Evolution of hydrological regime in middle and lower reaches of Han River driven by water conservancy project and countermeasures

Yangyang Liu¹, a*, Bojuan Liu², b, Dandan Shen³, c

¹ Changjiang Water Resources Protection Institute, Wuhan, Hubei, China
² Hubei Investigation and Design Institute of Water Conservancy and Hydropower Wuhan, Hubei, China
³ Changjiang Water Resources Protection Institute, Wuhan, Hubei, China

a email: yhfang@hhu.edu.cn, b email: shirleylbj@foxmail.com, c email: 517173700@qq.com

*Corresponding author’s e-mail: yhfang@hhu.edu.cn

Abstract: The Han River is not only an important water supply source in China, but also a treasure trove of water resources for the economic and social development of Hubei Province. In this paper, the evolution characteristics of hydrological regime in the middle and lower reaches of the Han River (MLHR) under the influence of numerous water conservancy projects were studied, and the related problems of resource and environment were analysed, and then corresponding countermeasures were proposed. The results showed that the mean annual flow in Huangjiagang and Huangzhuang section decreased by 20.3% and 5.5%, respectively, during the four years before and after the operation of the Middle Route of South-to-North Water Diversion Project (MRP). Meanwhile, there were a decrease in the duration of the medium and high runoff and an increase in the duration of low runoff, leading to an enhancement of the attenuation effect of the annual runoff process. Moreover, a pattern formed that natural rivers and reservoirs appeared alternately after the construction of cascade reservoirs. Furthermore, with the variation of hydrological regimes in the MLHR, there were some problems of the contradiction between water supply and water demand, the evolution of river regime, the reduction of suitable aquatic habitats and others. In these regards, for providing technical support for the construction of the Han River Ecological Economic Belt, some countermeasures and suggestions were proposed, such as rational allocation of water resources, the promotion of the construction of the follow-up water supplement project and the implementation of ecological regulation in the MLHR.

1. Introduction

At present, the degree of development and utilization of water resources in the Han River Basin is gradually increasing, especially the construction of Danjiangkou reservoir and the MRP, which not only alleviated the contradiction between water supply and water demand in the northern receiving area, but also changed the original hydrological regime in MLHR and affected the development of river ecosystem [1]. Many researchers have carried out related studies on the hydrology and water resources of the MLHR. For example, Guo et al., analysed the variation characteristics of the runoff in MLHR before and after the construction of Danjiangkou reservoir [2]. Ban et al., analysed the trend and
causes of meteorological and hydrological variation in the Han River Basin, and it was considered that human activities were the major driving force of runoff variation in the Han River Basin [3]. Zhu et al., conducted the trend detection and abrupt test on the flow of Huangjiagang, Huangzhuang and Xiantao hydrologic stations from 1990 to 2016 [4]. Wang et al., studied the coupling effects of Danjiangkou, Wangfuzhou and Cuijiaying cascade reservoirs before and after joint operation on the hydrological regime and alteration in MLHR [5]. Bo et al., conducted the variation analysis of sensitive hydrological indicators for the four domestic fishes and water blooms by evaluating the trunk section of the Han River with the largest variation of hydrological parameters and the types of eco-hydrological characteristic indicators [6]. These studies play an important role in the objective cognition of the temporal and spatial variation of hydrological regimes in the MLHR. With numerous water conservancy projects built and under construction in the MLHR, the cumulative influence on the hydrological regime has been revealed. Whereas there is a lack of systematic study on multi-hydrological factors driven by the combination of water conservancy projects in the MLHR, in this paper the evolution characteristics of the hydrological regimes before and after the operation of water conservancy projects were analysed. Accordingly, the problems of resources and environment were addressed, and countermeasures and suggestions were proposed, so as to better serve regional water resources management and support scientific evidence of ecological environment protection of water conservancy projects.

2. Materials and methods

2.1 Study area

The region of MLHR is located between 111°E to 115°E and 30°N to 33°N, that is the section from Danjiangkou dam site to the estuary of the Han River, with a length of 652km and a catchment area of 64000 m². The topography of MLHR are high in the northwest and low in the southeast. The mean annual flow of Huangjiagang, Huangzhuang and Xiantao hydrologic stations, locating from top to bottom of the trunk stream, are 1135m³/s, 1481m³/s and 1262m³/s, respectively.

2.2 Overview of main water conservancy projects

(1) Middle route of the south-to-north water diversion project (MRP)
The MRP with the designed scale of 9.5 billion m³ takes water from Danjiangkou reservoir to provide domestic and industrial water for water receiving cities, that is, Beijing, Tianjin, Hebei and Henan. The water source of the MRP is Danjiangkou reservoir of the Han River. The major water conveyance canal starts from the head of Taocha canal of Danjiangkou reservoir and runs from south to north in general. It crosses the Yangtze River, Huai River, Yellow River and Hai River and straight reached Beijing and Tianjin with the water conveyance distance of 1432 km. In December 2014, the MRP was officially put into operation. By October 2020, Danjiangkou reservoir had transferred more than 34 billion m³ of water to the northern receiving areas.

(2) Water transfer project from the Yangtze River to the Han River (WTP)

The WTP is one of the MRP in the MLHR. The water inlet of the WTP is located in the trunk stream of the Yangtze River in Libu Town, Jingzhou City, and the outlet is located in the trunk stream of the Han River in Gaoshiebi Town, Qianjiang City. The length of total canal is 67.23km, and the designed water diversion scale is 3.1 billion m³. The WTP is mainly to meet the requirements of ecological environmental water demand, irrigation outside the river, water supply and shipping in the lower reaches of Xinglong of the Han River, so as to reduce or eliminate the adverse impact of the MRP on the MLHR. The WTP has been completed in September 2019. By April 2020, more than 16 billion m³ of water had been supplied to the Han River.

(3) Cascade reservoir projects

There are planned and built cascade reservoir projects in the MLHR, including Danjiangkou, Wangfuzhou, Xinji, Cuijiaying, Yakou, Nianpanshan and Xinglong projects, which are 7 cascades in total. Thereinto, Danjiangkou, Wangfuzhou, Cuijiaying and Xinglong projects have been built, while Xinji, Yakou and Nianpanshan projects are still under construction. The characteristics of each cascade project are presented in Table 1.

| Characteristics                  | Unit             | Danjiangko (dam heightening) | Wangfuzhou | Xinji | Cuijiaying | Yakou | Nianpanshan | Xinglong |
|----------------------------------|------------------|-----------------------------|------------|-------|------------|-------|-------------|----------|
| Mean flow                        | m³/s             | 1230                        | 1215       | 1282  | 1470       | 1520  | 1569        | 1569     |
| Normal water level               | m                | 170                         | 86.23      | 76.23 | 62.73      | 55.72 | 50.72       | 36.23    |
| Regulated storage capacity       | Hundred million m³ | 163.6                       | 0.288      | 0.206 | 0.40       | 0.67  | 0.83        | unregulated |
| Regulation performance           |                  | Incomplete multi-year       | Danjiangkou reverse regulation | daily | daily | daily | unregulated |
| Development task                 |                  | Flood control, water supply, power generation and shipping | Power generation, shipping, irrigation, breeding, tourism | Power generation, shipping | Power generation, shipping | Power generation, shipping, irrigation | Power generation, shipping, irrigation |
| Implementation situation         |                  | Completed in 2009            | Completed in 2010 | Under construction | Completed in 2014 | Under construction | Under construction |

2.3 Materials and methods

In this paper, the flow data from 2011 to 2018 of three hydrologic stations, that are Huangjiagang, Huangzhuang and Xiantao hydrologic stations in the MLHR, were collected. Besides, reports of the retrospective study on environmental impact assessment of cascade development in the trunk stream of the Han River, the environmental impact report of the MRP and the environmental impact report of
Xinglong water conservatory project in the Han River were collected as well. In this paper, statistical analysis and attribution analysis methods were used to study the evolution characteristics of hydrological regime in MLHR before and after the operation of numerous water conservancy projects, based on which the problems were analysed and countermeasures were proposed.

3. Results and Discussion
The influence of water conservancy projects built in the MLHR on the hydrological regime was mainly reflected in the flow, velocity, and water morphology and so on. The annual runoff variation of the MLHR was mainly affected by the Danjiangkou reservoir regulation, the water diversion of the MRP, and the water supplement of the WTP. The established Wangfuzhou and Cuijiaying projects only have daily regulation performance, while Xinglong project is a low-head runoff water conservancy project, which basically has no regulation performance. Therefore, these three cascades above barely had influence on the annual runoff process of the Han River, whose influence is mainly reflected in the variation of local reach velocity and water morphology.

3.1 Analysis of runoff evolution in the MLHR under the Influence of Projects
Taking the period from 2011 to 2018 as the research period, before the MRP was put into operation in December 2014, the impounded level of Danjiangkou reservoir was greatly increased in September and October during the flood season, and the discharge of MLHR was significantly reduced. Therefore, September 2014 was taken as the time breakpoint to analyze the variation characteristics of runoff in MLHR before and after the operation of the MRP.

3.1.1 Variation of outflow and inflow of Danjiangkou reservoir
After the MRP was put into operation, the inflow was relatively low compared with that before, and the mean annual inflow decreased from 1047m³/s to 865m³/s, with a decrease of 18% or so. Compared with the outflow of Danjiangkou reservoir in the same period (Fig. 2), the outflow process after the operation of the MRP attenuated than that before, especially during the period from September 2015 to August 2017, when it was regulated by Danjiangkou reservoir according to the inflow, and the mean monthly outflow basically maintained at 500 m³/s or so. In September and October of the flood season in 2014, the mean monthly outflow before the operation of the MRP were 89% and 66% less than the inflow, and the water level raised rapidly to meet the demand of water diversion. In September and October of the flood season in 2017, the impounded level was raised by massive inflow from upstream after the operation of the MRP, and the mean outflow in September and October reduced by 61% and 16%, respectively, compared with the inflow.

![Figure 2. Variation process of inflow and outflow of Danjiangkou reservoir (2011.1 ~ 2018.12)](image)

3.1.2 Monthly mean flow variation of major control sections in the MLHR
Huangjiagang hydrologic station is located 6 km downstream of Danjiangkou dam, and there is no large tributary in the section, therefor the station could directly reflect the influence of Danjiangkou
regulation. The mean annual flow of Huangjiagang was 954 m$^3$/s before the operation of the MRP, while the mean annual flow of Huangjiagang was 760 m$^3$/s after the operation, that was a decrease of 20.3%. First, the Han River was in continuous dry years. Second, the accumulated water diversion exceeded 18 billion m$^3$ in four years after the MRP, which also had a certain impact on the runoff in the MLHR. It is depicted in Figure 3, that the mean flow of Huangjiagang in May, June, July and October increased by 8.8% ~ 42.7% after the operation of the MRP, and it decreased by 6.8% ~ 73.8% in other months. Since 2015, the inflow of Han River has been relatively low. After various water supply demands were fulfilled by Danjiangkou reservoir, the flow of Huangjiagang in the normal and dry seasons reduced to a certain extent compared with that before. In the wet season, the increased reservoir capacity is fully utilized for peak clipping and water storage according to the inflow, thus enhancing the attenuation effect of the annual flow process.

Huangzhuang hydrologic station is located at the junction of the MLHR. The mean annual flow of Huangzhuang was 1178 m$^3$/s before the operation of the MRP, while the flow was 1113 m$^3$/s after the operation, that is a decrease of just 5.5%. And the water supply from the major tributaries of Nanbei River, Tangbai River and Man River alleviates the impact of water diversion to a certain extent. It is thus clear from Figure 3 that after the operation the mean flow of Huangzhuang from April to July and October increased by 16.7% ~ 76.2%, and decreased by 19.8% ~ 67.9% in other months. The variation trend of annual mean monthly flow process in Huangzhuang was consistent with that in Huangjiagang, which was affected by the inflow of Han River and the regulation of Danjiangkou reservoir, the variation of flow process of tributaries as well. Generally speaking, it showed the attenuation of hydrologic process and the variation of flood rhythm.

Xiantao hydrologic station is located below the outlet of the WTP in the lower reach of the trunk Han River. The mean annual flow of Xiantao was 987 m$^3$/s before the operation of the MRP, while the flow was 992 m$^3$/s after the operation, that is a slight increase of 0.5%. The WTP was built 110 km upstream of Xiantao, aiming to solve the problem of water reduction in the section below Xinglong caused by the MRP. After the operation of the MRP, the water from the Yangtze River was diverted into the Han River according to the variation of upstream inflow, which acquired obvious benefit of supplementing drought. Therefore, the mean annual flow of Xiantao seldom varied compared with that before. It is found from Figure 3 that after the operation the mean flow of Xiantao from April to July and October increased by 22.5% ~ 69.2%, and decreased by 6.9% ~ 66.3% in other months.
3.1.3 Diachronic variation of classified runoff of major control sections in the MLHR

The runoff in the MLHR is divided into four levels, which are dry runoff ($Q \leq 500 \text{ m}^3/\text{s}$), low runoff ($500 < Q \leq 800 \text{ m}^3/\text{s}$), medium runoff ($800 < Q \leq 1000 \text{ m}^3/\text{s}$) and high runoff ($Q > 1000 \text{ m}^3/\text{s}$), so as to analyze the duration of the classified runoff before and after the operation of the MRP. The duration of the dry and low runoff of Huangjiagang increased by 17% and 7%, respectively, while the duration of the medium and high runoff decreased by 10% and 13%, respectively, which is mainly related to the low inflow from the Han River in recent years and the peak clipping and water storage of Danjiangkou reservoir during the period of medium and high runoff after the operation of the MRP. The duration of low runoff in Huangzhuang increased by 23% after the operation, while the duration of dry runoff, medium runoff and high runoff decreased by 8%, 2% and 12%, respectively. After heightening of Danjiangkou dam, it was benefit to the increase of the dry runoff in Huangzhuang. However, the peak clipping and water storage of the reservoir reduced the duration of high runoff. The duration of low runoff increased by 25% after the operation of the MRP, while the duration of dry runoff, medium runoff and high runoff decreased by 14%, 4% and 7%, respectively. After the operation of the WTP, water was replenished to the lower reach of Xinglong when the inflow from upstream was low. Thus, the duration of dry runoff ($Q \leq 500 \text{ m}^3/\text{s}$) reduced, and the duration of low runoff ($500 \sim 800 \text{ m}^3/\text{s}$) increased.

From the aspect of the variation of mean dry runoff, the mean low runoff of Huangjiagang, Huangzhuang and Xiantao were 412$m^3$/s, 425$m^3$/s and 399$m^3$/s, respectively, before the operation of the MRP, while the values were 438 $m^3$/s, 483 $m^3$/s and 473 $m^3$/s, respectively, after the operation, showing the increases of 6%, 14% and 19%, respectively. This indicates that the operation of Danjiangkou dam heightened is beneficial to the increase of dry runoff.
3.2 Analysis of water morphology and velocity evolution in the MLHR under the Influence of the Projects

After the construction of the cascade project, the river width and depth of the reach where the project is located varied significantly, and the variation of water morphological parameters are shown in Table 2. After the operation of Wangfuzhou project, the river surface area, river width and depth were 3.1, 4.5 and 6.1 times of those under natural conditions. Besides, after the operation of Cuijiaying project, the river surface area, river width and depth were 1.4, 3.5 and 6.1 times of those under natural conditions [7]. In general, the construction of the trunk cascade in MLHR has greatly influenced the water morphology of the Han River. Compared with the natural river before the construction, the water level raised, and the river surface area increased, and the river depth increased, which made the natural river with good connectivity into alternate pattern of rivers and reservoirs.

Table 2. Comparison of hydrologic parameters before and after operation of Wangfuzhou and Cuijiaying reservoirs

| Reservoir  | Hydrologic parameters   | Unit   | Before the construction | After the construction | After the construction / Before the construction |
|------------|-------------------------|--------|------------------------|------------------------|-----------------------------------------------|
| Wangfuzhou | Reservoir area          | km²    | 9.8                    | 30.8                   | 3.1                                           |
|            | Mean water surface width| m      | 328.0                  | 1488.0                 | 4.5                                           |
|            | Mean river depth        | m      | 0.8                    | 4.9                    | 6.1                                           |
|            | Mean volecit            | m/s    | 0.51                   | 0.17                   | 0.3                                           |
|            | Reservoir area          | km²    | 5.15                   | 71.6                   | 1.4                                           |
|            | Mean river surface width| m      | 627.0                  | 2196.0                 | 3.5                                           |
|            | Mean river depth        | m      | 0.7                    | 4.0                    | 6.1                                           |
|            | Mean volecit            | m/s    | 0.83                   | 0.16                   | 0.2                                           |

After the operation of Wangfuzhou and Cuijiaying reservoirs, the flow velocities in the reservoir area reduced due to the morphological variation and the mean flow velocities in the reservoir area were 0.3 times and 0.2 times of that in the natural river respectively [7]. After the operation of Xinglong reservoir, the annual mean flow velocity in the reservoir area decreased from 1.1m/s to 0.52m/s. Because Xinglong reservoir operated as a runoff power station, resulting in the frequent water exchange, the flow velocity in the reservoir area still retained to a certain extent [8].

![Figure 4 Comparison of duration of different runoff levels in Huangjiagang, Huangzhuang and Xiantao before and after the operation of the MRP](c)
3.3 Major resource and environmental problems and countermeasures in the MLHR on the condition of hydrological regime variation

3.3.1 Analysis of major resource and environmental problems

(1) Suffering from continuous dry years in the Han River and difficulties of the contradiction between water supply and demand

In recent years, the inflow of Danjiangkou reservoir has decreased. According to four-year moving average analysis, the mean natural inflow of Danjiangkou from 2013 to 2016 was 25.1 billion m³, when it was the driest four-year in the long series. It is predicted that the total production and domestic water consumption in Han River Basin would increase from 14.6 billion m³ in 2017 to 18.7 billion m³ in 2035. Considering the water diversion from the Han River to the Wei River, the MRP and the North Hubei project, which transfer water from the Han River and water consumption in the middle and upper reaches of the Han River, the water development and utilization rate in Danjiangkou reservoir dam site section would reach 43% in 2035. Thus, with economic and social development and the increasing water demand in and outside of the basin, there are difficulties of water resources development and protection in the Han River Basin, especially in the dry year, the contradiction between water supply and demand is prominent, which is difficult to reconcile.

(2) Variation of hydrological regime resulted in the decrease of suitable aquatic habitat and variation of aquatic community structure

The fish habitat in the middle and lower reaches of trunk Han River was blocked by the construction of cascade reservoirs, and the number and scale of spawning grounds for drifting egg fish decreased significantly. In 1976, there were 8 spawning grounds in the middle reaches of Han River, including Wangfuzhou, Cihe, Xiangfan, Yicheng, Zhongxiang, Maliang, Guotan and Bukou of Tang River and Bai River. Now there are only 3 spawning grounds. The spawning amount of the four domestic fishes is very few or barely be monitored. At present, the catch of MLHR has changed from drifting egg fishes to the settled sticky or sinking eggs fishes. The proportion of small and medium-sized fish has increased, and individual fishes obviously trend to be younger and smaller.

(3) Disadvantage of the reproduction and spawning of fish with the variation of hydrological regime, and influences of the species diversity and genetic diversity of fish

After the regulation of Danjiangkou reservoir, the duration of medium and high runoff decreased to a certain extent, especially the regulation of peak clipping and water storage in dry years resulted in the attenuation of flow process and the reduction of flood peak process, which made it difficult to meet the requirement of hydrological conditions to stimulate fish spawning and reproduction. After the construction of Wangfuzhou, Cuijiaying and Xinglong projects, mean flow velocity in the reservoir area decreased to various extent, resulting in the shortage of spawning process and the significant decline of incubation survival rate.

3.3.2 Suggestions and countermeasures of resources and environment protection

(1) Improving water resources allocation and load capacity in Han River Basin

According to the requirements of the strictest administration system of water resources from aspects of the nation and Hubei Province, it is required to allocate water resources efficiently and reasonably, strengthen the development, utilization, supervision and management of water resources, and ensure that the water consumption and water efficiency meet the requirements of decomposition index. Making full use of Danjiangkou reservoir regulation ensure the ecological flow of main control sections in the MLHR. In addition, it is necessary to actively promote the implementation of follow-up water replenishment projects, and by enhancing the water resources allocation capacity of Han River Basin, the contradictions in dry years between external water transfer and water consumption in the basin, water consumption in the and outside the river, water utilization and water ecological environment protection could be solved.

(2) Implementing cascade joint ecological regulation to promote spawning and reproduction of "four domestic fishes" in the Han River
According to the relevant requirements of "joint ecological regulation scheme for cascades in the downstream of Danjiangkou of the trunk Han River in Hubei Province (Trial)", combined with flood control, water supply regulation of Danjiangkou reservoir and inflow from tributaries, the joint ecological regulation for cascades open discharge in the MLHR is suggested to implement to create a suitable flood process, which is benefit to promote the spawning, reproduction and unimpeded migration channel of four domestic fishes in the Han River.

(3) Strengthening aquatic ecological monitoring and construction of fish passing facilities of cascade reservoirs

Aiming at the protection areas of aquatic germplasm resources in the MLHR, combined with the operation of cascade reservoirs, it is suggested to carry out long-term dynamic aquatic ecological monitoring to accumulate basic data for the implementation of ecological regulation and effect analysis. Further, it is suggested to build fish passing facilities of cascade reservoirs to restore river connectivity.

4. Conclusions

In recent years, the variation of hydrological regime in the MLHR is closely related to natural inflow, Danjiangkou reservoir regulation, the operation of the MRP, and the development of cascade reservoirs. With the comparison of four years before and after the operation of the MRP, the mean annual flow of Huangjiagang and Huangzhuang section decreased by 20.3% and 5.5%, respectively, while the flow of Xiantao section barely variated, which was mainly affected by the inflow from the Han River and the regulation of Danjiangkou reservoir. On the whole, the attenuation effect of runoff process was enhanced and the flood process was weakened obviously in the MLHR, which indicated that the benefit of water diversion from Yangtze River to reaches of the Han River below Xinglong is obvious. In the same period of the project operation, the duration of medium and high runoff in Huangjiagang, Huangzhuang and Xiantao sections decreased to a certain extent, while the duration of low runoff increased to a certain extent. After the construction of Wangfuzhou, Cuijiaying and Xinglong projects, the water morphology of MLHR has been greatly changed, which resulted in a decrease in flow velocity, an increase in the river surface and depth, making the natural river with good connectivity into alternate pattern of rivers and reservoirs.

The variation of hydrological regime in the MLHR led to some resource and environmental problems, mainly including the irreconcilable contradiction between water supply and water demand due to the continuous dry years, and the variation of the structure of aquatic community affected by water morphology and hydrological process variation, which also affected species diversity and genetic diversity of fish species to a certain extent. For solving these problems, it is required to allocate water resources efficiently and reasonably, optimize the regulation of Danjiangkou reservoir, actively promote the implementation of follow-up water replenishment projects, and enhance the allocation capacity of water resources in Han River Basin. In addition, it is necessary to actively implement the joint open discharge ecological regulation of MLHR for a suitable flood process to create a suitable flood process, and then promote the spawning, reproduction and unimpeded migration channel of four domestic fishes in the Han River.

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