Water Research 165 (2019) 114984

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

# Is water shortage risk decreased at the expense of deteriorating water quality in a large water supply reservoir?

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ARTICLE INFO

*Article history:*
Received 14 May 2019
Received in revised form
2 August 2019
Accepted 12 August 2019
Available online 13 August 2019

*Keywords:*
Reservoir eutrophication
Water quality modeling
Reservoir operation policy
Biogeochemical process
Water supply security

ABSTRACT

Reservoir operations affect both the quantity and quality of stored and discharged water. Hedging rules (HRs) are commonly used in water supply reservoir operations to ration water delivery and decrease water shortage risk. However, the increased carryover storage with hedging may aggravate reservoir eutrophication through complex effects on hydrodynamic, temperature, light, nutrient, and sediment conditions. The influencing mechanisms are unclear and require further investigation. This study applies a mathematical modeling approach to comparing the effects of standard operation policy (SOP) and HR, discussing the processes and driving factors, and exploring the relationship between water shortage and water quality indicators. We simulate reservoir operation by SOP and optimize HR to generate water supply schedules, and run a quasi-3D water quality model to simulate reservoir hydrodynamic conditions, nutrient cycles, water-sediment exchanges, and algal dynamics under various water supply schedules. The Danjiangkou Reservoir, the water source for China's South–North Water Transfer Project, is used as a case study. The HR for this reservoir decreases its water shortage risk from 22% under SOP to 8%. Modeling results find that the HR increases sediment phosphorus (P) release by 285.3 tons (5.7%) annually as a consequence of extended reservoir submerged area and aggravated hypolimnetic hypoxia. Increased P release can support algal growth, but this effect is set off by the enhancement of light limiting effect caused by higher storages under HR, consequently decreasing the annual mean chlorophyll *a* concentration in the deep reservoir by 18%. The HR also improves the horizontal mixing of water by changing the hydraulic retention time and flow velocity field, which mitigates algal bloom risks in the surrounding shallow-water zones but deteriorates water quality of the release to downstream. The water quality analysis offers implications for reservoir managers to coordinate their efforts in mitigating risks of water shortage and water quality degradation.



## 1. Introduction

Reservoirs have been constructed throughout the world by impounding dams, and the global cumulative storage capacity exceeds one-sixth of total annual river flow into the oceans (Lehner et al., 2011). Reservoirs provide important human services, but also cause considerable water quality problems both upstream and downstream of the dams (e.g., eutrophication), resulting in great economic loss and aquatic ecosystem degradation (McCrackin et al., 2017; Paerl and Paul, 2012; Tang et al., 2019). Reservoir operation strategies determine water storage and release decisions and then the trophic state of reservoirs through affecting biogeochemical processes associated with nutrient cycling and algal dynamics (Yang et al., 2013). Understanding the influencing mechanisms underlying reservoir operations on water quality would provide scientific support to enable hydraulic regulations as effective methods for water quality protection while sustaining the water supply service of reservoirs around the world (Lürling et al., 2016).

The regulation of inflow for water quantity is the primary

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https://doi.org/10.1016/j.watres.2019.114984
0043-1354/

objective in current water supply reservoir operations. Hedging rule (HR) is a common operation policy for rationing water supply quantities between now and future to reduce water shortage risk in future periods (Draper and Lund, 2004; Kumar and Kasthurirengan, 2018; You and Cai, 2008). For a water supply reservoir, water can be released to satisfy current water demands or retained in the reservoir for future usage. It is not always beneficial to fully meet the immediate demand, even when enough water is available, due to the possibility of future drought events and the nonlinearity in water use benefits (Xu et al., 2017a). Instead, the rational way is to curtail the current supply by a certain extent and retain some water for high-value usages during subsequent dry periods when water availability is below a certain threshold. To address this, HR is used in reservoir operations to answer the questions of when and how much water should be curtailed from current release and retained for future use, which represents a tradeoff between current and future water usage (Shiau, 2011; Tu et al., 2008; You and Cai, 2008).

Despite the benefits in rationing the quantity of water delivery, HRs may also result in multiple negative effects on reservoir water quality. First, HRs typically decrease water flow and increase the hydraulic retention time in a reservoir. It has been widely shown that a low flow velocity and long hydraulic retention time weaken water exchange and the flushing effect on algal communities, which is beneficial for algal proliferation (Gao et al., 2018; Yang et al., 2013). Second, HRs promote higher reservoir storage levels during some periods and may aggravate seasonal thermal stratification. According to the critical depth model (Sverdrup, 1953), the ratio of euphotic depth to mixing depth in the water column determines the algal bloom potential, which is restrained when the ratio is below a critical value (Liu et al., 2012). Thermal stratification benefits algal bloom proliferation by decreasing the mixing depth (Li et al., 2015). In addition, HRs can affect nutrient cycling in a reservoir, especially matter exchanges between the water and sediment. In particular, reservoir sediments can act as a phosphorus (P) sink (Maavara et al., 2015; Vollenweider, 1975). However, when external P loads are under controlled, P stored in reservoir sediments releases, and sediments therefore act as an internal P source (Hamilton, 2012; Shu et al., 2017). This phenomenon is referred to P legacy (Sharpley et al., 2013). Oxygen is an important controller of sediment P release (Gerling et al., 2014; Zhang et al., 2015). HRs can enlarge the submerged area of reservoirs and may aggravate hypolimnetic hypoxia caused by higher water depths during water stratification season, thereby promoting sediment nutrient release.

Besides the negative effects listed above, HRs can also have positive effects on water quality. For example, HRs increase the dilution storage of a reservoir by retaining more water within the reservoir. To analyze these complex negative and positive effects, a comprehensive, quantitative examination is needed to assess reservoir hydrodynamic, temperature, light, nutrient, and sediment conditions under the various reservoir operation policies. Existing research concerning the impacts of reservoir operations on water quality have mostly focused on water quality downstream of dams (e.g., Dhar and Datta, 2008; Park et al., 2014; Weber et al., 2017) or in tributaries to reservoirs (Yang et al., 2013). There are a few studies on the impacts on water quality in reservoirs, but those generally considered single water quality factors only, such as P (Huang et al., 2015), temperature (Li et al., 2018b), or sedimentation (Lee and Foster, 2013). In particular, a few studies have addressed water quality within a reservoir through reservoir operation optimization (e.g., Castelletti et al., 2013; Chaves and Kojiri, 2007; Kerachian and Karamouz, 2006). Those studies all employed zero-dimensional (0D) or 1D water quality models without accounting for the horizontal distribution of water quality and did not analyze the factors and processes driving the water quality changes. Indeed, the influencing mechanisms underlying reservoir operations on temporal and spatial variations of different water quality factors in reservoirs and their releases, as well as the relationships between water supply and water quality are all important for reservoir operation policy evaluation. Research is needed to understand the mechanisms and explore the relationships for designing more appropriate reservoir operation policies to mitigate the conflicts between reservoir water supply and water quality.

In this study, we apply a comprehensive modeling approach to assess the impacts of water supply operation policies on temporal and spatial distributions of water quality in a reservoir and of the water release, and analyze the key factors and processes driving these impacts. We simulate reservoir operations by standard operation policy (SOP) and optimize HR to generate water supply schedules, and run a quasi-3D hydrodynamic-eutrophication-sediment model to simulate reservoir hydrodynamic conditions, nutrient cycles, water-sediment exchanges, and algal dynamics resulting from the water supply schedules under SOP and HR. The Danjiangkou Reservoir, which serves as the water source for the middle route of South–North Water Transfer Project (SNWTP) in China, is used as a case study. The implications of the results are discussed for the sake of sustainable reservoir operation considering both water quantity and quality.

## 2. Methodology

We first introduce the study area that is used to illustrate the methodology proposed in this paper. This will ease the description of the reservoir water quality simulation model, as well as help understanding the study issues involving tradeoffs between water supply and water quality, and between in situ reservoir and downstream environment.

### 2.1. Study area

The Danjiangkou Reservoir located in the Yangtze River basin is the second largest reservoir in China with a storage capacity of $29.05 \times 10^9$ $m^3$ at the normal pool stage (i.e., 170 m). The reservoir serves as the water source for the middle route of SNWTP (Fig. 1), a national key project in China and the largest inter-basin water transfer project in the world. The reservoir is scheduled to provide $9.5 \times 10^9$ $m^3$ water per year through the SNWTP to northern cities under high water stress, including two megacities, Beijing and Tianjin. The reservoir retains water that mainly derives from two tributaries of the Yangtze River, namely, the Han River and the Dan River. Inflow from the Han River is much greater. The Danjiangkou Dam controls the release of water for both downstream human and ecosystem usage; the Taocha Gate, which is located at the head of the SNWTP, controls water delivery to northern China (Fig. 1).

Meanwhile, eutrophication is a severe threat to water quality in the Danjiangkou Reservoir. The concentrations of total nitrogen (TN) and TP in the reservoir exceeded the established standard for drinking water; local algal blooms occurred several times during the period from 1992 to 2003 (Tang et al., 2014). Since then, nutrient concentrations in the reservoir have been increasing. Field monitored data during 2006–2012 showed that the TN concentration in the reservoir increased by about 50% while the TP concentration nearly doubled during a period of seven years (Ma et al., 2014). Additionally, investigations have found that P (in particular of loosely exchangeable form) storage in the soil surrounding the reservoir area is high (Tang et al., 2014). To enhance water supply reliability for the SNWTP, the reservoir storage was increased starting in 2014. Since then, sediment P release in the intermittent submerged zone surrounding the reservoir has been observed (Shu et al., 2017); the potential increase of algal bloom risk as a consequence of decreased flow velocities and increased hydraulic

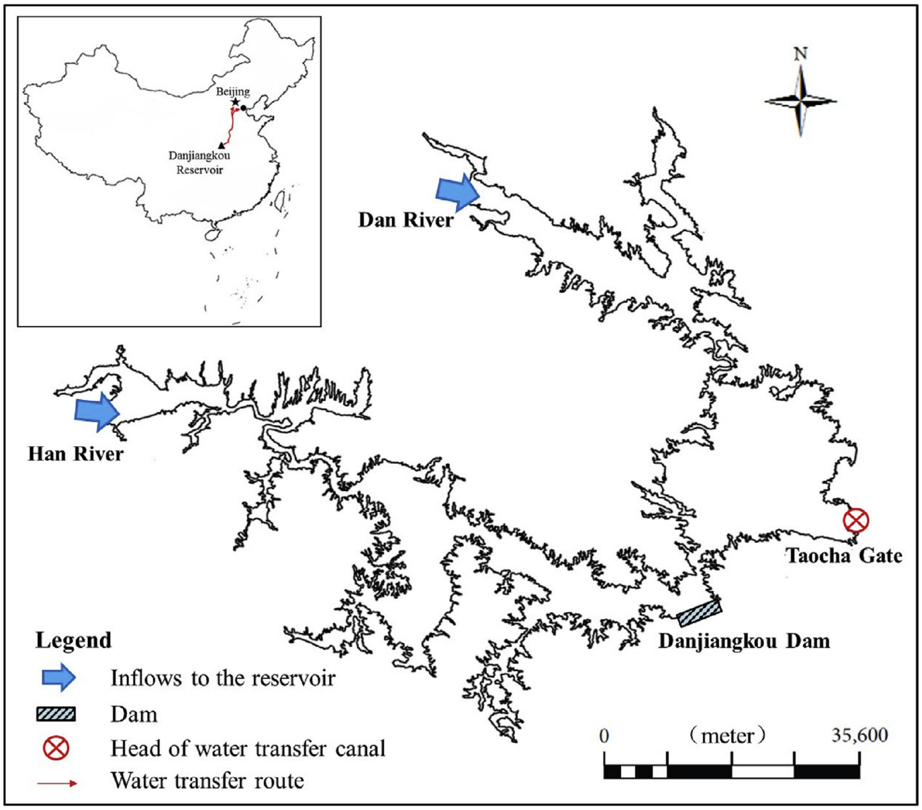


**Fig. 1.** Geographic location and boundary of the Danjiangkou Reservoir at the normal pool level (170 m) and the middle route of the South–North Water Transfer Project (SNWTP).

retention time has also been discussed (Pan et al., 2018).

### 2.2. Reservoir operation method

In general, water supply reservoir operations follow either SOP or HR (Zhao et al., 2011). SOP supplies water to the current demand as much as the water available allows and retains only surplus water (if the water available, i.e., the sum of the initial storage and reservoir inflow, exceeds the current demand) for future usage (Loucks et al., 1981; Stedinger, 1984). Thus SOP does not consider any future water shortage vulnerability. HRs are adopted for reservoir operations to reduce the risk of severe water shortages in the future as well as to improve overall water delivery benefits (Bower et al., 1962). Since the late 1970s, HRs have been extensively studied in reservoir operation research and widely employed for real-world practices (e.g., Kumar and Kasthurirengan, 2018; You and Cai, 2008).

Various methods have been proposed to determine HRs for reservoir operations. Among these, the reservoir operating rule curve is a common method (Tu et al., 2008; Yin et al., 2011) and is employed for the Danjiangkou Reservoir (Xu et al., 2017b). Fig. 2 shows typical reservoir operating curves, which divide a reservoir into four zones of different storage levels (Yin et al., 2011). Different operating rules (i.e., with different release rates) are applied to the various zones. A reservoir releases water to satisfy the full water demand when the reservoir storage is above the upper limit curve (i.e., Zone 1) with extraordinarily high water availability. However, when the reservoir storage is below this curve, a reservoir releases water to satisfy only a part of the current demand, namely, the water release is curtailed by $a\%$, $b\%$, and $c\%$ for zone 2, 3, and 4, respectively. More water is curtailed from current release when reservoir water availability is lower (i.e., $0 < a < b < c < 100$, resulting in decreasing levels of release for the demand at the current stage from Zone 1 to Zone 4), and no water is released when reservoir storage is below the dead level.

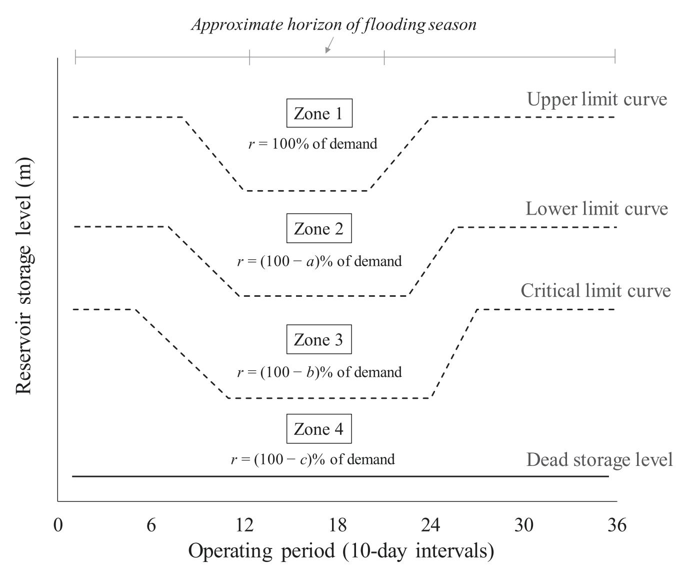


**Fig. 2.** Typical reservoir operating curves representing the zone-based hedging rule. $a$, $b$, and $c$ are the hedging rates of the different zones. $r$ is the reservoir's water supply rate ($m^3\ s^{-1}$). A one-year study period is divided into 36 sub-periods with an operation step of 10-day.

In this zone-based HR, $a$, $b$, and $c$ are the hedging rates of the different zones, and their values are typically determined empirically by reservoir managers regarding specified water supply reliability and acceptable deficits (Yin et al., 2011). The shapes and locations of these curves in Fig. 2 are typically determined through optimization. A common optimization model is formulated as below with an objective to minimize multi-year mean economic losses caused by water supply deficits, under a constraint of water shortage control. The economic loss is expressed as a quadratic function of the water deficit ratio (Draper and Lund, 2004; Tu et al., 2008). In the case of the Danjiangkou Reservoir, water shortage is defined as the water delivery rate below the critical value of 135 $m^3 s^{-1}$, which is the designed minimum flow rate for the SNWTP (Yang et al., 2017). We simulate reservoir operations under SOP and the designed HR (Yang et al., 2017) for the Danjiangkou Reservoir. The following model is used to optimize HRs for satisfying various demands on water shortage control.

$$obj = \min\left(\sum_{t=1}^{NP} \lambda \left(\frac{D_t - R_t}{D_t}\right)^2 \Big/ NY\right) \quad (1)$$

subject to:

$$S_{t+1} - S_t = I_t + P_t - R_t - A_t - E_t \quad (2)$$

$$0 \le R_t \le D_t \quad (3)$$

$$S_t \le SU_t \quad (4)$$

$$WSR = NP_{\text{shortage}}/NP \le X\% \quad (5)$$

where $D_t$ is the water demand ($m^3$) in period $t$; $R_t$ is the reservoir release for the demand ($m^3$); $\lambda$ is a constant, which implies that the economic loss is linear with the square of the deficit ratio (Hsu and Cheng, 2002; Tu et al., 2008); $NP$ is the total number of periods of reservoir operation modeling; $NY$ is the total number of years of reservoir operation modeling; $S_{t+1}$ and $S_t$ are the reservoir storage ($m^3$) at the beginning of periods $t$+1 and $t$ (respectively); $I_t$ is the inflow ($m^3$) in period $t$; $P_t$ is the precipitation ($m^3$); $A_t$ is the potential water abandoned ($m^3$) through the spillway during flood control periods; $E_t$ is the water loss ($m^3$) due to evaporation, which is a function of water surface area and varies with storage; $SU_t$ is the upper limit of reservoir storage ($m^3$) determined by the reservoir capacity and flood control demand; $WSR$ is an indicator of water shortage risk; $NP_{\text{shortage}}$ is the total number of periods that water supply shortages occur during modeling; and $X\%$ is a prescribed threshold on water shortage control. Based on the long-term (1955-2005) historical inflow data, it is found that the designed HR decreases the reservoir's water shortage risk (i.e., $WSR$) from 22% under SOP to 8%.

### 2.3. Reservoir eutrophication simulation

This study selects a quasi-3D water quality model developed with the Environmental Fluid Dynamics Code (EFDC) platform for reservoir eutrophication simulation. The EFDC is a state-of-the-art surface water modeling system supported by the United States Environmental Protection Agency, which includes modules for hydrodynamic, temperature, sediment, and water quality simulations (Hamrick, 1992; Tetra Tech, Inc., 2007). EFDC has been widely used to model various water body types including rivers, lakes, estuaries, and reservoirs (Chen et al., 2016). The hydrodynamic-eutrophication modules of the EFDC are capable of simulating a dozen water quality parameters, including dissolved oxygen (DO), chemical oxygen demand (COD), total suspended solids (TSS), algae groups (i.e., cyanobacteria (Bc), green algae (Bg), diatom algae (Bd), and stationary algae (Bm)) and multiple components of carbon (C), N, and P cycles. To better simulate realistic distributions, organic C, N, and P are represented by three reactive sub-classes, namely, labile particulate organic (LPO), refractory particulate organic (RPO), and dissolved organic sub-classes. The interaction processes between the various water quality state variables are illustrated in Fig. 3 (Tetra Tech, Inc., 2007).

Water quality is simulated on the basis of hydrodynamic and temperature simulations. Algae play a central role in the water eutrophication module. The EFDC accounts for algal growth, basal metabolism, predation, and settling in simulating algal dynamics. Algal growth depends on nutrient availability, ambient light and temperature. Main governing equations on these processes are provided in the supplementary material. The effect of reservoir operations on sediment nutrient release is a research topic of this study. To simulate the processes occurring in sediment and the matter flux at the water-sediment interface, the sediment diagenesis module in the EFDC is activated and coupled with the hydrodynamic-eutrophication modules. The sediment module considers basic processes that include: 1) the depositional flux of particulate organic C, N, and P from the water; 2) the diagenesis of particulate organic matter in sediment; and 3) the resultant flux of substances (e.g., phosphate, ammonium, and nitrate) and oxygen between the water and sediment. Details on simulation processes and governing equations can be found in Tetra Tech, Inc. (2007).

To simulate water quality in the Danjiangkou Reservoir, we follow our previous work and employ an existing hydrodynamic-eutrophication-sediment model developed by Chen et al. (2016) for the Danjiangkou Reservoir. The model simulates C, N, and P dynamics and two dominant algal groups (i.e., green algae and cyanobacteria) in the reservoir. To set up the model, bathymetry processing, mesh generation and boundary conditions setting were completed. Field bathymetry were conducted to detect the terrain

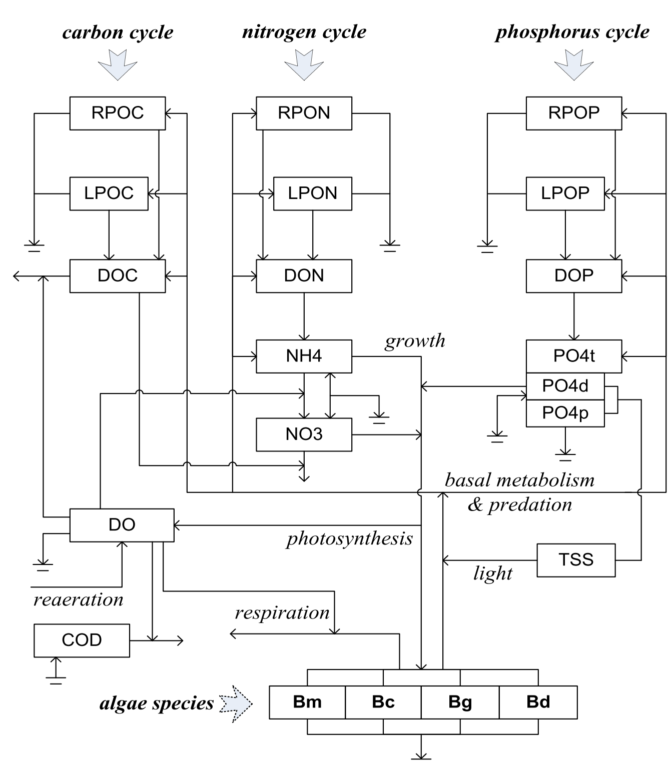


**Fig. 3.** Schematic diagram of water eutrophication simulation in the EFDC. DOC, DON, and DOP represent dissolved organic C, N, and P, respectively; $NH_4$ and $NO_3$ represent ammonium N and nitrate N, respectively; $PO_4$t represents total phosphate, including dissolved ($PO_4$d) and particulate ($PO_4$p) phosphate. Other variables are defined in the text.

in deep-water zones, and the field data were combined with an existing digital elevation model to determining the reservoir bottom topography (Chen et al., 2016; Xu et al., 2017b). Two types of grid systems were coupled for the mesh generation, i.e., a rectangular grid system for wide areas of the reservoir and an orthogonally curvilinear system for narrow channels connected to the reservoir. The final mesh of the model contains 10 000 cells on a horizontal plane with a cell size of 280 m. The reservoir is stratified into six vertical layers, allowing the simulation of the vertical distribution of water quality. The hydrological data used in the model were provided by local hydrological stations; the meteorological data, including air temperature, precipitation, evaporation, wind speed, solar radiation and cloud conditions, were obtained from the National Meteorological Information Center of China. A dynamic time step is used for modeling and the initial step is set as 2 s. The model was calibrated and validated for the Danjiangkou Reservoir using TN, TP, DO, and chlorophyll *a* (Chl *a*) field data obtained in 2009 and 2010 (Chen et al., 2016). For the current study, we select 2009 as the study period with necessary data on hydrological, meteorological, and pollutant loading conditions.

## 3. Results and discussion

For this case study of Danjiangkou Reservoir, we provide detailed modeling results under two representative reservoir operation policies, namely, SOP and the designed HR. By comparing the modeling outputs between the two policies, we show different influences on stored and discharged water quality, and discuss the processes and key driving factors. Finally, by comparing a number of scenarios with different hedging levels, we demonstrate the relationship between water shortage and reservoir eutrophication indicators.

### 3.1. Phosphorus dynamics and release from sediment

Globally, P is a limiting factor of algal blooms in many water bodies. Fig. 4 provides plane-averaged TP concentration variations for the different layers in the Danjiangkou Reservoir under SOP and the designed HR. Seasonal variations in plane-averaged TP concentration are found in the reservoir under both policies. TP concentrations are higher in summer and autumn (from June to November) than those in other seasons. This is attributed to the variation of matter exchange between water and sediment across seasons. Modeling results show that P release from sediment is significantly active in summer and autumn (Fig. 5) while the deposition of organic P particulates from water to sediment is a dominant process in spring and winter. A large amount of P releases from sediment during summer and autumn months, which significantly increases TP concentrations in the bottom layer while having a smaller effect on TP concentrations in the surface layer, which results in a situation that the TP concentration in the surface layer is much lower than that in the bottom during the summer and early autumn (from June to September) as displayed by DSB in

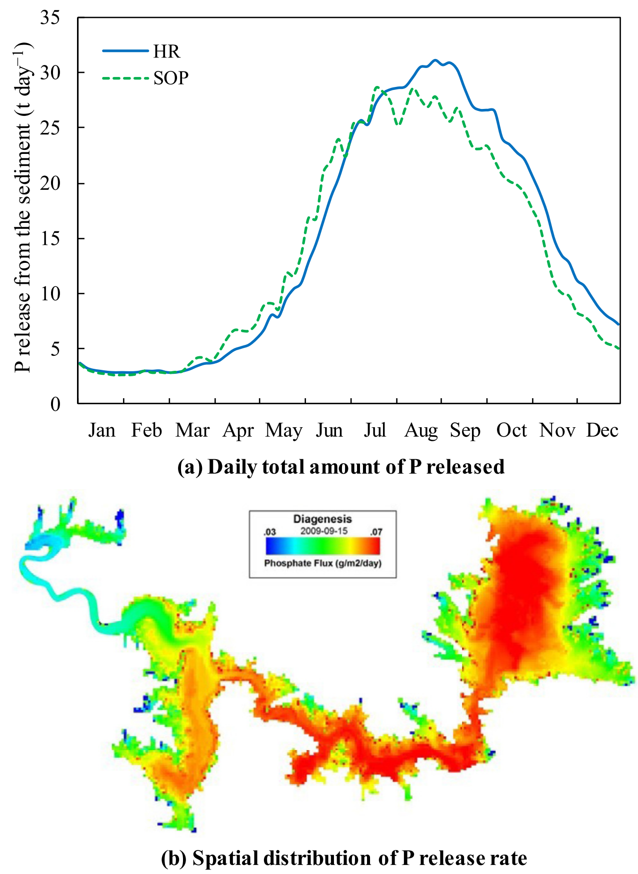


**Fig. 5.** P release from reservoir sediment to the water. (a) The daily total amount of P release under the two reservoir operation policies; (b) the spatial distribution of the P release rates on September 15 of the modeling year under HR.

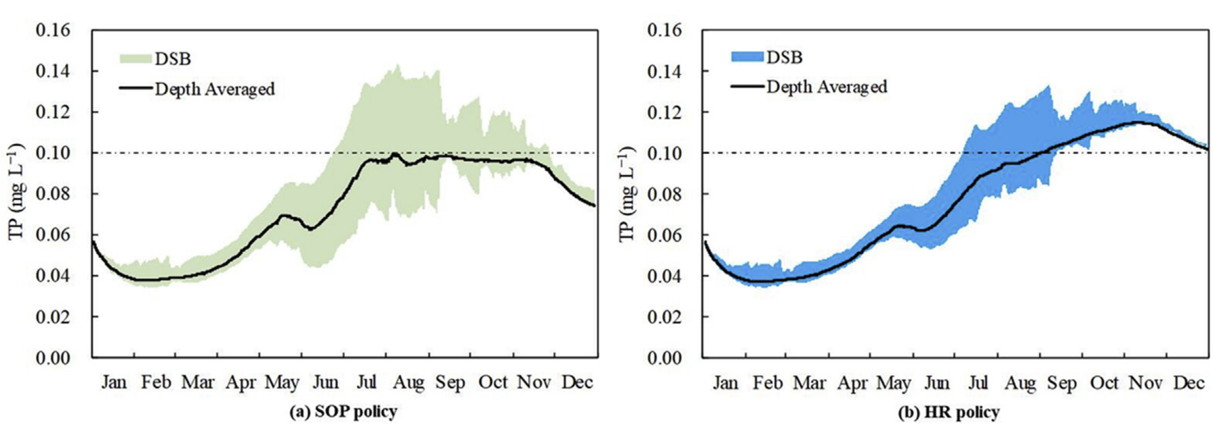


**Fig. 4.** Plane-averaged TP concentration variations in the reservoir under (a) SOP and (b) HR. DSB represents concentration differences between the surface and bottom layers; the upper boundary shows TP in the bottom layer and the lower boundary shows TP in the surface layer.

Fig. 4. This is caused by thermal stratification, which hinders the vertical mixing of reservoir water, a common phenomenon during the summer and early autumn. As thermal stratification dissipates in late autumn, vertical mixing is renewed in reservoir water, and the difference in TP concentrations between the bottom and surface layers becomes much smaller.

In the river basins contributing to the Danjiangkou Reservoir, flooding events typically occur during July to October. Before the flood season, reservoir storages under both SOP and HR are relatively low. Since HR curtails water releases to build up carryover storage, releases under SOP are larger and thus the reservoir storage levels are lower. Thus under SOP, the average flow velocity in the reservoir is higher than that under HR. It is found that disturbance accompanied with high flow velocities slightly increase sediment P release during April to June (Fig. 5a), which ends with a bit higher TP concentrations in the bottom layer under SOP than those under HR during May to July, as displayed by the upper boundary of DSB in Fig. 4.

As inflows significantly increase, the differences of TP concentrations under SOP and HR are much more significant since August. Compared to SOP, more water is retained in the reservoir during the flood season under the HR policy to decease water shortage risk during subsequent dry seasons; thus the reservoir dilution capability under HR is higher. However, Fig. 4 shows that starting in August the TP concentration under HR is higher than that under SOP. With the same external pollutant loads under the two policy scenarios, the result discussed above implies that HR increases the amount of P release from sediment. As shown in Fig. 5a, starting in August the daily P release rate under HR is higher compared to that under SOP; the difference is as high as 5.3 tons day$^{-1}$. The P release throughout the modeling year under HR is 285.3 tons (5.7%) higher than that under SOP. Two reasons explain this higher release rate since August. First, more water is retained in the reservoir under HR, and the submerged area of the reservoir is larger. The intermittent submerged zone surrounding the reservoir presents as a large P storage and contributes to the P loading into the reservoir. Second, the HR policy resulting in higher reservoir storage levels can aggravate hypolimnetic hypoxia during water stratification seasons (i.e., summer and early autumn). The absorption of phosphate onto iron oxyhydroxides is a crucial process affecting sediment P dynamics (Ding et al., 2016). Hypolimnetic hypoxia promotes iron oxyhydroxides dissolution and thereby improves sediment phosphate release (Chen et al., 2018; Testa et al., 2013). Oxygen at the bottom in deep-water zones are generally lower than that in shallow-water zones during water stratification seasons. Thus sediment P release rates in deep-water zones of the reservoir are generally higher than those in surrounding shallow-water zones, as displayed in Fig. 5b.

### 3.2. Algae dynamics and limiting factors

The Chl *a* concentration is used to represent algae conditions in the reservoir. Variations in seasonal Chl *a* concentration are modeled under both reservoir operation policies. The Chl *a* concentration in summer and autumn (from June to November) was considerably higher than that in other seasons (Fig. 6a). The vertical difference of the Chl *a* concentration is obvious among the six layers during these months (Fig. 6b), which is due to thermal stratification. Moreover, the Chl *a* concentration in the hypolimnion is much lower, and this is due to algal growth constraints with light limitations and low temperatures. Since the risk of an algal bloom at the surface layer is significantly higher, the following analysis focuses on the Chl *a* concentration in the surface layer (Fig. 6a). As presented in section 3.1, HR promotes P release from sediment and thereby increases the P concentration in reservoir water. However, it is also found that starting in April the plane-averaged Chl *a* concentration in the surface layer is generally lower under the HR policy (Fig. 6a). The annual mean value under HR is 11.08 μg L$^{-1}$, lower by 18% than that under SOP (13.45 μg L$^{-1}$). This is explained in the following with exploration on the potential factors on algal growth under different operation policies.

Main factors that may affect algal growth include N, P, light, and temperature. The limiting effects of these factors are described by indicators (Equ. 3-8 in the supplementary material) in the EFDC. The values of these indicators range from 0 to 1, where a lower value represents a stronger limiting effect. Modeling results show that the trend in intra-year algal variation is driven by temperature. Temperature suppresses algal growth during the period from January to April, in which the limiting indicator is generally lower than 0.3 under both operation policies (Fig. 7b). The limiting indicator is (or close to) 1.0 from June to September, which means that temperature is nearly optimal for algal growth. This explains why the Chl *a* concentration during these months is significantly high (Fig. 6a). The differences of temperature effects under the two operation policies are generally small throughout the modeling year (Fig. 7b), since water temperature is mainly driven by air temperature. However, slightly opposite effects are found between SOP and HR for two periods (April–June and October–December), i.e., temperature limiting effect is stronger during April to June and is weaker during October to December under HR than SOP. This is because water temperature varies slower than air temperature does and a delay effect exists. Water temperature increases with air temperature from April to June. Since reservoir storages under HR are larger than those under SOP, water temperature increases slower under HR. Thus, temperature limiting effect under HR is stronger during this period. Similarly, water temperature decreases with air temperature from October to December; it decreases slower and consequently the temperature effect is weaker under HR than SOP. Additionally, the delay of water temperature variation also explains the differences of temperature limiting effects in January and December. Actually, air temperature decreases sharply in November, and the air temperature in December is similar with that in January. However, water temperature decreases much slower. This explains the gradual decrease of temperature limiting indicator in November and December (Fig. 7b).

On the other hand, the limiting effect of light exhibits significant daily fluctuations (Fig. 7a) due to the various weather conditions (e.g., sunny, cloudy, or rainy conditions). Modeling results show that light limiting indicator is generally lower than 0.6 under both policies during June to October (Fig. 7a), when the limiting indicators of other factors (i.e., N, P, and temperature) are generally higher than 0.9. This means that light is the dominant limiting factor on algal growth in the reservoir during months when algal bloom risk is high (i.e., June to October). Water depth is an important factor affecting light limiting effect due to light attenuation in water bodies. The case study reservoir is located in a mountainous area with steep slopes (i.e., a V-shape reservoir), as many other reservoirs in the world. The reservoir is deep and thereby light limitation is strong, especially during summer and autumn when water inflows are generally high. Fig. 7a only shows the light limiting effect on algae within the surface layer, while light limitation is obviously stronger in the layers below the surface layer.

Reservoir operation affects water depths in the reservoir and thereby affects light limiting effect on algal growth. Reservoir storages under both SOP and HR are relatively low during the period from January to May, due to low inflows. Thus, the differences of light limiting effects under SOP and HR are small during this period (Fig. 7a). However, as inflow increases since June, the differences of reservoir storages under SOP and HR become more

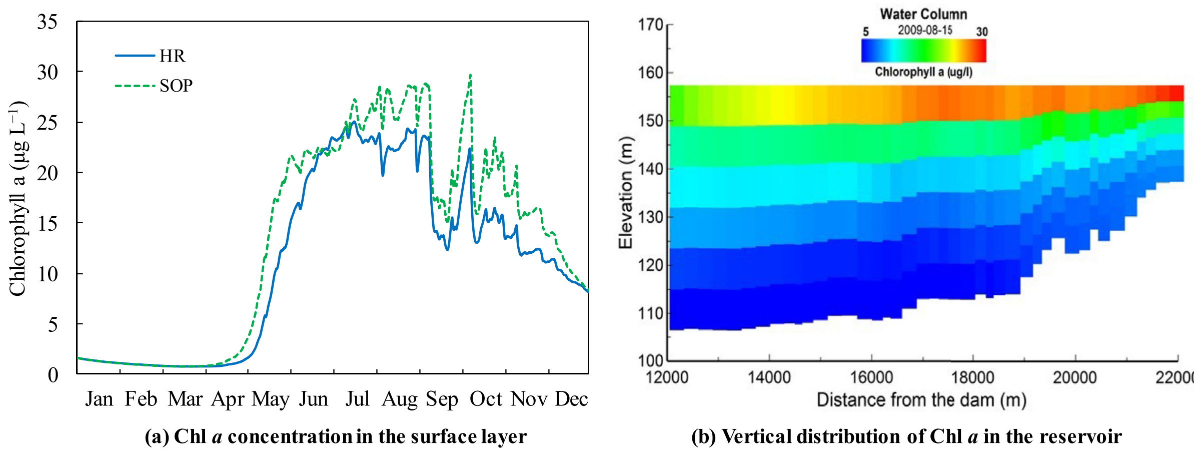


**Fig. 6.** Chl *a* concentration in the reservoir. (a) Plane-averaged Chl *a* concentration variations in the surface layer under SOP and HR; (b) the vertical distribution of the Chl *a* concentration in a 10 km profile in the reservoir on August 15 of the modeling year under HR.

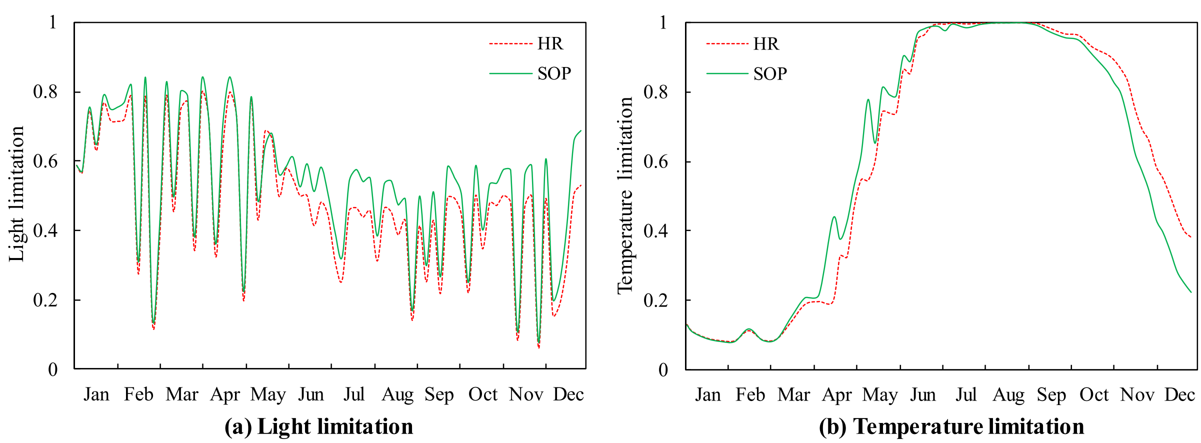


**Fig. 7.** Limiting effects of (a) light and (b) temperature on algal growth in the reservoir surface layer under SOP and HR. Lower values represent stronger limiting effects.

significant. HR results in considerably stronger light limitation than SOP starting from June (Fig. 7a). This is because the reservoir storage level under HR is higher, and a greater water depth weakens light access to algae. To summarize, opposite effects on algal growth exist with HR in summer and autumn, i.e., promoted P release from sediment (and thus mitigated P limitation on algal growth) and enhanced light limitation. Under both policies, during the months when algal bloom risk is high (i.e., June to October), P limitation is weak (indicator $> 0.9$) and light limitation is strong (indicator $< 0.6$) and presents as a dominant factor on algal growth. Therefore, despite promoting P release from sediment, HR decreases the space-averaged Chl *a* concentration in the reservoir (Fig. 6a) due to a strong light limitation effect on algal growth.

### 3.3. *Horizontal algal distribution in the reservoir and water quality of release*

Aside from the vertical distribution, horizontal distribution of the Chl *a* concentration is also significant in the Danjiangkou Reservoir under both SOP and HR. The Chl *a* concentration in the surrounding shallow-water zones is generally higher than that in deep-water zones (Fig. 8a and b), which is due to stronger light limitation in deeper water. Reservoir operation policies affect the horizontal distribution of algae by changing water depth and the horizontal flow velocity field. Under SOP, flow velocities along the route between the Han River entryway (the primary inflow source of the Danjiangkou Reservoir) and the dam are obviously higher than those in other reservoir zones (Fig. 8d). Given that high flow velocities are unfavorable to algal accumulation and weaken water mixing by reducing the hydraulic retention time, the Chl *a* concentration along the route between the Han River entryway and the dam is lower than that in other zones (Fig. 8b). On the other hand, HR increases the hydraulic retention time and enhances water mixing in the entire reservoir (Fig. 8c); thus, the Chl *a* concentration under HR ends with a more evenly distribution (Fig. 8a) than under SOP (Fig. 8b). An even distribution is beneficial for mitigating algal bloom risk in surrounding shallow-water zones, but it poses some negative effect on the water quality along the route between the inflow entryway and the dam, as displayed in Fig. 8a and b. Because of these positive and negative effects, the influence of HR on the water quality in the water delivery from the reservoir depends on the location of reservoir outlets, which is further discussed as follows.

The Danjiangkou Reservoir has two outlets, the dam and Taocha Gate (labeled in Fig. 8). The water quality in the release from the dam for downstream usage is provided in Fig. 9a and b. Since

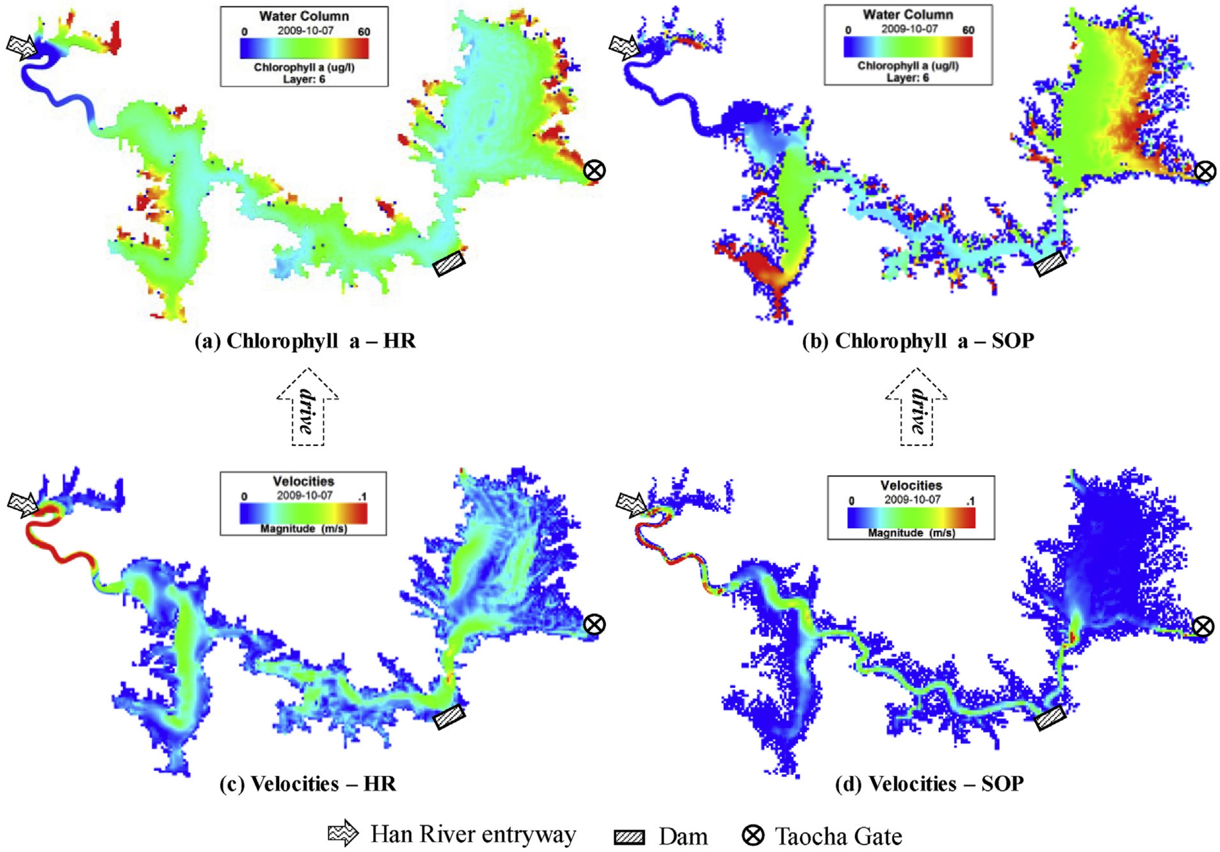


**Fig. 8.** Horizontal distribution of the Chl *a* concentration and flow velocity in the surface layer of the reservoir on October 7 of the study year under HR (a, c) and SOP (b, d).

sediment P release is not active and low temperture suppresses algal growth during January to April, the differences of water quality in reservoir releases under SOP and HR are hardly obvious in this period. However, the Chl *a* and TP concentrations are significantly higher under HR starting in June (Fig. 9a and b). As discussed above, HR enhances P release from sediment and increases Chl *a* concentration along the route between the inflow entryway and the dam by promoting horizontal mixing of water, thereby resulting in a negative effect on the quality of water release to downstream. On the other hand, HR also results in higher TP concentration in the water delivery from the Taocha Gate (Fig. 8d), but it leads to a positive effect on Chl *a* concentration (Fig. 8c), which is opposite to its effect on the water release from the dam. This is attributed to the locations of two outlets. The water depth of the reservoir at the dam is high, but at the Taocha Gate, where water is delivered to the SNWTP, the water depth is relatively low. HR promotes horizontal mixing of water, which increases Chl *a* concentration at the dam and in the water release, while decreasing Chl *a* concentration in shallow-water zones and thus the water delivery. These results show that a reservoir operation policy can effectuate opposite water quality effects at different outlets. In additional, water quality of different outlets under a given operation policy (SOP or HR) are different. By comparing Fig. 9a and c, the Chl *a* concentration in the water delivery via the Taocha Gate is significantly higher than that in the water release to downstream via the dam. This is because water release via the dam is from a deep layer of the reservoir while water delivery via the Taocha Gate is from the surface layer. The Chl *a* concentration in the deep layers of the reservoir is much lower than that in the shallow layers due to the stronger light and temperature limitations on algal growth.

### 3.4. Relationship between water shortage and eutrophication indicators

To explore the relationship between water shortage and eutrophication indicators, we create two additional reservoir operation HR policies by setting different hedging rates. Using multi-year (1955–2005) historical inflow records, the modeled water shortage risk is 22% for SOP, 8% for the designed HR, and 17% and 12% for the two additional HR policies. The means of Chl *a* and TP concentrations vs. water shortage risk from June to November in the reservoir, the release to downstream via the dam, and the delivery to northern China via the SNWTP are compared among the four operation scenarios (Fig. 10). Since HR promotes sediment P release, the reservoir space-averaged TP concentration increases as the water shortage risk decreases, implying a tradeoff between P pollution and water shortage mitigation (Fig. 10b). However, HR also promotes higher reservoir storage levels and then enhances light limitation on algal growth, which decreases the reservoir space-averaged Chl *a* concentration. Thus HR can be a win-win policy for Chl *a* concentration control and water shortage mitigation (Fig. 10a).

Furthermore, the results show that HR changes the horizontal distribution of algae in the reservoir and effectuates opposite effects on Chl *a* concentration at two outlets (Fig. 8). Due to improved horizontal mixing of water under HR, Chl *a* concentration increases in the water release via the dam, while decreases in the water delivery via the SNWTP (Fig. 10a). Given the opposite effects of HR on different water quality indicators (TP and Chl *a*) and on the water quality at the two outlets, to determine which policy is the best depends on managers' priorities on multiple water quality

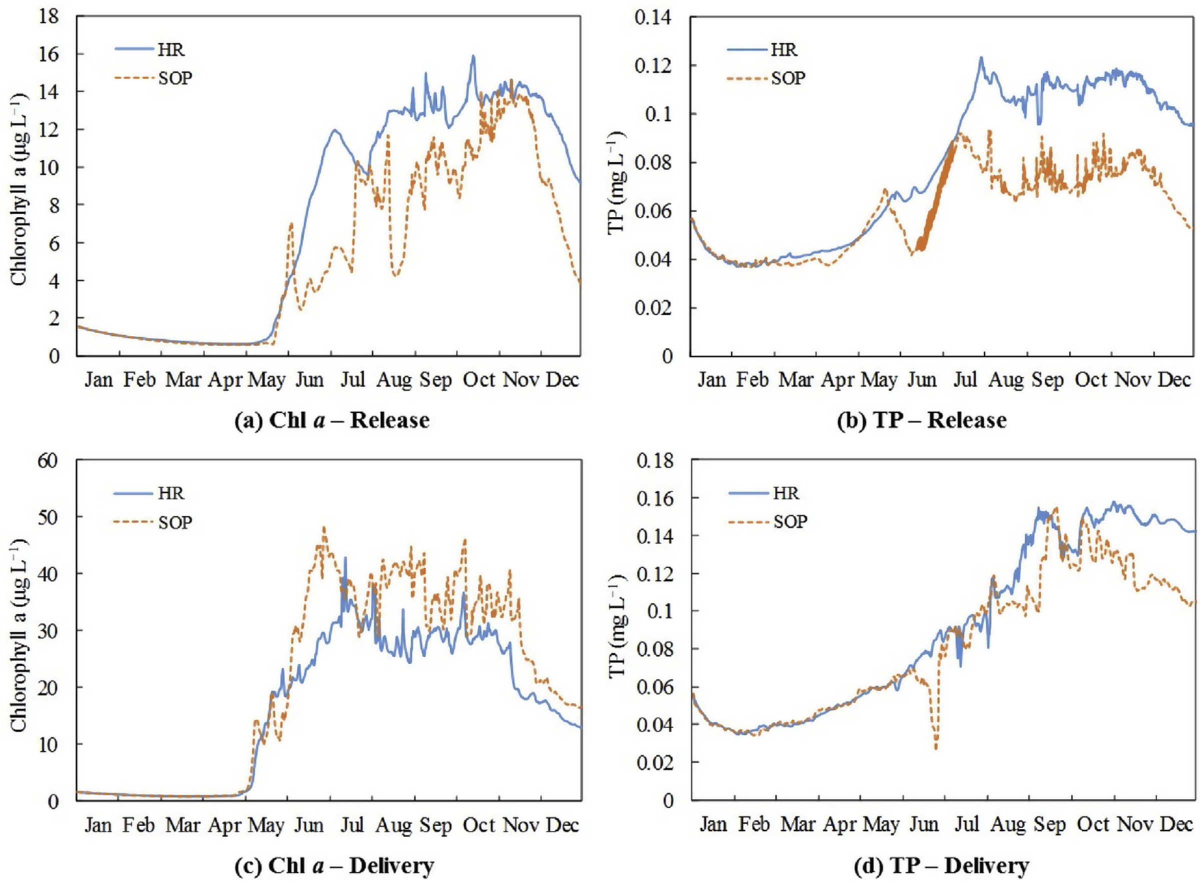


**Fig. 9.** The water quality of release for downstream usage (a, b) and delivery to northern China (c, d) under the two reservoir operation policies.

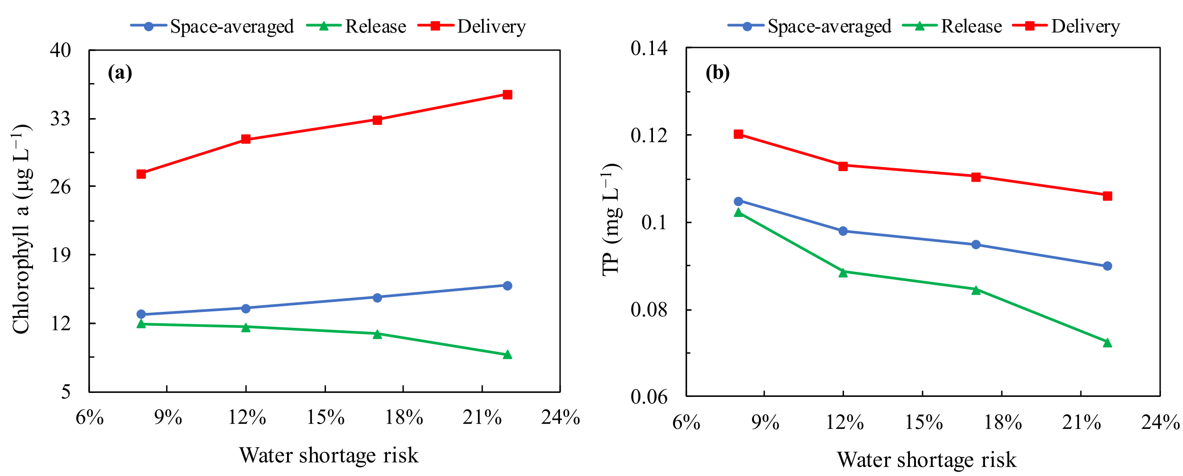


**Fig. 10.** The means of the (a) Chl *a* and (b) TP concentrations vs. water shortage risk from June to November in the reservoir, the release via the dam, and the delivery via the SNWTP under the four operation scenarios.

targets, as well as water conservation. Fig. 10 illustrates the relationships between the water quantity target and multiple water quality targets (i.e., control of TP and algae in the reservoir and in the water discharges). Taking advantage of the relationships, reservoir managers can choose their desirable operation policy based on their priorities on the various water quantity and water quality targets.

Additionally, this study finds no significant difference among the operation polices on the TN concentration in the reservoir. The mean space-averaged TN concentration in the reservoir throughout the year ranges from 1.14 (under the designed HR) to 1.19 (under SOP) mg $L^{-1}$ under all operation scenarios. HR results in a trivial and positive effect on decreasing reservoir TN concentration during July to October, which is opposite to the negative effect on TP concentration. According to the modeling results on sediment N release, nitrate release is weak under all operation policies, and HR promotes ammonium release from the sediment during summer and autumn as a consequence of the aggravation of hypolimnetic hypoxia. However, the increase of ammonium release caused by HR is small ($\leq$1.6% under three HR policies scenarios) and is offset by higher reservoir dilution capability. This explains the trivial and positive effect of HR policy on decreasing TN concentration in the reservoir.

Some field data reported in recent studies are helpful for validating the results described above. HR policy has been used in the Danjiangkou Reservoir for managing water delivery for the SNWTP since 2014. As a result, the mean annual storage level increased from 144 m in 2012–2013 to 154 m in 2015–2016 (Pan et al., 2018). Field monitoring results found that TP in the reservoir sediment decreased from 557 mg kg$^{-1}$ in 2012–2013 to 530 mg kg$^{-1}$ in 2015–2016 (Li et al., 2018a). The increase of storage level from 144 to 154 m extended the reservoir submerged area by 177 km$^2$ and the newly submerged land contributed to the P loading into the reservoir (Shu et al., 2017). Meanwhile, field sampling analysis found that phytoplankton biomass in the reservoir decreased from 7.4 mg L$^{-1}$ in 2014 to 4.9 mg L$^{-1}$ in 2015 and 2.3 mg L$^{-1}$ in 2016 (Pan et al., 2018). The biomass reduction can be explained by the increased reservoir dilution capability and the weakened light access to algae caused by significant water depth increase (Shen et al., 2015). Loiselle et al. (2007) demonstrated that light availability is dominant in controlling algal growth in many aquatic ecosystems and it is directly affected by hydrological conditions. These observations are consistent with the results from our study, i.e., HR policy ending with increased carryover storage can promote sediment P release but decreased Chl *a* concentration in the reservoir.

These findings provide implications for sustainable reservoir management. Since HR can cause opposite consequences to water quality (i.e., increased sediment P release but reduced algal concentration), reservoir managers need to use HR with caution to mitigate the negative impact on water quality and take advantage of the positive impact (e.g., reduced algal concentration). Given the significant spatial differences of water quality within a reservoir, the selection of appropriate outlet locations and water layers wherein to discharge water is important. Besides, given the temporal variation of water quality impact from reservoir operation, various water users (e.g., human, agriculture, industry, and ecosystem) with different water quality requirement should be coordinated to satisfy the multiple requirements. Using the methods presented in this study, future studies may extend the modeling period to explore the long-term influence of operation policies and account for the inflow variability and change caused by either human interference and/or climate change. In addition, external nutrient loads affect matter exchanges at the water-sediment interface. The influence of reservoir operations on sediment nutrient retention and release can be further explored under different external nutrient load scenarios, which can offer implications for the implementation of the Total Maximum Daily Load within watersheds contributing to a reservoir.

## 4. Conclusions

Hedging is typically used in water supply reservoir operations to regulate water supply quantities between now and future in order to reduce severe water shortage risk in the future. In this study, we develop a reservoir operation optimization model coupled with an integrated hydrodynamic-eutrophication-sediment model. Using the models, we assess the impacts of operation policies such as HR and SOP on the quality of stored and discharged reservoir water, which in turn can be used to optimize HR to consider both water quantity and water quality requirements. For the case study reservoir, the Danjiangkou Reservoir in China, the HR decreases the water shortage risk of the reservoir from 22% to 8% and increases the reservoir dilution capability by retaining more water in the reservoir; however, it increases reservoir P concentrations starting in summer due to the promotion of sediment P release. The annual P released under the HR in this reservoir is higher by 285.3 tons (5.7%) than that under the SOP.

The reservoir Chl *a* concentration (an indicator of the environment for algae condition) is significantly higher in summer and early autumn. Sediment P release promoted by HR can support algal growth. However, this effect is set off by the enhancement of light limiting effect resulting from higher storage levels under HR. Light is found to be the dominant limiting factor on algal growth in this deep eutrophic reservoir during summer and early autumn when reservoir storages increase significantly. Due to these two opposite effects, HR decreases the annual mean Chl *a* concentration by 18% (from 13.45 μg L$^{-1}$ under SOP to 11.08 μg L$^{-1}$). Additionally, vertical and horizontal differences in water quality are significant for this large reservoir, which can be related to the reservoir operation policies. HR improves the horizontal mixing of water in the reservoir through affecting the hydraulic retention time and the horizontal flow velocity field, which significantly deteriorates water quality along the route between the inflow entryway and the dam, while mitigating algal bloom risk in surrounding shallow-water zones. For the two outlets of the Danjiangkou Reservoir, HR deteriorates the water quality released to downstream via the dam but decreases algal concentrations in the water delivery to northern China. The quantified relationships between indicators of water shortage and water quality of the reservoir and of the release will support the reservoir managers to coordinate the mitigation efforts for controlling water shortage risk and eutrophication threats.

## Declaration of competing interest

None.

## Author contributions

Z. X., Z. Y., and X. C. proposed the idea and designed the study; Z. X., X. Y. and M. S. implemented the methods and analyzed the results; Z. Y., X. C. and Y. W. contributed to the discussion; and Z. X. wrote the main manuscript text. All authors approved the final version.

## Acknowledgement

This research was financially supported by the National Key R & D Program of China (No. 2017YFC0405900 & No. 2017YFC0404506) and the China Postdoctoral Science Foundation (No. 2018M640992). Co-author Cai's work was supported by US National Science Foundation (NSF) project EAR-1739788.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.watres.2019.114984.

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