Optimization of Drought Limited Water Level and Operation Benefit Analysis of Large Reservoir

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Abstract

As an important water conservancy engineering project, reservoir regulation plays a crucial role in the insurance of water resources supply and demand balance and sustainable development and utilization, especially during drought seasons. The drought limited water level (DLWL) is the characteristic controlling water level of reservoir regulation operation during dry seasons, and the construction of reliable controlling schemes of DLWL is of great significance for the improvement of regional water resources utilization efficiency. Therefore, basing on the variation analysis of water inflowing series and water resources utilization characteristics among different sectors of Meishan Reservoir in Shihe Irrigation Area of China, firstly, the Hausdorff Dimensional Fractal (HDF) method was applied to divide drought early-warning periods of Meishan reservoir. Then, the initial scheme of DLWL of reservoir was determined through reservoir water inflow and water supply processes analysis during each drought warning periods of different typical hydrological years. And finally, the optimal dynamic controlling scheme of DLWL, described by drought warning water level (DWWL) and drought depleted water level (DDWL) respectively, was eventually proposed in this study based on the establishment of simulation and regulation model of reservoir and irrigation areas system. Moreover, the reliability and effectiveness of the proposed optimal controlling scheme of DLWL was further testified in terms of drought risk analysis of reservoir and irrigation area system under typical consecutive and annual drought scenarios, and meanwhile, the agricultural crop yield loss risk due to drought events corresponding to different controlling schemes of DLWL was also determined. The related research findings of this study could be favorable and beneficial for guiding drought-resistance regulation of reservoir and irrigation area system during drought seasons and providing reasonable decision-making basis of water resources utilization schemes as well.

Keywords Drought limited water level · Agriculture drought · Risk analysis · Meishan Reservoir

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1 Introduction

To date, due to the comprehensive influence of climate change and human activities, water resource security related issues have becoming increasingly prominent in China, the occurrence of extreme hydrometeorological disaster as well as the contradiction between water resources supply and demand sides present a more severe evolution trends, which will undoubtedly restrict the sustainable development of the socio-economy and ecological environment (Xia et al. 2007; Khan et al. 2017; Cai et al. 2017). Generally, water resources demand of different sectors in a certain period is relatively stable, and water resources supply shortage of water cycle process caused by the abnormal weather conditions is the main reason for the occurrence of drought disasters (Citakoglu and Coşkun 2022; Sattar et al. 2019; Ullah and Akbar 2021). Drought is primarily featured with persistent water resources shortage, which is not only caused by the evident reduction of precipitation, but also closely related to water resources utilization processes of industrial, agricultural, municipal and ecological sectors (Ministry of Water Resources of PRC 2009; Tabari et al. 2013; Jin et al. 2016). Therefore, the concept of Drought Limited Water Level (DLWL) was firstly proposed to ensure the water resources supply security of lakes and reservoirs during dry seasons considering the influencing factors of elevation of water intake, the minimum water demand of agricultural production, industrial water consumption, residential water demand, navigation water level, and the minimum ecological water resources demand Cao (2008). In 2011, the National Flood Control and Drought Relief Headquarters Office of China proposed the definition of DLWL, *i.e.* the reservoir water level corresponding to the adoption of drought-resistance measures to ensure the security of residential water utilization, industrial and agricultural production as well as ecological environment sustainability when the water level and flow of rivers or lakes are continuously lower than average conditions. Nevertheless, the above determination method of DLWL is mainly applied for the annual regulating reservoir to deal with the drought related issues in the next several months, and the corresponding operation result is only comparatively verified with historical observed frequencies of reservoir water level, which is not applicable to guide actual reservoir regulation processes (Yang 2012; Wu 2016). Moreover, Liu et al. (2012) pointed out that the traditional calculation approach of DLWL was incapable to reveal the seasonal features of dry periods, because the occurrence of drought was caused not only by the lower water inflow of reservoir, but also large water demand and insufficient previous water storage of reservoir. Cao (2015) proposed the limited water-supply rules through the dynamic control of DLWL as well as the reservoir simulation and optimization regulation model during drought warning periods. Peng et al. (2016) established an optimal control model of DLWL for multi-year regulation reservoir aiming to the minimization of total water shortage losses during drought years, and finally developed the controlling strategies of DLWL corresponding to drought issues of different grades. Wu et al. (2019) discussed the variation of transferable water resources basing on the synchronous-asynchronous encounter probability, and eventually derived the control schemes of DLWL combining the features of reservoir water inflow and water resources demand. Li et al. (2019) predicted the evolution trend of reservoir water supply through the System Dynamics model, and then determined the control scheme of DLWL and also discussed its inter-annual variation characteristics. Chang et al. (2019) proposed a hedging policy triggered by seasonal DLWL schemes for reservoir operations during drought periods, and also constructed a modeling framework to determine the seasonal DLWL schemes under different drought conditions. Based on the above, it can be concluded that there are two shortages related to the current

determination approach of DLWL needing to be improved, (1) the current DLWL is constant throughout the whole reservoir water-supply period and ignores the variation between water supply and demand sides. (2) the current verification for the rationality of DLWL schemes is unable to reveal the impacts for the implement of DLWL controlling schemes during the annual and inter-annual processes (Kuo et al. 2003; Moradi-Jalal et al. 2004; Xing et al. 2015).

To sum up, it can be indicated that the application of DLWL as the controlling water level for reservoir regulation process during drought period has drawn extensive attention currently, and the main motivation of this manuscript is to try to further divide the static DLWL scheme into dynamic drought warning water level (DWWL) and drought depletion water level (DDWL). In other words, the primary innovation of this study can be concluded as follows, (1) the concepts of DLWL, including DWWL and DDWL, were proposed, which were determined through the reservoir comprehensive optimal regulation model based on Accelerating Genetic Algorithm (AGA) method. And (2) the reliability of the optimized schemes of DLWL was comparatively verified through the index of crop yield loss risk due to drought events under two scenarios of consecutive drought and typical yearly drought patterns. Moreover, the structure of the manuscript proceeds as follows, in Sect. 1, the reservoir drought warning periods were determined. In Sect. 2, the optimized dynamic controlling schemes of DWWL and DDWL of different drought warning periods were calculated. And in Sect. 3, the reasonability of the optimal dynamic controlling schemes of DWWL and DDWL were testified. And the calculation results indicated that the application of dynamic optimal controlling schemes of DWWL and DDWL proposed in this manuscript could be able to significantly improving the comprehensive utilization benefit of water resources system in reservoir irrigation areas, and will also provide technical decision-making basis for the development of regional water resources management strategies.

2 Study Area and Research Framework

2.1 Study Area and Data Sources

Meishan Reservoir (MSR), with a total watershed area of 1970 km^2, is located in the upper of Shihe River, the main tributary of Huaihe River in Jinzhai County, Anhui Province in China (as indicated in Fig. 1). MSR, with a total and dead reservoir capacity of 226 and 35.8 billion m^3 respectively, and designed irrigation area of 2.55 thousand km^2, is a typical and large multi-year regulation reservoir with tremendous operation benefit of flood control, irrigation and power generation. It is investigated that the actual operation of MSR was abnormal with the observed water level lower than dead water level (DWL) in most of the historical years because of unreasonable operation during the drought periods, and the monthly average water level of MSR in more than 11 years during historical years from 1965 to 2015, were lower than DWL, and even lower than 95.27 m in severe drought years, the minimum water level of irrigation water intaking location, which will undoubtedly reduce water resources utilization efficiency and cause annual and inter-annual water resources supply and demand contradiction.

MSR is the main source of Shihe Irrigation Area (SIA), and the water is delivered to the Shihe main canal through the Hongshizui Hub, Jidong Main Canal, Fengdong Main Canal and Fengxi Main Canal. The total designed irrigation area of SIA is 2550 km^2, including
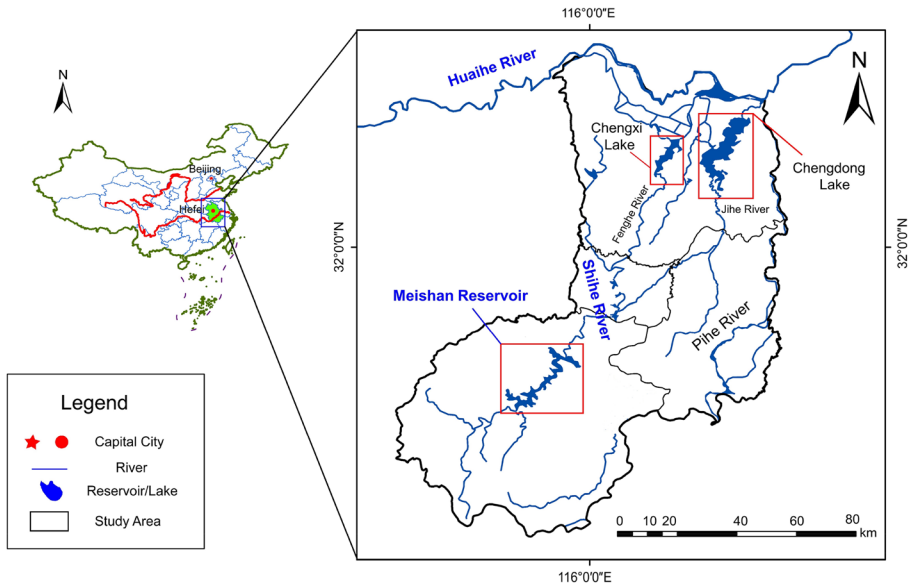
Fig. 1 Location of Meishan Reservoir (MSR) and Shihe Irrigation Area (SIA)

1898 km^2 in Anhui Province and 652 km^2 in Henan Province. In addition, too many small reservoirs and ponds within SIA also play important role for regulating water storage and increasing irrigating water resources. It has been investigated in 2012 that, there are approximately 600 small reservoirs in SIA, with total water capacity and valid regulating water storage nearly 274 and 180 million m^3 respectively, and about 50,591 ponds in SIA with total water capacity and valid regulating water storage nearly 259 and 190 million m^3 separately. In a word, the combined regulation of reservoirs and ponds through the implement of dynamic controlling schemes of DLWL of MSR during drought periods or years is crucial for ensuring the sustainable development of socio-economy and ecological environment of irrigation area.

Besides, all of the actual operation data series and regulation rules of reservoirs and ponds, agricultural drought loss data and characteristic parameters of reservoirs during the historical years utilized in this manuscript are provided by Pishihang Irrigation District Management Bureau in Anhui Province and Meishan Reservoir Management Office, or collected from Water Resources Bulletin of Anhui Province, Statistical Yearbook of Anhui Province, 2009–2018, and National EPS Statistic Data Platform (https://www.epsnet.com.cn/index.html#/Index).

2.2 Overview of Methodological Framework

On the whole, based on the availability for the historical observed regulation data series of water resources system in typical reservoir and irrigation area, the structure for the contents of this manuscript can be built as follows, in Sect. 1, the reservoir drought early warning

periods during flood and non-flood seasons were determined basing on Hausdorff Dimension Fractal (HDF) method in combination with the variation characteristic analysis of reservoir water inflow processes and water utilization among different sectors. Moreover, by analyzing the historical water inflow series of reservoir, the designed water inflow process of reservoir for different hydrological years was determined. In Sect. 2, the optimized dynamic controlling schemes of DLWL of MSR were obtained through the procedures of water supply and demand balance analysis of reservoir, determination of initial controlling schemes of DLWL, and integrated optimization model solving of DLWL through AGA approach. And in Sect. 3, the rationality for the proposed optimal controlling scheme of DLWL were further testified through its application in drought risk analysis of water resources system of reservoir and irrigation area, and eventually, agricultural crop reduction loss risk of middle rice due to drought events was ultimately obtained. The interrelationship of the above different modules of this manuscript was illustrated in Fig. 2.

3 Methodologies

3.1 Overview of DLWL of MSR

Drought limited water level (DLWL) is defined as the characteristic level to implement drought-resistance strategies when the water level of lake, river and reservoir is lower continuously and will affect water resources supply security of residential domestic, agricultural, industrial and environmental sectors. To make the controlling schemes of DLWL more operational, the DLWL was further divided into two characteristics water levels, drought warning water level (DWWL) and drought depleted water level (DDWL) according to the priorities and limited water-supply characteristics among different water utilization sectors in this manuscript, the DWWL and DDWL of MSR were determined according to the standard approach released by Ministry of Water Resources of PRC in 2014, as follows:

1. DWWL, if reservoir water level is higher than DWWL, water resources demand among all sectors will be satisfied. And if reservoir water level varies within DWWL and DDWL, water resources demand of the sectors with lower priorities will be restricted, i.e., nearly 30% of the agricultural irrigation water will be reduced in SIA, urban and ecological water resources demand will be fully satisfied, which can be denoted as "Level 1 water supply restricted scheme" (Level 1 Scheme for short).
2. DDWL, if reservoir water level varies below DDWL, water resources demand of all sectors will be restricted for a certain extent, i.e., approximately 50% of the agricultural irrigation water as well as 20% of urban and ecological water supply will be reduced respectively in SIA, which can be denoted as "Level 2 water supply restricted scheme" (Level 2 Scheme for short).

The relative relationship of starting water level of reservoir regulation, DWWL, DDWL, normal water level (NWL) and flood limited water level (FLWL) of reservoir was indicated in Fig. 3

To sum up, the calculation methods of DWWL and the DDWL can be expressed by Eqs. (1) and (2), as follows
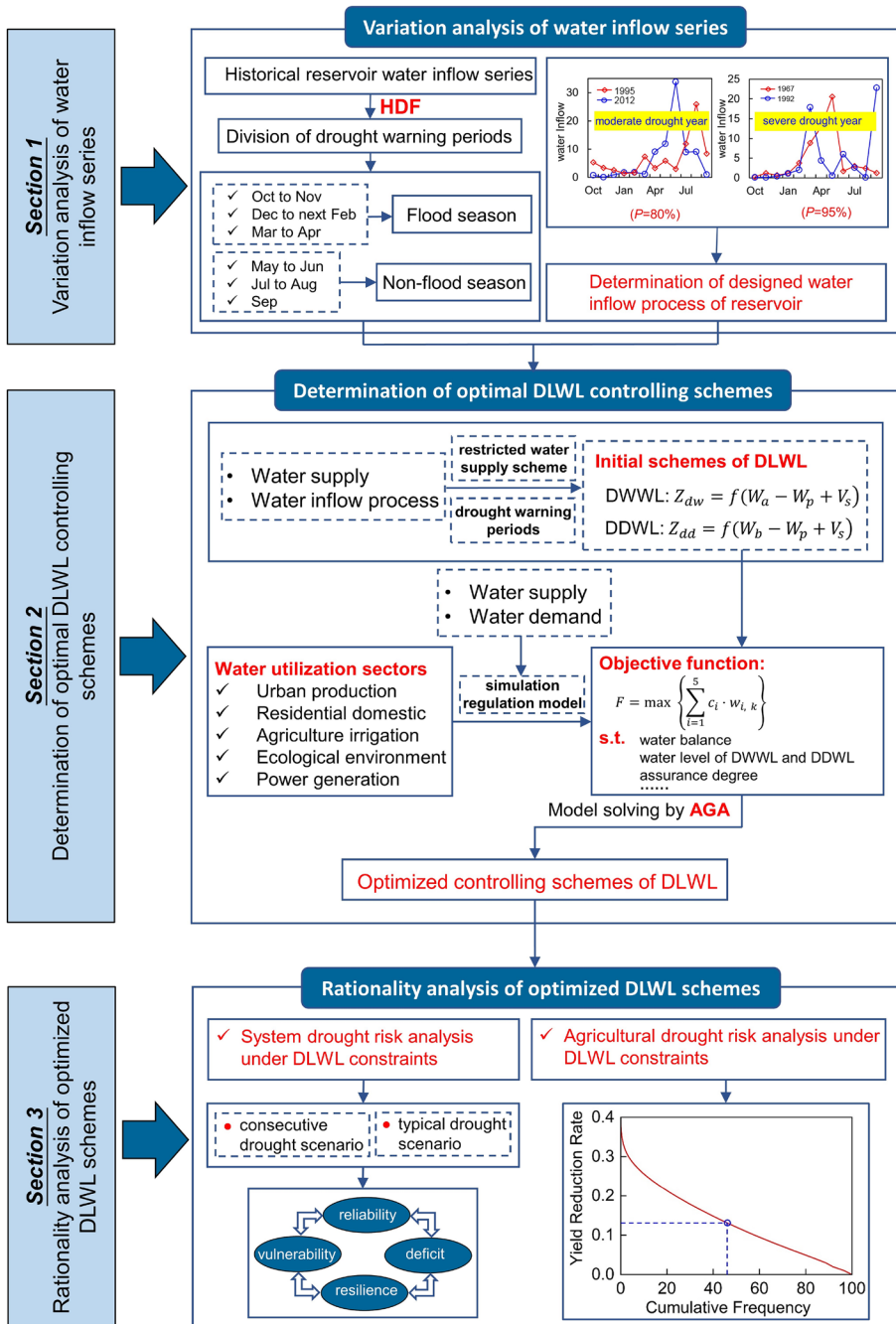
Fig. 2 Framework for the optimization of DLWL schemes and its rationality analysis
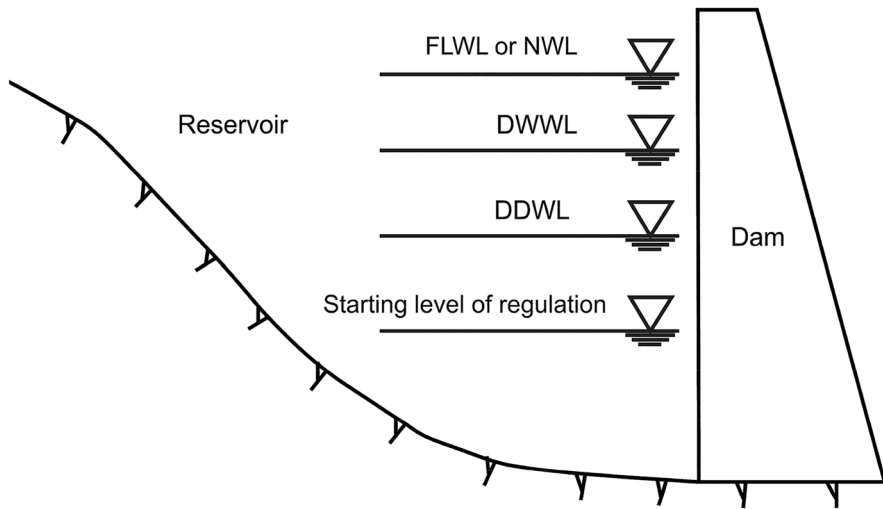
Fig. 3 Relationship of reservoir characteristic water levels

$$Z_{dw} = f(W_a - W_p + V_s) \tag{1}$$

$$Z_{dd} = f(W_b - W_p + V_s) \tag{2}$$

where, Z_{dw} and Z_{dd} represents the DWWL and the DDWL of MSR respectively; $f()$ is reservoir water level and capacity relationship function; W_a is the normal water supply for all sectors during the drought warning periods; W_b is the water supply of all sectors when starting the Level 1 Scheme during the drought warning periods; W_p represents reservoir water inflow with inflow frequency equaling to P during the drought warning periods, and $P = 80\%$ for DWWL in Eq. (1) and $P = 95\%$ for DDWL in Eq. (2) in this manuscript, and V_s is the starting water level of reservoir regulation operation, as indicated in Fig. 3, which equals to the dead water capacity plus reserved water storage of key drought warning periods in this manuscript.

3.2 Simulation Regulation under DLWL Constraints of MSR

The dynamic controlling scheme of DLWL including DWWL and DDWL is essentially a new additional constraints of reservoir regulation operation especially during drought periods or years. Therefore, to further verify the rationality of controlling schemes of DLWL in comparison with the actual operation processes of reservoir and irrigation area system, it is essential to develop the simulation regulation model of reservoir and irrigation area system basing on the water balance principle, and details about the simulation and regulation model of SIA can be referred from Zhang et al. 2014.

3.3 Optimal Determination of DLWL Schemes of MSR

3.3.1 Water Resources Supply and Demand Balance Analysis of MSR

1. Characteristic Analysis of Water Inflow Series of MSR

As discussed above, it is required to considering the reservoir water inflow features during the early warning period and water resources demand characteristics among different sectors as well to further divide the early warning period of DLWL schemes, in addition, it should be noted that the division result of warning period of DLWL schemes is suitable not only for the non-flood or drought seasons, but also for the entire or most of the flood season of reservoir. MSR of SIA is located in the Jianghuai hilly area, and is seriously affected by the western Pacific subtropical high, where the summer drought events, characterized by strong solar radiation, high temperature, low humidity, and high evapotranspiration, is frequently occurred. It is investigated that the summer drought or spring–summer consecutive drought events occur every 3 to 4 years in the area of southern Huaihe River and northern Yangtze river (Xiao et al. 2017; Zhang et al. 2015; Yan et al. 2014). Therefore, drought event will also possibly occur in the flood season in SIA, and the development of controlling scheme of DLWL during flood season of MSR is also necessary.

1. early warning period division of DLWL schemes, the flood reason of MSR is from May 1st to September 30th. Meanwhile, the warning periods of hydrological drought of MSR was eventually determined as Oct to Nov, Dec to next Feb, and Mar to Apr in the non-flood season, and May to Jun, Jul to Aug, and Sep in the flood season according to the utilization of Hausdorff Dimension Fractal (HDF) method (Hou et al. 1999; Hu 2015).
2. determination of designed water inflow process of different frequencies, basing on the hydro-meteorological characteristics of MSR in SIA, the water inflow frequency of DWWL scheme corresponding to moderate drought years of MSR is determined as 80%, and the water inflow frequency of DDWL scheme corresponding to severe drought years of MSR is determined as 95%. Therefore, the designed water inflow process of reservoir with the inflow frequency equaling to 80% and 95% corresponding to moderate and severe drought year respectively, can be obtained through frequency analysis basing on the historical water inflow series from 1965 to 2015 of MSR, as shown in Fig. 4.
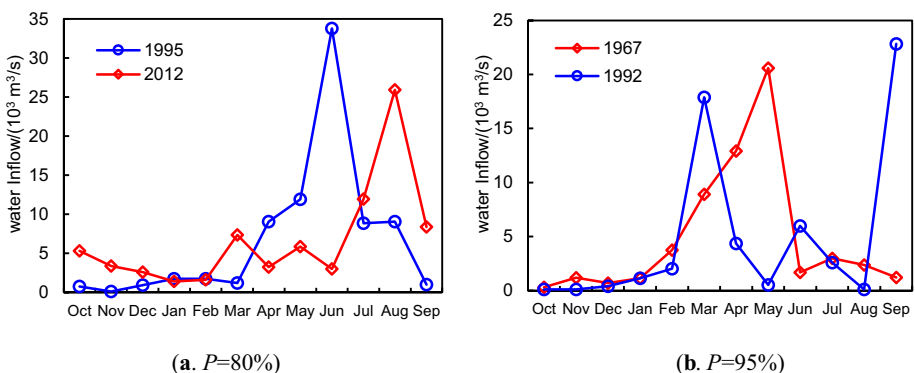

(**a**. *P*=80%) (**b**. *P*=95%)

Fig. 4 Designed water inflow process of moderate and severe drought year of MSR

2. Variation Analysis of Water Utilization Series of MSR

The water resources utilization sectors of MSR mainly includes the agricultural irrigation of SIA, urban production and domestic water utilization and ecological environment water usage of Shihe River, and water resources diversion of hydroelectric power generation is subjected to the other water demand sectors. According to the designed results of Pishihang Irrigation Area in 2010, the designed irrigation guarantee rate of SIA is 80%, and except for the interior water resources supply of SIA, the additional water resources supply by MSR is 1211 million m³, which is allocated in monthly scales basing on the average monthly allocation percentages of agricultural irrigation water processes of SIA. In addition, the urban production and domestic water resources utilization are determined through water consumption per ten thousand yuan of GDP and per capita domestic water quota, and water resources utilization of ecological environment for the lower reaches of Shihe River is 5.47m³/s, and eventually, the monthly water resources utilization process of MSR with the designed irrigation guarantee rate of SIA equaling to 80% is obtained, as shown in Table 1.

It can be revealed from Table 1 that, (1) the total water resources utilization is highest in June, accounting for about 26% to the total, in which, the proportion of agricultural irrigation water consumption from April to October is highest, with an average percentage of 84%. (2) the urban production and ecological water consumption present fluctuating trend throughout the year, which accounted for 3.9% and 12% respectively to the total.

3.3.2 Determination of Initial DLWL Schemes

According to the definition and calculation approaches of DWWL and DDWL as indicated by Eqs. (1) and (2) and combining the water resources demand characteristics during key drought warning periods, the reserved water capacity of MSR at the beginning of flood and non-flood periods were assumed in this manuscript, *i.e.*, the reserved water capacity was determined by 120 thousand m³ per km², and the total agricultural irrigation area for both SIA and Henan Irrigation area is 2520 km², and thus the corresponding irrigation water demand is about 300 million m³, and the starting water level of regulation operation of MSR for both flood and non-flood season are 658 million m³.

Therefore, the typical hydrological years with inflow frequencies equaling to 80% and 95% respectively were selected, and the corresponding outer enveloping lines were obtained through Eqs. (1) and (2) to represent the upper and lower limit of DWWL and

Table 1 Monthly allocation result of water resources utilization process of MSR

Sectors	Jan~Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov~Dec	Total
S_1	0	12,109	30,273	36,328	18,164	14,531	6055	3633	0	121,093
S_2	479	464	479	464	479	479	464	479	479	5640
S_3	1465	1418	1465	1418	1465	1465	1418	1465	1418	17,250
Total	1944	13,991	32,217	38,210	20,108	16,475	7937	5577	1897	143,983

S_1, S_2 and S_3 denote the sectors of agricultural irrigation, urban production and ecological environment respectively
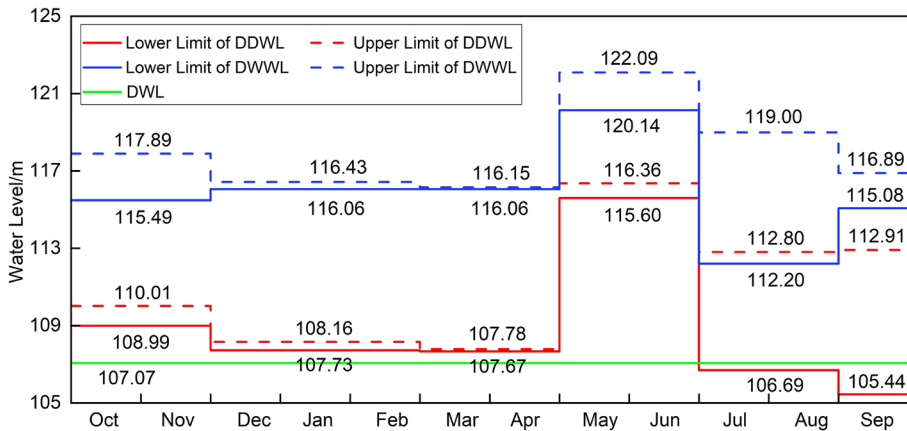
Fig. 5 Monthly variation for the initial controlling schemes of DLWL in MSR

DDWL variation, as indicated in Fig. 5, which was denoted as the initial controlling schemes of DLWL of MSR.

3.3.3 Determination of Optimized DLWL Schemes

The monthly variation of the initial controlling schemes of DLWL has shortages of large variation intervals, drastic variation during neighboring periods and even intersection in Jul, Aug and Sep, which is not favorable for actual operation of reservoir and needs to be adjusted and optimized to make it more operational. Therefore, the optimization model for the initial controlling schemes of DLWL of MSR was developed, as follows.

1. **Establishment Optimization Objective Function of DLWL Schemes**

Based on the simulation and regulation model of MSR as indicated in chapter 3.2, the optimization objective function aiming to the maximum comprehensive economic benefit of MSR (including urban production and domestic water utilization benefit, irrigation water utilization benefit, ecological environment water utilization benefit and the hydropower generation benefit) was proposed, as follows,

$$F = \max \left\{ \sum_{i=1}^{5} c_i \cdot w_{i,k} \right\} (k = 1, 2, ..., K) \tag{3}$$

where, c_i represents the price of reservoir water supply or power generation, $i = 1 \sim 5$, denoting the price of urban production, residential domestic, agricultural irrigation, ecological environment and power generation sectors respectively. $w_{i,k}$ indicates the amount of the reservoir water supply to ith water utilization sector ($i = 1 \sim 4$) or power generation to ith sector ($i = 5$) under the kth DLWL controlling scheme k. K is the number of the DLWL controlling schemes during different drought warning periods.

In combination with the practical historical operation processes of SIA and management requirements of MSR, the optimization variables of the above objective function were divided into two parts in terms of non-flood and flood seasons, *i.e.*, including five

optimization variables totally for both DWWL and DDWL schemes. And according to the variation of initial DLWL schemes, based on years of experience in the reservoir operation and scheduling, the variation intervals of the optimization variables were determined as follows, [114 m, 118 m] from Oct to next Feb, [115 m, 120 m] from Mar to Apr and from Jul to Sep, [112 m, 122 m] from May to Jun for DWWL schemes; [107.07 m, 113 m] from Jul to next Apr and [107.07 m, 116 m] from May to Jun for DDWL schemes. Additionally, the variation for the five optimization variables needs to satisfy the requirements including, water balance constraints of reservoir and irrigation area, characteristic water level or capacity limitations of reservoirs during different periods, water supply guarantee rate of different sectors, non-negative constraints etc.

2. **Derivation of Optimal DLWL Schemes**

The above optimization model of dynamic controlling schemes of DWWL, as described in Eq. (3), is a multi-dimensional and nonlinear complex system optimization problem, which was solved through the application of the AGA in this manuscript. The AGA approach is featured with simple parameter estimation, high computation efficiency and strong versatility, and has been widely utilized in the fields of nonlinear, non-convex and combinatorial optimization problems, and the detailed calculation procedures of the AGA method can be referred from Jin and Ding (2002). Therefore, the final optimized dynamic controlling schemes of DLWL of MSR can be obtained through model solution, which was described in Fig. 6.

4 Results Discussion of Optimized Schemes of DLWL

4.1 Drought Risk Analysis of Reservoir and Irrigation Area System Under DLWL Constraints

In this section, considering the reservoir regulation operation risk caused by the application of DLWL controlling schemes, firstly, four types of regulation scheme of MSR were
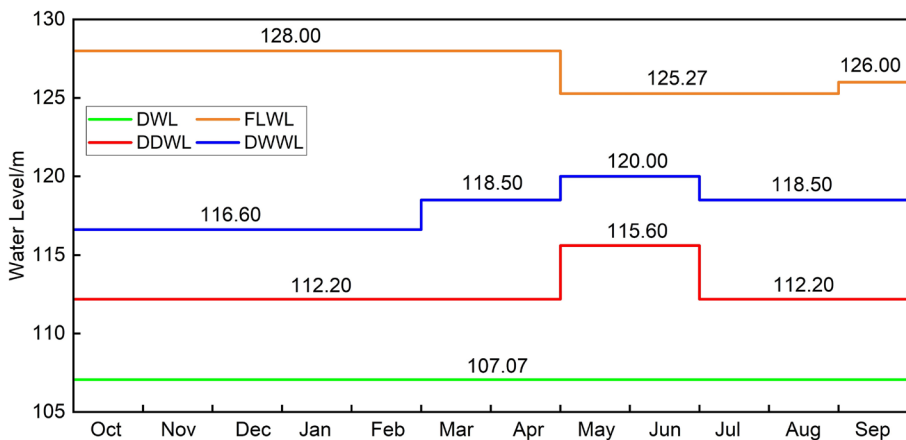

Fig. 6 Optimized dynamic controlling schemes of DLWL of MSR

developed to comparatively testify the rationality of the optimized dynamic controlling schemes of DLWL of MSR, which can be denoted as follows, (1) Scheme 1#, adopting current regulation rules of MSR without the constraints of DLWL. (2) Scheme 2#, the reservoir inflow process is regulated under general DLWL constraint, and restricted water-supply measures will be activated accordingly when reservoir water level reaches the limit of DWWL or DDWL without considering specific hydrological conditions. (3) Scheme 3#, the water inflow process of reservoir is regulated under specific DLWL constraint, *i.e.*, the controlling scheme of DWWL will be activated only if encountering the water inflow process with specific frequency P (supposing $P \geq 80\%$ in this manuscript). And (4) Scheme 4#, adopting the optimized dynamic controlling schemes of DLWL proposed in this manuscript. Secondly, the typical single drought year including 1978, 1981 and 1992, and typical consecutive drought processes including 1994~1995, 2011~2012, 1965~1967 and 1999~2001 were selected to further testify the rationality of the optimized DLWL controlling schemes in terms of two scenarios of single drought year event and consecutive drought process. And eventually, four typical rationality indicators including reliability degree, resilience degree, vulnerability degree and deficit degree were introduced to evaluate drought risk of reservoir and irrigation area system under different controlling schemes of DLWL (Hashimoto et al. 1982), as follows.

1. **Reliability degree**

The reliability degree represents the probability of calculation periods satisfying water supply demands during the whole regulation period, as follows

$$R_{ws} = 1 - \frac{1}{N} \cdot \sum_{i=1}^{N} f_{wsi} \tag{4}$$

$$f_{wsi} = \begin{cases} 1, \ Q_i \leq Q_{ui} \\ 0, \ Q_i > Q_{ui} \end{cases} \tag{5}$$

where, R_{ws} denotes the reliability degree, f_{wsi} is water supply failure function of reservoir, Q_i and Q_{ui} represent the outflow of reservoir and total water demand of water utilization sectors of the ith calculation period, m^3/s.

2. **Resilience degree**

The resilience degree represents the ratio of the total independent failure periods accounting for the total damaged periods, and can be indicated as follows

$$\gamma_{ws} = \frac{\sum\limits_{i=1}^{N-1} \left(Q_i \leq Q_{ui} \right) \cdot \left(Q_{i+1} > Q_{ui} \right)}{\sum\limits_{i=1}^{N} f_{wsi}} \tag{6}$$

where, γ_{ws} is the resilience degree of reservoir regulation operation.

3. **Vulnerability degree**

The vulnerability degree is a measuring index of average severity for water supply failure events, which can be represented as the ratio of the sum of maximum damage in independent failure periods to the total number of independent failure events, as follows

$$v_{ws} = \frac{\sum\limits_{i=1}^{N} \delta_{wsi}}{\sum\limits_{i=1}^{N} f_{wsi}} \tag{7}$$

$$\delta_{wsi} = \begin{cases} Q_{ui} - Q_i, & Q_i < Q_{ui} \\ 0, & Q_i \geq Q_{ui} \end{cases} \tag{8}$$

where, v_{ws} is vulnerability degree, and δ_{wsi} is water supply failure function.

4. **Deficit degree**

The deficit degree is a measuring indicator representing the overall damage severity during the reservoir regulation period, and can be denoted as the ratio of the total deficit to the total standard water demand during the reservoir regulation period, as follows

$$L_{ws} = \frac{\sum\limits_{i=1}^{N} \delta_{wsi}}{\sum\limits_{i=1}^{N} Q_{ui}} \tag{9}$$

where, L_{ws} is deficit degree of reservoir regulation period.

Therefore, the variation of drought risk of reservoir and irrigation area system under different DLWL constraint schemes can be represented through four statistical indicators in terms of two scenarios including typical year drought events and consecutive drought processes, as follows.

1. **Consecutive drought events scenario**

It can be concluded from Table 2 that, ① comparing with other three schemes, the reliability and resilience degrees of scheme 4#, with the average values of 0.7607 and 0.7875 respectively, are the highest for the entire four typical consecutive drought year scenarios, which indicated that the adoption of optimized dynamic controlling schemes of DLWL of MSR can effectively improve the satisfaction of water-supply demand and recovery capacity of drought disaster during reservoir regulation periods. ② the vulnerability and deficit degrees of scheme 4#, with the average values of 1170 and 0.0898 separately, are the lowest for the four typical consecutive drought year scenarios, which revealed that the application of optimized dynamic controlling schemes of DLWL can reduce the average severity and damage conditions of drought disasters because of the consideration of water inflow characteristics and comprehensive economic benefits of reservoir. ③ on the whole, the application of optimized dynamic controlling schemes of DLWL (scheme 4#) has better feasibility for practical regulation operation of reservoir, will play significant role for the reduction of drought disaster risk under consecutive drought year scenarios.

Table 2 Statistical results of rationality indicators under typical and consecutive drought scenarios

| Scenarios	Year	Name	Reliability Degree	Resilience Degree	Vulnerability Degree	Deficit Degree
consecutive drought events	1965–1967	Scheme 1#	0.597	0.632	2647.31	0.175
		Scheme 2#	0.583	0.619	2846.54	0.184
		Scheme 3#	0.604	0.637	2601.65	0.167
		Scheme 4#	0.611	0.642	2568.14	0.162
	1994–1995	Scheme 1#	0.821	0.846	478.15	0.072
		Scheme 2#	0.800	0.842	523.23	0.062
		Scheme 3#	0.835	0.857	378.15	0.061
		Scheme 4#	0.842	0.861	304.84	0.060
	1999–2001	Scheme 1#	0.643	0.672	1722.36	0.091
		Scheme 2#	0.629	0.663	1900.25	0.101
		Scheme 3#	0.649	0.678	1647.87	0.872
		Scheme 4#	0.657	0.682	1609.45	0.083
	2011–2012	Scheme 1#	0.912	0.962	203.36	0.056
		Scheme 2#	0.891	0.964	201.87	0.055
		Scheme 3#	0.933	0.964	200.93	0.054
		Scheme 4#	0.933	0.965	200.78	0.054
typical year drought events	1978	Scheme 1#	0.554	0.584	2563.26	0.215
		Scheme 2#	0.554	0.574	2688.18	0.225
		Scheme 3#	0.576	0.601	2438.46	0.204
		Scheme 4#	0.595	0.611	2368.14	0.194
	1992	Scheme 1#	0.744	0.788	523.64	0.047
		Scheme 2#	0.744	0.789	635.18	0.049
		Scheme 3#	0.762	0.791	493.15	0.045
		Scheme 4#	0.786	0.791	477.25	0.044
	1981	Scheme 1#	0.646	0.642	1463.25	0.143
		Scheme 2#	0.688	0.637	1508.36	0.152
		Scheme 3#	0.713	0.645	1398.78	0.139
		Scheme 4#	0.730	0.647	1331.56	0.131

2. **Typical drought year events scenario**

It can be revealed from Table 2 that, ① as compared with other three schemes 1#, 2# and 3#, the vulnerability and deficit degrees of scheme 4# are all reduced, and the reliability and the resilience degrees of scheme 4# are all increased to a large extent for both the severe drought years of 1978 and 1992 and ordinary drought year of 1981. More specifically, as for typical severe drought years of 1978 and 1992 and ordinary drought year of 1981, the maximum reducing extent of vulnerability degree of scheme 4#, the adoption of optimized dynamic controlling schemes of DLWL, are approaching to 12%, 12% and 25% respectively, and the maximum increasing extent of reliability degree of scheme 4# are

approximately 7%, 12% and 6% separately. ② it is apparently that the rationality indicators of scheme 4# are all improved, which indicated that the application of optimized dynamic controlling schemes of DLWL is capable of reducing the average severity and occurring risk of drought event and improving the reliable conditions of reservoir regulation strategies especially for severe drought year scenarios. ③ overall, the optimized dynamic controlling schemes of DLWL proposed in this manuscript, as a result of the consideration of water inflow and comprehensive economic benefits characteristics of reservoir, is more reasonable and effective to guide the practical regulation operation of reservoir.

4.2 Agriculture Drought Risk Analysis Based on Optimized DLWL Schemes

In order to reveal the differences of crop yield loss risk due to drought events under different dynamic controlling schemes of DLWL, the Crop Yield Loss Risk Assessment Model (CYLRA) based on the cross-validation and information diffusion approaches was applied in this manuscript to quantitatively evaluate the yield loss risk of medium rice due to the drought events in SIA (Byeong and Marron 1990; Zhang 2016). The CYLRA model applies the cross-validation method to improve the accuracy of window width calculation, and the normal diffusion function to construct crop yield loss sample sets basing on the observed drought disaster statistics, which could overcome the shortages of evaluation uncertainties due to insufficient samples, and is suitable for drought disaster risk evaluation analysis with unknown probability distribution patterns and inadequate samples (Byeong and Marron 1990). Therefore, the variation of crop yield loss rate of medium rice due to drought events under different dynamic controlling schemes of DLWL in SIA can be obtained as shown in Fig. 7.

Fig. 7 Cumulative frequency distribution of yield reduction rate of medium rice
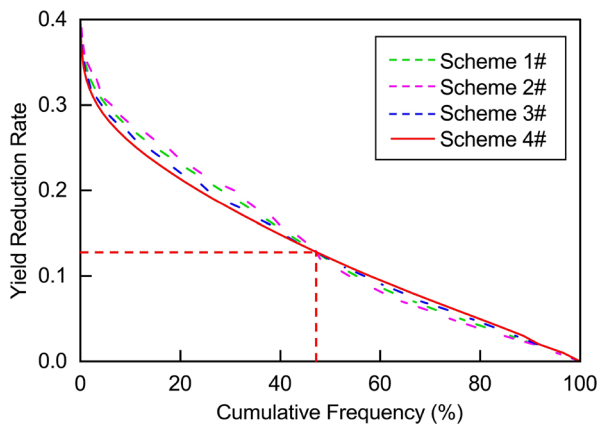
It can be concluded from Fig. 7 that, (1) the intersection of cumulative frequency distribution of yield reduction rate of medium rice under different dynamic controlling schemes of DLWL is approximately 48%, that is to say, the yield reduction rate of medium rice corresponding to the application of optimized controlling schemes DLWL (Scheme 4#) is lowest comparing with other schemes when the cumulative frequency varies lower than 48%, and the varying trend will be opposite if the cumulative frequency exceeding 48%. (2) it is evidently that the lower crop yield reduction rate of medium rice will occur with higher probability for scheme 4#, while higher crop yield reduction rate of medium rice varies with lower occurring probability, which is exactly the motivation of this study and also the primary benefit for the optimization of dynamic controlling schemes of DLWL of MSR.

Furthermore, the statistical results of excepted value of crop yield reduction rate of medium rice under different controlling schemes of DLWL when the cumulative frequency equals to 5%, 10%, 15%, 20%, 25% and 30% respectively were also obtained, as indicated in Fig. 8.

It can be indicated from Fig. 8 that, (1) the crop yield reduction risk corresponding to different cumulative frequencies of scheme 2#, because of the ignorance of variation characteristics of reservoir water inflow and comprehensive economic benefit, is the highest comparing with other schemes. (2) according to the expected values of crop yield reduction corresponding to different cumulative frequencies, the four dynamic controlling schemes of DLWL could be sorted as, scheme 2# > scheme 1# > scheme 3 # > scheme 4#, it is obvious that the optimized dynamic controlling scheme of DLWL (scheme 4#) has lowest crop yield reduction risk, and the maximum reducing extent
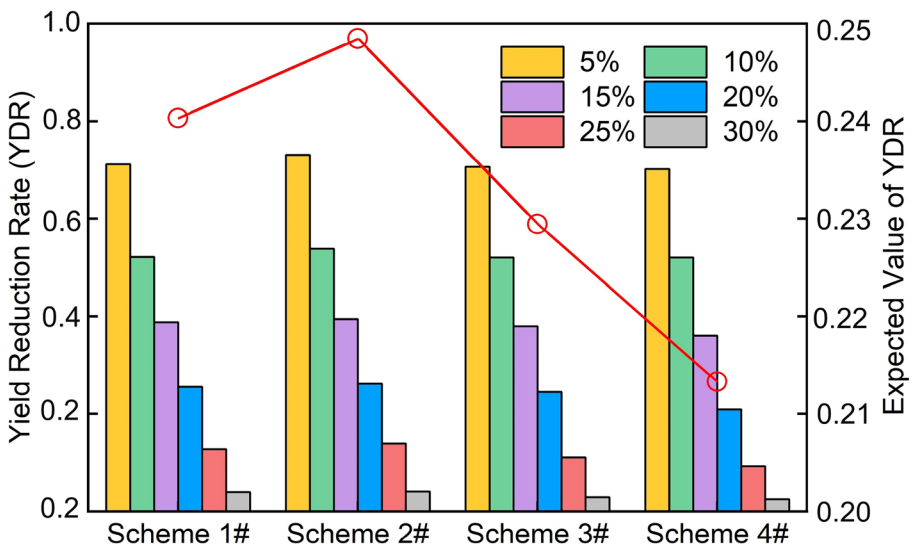

Fig. 8 Variation of crop yield reduction rate of medium rice of different cumulative frequencies

of scheme 4# nearly approaches to 3.52%. (3) the optimization of dynamic controlling scheme of DLWL (scheme 4#) will reduce crop yield reduction risk of irrigation area significantly, which is more favorable and acceptable to the decision-makers (Appendix Table 3).

5 Conclusion

In order to reasonably guide reservoir regulation operation and reduce crop reduction loss risk due to drought disasters in irrigation area, the optimization model of DLWL and optimal dynamic controlling schemes of DWWL and DDWL of reservoir were proposed in this manuscript through water supply and demand balance analysis and simulation regulation calculation of water resources system in typical irrigation area, and the primary conclusions can be summarized as follows,

1. Basing on the hydrological staging of reservoir, the drought early warning periods of MSR was determined in combination with the variation features of reservoir water inflow and water utilization among different sectors, *i.e*., from March to April, December to next February, and October to November for non-flood season, and from May to Jun, and Jul to Aug, and Sep for flood season, which could provide fundamental support for the optimization of dynamic controlling schemes of DLWL.
2. Combining with practical regulation rules of MSR in SIA, the optimization model of controlling schemes of DLWL aiming at the maximum comprehensive economic benefit of irrigation area (including urban production and domestic water utilization benefit, irrigation water utilization benefit, ecological environment water utilization benefit and the hydropower generation benefit) was proposed, and the optimal schemes of DWWL and DDWL of MSR was ultimately proposed through the optimization model solving by AGA method.
3. Basing on the rationality verification for the developed optimized dynamic controlling schemes of DLWL of MSR through its application in the drought risk analysis of water resources system in reservoir and irrigation areas under typical consecutive and annual drought scenarios, the proposed optimal controlling schemes of DLWL was eventually applied to evaluate the agricultural crop yield reduction loss risk of middle rice due to drought events.

All in all, comparing with traditional constant DLWL of reservoir, the optimized dynamic controlling schemes of DWWL and DDWL of MSR proposed in this manuscript, closing considering the variation of reservoir water inflow and economic benefits, can be recommended for incorporating as a controlling characteristic water level of reservoir regulation especially during drought seasons, which is beneficial to improve water resources utilization efficiency of irrigation area and ensure optimal operation of regional water resources system.

Appendix

Table 3 Description for the abbreviations in this manuscript

Abbreviation	Description
MSR	Meishan Reservoir
SIA	Shihe Irrigation Area
DLWL	Drought Limited Water Level of Reservoir
DWWL	Drought Warning Water Level of Reservoir
DDWL	Drought Depleted Water Level of Reservoir
FLWL	Flood Limited Water Level of Reservoir
DWL	Dead Water Level of Reservoir
Scheme 1#	Without Constraint Scheme of DLWL
Scheme 2#	General Constraint Scheme of DLWL
Scheme 3#	Specific Constraint of DLWL
Scheme 4#	Optimized Controlling Scheme of DLWL

Authors Contributions Libing Zhang: conceptualization, methodology, validation, formal analysis, writing-original draft, reparation, writing-review and editing; Chuanyu Kang: conceptualization, writing-original draft, reparation; Chengguo Wu: methodology, writing-original draft, preparation; Haiguan Yu: data curation; Yuliang Zhou and Juliang Jin: validation, funding acquisition; Ting Zhou: investigation, data curation, funding acquisition.

Availability of Data and Materials The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical Approval Not applicable.

Consent to Participate All the authors agree with the participation of this article.

Consent to Publish All the authors agree with the publication of this article.

Competing Interests The authors declare that there is no conflict of interest regarding the publication of this article.

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