs and predict by analogy the water temperature distribution of unbuilt reservoirs with similar conditions, but the accuracy of the method is not high because the hydrological conditions, material structure and actual operation of the reservoirs are quite different. The numerical analysis software for reservoir water temperature (NAPRWT), developed in China, has been applied in various domestic projects considering four major elements, including the shape of the reservoir, hydro-meteorological conditions, reservoir operation conditions, and initial reservoir storage conditions [17]. In addition, MIKE software is applied to establish a prediction model of the effect of hydropower development on water temperature focusing on the cumulative effect of water temperature caused by cacsade hydropower development. Some scholars have conducted a more in-depth study on the effect of basin cascade power stations on water temperature, Huang Feng and Wei Lang et al [18] further carried out the effect of different water temperature structure cascade power stations on the downstream water temperature, water temperature time accumulation effect and water temperature spatial accumulation effect, their research shows that the stratified reservoir has the greatest change on natural water temperature, the stable stratified reservoir has a positive effect on water temperature accumulation, the mixed reservoir has a the negative effect (i.e., the temperature difference decreases due to the regulating effect of the reservoir), and the transitional reservoir is in between. Liang Ruifeng and Deng Yun et al [19] studied the relationship between the number of staircases and the delay time of discharging water temperature, and found that the delay time of discharging water temperature of joint dispatch increased with the increase of the number of staircases, and the discharging water temperature of each staircase was flattened, and the temperature difference of discharging water temperature tended to be stable.

At present, scholars at home and abroad have successively carried out research work on the effects of watershed cascade power stations on water temperature. The construction of cascade power stations improves the utilization of water resources, but changes the spatial and temporal distribution processes of natural river runoff and heat. Because the transferability and cumulative nature of water temperature changes along the course, without sufficient attenuation distance, the changing effects of water temperature accumulate with the increase in the number of cascade reservoirs, which will finally cause a series of group, systematic and cumulative environmental impacts in the watershed [20]. Zhang Qianwen [21] conducted a statistical analysis of the water temperature monitoring data of the Dang River basin from 1985 to 2015 based on the hydrological station of Dangchengwan, and concluded that the water temperature showed an increasing trend about 1 °C during the 31 years from 1985 to 2015. Large reservoirs cause water temperature stratification, with the water temperature of the lower layer being high in winter and low in spring, summer and autumn. The lower layer of water is discharged, causing the water temperature of the downstream river high in winter and low in spring, summer and autumn. Liu Xiaoai et al. [22] pointed out that after the construction of the cascade power stations in the Lixian River basin, the annual average value of water temperature behind the dam was basically the same as that of the original natural river, but the average water temperature changed significantly month by month during the year, and the water temperature at the exit point in spring and summer decrease by about 0 °C-2 °C. Due to the increase of water area, the thermal effect of the water body in the reservoir area of the the construction of cascade hydropower stations leads to the improvement of local environmental quality and terrestrial climate, such as the increase of rainfall, humidity, the increase of annual average temperature and the decrease of temperature difference. The degree of impact has a positive correlation with the degree of increase of water area.

In general, the current research results on the influence of the current basin cascade power stations development on water temperature have the following shortcomings: First, the existing results are not highly universal, the temperature change is complex and closely related to the hydrology of the basin, climatic conditions, the degree of development of the cascade power stations, etc. Therefore, the change law is only applicable to part of the project, and cannot fully and completely reflect the water temperature change law of the joint operation of the cascade reservoirs. Second, the water temperature change law is still at the exploration stage, and the application is low. The law of change of water temperature is still in the exploration stage, the application isn't extensive. The simulation and application of temperature law is more used in the design stage before the development of power station, after the power station is put into operation, the change of water temperature on the downstream hydrological situation and water environmental conditions can not be applied to control the use.

3.1.2 Flow

Before the construction of the cascade power stations, the river flow and velocity were continuous. After the construction of cascade hydropower stations, the development of dams and diversion tunnels showed a serious isolation effect on the natural river channels, and the continuity of river flow was disrupted. Ma Cong et al. [23] studied the changes in downstream runoff before and after the construction of Ankang reservoir and found that the average monthly runoff decreased by 690 million m3/month from April to November and increased by 100 million m^3/month from December to March after the construction of the reservoir, and that the construction of the reservoir was the most direct factor contributing to this result. Taking the Lancang River as an example, Gu Ying et al. [24] found that after the operation of the cascaded power station, the average multi-year runoff decreased by 10.64% in the rainy season and increased by 45.94% in the dry season, while the average annual flow remained almost unchanged. The annual water level-time course of the river after such regulation tends to be flat, with little change in runoff during the year, which has a peak-shaving and peak-staggering effect on large floods and helps to reduce the hazards caused by floods. However, due to the lack of unified planning and management of river hydropower development, the development of cascade power stations also brings some negative effects on water resources utilization. Studies have shown that the construction of cascade power stations can lead to a reduction in river runoff, and even the phenomenon that some rivers break and disappear [25], changing the hydrological rhythm of large and small rivers [26]. Li Chaoxia and Fan Yi [27] pointed out that during the dry period when the natural runoff is less than the diversion volume, the river channel may break. Lianfang Xue [28] and Bin Fu [29] pointed out that the longer the diversion pipeline and the higher the diversion flow rate, the more likely the river channel is to break during the construction of diversion-type cascade power stations. Fan Jihui [30] and Zou Shuzhen [31] conducted a field study on the current status of cascade development in the upper reaches of the Minjiang River and the middle reaches of the Ganjiang River, respectively, and found that unreasonable hydropower development has caused some rivers to break and other phenomena. Zhang Qianwen [21] studied the impact of the construction of the Party River cascade power stations on runoff changes and found that the river flow of the power stations with too large design diversion flow cannot meet the maximum diversion flow required for power generation in the cascade power stations. The river is prone to breakage in the season when the flow of the Party River is low; the river section where the diversion flow required by the cascade power station is high is also prone to river breakage. Moreover, the cumulative effect of the cascade power station will make the phenomenon of river breakage more significant. The river bed is exposed, the vegetation along the river bank is extinguished, and the aquatic organisms cannot survive and reproduce, and other serious adverse ecological effects are caused by the river break. The river ecosystem is closely related to the river runoff, and the gradient development will cause drastic changes in the river runoff, and these drastic changes will inevitably cause a huge impact on the river ecosystem as well.

From these research results, it seems that the construction of cascade power stations significantly affects the flow variability of rivers, and its impact has both advantages and disadvantages. The variation of river flow is closely related to the topography, hydroclimatic conditions, and the degree of development of the cascade power stations, etc. The universal results of runoff variation under the influence of the cascade power stations have not been obtained yet. In addition, further studies should be conducted to control the negative impacts such as the reduction of river runoff and even disconnection caused by the construction of the cascade power stations.

3.1.3 Sediment Accumulation

The development of the basin's cascade power stations leads to changes in the hydrodynamic conditions of the river, with reduced flow and river disconnection, which in turn leads to changes in the properties of particulate matter and nutrients in the water body, and the scouring effect of the river on the river becomes smaller, so that a large amount of sediment is retained in the water body [32]. In addition, the sand retention effect of the barrage of the cascade power stations affects the sand transport function of the river and disrupts the original sand transport balance of the river, which leads to the incoming sand from the upstream stopped in the cascade reservoir area, causing sediment siltation near the cascade power station and a large reduction in the sand content in the downstream water, and the sand content in the downstream river and water body becomes less accordingly. Matti et al [33] found that the average reduction in sand content in the lower Mekong River was about 20.3% in the initial period after the construction of Manwan Dam. Kou et al [34] found that the sand content in the downstream of the reservoir was significantly reduced and siltation in the reservoir area through a study of the Long Yangxia-Liujiaxia section of the upper Yellow River, which has a high degree of cascade development. Weng, Wenlin et al [35] found that the sand content in the lower reaches of the Yangtze River was greatly reduced after the construction of the reservoir group in the upper reaches of the river, with a decrease of 26.5% to 84.2%. The river water in the lower reaches, which originally carried a large amount of sediment and was mainly used for siltation and land formation, became sediment deficient, which strongly eroded the river section below the dam, scoured and deformed the riverbed, and threatened the river banks as well as the buildings on both sides [36]. At the same time, the development of the basin cascade has a cumulative effect on sediment siltation and increases the severity of sedimentation substantially.

Based on the current research, the impact of the construction of the cascade power stations on sedimentation is mainly negative, and how to take corresponding remedial measures is also a very realistic and new problem. For this reason, it is necessary to further study the optimal scheduling of sediment in the group of cascade reservoirs. Firstly, how to slow down the process of sediment siltation as much as possible; secondly, how to regulate the amount of sediment siltation among the group of cascade reservoirs under the condition that the total amount of siltation is certain, so that the total benefit of the reservoirs group can be optimized.

3.2 River Morphology

The construction of cascade hydropower stations transforms natural rivers into water bodies consisting of multiple reservoirs of various sizes and regulation properties, water-reducing reaches and undeveloped reaches, and changes the vertical continuity. This change in water form and area is more prominent for mountainous rivers than for plain rivers. For example, after the completion of the Lancang River cascade hydropower stations, the area of the eight cascade reservoirs totaled 62,112 km^2, and their water area increased by about 53,211 km^2 compared with that of natural rivers, which is seven times as the natural water surface area [37]. The scouring of the river channel by the discharge of clear water may make the river channel shift sideways and the river is cut and straightened. Compared with a straight channel, a meandering river reduces the slope drop, decreaseing the river flow velocity and water and sand transport capacity, which facilitates the formation of a diverse aquatic environment to protect the species diversity of aquatic organisms. Therefore, the change of river morphology can also have a negative impact on river ecosystems.

3.3 Aquatic Organism

The development of the cascade has changed the hydrological conditions of the original aquatic ecosystem, causing fragmentation of aquatic habitats, resulting in breakage and siltation of river sections, and bringing significant impacts to aquatic organisms.

The formation of reservoirs and the amount of water discharged from them during dry periods raises the water level in the lower reaches of the river, inundating the loss of floodplains, wetlands, and riparian vegetation zones [38], and the construction of cascaded reservoirs will superimpose and amplify these effects. The riparian zone is unable to filter out or absorb sediments, nutrients, and pollutants before they flow into the river, and changes in water quality will occur. Fanyang et al. [39] studied the Three Gorges Project of the Yangtze River as an example and found that a large proportion of riparian vegetation disappeared and was affected mainly by the reversal of floods, the prolongation of flood duration, and the creation of new fallout zones.Ouyang et al. [40] studied and developed an analytical technique for identifying and predicting the impact of cascade development on riparian vegetation, using the upper Yellow River as an example The analysis technique can provide basic guidance for reducing the impact of cascade development on river banks.

The construction of cascade hydropower stations has threatened the survival and reproduction of fish, and reduced their populations and numbers. It also increases the population biomass of phytoplankton and reduces the number and species of benthic animals. Ming et al. [41] found that the density of macrobenthos decreased significantly at the beginning of water storage in Three Gorges Reservoir; however, after a certain period of adaptation, the total density of macrobenthos increased significantly from 2005 onwards, and showed a clear seasonality, with the lowest in winter and the highest in autumn. At later stages of development, the reservoir ages, at which time both macrobenthic community diversity and density decrease, forming a single structure with fouling-tolerant species as the dominant taxa [42]. The main reason for this is that the survival rate of fish through hydraulic structures such as barrages is zero. The river flow is sharply reduced or even cut off cannot satisfy the basic habitat for fish. Hydroelectric power plants use drop-offs to intensify the scouring of downstream rivers by water bodies, resulting in the migration or disappearance of fish spawning grounds and changing important habitats such as fish overwintering grounds, spawning grounds and baiting grounds. Due to the dam blocking the river, the natural passage of fish and other aquatic organisms is cut off, resulting in the regionalization of fish habitat, blocking the genetic exchange between fish populations, causing inbreeding of fish and reducing the quality of fish populations. The siltation of sediment creates difficulties for fish feeding. Water temperature also affects fish reproduction. Large reservoirs cause stratification of water temperature, with high lower layer water temperature in winter and low lower layer water temperature in spring, summer and autumn; after the lower layer water is released, the water temperature in the downstream river is high in winter and low in spring, summer and autumn, which interferes with the fish reproduction process. It has been found that the spawning time of Chinese sturgeon and the four major fish species in the Yichang River section downstream was delayed and the spawning size was significantly reduced after water storage in Three Gorges Reservoir [43]. After the construction of the cascade power station, the water temperature becomes higher and the flow velocity slower, which is suitable for the growth of plankton, and the population and quantity of plankton increase. The siltation reduces the area where benthic animals can attach, and the population and number of benthic animals decrease.

In summary, various perturbations to the river systems from the construction of the cascade power stations will affect the species composition, distribution and activity patterns of aquatic organisms. Previous studies have mostly focused on the response of single aquatic organisms to power stations construction, while relatively few studies have considered different aquatic organisms. Since different aquatic organisms have different life history characteristics and environmental adaptability, considering the response of plankton, benthos, fish and other aquatic organisms to power stations construction can reflect the impact of power stations construction on aquatic ecosystems more comprehensively, and also provide basic data and scientific basis for rational hydropower development and management.

4. Countermeasures

4.1 Ensure the Minimum Influence of the River

The need to ensure the minimum ecological flow of the river is the primary condition for maintaining the dynamic balance of the river ecosystem and ensuring a healthy river ecosystem [44]. To ensure the minimum ecological volume of the river, i.e., to ensure the normal ecological water consumption and water quality requirements, and to reduce the impact of the construction of the cascade power stations on aquatic organisms, the barrage discharge must meet the minimum discharge flow requirements. The historical flow method, also known as the Tennant method [45], is used to calculate the minimum flow requirements for rivers, and it is believed that when the flow is less than 10% of the average flow, the flow velocity and water depth decay and will provide only transient conditions for the survival of aquatic organisms. This shows the importance of ecological flow for river ecosystems. At present, there are several methods to estimate the minimum ecological flow in China and abroad. Accordingly, the minimum ecological demand within the construction section of each cascade power station is calculated, and supervision and protection measures are taken. For example, supervising and managing the cascade power stations to ensure that the power stations install online flow measurement devices; not conducting diversions and discharges during the dry season when the river flow itself is low; and directly releasing the river when the minimum ecological flow of the river is more difficult to guarantee. Reduce the occurrence of river disconnection, minimize the impact on aquatic organisms, and ensure the balance of river sand transport.

In view of the adverse effect of water temperature in cascade power stations, the measures to adjust the lower discharge water temperature include stratified intake of water and optimization of reservoir operation mode. Zheng et al. [46] have took Maji Reservoir as an example, and the outlet temperature of different power stations under the current reservoir operation mode was compared and analyzed. They concluded that the higher the water intake location is, the higher the water temperature will be in spring. The stratified water intake is effective to mitigate the influence of cold water. Zhang et al. [47] also found that when getting water on a single-layer of reservoir, the reservoir has a great influence on the downstream water temperature. However, when the water draw by the layered water intake with stacked beam gate, the influence of the low-temperature water effect on the downstream is effectively slowed down. In order to solve the problem of sediment deposition, Yan and Liu pointed that the transported-sand device need to be located. The device can discharge flood water and remove part of the sediment in the reservoir, which can reduce the sediment accumulation in upstream side [48].

4.2 Establish Fish Protection Zones

Select 1 or 2 suitable tributaries in the development section of the cascade power station as fish “protection zones” no longer for hydropower development. Establish 1 “fish augmentation station” at a suitable location as a supplementary measure for fish protection in the basin. In view of the complexity of fish enhancement and release techniques, it is necessary to carefully study the enhancement and release techniques in order to give full play to them. The stocking of exotic fish species in the reservoir must be prohibited after the completion of the hydropower station; destructive and indiscriminate fishing is prohibited.

4.3 Establish a Sound Environmental Impact Assessment System and Speed Up Legislation

Promote the hydropower basin planning environmental impact assessment and hydropower basin planning in order to pay attention to the ecological environment from the source, the development of the overall situation of the impact on the ecological environment issues, the basin development of the ecological environment to minimize the impact of the watershed to maximize the benefits of water development and minimize the impact on the ecological environment. In future power stations construction work, local governments should strengthen regulations and legislation to strictly manage the orderly development of hydropower, environmental assessment and project approval of relevant projects must be strictly required. If a watershed must be opened for the construction of a new power station, it must meet the minimum ecological flow of the river to minimize its adverse impact on the ecological environment [49].

5. Conclusions

The construction of cascade power stations in mountain rivers is becoming more and more widespread, and the current reservoir dispatch is generally aimed at flood control and profit generation, often neglecting the health of river ecosystems. With the strengthening of people’s awareness of river ecology, research on the impact of the construction of cascade hydropower stations on mountain river ecosystems has been carried out, and a lot of results have been achieved, but there still have shortcomings.

On the one hand, there are more studies on the ecological impact of single hydropower projects and the quantitative level is higher, while there are fewer quantitative studies on the cumulative impact of river the construction of cascade hydropower stations on watershed environment, and even fewer studies on mountain rivers. On the other hand, most of the scholars only study how and to what extent the the construction of cascade hydropower stations affects various aspects of river ecology, but little research has been done on the impacts of different scales of the construction of cascade hydropower stations on different scales of rivers, and there is no further research on how to avoid or reduce these impacts through engineering or non-engineering measures. Also there is no model or equational relationship on the data that can be used to analyze changes in ecological elements comprehensively. Therefore, this paper argues that in the future, based on previous research results, we need to study the ecological impacts caused by building cascaded power stations of different sizes on mountain rivers at different scales, and apply relevant evaluation models to evaluate each ecological element.

Funding

This research was funded by Guangxi key R & D program (Guike AB19259015) and Guangxi key R & D program (Guike AB20297017); Guangxi Key Laboratory of Water Engineering Materials and Structures fund program (GXHRI-WZMS-2020-07).

References

[1] Jia J.Sh., Yuan, Y.L., Zheng, C.Y., et al., 2010. A brief discussion on the statistical and technical progress and concerns of reservoir dams in China. Hydroelectricity. 36(01), 6-10.

[2] Chang, X.L., Liu, X.H., Zhou, W., 2010. Hydropower in China at present and its further development. Energy. 35(11), 4400-4406.

[3] Ministry of Water Resources of the People's Republic of China, 2021. National statistical bulletin on water resources development in 2020. Beijing: China Water Conservancy and Hydropower Press.

[4] Zheng, J.T., 2013. Modeling the impact of hydropower development on mountain river ecosystems and its application. North China University of Electric Power.

[5] Yue, J.T., Gan, Z.G., Liao, W.H., et al., 2016. A review of the impact of cascade development on river hydrology and ecosystem. China Rural Water Conservancy and Hydropower. 10, 31-34.

[6] Jiang, J.B., 2020. The impact of hydropower project construction on ecological environment. China comprehensive utilization of resources. 38(01), 144-146.

[7] Li, Zh.X., Niu, W.J., 2009. Evaluation model and application of the ecological environment impact of hydropower gradient development. Journal of Hydro-power Generation. 28(02), 35-40.

[8] Lewin, J., 1981. British River. George Allen and Unwin. pp. 216.

[9] Qian, N., Zhang, R., Zhou, C.D., 1998. Evolution of riverbeds. Beijing: Science Press. 39.

[10] Zhang, G.K., 1999. Study on some characteristics of mountain rivers. Journal of Sichuan United University (Engineering Science Edition). 01, 14-22.

[11] Wang, X.K., Yi, L.Q., Fang, D., et al., 1999. Preliminary study on the hydrological characteristics of mountain rivers. Sichuan Hydropower. 02, 15-17.

[12] Chen, Y.Q., 2007. Analysis of the impact of hydro energy development on ecological environment. China Water Energy and Electrification. 03, 15-18.

[13] Ding, B.Y., et al., 1982. Investigation and study of reservoir water temperature. Proceedings of scientific research of the Research Institute of Water Resources and Hydropower (Collection 9). Beijing. Water Resources and Electricity Publishing House.

[14] Hu, P., Liu, Y., Tang, Z.M., Wang, J.H., 2010. Numerical prediction method of reservoir water temperature. Journal of Water Resources. 41(09), 1045-1053.

[15] Zhang, P., Liang, R.F., Li, Y., Li, K.F., 2018. Effects of joint scheduling of the Batang River section terrace power plants on water temperature. Sichuan Environment. 37(02), 50-58.

[16] Zhu, B.F., 1999. Temperature stress and temperature control of mass concrete. Beijing: China Electric Power Publishing House.

[17] China Institute of Water Resources and Hydropower Science, 2004. Numerical analysis software for reservoir water temperature (NAPRWT) [CP]. Beijing: National Copyright Administration of the People's Republic of China.

[18] Huang, F., Wei, L., Li, L., Zhu, W., 2009. Cumulative effect of water temperature on hydropower gradient development in the middle and upper reaches of the Wujiang River. Yangtze River Basin Resources and Environment. 18(04), 337-342.

[19] Liang, R.F., Deng, Y., Tuo, Y.C., Li, J., 2012. Characterization of cumulative water temperature impact of basin hydropower gradient development. Journal of Sichuan University (Engineering Science Edition). 44(S2), 221-227.

[20] Chen, K.Q., Wang, D.Sh., Liu, L.F., et al., 2005. Characteristics and research directions of environmental impact assessment of basin terrace planning. Journal of China Institute of Water Resources and Hydropower Research. 3(2), 79-84.

[21] Zhang, Q.W., 2016. The impact of the construction of the Danghe River Tertiary Power Station on the ecological environment. Lanzhou University.

[22] Liu, X., Li, J.W., 2007. Impacts of the developmentof the Li Xian River Basin cascade power station on ecological environment and prevention and control measures. Journal of Environmental Science. 02, 69-72.

[23] Ma, C., Lu, C.H., Li, Y.Q., et al., 2013. Evolution of runoff downstream of Ankang Reservoir and analysis of the impact of reservoir operation on runoff. Yangtze River Basin Resources and Environment. 22(11), 1433-1440.

[24] Gu, Y., Lei, S., Liu, J.N., 2008. Impact of the construction of the Lancang River step power station on the downstream hydrological situation. Water Resources and Hydropower Technology. 39(4), 20-23.

[25] Huang, Y., 2016. Ecological impact study on the development of river terrace hydropower in southwestern mountains. Northeast Forestry University.

[26] Magilligan, F.J., Nislow, K.H., 2005. Changes in hy-

drologic regime by dams. Geomorphology. 71(1-2), 61-78.

[27] Li, Zh.X., Fan, Y., Nima, T., Wang, W.Ch., 2011. Impact of Bahe hydropower gradient development on ecological environment. People's Yellow River. 33(05), 63-65+68.

[28] Xue, L.F., 1997. Study on the environmental impact of Dongjiang hydropower station. Hydroelectric power plant design. 13(3), 79-83.

[29] Fu, B., 2010. Environmental impact and countermeasures of the Jiulong River Basin Step Hydropower Station. Chemical Engineering and Equipment. 04, 192-194.

[30] Fan, J.H., Cheng, G.W., Zhang, Y., Liu, Q., Chen, J.F., 2005. Problems and suggestions for the development of the upper reaches of Minjiang River hydropower gradient. China Water Resources. 10, 47-49.

[31] Zou, Sh.Zh., 2011. Study on the impact of large hydropower projects on fish and their ecological environment in the middle reaches of Ganjiang River. Nanchang University.

[32] Xu, H.L., Xiang, Y., 2003. Sedimentation management in Tiandian Hydropower Station. China Ru- ral Water Conservancy and Hydropower. 01, 63-64.

[33] Kummu, M., Vans, O., 2007. Sediment-related impacts due to upstream reservoir trapping, the Lower Mekong River. Geomorphology. 85(3-4), 275-293.

[34] Kou, X.M., Niu, T.X., Huang, Y.Sh., Pan, W.G., Yang, Zh.M., 2009. Cumulative effects of water environment of built terrace power stations in the upper reaches of the Yellow River. Northwest Hydropower. 06, 11-14.

[35] Weng, W.L., Liu, Y.C., Zhou, X.C., 2013. Analysis of the impact of reservoir construction on water and sand situation in the upper Yangtze River. Journal of the Yangtze River Academy of Sciences. 30(05), 1-4.

[36] Liu, L.F., 2002. Study on the environmental benefits and main environmental problems of river hydropower development. Journal of Water Resources. 33(8), 121-128.

[37] Zhong, H.P., Liu, H., Geng, L.H., 2007. Cumulative ecological and environmental effects of cascade development in the Lancang River basin. Journal of Water Resources. S1, 577-581.

[38] Chen, Q.W., Liu, L.F., Liu, C.M., 2007. Study on the effect of dam construction on river ecosystem and ecological scheduling of reservoirs. Journal of Beijing Normal University (Natural Science Edition). 43(5), 578-582.

[39] Yang, F., Liu, W.W., Wang, J., et al., 2012. Riparian vegetations responses to the new hydrological regimes from the Three Gorges Project: clues to revegetation in reservoir water-use management. revegetation in reservoir water-level-fluctuation zone. Acta Ecologica Sinica. 32(2), 89-98.

[40] Ouyang, W., Hao, F.H., Zhao, C., et al., 2010. Vegetation response to 30 years hydropower cascade exploitation in upper stream of Yellow River. Communications in Nonlinear Science and Numerical Simulation. 15(7), 1928-1941.

[41] Zhang, M., Shao, M., Xu, Y., et al., 2010. Effect of hydrological regime on the macroinvertebrate community in Three-Gorges Reservoir, China. Quaternary International. 226(1), 129-135.

[42] Popp, A., Hoagland, K.D., 1995. Changes in benthic community composition in response to reservoir aging. Hydrobiologia. 366, 159-171.

[43] Guo, D., Wang, H.X., Xu, J.X., et al., 2011. Study on the influence of Three Gorges Reservoir on the eco-hydrological situation of downstream important fish spawning period. Journal of Hydropower Generation. 30(3), 22-26.

[44] Dong, Zh.R., Zhang, J., Zhao, J.Y., 2020. The scientific connotation of ecological flow. China Water Resources. 15, 15-19.

[45] Acreman, M., Dunbar, M.J., 2004. Defining environmental river flow requirements - a review. Hydrology and Earth System Sciences. 8(5).

[46] Zheng, J.T., Wang, L.P., Zhou, T., et al., 2012. Influence of Cascade Hydropower Development on Water Temperature in Nujiang River and Its Countermeasures. Hydroelectric Power. 38(8), 4.

[47] Zhang, P., Liang, R.F., et al., 2018. Influence of Joint Operation of Cascade Hydropower Stations on Water Temperature in Batang River Reach. Sichuan Environment. 37(2).

[48] Yan, X.D., Liu, X.D., Li, G.Q., Li, Ch.Q., et al., 1990. Low head diversion and sand prevention hub. Water conservancy and electric power.

[49] Liu, X.C., Yang, J.H., 2012. Impact of the construction of Pingtou hydropower station on the aquatic ecology of the river and protection measures. Hydropower Station Design. 28(2), 90-92, 106.