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Research on benefit of reservoir flood resources utilization based on the dynamic control of limited water level

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ABSTRACT

With the rapid development of the social economy in China, the utilization of surface water and groundwater can hardly meet all demands of production and living. On the one hand, the shortage of water resources restricts the development of economy and society; On the other hand, flood control and storm drainage are carried out to protect the safety of life and property of people during flood seasons. The phenomenon of the shortage of water and flood also creates opportunities for the utilization of flood resources. As the determination of limited water level is the key for reservoir to keep a balance between impounding and flood control regulation, adjusting it appropriately can make better use of flood water resources. In this paper, based on the determination of the staged design flood, flood routing is carried out under different frequencies of upland water. The dynamic control scheme of limited water level is obtained by the method of comparing. Through the analysis, in the case that the upstream water of reservoir has obvious seasonal change, design flood by stages can be used to calculate the limited water level by stages. According to the transformation rules of local climate and rainfall, the flood season is staged; Based on the flood control standard of engineering, the design flood by stages is calculated. And the initial water level is determined to carry out flood routing for design flood by stages according to the primary operation regulations and rules. Calculation was carried out on the stage design flood respectively. The value of limited water level by stages is selected according to the results of flood routing, which simultaneously satisfy flood control standards of reservoir and downstream at different initial water level. Furthermore, the benefit after performing is calculated by the use of value-added of industry, as well as the method of share coefficient of benefit, which contains industrial water supply, irrigation and living water supply. Shilianghe reservoir is taken as a case study. The results show that the average annual benefit of flood resources utilization can be increased by 41.625 million RMB. The research results will draw some reference to the potential benefit of existing reservoir.

Keywords: Flood routing; Dynamic control of limited water level; Value-added of industry; Methods of share coefficient of benefit; Benefit

1. Introduction

With the rapid development of the social economy in China, the utilization of surface water and groundwater can hardly meet all demands of production and living [1]. On the one hand, the shortage of water resources restricts the development of economy and society; On the other hand, flood control and storm drainage are carried out to protect the safety of life and property of people during flood seasons. The phenomenon of the shortage of water and flood also creates opportunities for the utilization of flood resources [2,3]. So far, although a systematic study of limited water by stages has not been realized, there are a lot of practical examples in the field of reservoir operation. Yeh (1985) reviewed all methods of the reservoir optimization, and pointed out the

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superiority of stochastic simulation operation [4]. Labadie (2004) introduced the stochastic simulation and optimization technologies of reservoir group, and explored the neural network and genetic algorithm in the application of the reservoir operation [5]. Rani [6] reviewed application and scope of computational intelligence techniques, such as, evolutionary computations, fuzzy set theory and artificial neural networks in reservoir system operation, in addition to classical optimization techniques. Akbari-Alasht [7] developed a new method for real-time operation of reservoir systems. Results showed that the FLGGP method is a powerful and efficient tool without the limitations of GP and can be used as a suitable replacement to GP. The domestic research of the limited water level of reservoirs began in the 1950s, mainly experiencing two stages. The first stage was to use the current design flood method by stages. But the researchers questioned on it. Ye [8] pointed out that it was calculated with a certain experience, and there is no quantitative analysis for the risk rate of flood control after carrying out reservoir operation by stages. In the second stage, the method was put forward to by making the joint return period of design flood by stages equal to that of the original design flood, in order to ensure that the original design standard of the flood control was not reduced after reservoir operation by stages. The use of Gumbel-Hougaard Copula helped to establish the correlation relation between the maximum flood by stages. Xiao [9] got the joint distribution and joint return period of the maximum flood by stages. Although fuzzy analysis and the multi-objective optimization design method focus on the determination of the limited water level by stages, the design flood method by stages is still recommended by the specification [10]. As a result, Shilianghe reservoir is taken as a case study. The design flood method by stages is adopted to calculate the limited water level by stages, to make full use of the transit of flood resources.

2. Research materials

2.1. The general situation of engineering

Shilianghe reservoir is the key project of diverting water from east to south in Yishusi rivers basin. As the largest reservoir in Jiangsu Province, it is located in the junction of Donghai county and Ganyu county, neighboring Linshu county, Shandong province to the west, and is about 35 km to Lianyungang city to the east. The reservoir undertakes releasing runoff between upstream of Xinshu river, Yi river and Shu river, with the catchment area of about 15365 km^2 and total storage capacity of 531 million m^3. The reservoir was built in 1958. A hydroelectric power station was constructed in 1970, with 7 sets of generators installed and total capacity of l120 kW. It was designed by a hundred year frequency of flood, and checked by 2000 year frequency, with design flood level 26.81 m, check flood level 27.95 m and maximum discharged flow 10,131 m^3/s. Shilianghe reservoir undertake the primary function of flood regulation in Yishusi rivers basin, and protecting Lianyungang City against flooding. In addition, Shilianghe reservoir is the second water source of domestic and industrial water in Lianyungang city, which brings huge comprehensive benefits since the completion. The location of Shilianghe reservoir is shown in Fig. 1.

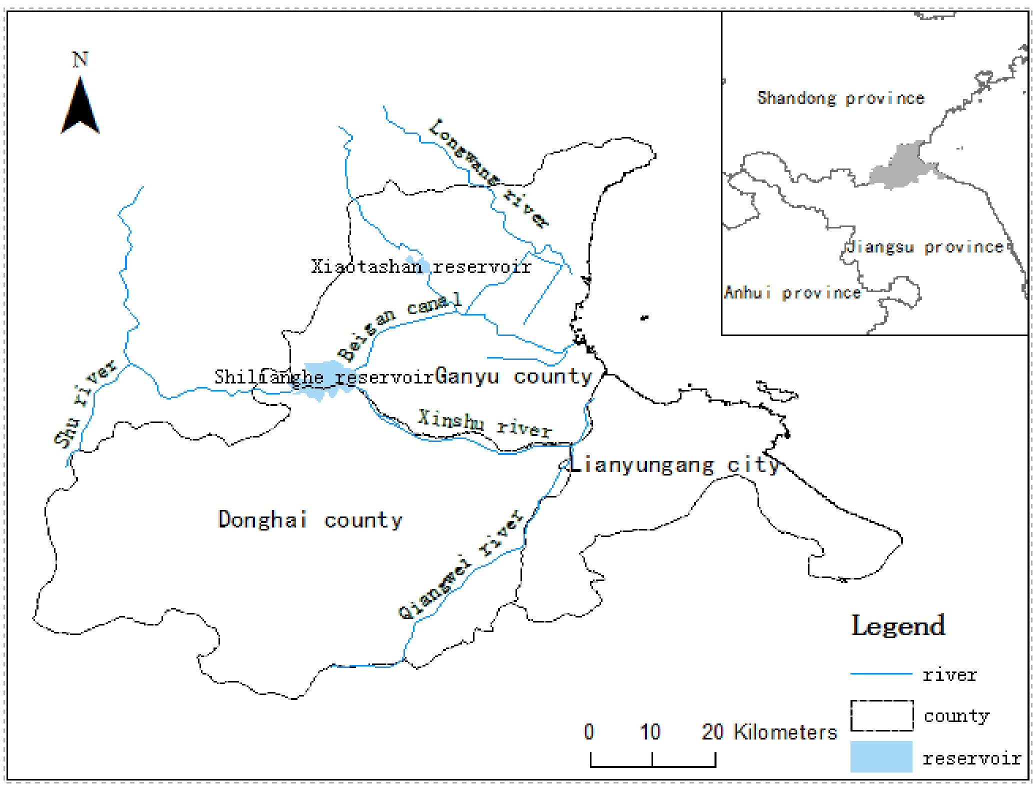

Fig. 1. Geographic location of Shilianghe reservoir.

2.2. Operation rules of Shilianghe reservoir

In the full measure of the relationship among river, reservoir and downstream, the operation rules of Shilianghe reservoir are as follows: (1) under the condition of upstream flood without local rainfall, Shilianghe reservoir can drain in advance under the control of discharge no more than 3000 m^3/s, ensuring the security of Xinshuhe river levees; (2) under the condition that the local place and upstream occurred the same frequency of excessive flood, Shilianghe reservoir should control discharge to let the downstream river channels, urban areas and farmland drain flood, reducing the disasters of downstream. Discharging flood with large flow, shortening the time of flood discharge, and regulating the peak, the river channels are released to eliminate the downstream flood; (3) under the condition that the local place and upstream occurred in the same frequency of flood within standard, regulating the peak is used to give full play to the reservoir flood storage, allowing time for the downstream rivers, downtown, and irrigation to drain flood, to alleviate the downstream flood, and to use transit flood resources as many as possible at the same time.

Reservoir control by stages is explained as follows: When water level is 23.5 m to 24.0 m, the discharge is controlled by no more than 5000 m^3/s; When water level is 24.0 m to 26.3 m, the discharge is controlled by 6000 m^3/s. When water level is 26.3 m to 27.0 m, the discharge is controlled by 7000 m^3/s. When water level is more than 27.0 m, the spillway sluices are fully opened for flood discharge.

3. The research on limited water level by stages

3.1. The method for determining the limited water level by stages

Through the analysis, in the case that the upstream water of reservoir has obvious seasonal change, design flood by stages can be used to calculate the limited water level by stages [11]. According to the transformation rules of local climate and rainfall, the flood season is staged; Based on the flood control standard of engineering, the design flood by stages is calculated. And the initial water level is determined to carry out flood routing for design flood by stages according to the primary operation regulations and rules. Calculation was carried out on the stage design flood respectively. The value of limited water level by stages is selected according to the results of flood routing, which simultaneously satisfy flood control standards of reservoir and downstream at different initial water level [12].

3.2. The determination of characteristic water level under different conditions

Shilianghe reservoir was built in 1958, which was listed in the second batch of national key water conservancy dilapidated reservoirs in 1992. Since then, it operates on low water level. The original design characteristics water level and of present characteristic water level of reservoir are shown in Table 1.

Danger removal and reinforcement projects were implemented on Shilianghe reservoir from 1999 to 2001. The Xinshuhe river treatment engineering started at the end of 2008. Xinshuhe river capacity of flood carrying will increase to 50 times a year after completion, creating conditions for Shilianghe reservoir returns to normal use in the future. Therefore, it is suggested that the flood utilization water level of Shilianghe reservoir can be restored to the original design goal 26 m. Design flood level and check flood level are back to 27.65 m and 28.0 m respectively. And the study on limited water level by stages of Shilianghe reservoir is based on these.

3.3. Flood season staging

Flood season staging belongs to high-dimensional time series of clustering problems, mainly solved by the fuzzy set analysis method, the fractal method, the change point analysis method and the dynamic clustering method [13]. In comprehensive analysis of upstream inflow of Shilianghe reservoir, local factors' rainfall, regional climate and extreme weather, the flood season of Shilianghe reservoir is divided into pre-flood season, main flood season and latter flood season in combination with the practical situation of river basin and regional flood control (Table 2).

Table 2
Results of Shilianghe reservoir flood season staging

Stages	Time
Pre-flood season	June 1–June 30
Main flood season	July 1–August 15
Latter flood season	August 16–September 30

Table 1
Characteristic stage of Shilianghe Reservoir under different conditions

Condition	Normal water level (m)	Design flood level (m)	Check flood level (m)	Limited water level (m)		
				Pre-flood season	Major flood season	Latter flood season
Present condition	24.5	26.81	27.95	24.5	23.5	24.5
Design	Recent period 25.0 Forward 26.0	27.65	28.0	23.5		

3.4. Seasonal design flood

(1) Design standard

The flood control standard of Shilianghe reservoir is designed by once-in-a century and checked by once in 2000 years. In this paper, design flood by stages chooses the same standard.

(2) Design peak flood discharge by stages

Studying on inflow floods of Shilianghe reservoir from 1980 to 2009, the maximum inflow is selected year by year according to the different stages to make up the series of peak flow. The frequency curve of seasonal flood is acquired by curve-fitting method to obtain the design flood peak corresponding to the design standard. Considering the significance of the upstream water of Shilianghe reservoir and weather changes, there is a chance in the time that the floods occur in many years. Based on the possibility of being early and late, the inter-temporal sampling method is used. The sampling extends 5 days forward and backward on the stage based on the original time.

(3) Stage design flood

The year 1974 is chosen as the typical flood process of Shilianghe reservoir. It is enlarged according to design flood peak by stages and the ratio of design flood peak. The design and check flood process of re-flood season and latter flood season are calculated, as shown in Table 3 [14].

3.5. Limited water level by stages

In this paper, the calculation method of the limited water level of reservoir by stages is as follows: under the condition of the determination of design flood by stages and characteristic stage of water level under different conditions, flood routing is calculated to ascertain the limited water level according to the principle of the reservoir operation. The flood regulating results of stage design flood and check calculation results are shown in Tables 4 and 5 respectively.

According to the flood regulating results of stage design flood and check flood, the limited water levels for all stages are shown in Table 6.

Based on the comprehensive analysis in comparison with the flood regulation results of stage design flood and check flood, the limited water level of Shilianghe reservoir take the smaller one and round up to the results, to ensure the safety of reservoir and the convenience of dispatch control, as shown in Table 7.

3.6. The benefit of limited water level by stages

The effect calculation principle of effect of limited water level by stages is as follows: according to abandoned water of Shilianghe reservoir for all stages during 1991–2009, as shown in Table 8, the corresponding water storage capacity of increment is determined after adjusting the limited water level .When abandoned water for all stages is less than the due to the limited water level

Table 3
Results of different seasonal design flood

Stages	Q_m (m^3/s)	C_v	C_s/C_v	Peak discharge Q_p(m^3/s)		Seven days' flood volume W_p (10^8 m^3)	
				1%	0.05%	1%	0.05%
Pre-flood season	2391.9	1.03	1.0	8029.6	11264.7	27.55	29.28
Main flood season	–	–	–	10017	15799	34.36	41.07
Latter flood season	2493.8	0.96	1.0	8026.2	11247.2	27.53	29.31

Table 4
Results of flood regulation under seasonal design flood (P = 1%)

Stages	Initial water level (m)	Maximum water level (m)	Maximum inflow (m^3/s)	Maximum discharged flow (m^3/s)	Maximum storage capacity (10^4 m^3)
Pre-flood season	26.02	27.65	8029.6	7000	50044
Main flood season	24.65	27.65	10017	7000	50053
Latter flood season	25.83	27.65	8026.2	7000	50053

Table 5
Results of flood regulation under seasonal check flood (P = 0.05%)

Stages	Initial water level (m)	Maximum water level (m)	Maximum inflow (m^3/s	Maximum discharged flow (m^3/s)	Maximum storage capacity 10^4 m^3)
Pre-flood season	26.14	28.00	11264.7	10131	53137
Main flood season	24.52	28.00	15799	10131	53103
Latter flood season	25.87	28.00	11247.2	10131	53081

by increasing storage capacity after adjusting the limited water level, the increasing water storage is equal to the abandoned water. On the contrary, the increasing water storage is equal to the increasing storage capacity after adjusting the limited water level [15]. As a result, the calculation of the benefit of limited water level by stages is shown in Table 9.

Table 6
Contrast of limited water level for all stages

Frequency P	Pre-flood season (m)	Main flood season (m)	Latter flood season (m)
1%	26.02	24.65	25.83
0.05%	26.14	24.52	25.87

Table 7
Results of limited water level for all stages

Flood season staging	Limited water level (m)
Pre-flood season June 1–June 30	26.0
Main flood season July 1–August 15	24.5
Latter flood season August 16–September 30	25.8

Added industrial value and benefit-sharing coefficient method are used to compute the benefit of flood resource utilization in agricultural irrigation and industrial water supply. The two former benefits are calculated as follows:

$$B = Vqk = (I / W) fqk \tag{1}$$

The effect of domestic water supply is calculated as follows:

$$B = Vqk = (re / p) fqk \tag{2}$$

where B is the water supply benefit; V is the value of unilateral water; q is the added water supply quantity; k is the utilization of water resources; I is the added producing value; W is the total water consumption; f is the apportionment factor; r is the residents' disposable income; e is the Engel coefficient; p is the water consumption per capita.

The benefit of flood resources utilization consists of agriculture, industry and domestic water supply. According to the statistical yearbook and the official reports on water resources of Lianyungang city in 2013. The allocation proportion of water resources on industry, agriculture and domestic water supply is 32%, 64% and 32% respectively. The distribution of flood resources utilization rate also takes the above ones. The first two industrial added value are: I_i = 6.548 billion RMB, I_a = 1.24 billion RMB, and the efficiency of water resources utilization is 0.9. The allocation coefficients of water benefit are: f_i = 0.05, f_a = 0.45,

Table 8
Surplus water of Shilianghe reservoir for all stages during historical seasons $V/10^4$ m^3

Year	Non-flood season	Pre-flood season	Main flood season	Latter flood season	Total
1991	12546	16910	23770	290	53516
1992	710	0	94	0	804
1993	9449	260	18760	820	29289
1994	3590	200	7446	26170	37406
1995	370	1117	460	23970	25917
1996	0	380	13360	0	13740
1997	0	680	0	3580	4260
1998	10830	0	31120	51090	93040
1999	0	0	248	0	248
2000	0	0	0	29450	29450
2001	460	266	13776	0	14502
2002	0	1920	0	0	1920
2003	6430	0	31180	39260	76870
2004	0	0	12570	840	13410
2005	2450	0	7530	46830	56810
2006	0	0	0	0	0
2007	190	0	23590	17950	41730
2008	3590	260	84270	41840	129960
2009	0	0	12623	3850	16473
Total	50615	21993	280797	285940	639345
Annual	2664	1158	14779	15049	33650

Table 9
Benefit of water storage increased by staging limited water level during flood season

Project	Non-flood season (10.1–5.31)	Pre-flood season (6.1–6.30)	Main flood season (7.1–8.15)	Latter flood season (8.16–9.30)	Total
The present limited water level (m)	–	24.5	23.5	24.5	–
The adjustment of limited water level (m)	–	26.0	24.5	25.80	–
Normal water level (m)	24.5	–	–	–	–
The adjustment of normal water level (m)	26.0	–	–	–	–
The increasing storage capacity (10^4 m^3)	10084	10084	5761	8685	–
The total increasing storage capacity (10^4 m^3)	47407	15167	69934	78860	211368
Annual average increasing storage capacity (10^4 m^3)	2495	798	3681	4151	11125

Table 10
The calculation of risk benefit

Increased water storage (10^4 m^3)	Water allocation and benefit of industry		Water allocation and benefit of agriculture		Water allocation and benefit of living water		Total benefit (10^4 RMB)
	Water allocation (10^4 m^3)	Benefit (10^4 RMB)	Water allocation (10^4 m^3)	Benefit (10^4 RMB)	Water allocation (10^4 m^3)	Benefit (10^4 RMB)	
11125	8455	1921.3	2225.0	1365.9	445.0	875.3	4162.5

$f_1 = 0.3$ [16]. Based on the statistical yearbook of Lianyungang city from 2009 to 2013, the disposable income of residents is 12000 RMB. Engel's coefficient is 0.36, and the per capita water consumption is 593 m^3. The benefit of flood resources utilization on Shilianghe reservoir is calculated, as shown in Table 10.

4. Conclusion

1. After restoring the original design water level and carrying out the limited water level by stages, annual average storage capacity can increase 111.25 million m^3, and total effect is 41.625 million RMB, which will greatly improve the efficiency of flood resources utilization in Lianyungang, and relieving the pressure on the water problem contradiction in the surrounding areas to some extent.
2. After restoring the original design water level and carrying out the limited water level by stages, normal storage level is increased from 24.5 m to 26 m. At the same time, the characteristic design flood level such as limited water level and design flood level increased, will cause the increase of the reservoir water area and overflow forecast. It is easy to initiate the social problems such as reservoir immigrants. And it also has a certain effects on the reservoir area ecological environment and local climate.

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