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Dam Retirement and Decision-Making

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Abstract

Reservoir is an important part of water conservancy engineering system and an important infrastructure for economic and social development. However, with the increase of operating time, as well as the change of social demand and operating environment, the safety, function, benefit, cost, and other characteristics of the reservoir are also changing. Like living things, reservoirs also have a life cycle of “birth, old age, illness, and death.” The retirement of a dam is an inevitable stage in the life cycle management, as well as a means of resource readjustment and rational utilization. Combined with dam retirement cases that caused severe impacts in history, generalized dam removal eco-environment influence factors are obtained from aspects of materializing, ecology, society, and economy. Based on economic rationality theory and flood consequence assessment, two decision-making methods of dam retirement are put forward. The flood consequence method is applied on the case of Heiwa reservoir; key evaluation indexes are compiled from the aspects of ecology, economy, and society; and the evaluation system based on single index is constructed.

Keywords: risk assessment, risk reduction, dam retirement decision, dam removal

1. Introduction

After the dam removal, the ecosystem balance formed by the long-term storage of the reservoir will be broken, which is not a simple adverse process of the ecological environment impact of the dam construction, and may pose a new threat to the river ecosystem. Therefore, it is of great theoretical significance and practical value to establish a method to assess the impact of removal decision. In order to achieve that, key factors need to be identified first.

2. Comprehensive impact of reservoir removal

After a period of operation, the lake ecosystem formed by reservoir storage tends to be stable. After the reservoir was scrapped and the dam was dismantled, the river was reconnected, the hydrological situation was restored to the natural state, and the lake ecology gradually returned to the river ecology. However, this is not a simple reverse process. After the balance is broken again, if scientific control measures are not taken, the natural evolution may generate new stresses on the ecological environment.

In history, some cases have made delightful improvement; some of the others have led to irreparable impacts. Avoid going astray by reviewing the past, which is significant to generalized dam removal eco-environment influence factors.

2.1 Impact characteristics

The research on the impact of reservoir removal on ecological environment involves engineering technology, ecological environment, social economy, human history, and other fields. This paper summarizes the research results and practical cases of reservoir removal around the world. The characteristics of reservoir removal impact on ecological environment are comprehensiveness, contradiction, time-space continuity, and uncertainty.

2.1.1 Comprehensiveness

As with other water resource management behaviors, the impact of dam demolition is comprehensive. This characteristic is reflected in the comprehensive impact of physical, biological, ecological, social, economic, and cultural factors on the ecological environment after the dam is dismantled.

2.1.2 Contradiction

The contradiction reflects the two sides of the impact of dam demolition, that is, while it is beneficial to one element, it is harmful to the other. For example, the removal of dams to restore the connected state of rivers is conducive to the breeding of migratory fish but also easy to cause species invasion.

2.1.3 Space-time continuity

The impact caused by reservoir removal can be spatially from the upstream to the downstream of the dam site, from the river where the dam site is located to the river, and even from the river basin. The time span can be days, months, or even decades. Short-term effects have been generated in the process of dam removal, such as sediment release from the reservoir area, pollution caused by sediment output, water oversaturation, etc. Long-term effects include natural water recovery, the reservoir area becoming a flowing river again, the change of river temperature, the gradual recovery of sediment movement, and so on.

2.1.4 Uncertainty

As a result of subjective and objective reasons, the impact of reservoir removal is uncertain. The subjective reason is that relevant researches are not in-depth and comprehensive enough, and many problems are difficult to be accurately explained from the mechanism. For example, there are still many disputes about the evolution process and mechanism of river channel in the reservoir caused by sediment output, and how to scientifically determine the goal of ecosystem restoration after dam removal is still an academic problem. The objective reason is mainly the impact of global climate change, which is also a difficult problem faced by all water resource management activities.

2.2 Reservoir removal impact classification

Reservoir removal may reshape or even destroy rivers and coastal ecosystems, causing a series of new problems. In this section, hydrological sediment,

topography, water quality, ecological environment, social and economic aspects, and the impact of reservoir removal are classified and analyzed.

2.2.1 Hydrological influence

The construction of the dam will lead to changes in the flow rate, change frequency, duration, occurrence timing, and change rate of the hydrological situation of the river. After the dam is dismantled, the flow rate and water level of the river will change with the seasons, get rid of human intervention, and return to the natural hydrological situation, which will completely reverse the hydrological situation of the river.

After the dam is removed, the river will be reconnected, and the lower reaches of the river will be continuously restored. The shrinking condition of the lower reaches of the river will be alleviated, and the groundwater supply in the lower reaches of the river will be basically restored to nature. However, if the downstream channel has insufficient sediment transport capacity, sediment deposition, and riverbed elevation, the downstream section flow capacity decreases, the channel specific decline becomes slow, the flood discharge capacity weakens, and the reservoir regulation and storage protection are lost; the downstream river level is raised during the flood period, increasing the flood risk in the downstream region.

2.2.2 Sediment impact

Sedimentation is one of the main causes of reservoir removal in China. After the dam is removed, the sediment in the reservoir area will move again. Sediment deposition is the result of the decrease of water flow carrying capacity which is controlled by the backwater effect and velocity of reservoir. If the operation time of reservoir dam is short or the impact of dam on sediment transport is small, the impact of removal on sediment transport is relatively small. On the contrary, the law of sediment transport will change greatly after the reservoir is scrapped. When a small radial reservoir is abandoned, the silt deposited may be mostly carried downstream by the current. After the reservoir with large capacity is scrapped, there may still be a large amount of sediment in place.

Sediment in reservoir area is transported downstream with current, which not only increases turbidity of downstream river segment but also usually leads to sediment deposition in downstream river segment and changes topography of downstream river channel. Fine sediment may cover the original habitat, block the gap between the bed matrices, and destroy the spawning habitat of fish, resulting in the death of fish. It may also block downstream waterways and water intakes, which will adversely affect human production and life.

When pollutants are contained in the sediment, the sediment carrying pollutants to the downstream diffusion after dam removal is bound to have a significant impact on the downstream river habitat. The content of fine sediment and the way of land use upstream are the important factors influencing the pollutant load in the reservoir. This is because fine-grained sediment has a large specific surface area and can absorb more pollutants than coarse sediment. In addition, the upper reaches of the reservoir land use mode can directly affect the reservoir sedimentation, sediment gradation, and pollutant content. Studies have shown that in the basins dominated by agricultural production, the riparian soil is eroded, and the nonpoint source pollution of the river is serious, resulting in a large amount of fine sand and rich nutrients in the silt in the reservoir area. For the watershed dominated by forest land, the sedimentation amount of reservoir is usually small, and the nutrient content of sediment is low [1, 2].

Fort Edward Dam, New York, the United States, was dismantled in 1973. No measures were taken to remove sediment from the reservoir before the dam was dismantled. After the dam was dismantled, serious problems occurred in downstream water quality and navigation. Pollutants—polychlorinated biphenyls (PCBs)—spread with sediment transport and had catastrophic effects on downstream river ecosystems, leading directly to New York state's ban on fishing in the Hudson River in 1976 and posing risks to downstream public health. In addition to pollution, most of the Hudson's waterways, docks, and industrial parks are blocked, reducing the river's ability to cross water, increasing the risk of flooding downstream towns, and causing millions of dollars in economic losses to fishing and shipping [3].

2.2.3 Impact of topography and landform

2.2.3.1 Erosion in the reservoir

The reconnection of rivers, the restoration of natural state of river flow, the reservoir area, and the sediment deposited upstream by the erosion of water to the downstream lead to erosion in the reservoir. The main factors influencing sediment transport in the reservoir include channel flow, sediment particle size and its type, deposition amount, and dam removal mode [4].

This is a slow process of development, at the site of the dam, to form a clear groove head, constantly expanding upstream. From the longitudinal perspective, the depth of topographic erosion in the reservoir area gradually increases, and the specific drop of the river course is greatly adjusted until it encounters impervious obstacles or the specific drop reaches a stable state, and finally the upper and lower reaches of the dam site reach a new dynamic balance [5]. The new balance is sometimes similar to that before the dam was built, but in most cases, some of the sediment remains in place, unwashed downstream by the current.

2.2.3.2 Downstream adjustment

The increase of river sediment content and sediment carrying load forces a series of new adjustments in the lower reaches of the river. At present, it is generally believed that sediment release after dam removal will determine the change of riverbed elevation and sediment transport in the lower reaches, and the process of sediment release can be approximately simulated by sand wave model.

In the early stage after dam removal, the downstream channel adjustment results in the change of bed matrix and channel morphology, and the final result is the evolution of river floodplain system. After a long time, the sediment content of the river reverts to the natural level, which may lead to the transverse movement of the river and the erosion of the floodplain surface.

2.2.4 Impact on water quality

With the increase of water retention time, the reservoir water has adverse effects of low oxygen content, changes in water temperature and pH value, serious eutrophication, and high pollutant concentration. After the dam is dismantled, the continuity of the river is restored, and the adverse effects on the water quality above are alleviated. However, the removal of sediment deposited in the reservoir will lead to the increase of turbidity of the downstream river body, especially when the sediment adsorption has pollutants, which may seriously affect the water quality of the downstream river.

2.2.5 Habitat impact

2.2.5.1 Aquatic habitats

As one of the important characteristics of habitat, bed matrix will change with the adjustment of channel morphology and the change of sediment erosion and deposition after the dam is removed.

The study found that the fine sediment in the reservoir is eroded by the current, exposing the underlying gravel and pebble layers, thus improving the habitat quality of fish and increasing the biodiversity. After the dam is removed, the habitat quality of fish will be improved, the barrier of fish migration will be removed, fish can reach the upstream spawning area, the number of migratory fish often rises, and the number and diversity of aquatic insects and other organisms may increase [6]. The salmon population, which had been sharply reduced, has been recovered to 80% of what it was before the dam was built, after four dams on the Snake River in the United States were dismantled [7].

There are studies showing that, for downstream regions, fine sediment deposition in the downstream reduces riverbed permeability; affects the spawning and breeding habitats of fish; reduces the survival rate, diversity, and abundance of aquatic organisms; and brings adverse effects on downstream habitats [8]. After the removal of the Colorado Dam in the United States, a large amount of sediment released was deposited in the deep pool of the river within 12 km downstream, blocking the gap between coarse particles of sediment, resulting in the death of thousands of fish and the reduction of population density and composition change of large invertebrates. Some scholars have found that the above adverse effects can be eliminated naturally and the rate and recovery degree are related to the biological characteristics. For example, organisms with long life cycle and fixed growth are deeply disturbed and slow in self-recovery. On the contrary, species with short life cycles can recover quickly in a short time [9].

2.2.5.2 Wetlands

Reservoir removal will change the hydrological state of surface water and groundwater as well as the law of river sediment transport, thus leading to a variety of changes in upstream and downstream riverside wetlands. The type and scale of this impact vary from place to place.

The changes of surface and groundwater hydrological state are the main influencing factors of upstream wetlands after dam removal. Some of these influences are seasonal, while others are long-term. For the downstream wetlands, the law of sediment transport and the change of groundwater hydrological state are the main influencing factors. Reservoir removal causes silt deposition in the lower reaches of the river, which may lead to the invasion of wetland plants in the silt area, thus forming a new wetland habitat.

2.2.6 Social impact

The loss of reservoir function, and no other projects to make up for it, may cause serious social problems. For example, if water supply or agricultural irrigation is the main reason for the removal of reservoirs and if the water supply and irrigation needs of residents cannot be effectively solved, serious social problems will arise. In addition, the scour of reservoir area silt may cause the similar problem enters downstream river course along current, silt up downstream channel or channel take water entrance, affect safety of local traffic carriage and production and domestic

use seriously. All these impacts need to be analyzed during the demonstration and planning and design of reservoir removal, and appropriate measures should be taken, such as building alternative projects, dredging river channels, rebuilding or building new water intakes, etc., so as to reduce the adverse impact on society [10].

The right to use the land in the reservoir area and the change of the value of the original lakeside land also belong to the social impact that may be caused by the removal of the reservoir, but compared with the above problems, the social impact of this problem is relatively small.

2.2.7 Economic impact

In China, the primary consideration of reservoir removal is public safety, followed by economic problems. Economic impact analysis is helpful for reservoir stakeholders and their management agencies to compare and choose dam removal schemes and posttreatment measures and optimize schemes [11]. While not every reservoir to be scrapped will undergo a formal cost-benefit analysis, basic economic assessments are needed.

Generally, the economic impact of reservoir removal is divided into two categories: cost and benefit. Cost is regarded as negative impact and benefit as positive impact. The saving of reservoir operation and maintenance cost is often regarded as the positive impact of removal, while the loss of reservoir social and economic benefits is considered as the negative impact of removal. In principle, economic value assessment can be carried out for all kinds of impacts mentioned above, which can be finally reflected through economic impact. However, it is difficult to accurately define the impact category for a small part of the influences, and quantitative and quantitative assessments are difficult for existing influences. Therefore, at current stage, it is difficult to accurately analyze the economic impact of reservoir removal.

3. Decision-making method for reservoir removal

Although many cases have proved that reservoir removal can play a positive role in ecological environment restoration, due to the limitations of people's cognition of the impact of dam demolition and the complexity and unpredictability of the impact of reservoir removal, we cannot blindly be optimistic about the ecological consequences of dam demolition.

Scientific decision analysis and systematic evaluation of the impact of dam removal should be carried out before dam removal. With the help of science and technology and case data, the feasibility of scrapped schemes will be studied by conducting analysis or comprehensive evaluation on the ecological environment, social economy, dam demolition consequences, and other aspects. General, mature, and simple methods, such as mathematical model, physical model, analogue analysis, and professional judgment, should be used when making decisions.

Due to the unpredictability of social, economic, and ecological environment, it is difficult to comprehensively evaluate the impact of reservoir removal on ecological environment. In addition, multi-criteria system decision-making focuses on reflecting external interference as a whole, and it is difficult to reflect the mechanism of influencing factors on decision-making objectives, and the interaction between influencing factors is not conducive to managers to improve the decision-making scheme [12]. In contrast, in-depth study of the sensitivity of a single criterion to a specific pressure response can not only strengthen the comparative study of various schemes but also improve the sensitivity [13]. Therefore, the reservoir removal decision based on a single criterion is highly operable and sensitive.

The selection of removal criteria shall reflect the characteristics of reservoir dam. If the reservoir disease risk is serious and the function atrophy, the economic theory can be used to analyze whether it is reasonable to reinforce the reservoir economically. If attention is paid to the impact of changes in the scrapped reservoir flood situation on the flood safety of downstream towns, it is necessary to conduct targeted flood risk analysis of downstream regions and evaluate the impact of river inflow on downstream towns after the scrapped reservoir. Similarly, if serious reservoir siltation is concerned about the sediment transport process after dam removal, a model can be established to simulate the development process of river sediment transport after dam removal and evaluate the impact of sediment transport with water flow.

At present, reservoir removal is composed mainly of the small reservoir in China. The social and economic benefits of reservoir, operation and maintenance, risk removal, and reinforcement costs can be measured when making decisions. From the perspective of dam economics, the rationality of risk removal and reinforcement plans and dam removal and reinforcement plans can be evaluated. In addition, some small reservoirs may still play a certain role in the urban flood control system. Although the removal of the reservoir can eliminate the risk of dam break, it will increase the risk of flood downstream if it leaves the regulation and storage function of the reservoir.

3.1 Economic decision-making methods

This method is suitable for reservoirs which lost main function and high maintenance costs.

Generally speaking, in the early stage of reservoir operation, only a small amount of cost is needed to meet the needs of operation, maintenance and daily management, during this period, the economic benefits of the reservoir are obvious, and greater social and economic benefits can be obtained. However, with the increase of dam age and the aging of materials and facilities, the cost of operation and maintenance increases. In contrast, long-term operation of the reservoir leads to problems such as deposition, which reduce the social and economic benefits of the reservoir. In a word, the relationship between reservoir cost input and benefit output varies from time to time with reservoir state and operation age.

Peng Hui proposed to establish the evaluation model of dam removal with the help of economic theory and according to the annual economic loss and benefit of the dam [14]. The economic loss and benefit were measured by this model, and the decision was not made from the perspective of reservoir disease risk. Based on its research, this paper proposes the economic decision-making method of reservoir removal. By analyzing the payback period of investment in reservoir restoration project, this method evaluates whether the reservoir restoration project is economically reasonable or not.

The annual cost of reservoir includes daily operation and management costs (V_o), maintenance costs of dam and facilities (V_m), etc. The annual costs of reservoir can be expressed as follows:

$$C = V_o + V_m \quad (1)$$

The annual benefits of the reservoir include the economic benefits from the functions of water supply, irrigation, power generation and shipping (V_e), the social benefits from flood regulation and storage (V_s), the recreational benefits from the reservoir landscape (V_r), etc. The annual income of the reservoir can be expressed as follows:

$$B = V_e + V_s + V_r \quad (2)$$

According to the annual cost (Eq. (1)) and income (Eq. (2)), the annual cost-benefit map of the reservoir is drawn, and the change process of the cost and benefit of the reservoir is obtained. Generally speaking, the input cost of the reservoir increases gradually with the operation time, while the benefit of the reservoir is on the contrary, decreasing year by year with time. Regression analysis is carried out on multi-year data to fit the time functions $c(t)$ and $b(t)$ of annual cost and benefit, as shown in **Figure 1**.

With the increase of operation time, the annual input cost increases. When the reservoir is considered to make decision of retirement, the annual input cost shall be the historical maximum, denoted as the t_1 in that year and the input cost as C_1 . Assuming that the benefits and costs only change over time, the time function of the benefit and cost can be estimated according to the actual cost and benefit function, remember $c'(t)$ and $b'(t)$. When the cost of the $c'(t)$ reservoir in the t_2 year reaches C_1 again, it will be deemed that the reservoir state returns to the initial decision state, and the interval from t_1 to the t_2 is the service life of the reservoir restoration measures. Within the interval of $[t_1, t_2]$, the multi-year net income A (i.e., the shaded area in **Figure 2**) and the multi-year average net income R can be calculated as follows.

$$A = \int_{t_1}^{t_2} [b'(t) - c'(t)] dt \quad (3)$$

$$R = \frac{A}{(t_2 - t_1)} \quad (4)$$

At t_1 time point, one-off investment cost for consolidation F was input, which needs to be compensated by net income A obtained over many years during the period of time $\Delta t = t_2 - t_1$. According to the payback period method of investment, the payback period of reinforcement investment F is set as T .

$$F(1+i)^T = R(1+i)^{T-1} + R(1+i)^{T-2} + \dots + R(1+i) + R \quad (5)$$

$$T = \frac{\lg R - \lg(R - iF)}{\lg(1+i)} \quad (6)$$

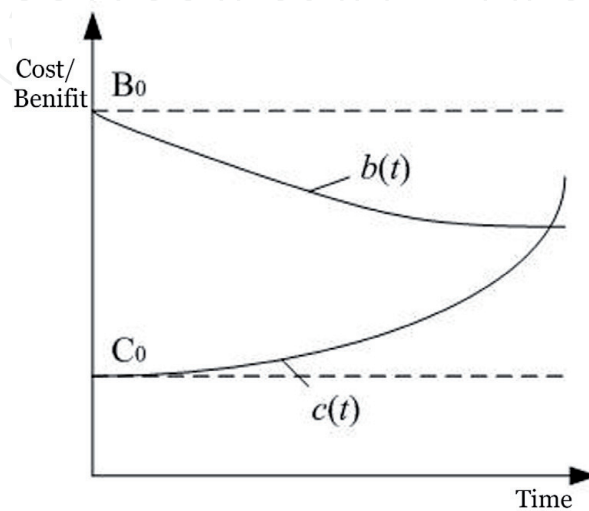


Figure 1.
Time function diagram of annual cost and annual income of a reservoir.

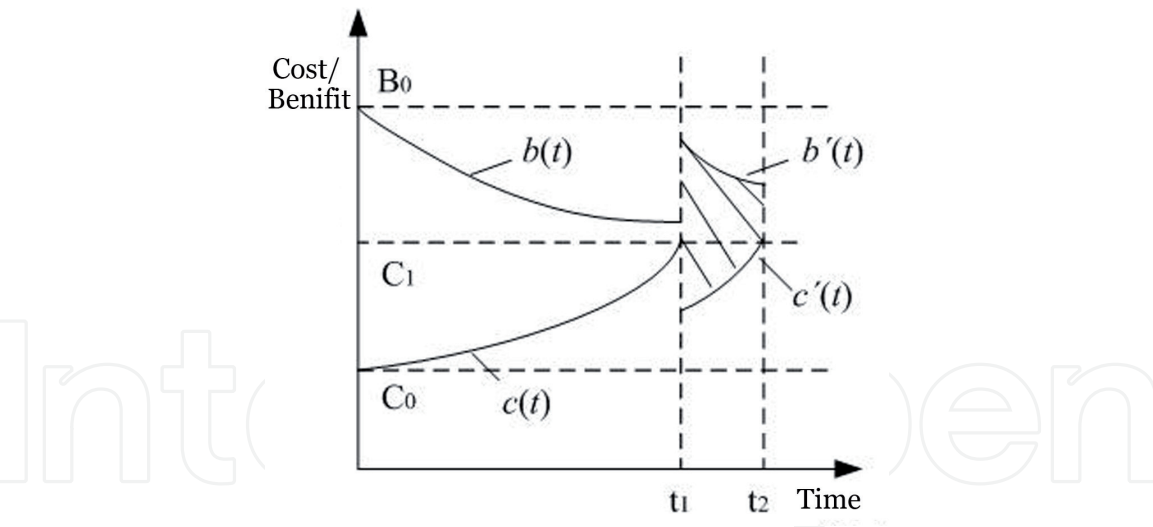


Figure 2.
Time t_2 calculation diagram of occurrence of new disease risks of the dam after reinforcement.

In the equations above, i stands for social discount rate.

The extended service life of the reinforcement project is less than the recovery life of the project cost, which indicates the project is economic irrationality and disposal can be considered; in the same way, if $T \leq \Delta T$, indicates the project is economically feasible

3.2 Consequence decision method

Flood impact is an important evaluation content of reservoir removal decision under the urban background, and simulating the impact of reservoir removal on flood situation is conducive to proposing targeted reduction measures and improving the decision-making scheme.

The assessment framework for the consequences of reservoir removal covers six steps, namely, the formulation of a plan, the establishment of an assessment index system, the determination of flood loss indicators, the establishment of a flood risk model, the calculation of flood loss, and the program assessment.

At least two schemes are selected for evaluation, and the evaluation results are compared with each other. Two schemes of reservoir current flood control and reservoir removal are usually used to evaluate the flood changes of reservoir removal scheme based on the current flood control of reservoir.

The evaluation index system criterion layer constructed in this paper consists of economy, society, and environment.

Flood economic losses are divided into direct economic losses and indirect economic losses. Direct economic loss refers to the total loss of physical damage caused by flood, usually including loss of farmland production, damage to housing and facilities, and financial losses [15]. Indirect economic losses are considered to be other losses caused or implicated by direct economic losses, specifically, the stoppage and production reduction losses caused by flood disaster, the economic losses caused by the increase of intermediate investment backlog, and the loss of investment premium [16].

The inundation of downstream cities caused by the flood will affect human normal activities to varying degrees, which is the embodiment of the social impact of the flood. The degree of the impact can be measured by the number of people affected by the flood and the inundation range.

The impact of flood on urban environment is divided into landscape damage and soil erosion. On the one hand, the water will carry the bare soil in the erosion

area, causing a large amount of soil loss; on the other hand, the vegetation of flood areas is damaged by floods, causing losses to the urban landscape.

Take Heiwa reservoir as an example. Heiwa reservoir, located in the southwest of Chuzhou city, Anhui province, was spontaneously built and operated by villagers. It was completed and started operation in 1977 with a capacity of 560,000 m³. The maximum height of the dam is 12.2 m. With the advancement of urbanization, the farmland in the lower reaches turned into urban area. The spillway goes straight through the new campus of Chuzhou College, which is less than 2 miles away. Buildings and population are numerous and dense, as shown in **Figure 3**. The reservoir has been identified as dangerously weak, due to poor construction quality and capacity of management, which makes downstream region a high-risk zone. Besides that, the reservoir's main function has changes from agricultural irrigation as designed to urban flood control.

In general, Heiwa reservoir, which has lost design function, needs continuously huge investment in improving dam state to prevent dam break. It is a typical case for dam removal discussion.

The lower reaches of the reservoir pass through the main urban area of Chuzhou city from the southwest to the northeast (see **Table 1** for details). Along the way, residential areas, schools, medical care, administrative institutions, and commercial shops are distributed. As shown in **Figure 4**, in case of dam break danger, huge economic loss and significant social impact will be caused.

To improve the city's flood control system, the Chuzhou water conservancy department has established an urban flood control plan by intercepting the flood in the western mountainous area of Chuzhou and protecting the central urban area and the industrial zone between the Qingliu River west and the Beijing-Shanghai railway. The key point of this plan is to discharge the reservoir water from the southwest hilly region into the Qingliu River via the newly built flood interception ditch, around the west side of the main urban area to the south side (see **Figure 4**). The western flood interception ditch intersects the reservoir channel at point B. If the flood interception ditch is completed, the flood discharge pressure of river section will be relieved. The designed maximum discharge at point B of the flood interception ditch is 50 m³/s. There is a flood gap on the left bank of point B, and the flood exceeding the designed flow rate will be discharged into the Qingliu River by the spillway at a maximum flow rate of 8 m³/s through the urban river channel.



Figure 3.
Satellite map of Heiwa reservoir location.

No.	River section	River section information
1	The reservoir—A	The reservoir spillway
2	A—B	South campus of Chuzhou University
3	B—C	Residential landscape section
4	C—D	Underground drainage ditch section
5	D—E	Joining the drainage flow of Yujiawa reservoir and flowing into the open channel section
6	E—Qingliu River	Joining Qingliu River

Table 1.
Downstream channel information of reservoir.



Figure 4.
Regional distribution and river channel diagram of the lower reaches of the reservoir.

3.2.1 Evaluation scheme

In this section, three evaluation schemes are proposed for Heiwa reservoir under the condition that it encounters a flood once every 50 years: (1) flood regulation scheme for the reservoir. Under the current situation of Heiwa reservoir, the peak discharge from the reservoir to the discharge from the reservoir is $34.1 \text{ m}^3/\text{s}$; (2) the scheme of reservoir removal, and the peak inflow of the reservoir, is $54.9 \text{ m}^3/\text{s}$, and point D of the river meets the incoming water from Yujiawa reservoir; and (3) the reservoir was scrapped, and the city's flood control system was improved. The flood interception ditch shared the discharge of some of the water from Heiwa reservoir and Yujiawa reservoir, and the excess discharge still flowed from the river section into Qingliu River. The flow data of each scheme are shown in **Table 2**.

Based on the flood consequence criteria, a two-dimensional hydrodynamic mathematical model was established to simulate the flood evolution process, result as below.

Without the effective urban flood control planning, the city's flood discharge capacity of the urban channel system is insufficient, and the city was seriously affected by the flood return period of 50 years. As shown in Figure **Figure 5**. Especially, due to confluence of Heiwa reservoir flood drainage and Yujiawa reservoir flow at the open channel of Huifeng Road, both sides of the road were flooded; the average water depth was about 0.25 m, maximum depth of 1.72 m; and Chuzhou Development Zone was affected seriously, with submerged depth of the water at about 0.7 m. The low-lying depression area on the east side of Beijing-Shanghai

Scheme number	Scheme description	Flow rate (m ³ /s)		
		Point A	River section BD	River section DE
1	Reservoir flood routing	34.1	34.1	71.6
2	Reservoir removal	54.9	54.9	92.4
3	Reservoir removal + flood control planning	54.9	33.7	33.7

Table 2.
Flow point data of flood simulation scheme.

railway was the most seriously flooded with a maximum depth of 3.77 m. This area is located outside the main urban area of Chuzhou and has a low population density.

Under the scheme of reservoir removal, the discharge rate of the lower discharge increases from 34.1 to 54.9 m³/s, and the flood discharge pressure of the drainage ditch system increases; the average submerged depth is about 0.84 m, and the maximum submerged depth is 4.02 m. The submerged range increases from 1.63 to 1.83 km²; the newly added flooded area is mainly located in the housing area downstream of the dam site, as shown in **Figure 6**.

Under the new flood control system, the flooded area and water depth of the reservoir scrapping scheme are significantly less than that of the reservoir flood control before the implementation of the plan, as shown in **Figure 7** for details. After the implementation of flood control planning, the Xipie flood interception ditch can accommodate the flow rate of 21.2 m³/s, and the flow rate of the flood flowing into the urban river course is 33.7 m³/s, slightly lower than the regulated flood volume of the reservoir 34.1 m³/s. Although the flow rate is similar, the submerged area of the former is only 35% of that of the latter. The inundation area of the downstream risk area is 0.58 km², mainly concentrated in underground drainage ditch CD river section. The maximum depth was reduced from 4.02 to 2.66 m; the water depth of the Beijing-Shanghai railway decreased from 1.72 to 0.30 m.

The simulation results show that, after the removal of Heiwa reservoir, the reservoir completely loses the capacity of regulating and storing. Although the discharge volume under the channel will increase by 56%, the inundation range and average inundation depth will increase by only 11 and 12%, which is relatively small compared with the flood control scheme of the reservoir. This is because the downstream

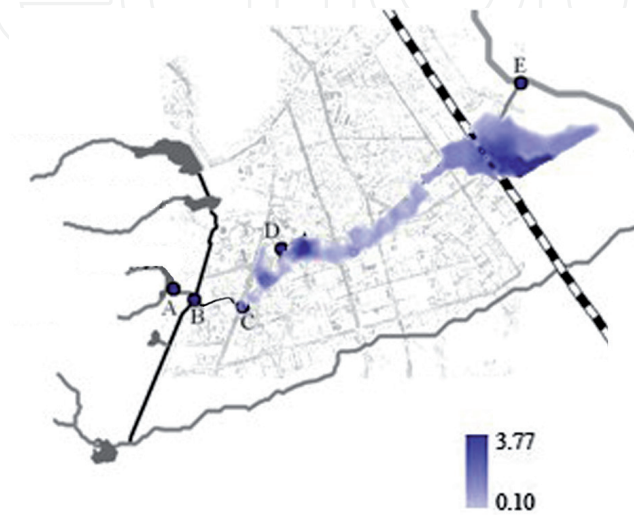


Figure 5.
Flood depth of the lower reaches of the reservoir flood control scheme in case of a flood once every 50 years.

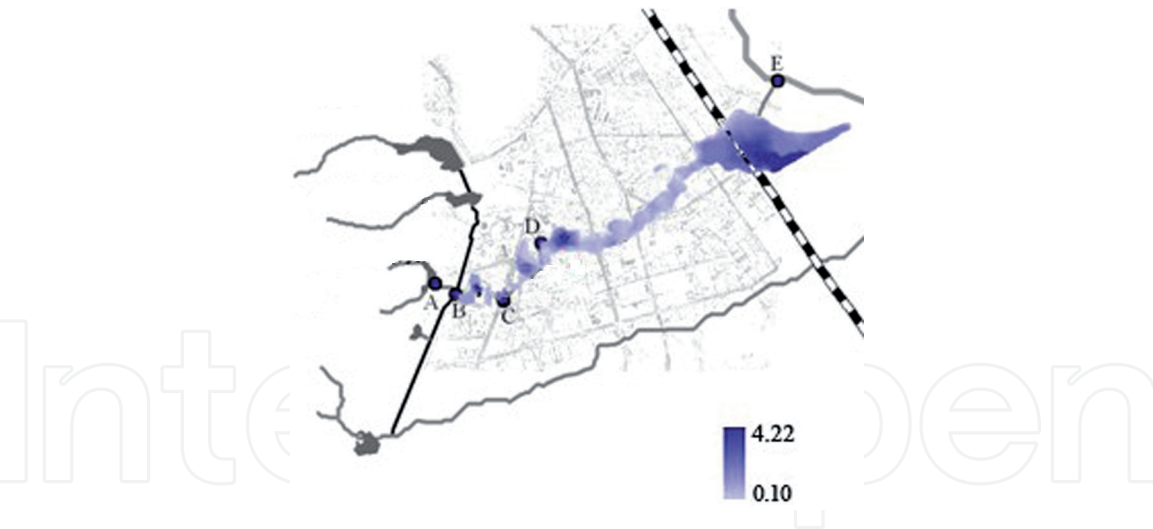


Figure 6.
Flood depth downstream of reservoir abandonment scheme in case of a flood once every 50 years.

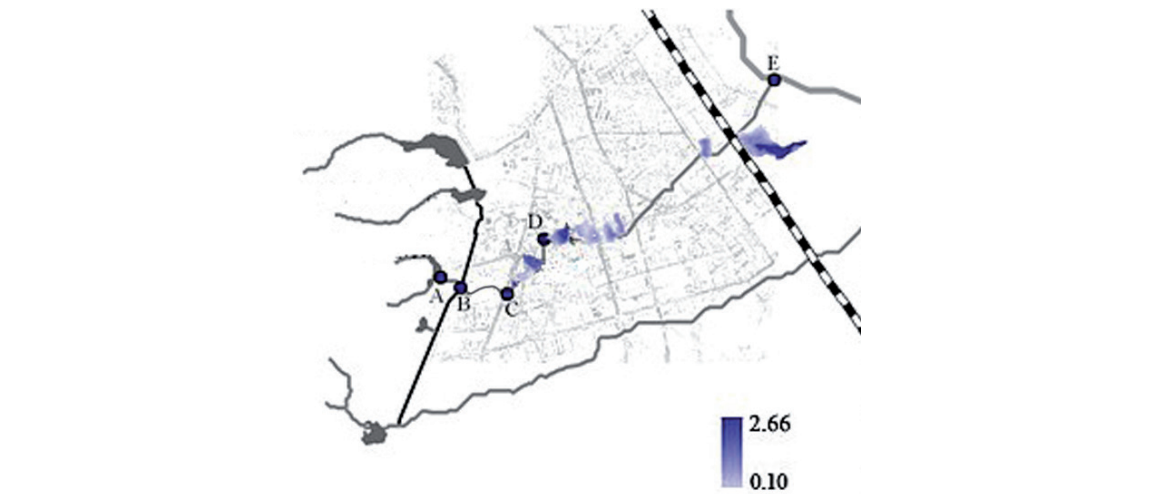


Figure 7.
Flood depth in the lower reaches of the joint flood control planning scheme for flood once encountered every 50 years.

discharge volume of the reservoir far exceeds the flood discharge capacity of the downstream urban channel system. In other words, the flood control effect of the reservoir is not significant, and even if the reservoir is removed, it will not significantly increase the inundation range and water depth. In comparison, although the reservoir has been scrapped and lost its flood control capacity, the flooded area of the lower reaches of the reservoir has been significantly reduced after combining with the urban flood control planning. Compared with the reservoir scrapped plan before the implementation of the planning, the flooded area of the latter has been reduced by 69%.

3.2.2. Flood impact assessment

According to the characteristics of the calculation region and the loss data of agricultural and commercial assets in typical flood disasters in history, the loss rate was determined, and the corresponding relationship between the loss rate and water depth was finally determined, as shown in **Table 3**.

According to the flood analysis and results of three schemes, combined with the regional feature distribution, to measure socio-economic indicators including

the flood area population, submerged area, submerged residential area, affected length of road and railway, affected population and GDP of each scheme. Results are shown in **Table 4**.

See **Table 5–7** for the flood loss values under different water depth levels of each simulation scheme.

The result of loss assessment shows that the building loss is between RMB 3.04 million and 26.48 million, the landscape loss is from RMB 933,300 to 8.39 million, the road loss is from RMB 14,000 to 86,100, the railway loss is from RMB 0 to 1.36 million, and the total loss is from RMB 3.99 million to 3.63 million. Among the three schemes, the total loss of scrapped reservoir is the largest, among which the loss of buildings is the largest, followed by the loss of landscape.

Depth (m)	Building	Vegetation	Railway	Roads
0.05–0.5	0	5	1	2
0.5–1.0	1	10	2	3
1.0–2.0	5	19	6	10
2.0–3.0	18	50	22	28
> = 3.0	24	68	32	39

Table 3.
Ground object loss rate: water depth relationship (unit, %).

Scheme number	Submerged area (km ²)	Submerged area of buildings (km ²)	Affected road length (km)	Affected railway length (km)	Affected landscape area (km ²)	Total GDP affected (RMB 10,000)	Total population affected (person)
1	1.63	0.97	3.15	0.70	0.58	6337	2798
2	1.83	1.12	3.52	0.76	0.66	7100	3184
3	0.58	0.24	0.97	0	0.21	2250	997

Table 4.
Calculation of the statistical table of flooded surface features in the region.

Depth grade (m)	Building loss	Landscape loss	Railway loss	Road loss	Total
0.05–0.5	0.00	154.66	126.00	4.41	285.07
0.5–1.0	208.00	186.66	0.00	4.20	398.86
1.0–2.0	520.00	30.40	0.00	0.00	550.40
2.0–3.0	144.00	53.33	0.00	0.00	197.33
≥3.0	192.00	72.53	0.00	0.00	264.53
Total	1064.00	497.57	126.00	8.61	1696.18

Table 5.
Scheme 1: flood loss table of water depth at all levels unit: RMB 10,000.

Depth grade (m)	Building loss	Landscape loss	Railway loss	Road loss	Total
0.05–0.5	0.00	175.99	136.80	4.41	317.20
0.5–1.0	296.00	213.32	0.00	4.20	513.52
1.0–2.0	720.00	324.25	0.00	0.00	1044.25
2.0–3.0	1440.00	53.33	0.00	0.00	1493.33
≥3.0	192.00	72.53	0.00	0.00	264.53
Total	2648.00	839.41	136.80	8.61	3632.82

Table 6.
Flood loss table of water depth at all levels in Scheme 2 unit: RMB 10,000.

Depth grade (m)	Building loss	Landscape loss	Railway loss	Road loss	Total
0.05–0.5	0.00	56.00	0.00	1.40	57.40
0.5–1.0	80.00	37.33	0.00	0.00	117.33
1.0–2.0	80.00	0.00	0.00	0.00	80.00
2.0–3.0	144.00	0.00	0.00	0.00	144.00
≥3.0	0.00	0.00	0.00	0.00	0.00
Total	304.00	93.33	0.00	1.40	398.73

Table 7.
Flood losses of all levels of water depth in Scheme 3 unit: RMB 10,000.

4. Conclusion

Due to the aging, poor construction quality, and maintenance, water dam-age and other adverse factors make it a prominent risk for the Chinese reservoir management institution. In the face of the long-term challenges of the disease-risk reservoirs, it is an effective way to solve the problems of the disease-risk reservoirs by disposing of the ones with serious disease risk, shrinking function, and techni-cally unfeasible and economically unreasonable danger reservoirs while taking engineering measures to remove and reinforce them.

Based on economic rationality theory and flood consequence assessment, two decision-making methods of dam retirement are put forward. The flood conse-quence method is applied on the case of Heiwa reservoir; key evaluation indexes are compiled from the aspects of ecology, economy, and society; and the evaluation system based on single index is constructed. Comparing the plans of current dam situation, dam removal, and dam removal combined with urban flood control measure, the flood risk influence is evaluated. The evaluation results show that the reservoir scrapping will not have significant effects on the flooding situation in downstream cities. Besides, the urban flood control regulation measures could greatly mitigate the urban flood risk.

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