A reservoir operating method for riverine ecosystem protection, reservoir sedimentation control and water supply

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SUMMARY

Riverine ecosystem protection requires the maintenance of natural flow and sediment regimes downstream from dams. In reservoir management schedules this requirement should be integrated with sedimentation control and human water supply. However, traditional eco-friendly reservoir operating methods have usually only considered the natural flow regime. This paper seeks to develop a reservoir operating method that accounts for both the natural flow and sediment regimes as well as optimizing the water supply allocations. Herein, reservoir water level (RWL), sediment-occupied ratio of reservoir volume (SOR) and rate of change of SOR (RCSOR) are adopted as three triggers of a drawdown-flushing-based sediment management policy. Two different groups of reservoir operating rule curves (RORCs) are designed for sediment-flushing and non-sediment-flushing years, and the three triggers, RWL, SOR and RCSOR, are used to change the "static" RORCs to "dynamic" ones. The approach is applied to the Wangkuai Reservoir, China to test its effectiveness. This shows that the approach can improve the flexibility of reservoir operators to balance the reservoir management, water supply management and the flow and sediment needs of the downstream riverine ecosystem.

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1. Introduction

By 2005, more than 45,000 reservoirs with dams over 15 meters high had been constructed across the world (Nilsson et al., 2005). These reservoirs impose obvious changes of flow and sediment transfer to the downstream rivers. The alteration of the natural flow regime has been a key factor leading to the degradation of riverine ecosystems (Bunn and Arthington, 2002), and the interruption of sediment fluxes has deprived downstream river ecosystems of important sediment supplies to rejuvenate benthic, riparian and floodplain habitats (Petts and Gurnell, 2013). The trapping of sediment in reservoirs also results in a loss of reservoir capacity and a reduction in reservoir life (Kondolf, 1997). In reservoir operating schemes, both the needs of reservoirs and the twin needs of river ecosystems, natural flow and sediment regimes should be considered and must be balanced against the needs of water supply to humans.

Incorporating environmental flows (e-flows) into reservoir operating rules is becoming a key method to maintain the sustainability of riverine ecosystems downstream from dams. Usually, only the minimum e-flows are considered in dam operating schemes (Homa and Vogel, 2005; Jager and Smith, 2008). However, because the provision of minimum e-flows cannot sustain the whole river ecosystem, which requires the entire range of flow variability (Poff et al., 1997), many researchers tried to establish new e-flow provision methods that could reduce the alteration of natural flow regimes. For example, Suen and Eheart (2006) set the minimization of natural flow regime alteration as the objective of e-flow provision. Yin et al. (2010, 2011, 2012) also proposed three types of e-flow management strategies and suggested to trigger different strategies according to the water storage in a reservoir. These methods are suitable for rivers with low sediment load and reservoirs without an obvious sedimentation problem. For rivers with high sediment loads, strategies should be developed to reduce reservoir sedimentation and deliver sediment to the downstream rivers, mimicking the natural sediment conditions. Failure to supply sediment to downstream rivers has led to rapid and dramatic change to downstream riverine ecosystems (Petts and Gurnell, 2013).

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To reduce reservoir sedimentation and deliver sediment to the downstream rivers, sediment flushing has been proposed due to its relatively high effectiveness and low cost (Shen and Lai, 1996; Chang et al., 2003; Khan and Tingsanchali, 2009; Wang and Hu, 2009). Sediment flushing needs to be balanced with other objectives of reservoirs such as water supply. Reservoir operating rule curves (RORCs) are the most commonly used tools to direct water supply. Thus, some scientists have tried to balance the requirements of water supply and sedimentation control by incorporating sediment flushing needs into the determination process of RORCs. Chang et al. (2003) were the first to conduct this research. They innovatively adopted the water inflows in May (the beginning of monsoon) as the trigger of full drawdown sediment flushing (i.e., starting the flushing operation if the reservoir inflow is greater than the specified criteria) and applied the genetic algorithm to optimize the flushing operating rule curves. Because this method applied the sediment evacuation routine only during the flushing period, Khan and Tingsanchali (2009) proposed the Reservoir Optimization–Simulation with Sediment Evacuation model with sediment evacuation routines applied at each time step throughout the simulation duration and adopted the reservoir inflow and water level during the wet season as the triggers of sediment flushing. The model also utilized genetic algorithm based optimization capabilities and embedded the sediment evacuation module into the determination process of RORCs. These methods incorporate sediment flushing into regular reservoir operation, and are useful to address the sedimentation problem and deliver sediment to the downstream rivers. From the perspective of river protection and water supply, the following issues need to be further considered. First, the provision of e-flows is not considered in these new methods. It is necessary to combine e-flow provision with water supply and sediment flushing. E-flow provision should not only consider the minimum e-flows, but should try to reduce the alteration of the natural flow regime (Poff et al., 2010). Second, drawdown flushing requires the reduction of reservoir water level. Water releases from a reservoir are directed by RORCs, originally designed to direct water supply, and thus essentially the present style of RORCs may not be effective enough to address the two conflicting needs of high water supply and high sediment flushing. RORCs tend to be fixed to one group of curves, i.e., "static" curves. An alternative is to adopt different groups of RORCs for sediment-flushing and non-sediment-flushing years, i.e., "dynamic" curves. It is valuable to do research on how to change the "static" RORCs to "dynamic" ones aimed at addressing the conflicting needs of high water supply and high sediment flushing.

In this research, a reservoir operating method is developed to (a) supply flows and sediments to downstream riverine ecosystems, (b) extend the life of reservoirs and (c) meet the planned human water supplies in a river with moderate sediment loads. For river protection, the twin needs of river ecosystems, natural flow and sediment regimes, are considered simultaneously. E-flows management rules are combined with water supply and sediment flushing rules, and RORCs are changed from "static" to "dynamic" ones. The proposed method is applied to the Wangkuai Reservoir, China to demonstrate its effectiveness.

2. Methods

2.1. Sediment management rules

Sediment is delivered to downstream rivers together with daily water releases for e-flow provision and water supply and also by occasional drawdown flushing. Due to the conflict between water supply and drawdown flushing, it is not necessary to conduct sediment flushing every year. A reasonable alternative is to trigger the drawdown flushing under specified conditions. The favorable sediment-flushing conditions should be low reservoir water level (so less water is lost when the reservoir is drawn down) and high sediment-occupied ratio of reservoir space (so enough deposited sediment is available for flushing) before the drawdown flushing. The triggers and flushing frequency depend on the planned water supply reliability, e-flow provision target and planned lifetime of the reservoir, etc. In this research, we propose three triggers for sediment flushing, i.e. the water level at the beginning of the wet season H_{ft}, the sediment-occupied ratio of reservoir space (in this research, the reservoir space is set equal to the sum of the dead and effective storage spaces) at the beginning of the wet season R_{ft}, and the increase of R_{ft} (RR_{ft}) during one previous year. Combining the three triggers, we design the following sediment flushing rules.

(1) When the water level H_{ft} is lower than the specified reservoir water level H_f at the beginning of the wet season,
- if the present sediment-occupied ratio of reservoir space R_{ft} is greater than a specified ratio $R_{f,1}$ at the beginning of the wet season, sediment drawdown flushing will be conducted in this year;
- if the present ratio R_{ft} is less than or equal to $R_{f,1}$ at the beginning of the wet season, sediment drawdown flushing will not be conducted in this year.

(2) When the water level H_{ft} is greater than or equal to the specified reservoir water level H_f at the beginning of the wet season,
- if the present ratio R_{ft} is greater than a specified ratio $R_{f,2}$ ($R_{f,2} \geqslant R_{f,1}$) at the beginning of the wet season and the increase of R_{ft} (RR_{ft}) during one previous year is greater than a specified ratio RR_f, sediment drawdown flushing will be conducted in this year;
- if the present ratio R_{ft} is less than or equal to $R_{f,2}$ at the beginning of the wet season or the increase of R_{ft} during one previous year is less than or equal to RR_f, sediment flushing will not be conducted in this year.

In these sediment flushing rules, one previous year's increase of R_{ft} is adopted as an additional condition for drawdown flushing when the water level is not low enough at the beginning of wet season. If this trigger is not used, the drawdown flushing would be very frequent after many years of sediment accumulation, which would significantly reduce the water supply. The method to determine the parameters H_f, $R_{f,1}$, $R_{f,2}$ and RR_f will be given in Section 2.6. In addition, other reservoir operating parameters also need to be optimized to promote sediment delivery to downstream reaches together with daily water releases.

2.2. Human water supply rules

RORCs are the most widely used tools for directing water supply. Typically, three RORCs are used: the upper, lower and critical limit curves (Fig. 1). The main function of the upper limit curve is for flood control. It is determined by means of simulations during reservoir design without the consideration of sediment management. It seeks to be high enough to store more water in the reservoir for future use under the condition of maintaining the reservoir's flood control function. This curve will also obviously influence sediment drawdown flushing. High location of the upper limit curve can result in high reservoir water level, which is beneficial for water supply. However, the water level may not be drawn low enough for flushing before the sediment flushing period; consequently, reservoir operators need to release a great amount of water within a short time to draw down the reservoir water level, which could cause severe negative impacts on riverine ecosystem. Conversely, if the upper limit curve is set low enough, the water
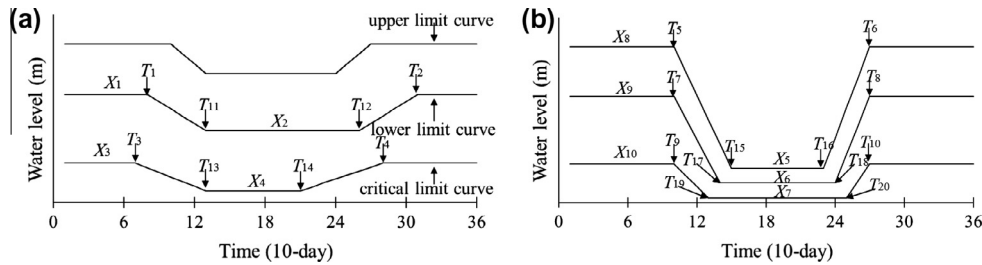
Fig. 1. Reservoir operating rule curves in the (a) non-sediment-flushing and (b) sediment-flushing years.

level can be drawn low enough for flushing but during the non-sediment-flushing years this will lead to considerable water loss.

In this paper, we design two groups of RORCs for the non-sediment-flushing (Fig. 1a) and sediment-flushing (Fig. 1b) years. The upper limit curve for the non-sediment-flushing year adopts the original curve established during reservoir design stage to maintain the reservoir's flood control function, while the lower and critical limit curves are optimized. The RORCs for the sediment-flushing year will be designed to effectively promote sediment flushing.

Following Yin et al. (2011), we use the following rules for human water supply, and they are applied to both the sediment-flushing and non-sediment-flushing rule curves.

(a) If a high flow event (flood or high flow pulse) is to be released to the downstream river, the needs of the human population are met first.
(b) If the high flow event is to be stored by the reservoir, different hedging rules are adopted for water supply.
- when the reservoir water level is above the upper limit curve, the release should be increased to lower the water level to the upper limit curve, which will still ensure adequate water supply for human populations;
- when the reservoir water level is between the upper and lower limit curves, the planned water supply can be delivered;
- when the water level is between the critical and lower limit curves, the water supply will be decreased by α percent;
- when the water level is below the critical limit, the water supply will be decreased by β percent.

where the coefficients α and β are determined by reservoir operators empirically (Tu et al., 2008). The parameters X_i ($i = 1, 2, \ldots, 10$) and T_j ($j = 1, 2, \ldots, 20$) will be optimized in this research.

The reservoir water level H_{ft}, sediment-occupied ratio of reservoir space R_{ft} and increase rate of R_{ft} are the triggers of the sediment flushing process, and are also triggers of different groups of RORCs. With the help of the three triggers the RORCs will not fix to one group and can change from "static" to "dynamic" ones.

2.3. Environmental flow management rules

In the previous research by Yin et al. (2011), an e-flow management method was developed, which consisted of preferred, acceptable and basic e-flow management strategies corresponding to different expected levels of river ecosystem protection. The preferred strategy seeks to maintain the key ecological functions of flows, in which all the high flow events (floods and high flow pulses) are required to be released with the modification of flow magnitude. Its use is restricted to the situation of sufficient water available because of its high allocation of water to ecosystem needs. The acceptable strategy seeks to sustain specific ecological functions, in which the number of released high flow events is

no more than specified values. The basic strategy seeks to provide a minimum degree of ecosystem protection, in which all the high flow events is trapped in the reservoir. The reservoir space is divided into three zones. When the water level is in different zones, different e-flow management strategies are adopted. This method can effectively maintain the key ecological functions of rivers, and is also effective to balance the water requirements of humans and ecosystems. In this method, several parameters need to be determined, including H_1 and H_2 (for simplicity, the parameters H_1 and H_2 are time-independent in this paper), which are the parameters used to divide the reservoir space, I_i ($i = 1, 2, 3$), which is the parameter used to divide the inflow into four flow periods, and M_a ($a = 1, 2, \ldots, 12$), which is the parameter specifying the planned maximum number of high flow events in each month. The method to determine these parameters will be given in Section 2.6. The details of the e-flow management method can refer to Yin et al. (2011).

In this research, we adopt the e-flow management method with one modification. During the wet season of a sediment-flushing year, the preferred e-flow strategy (a strategy that releases the greatest amount of water among the three strategies) is always adopted to effectively draw down the reservoir water level and also benefit riverine ecosystems.

Besides, The RORCs are always used to direct water supply under different e-flow management strategies due to their wide application. This setting can facilitate the application of the proposed method in real-world reservoir operation. However, we don't propose to design different groups of RORCs for different e-flow management strategies. If three different groups of RORCs are respectively designed for the three types of e-flow management strategies, together with the requirements of two different RORCs for the sediment-flushing and non-sediment-flushing years, six groups of RORCs need to be designed and applied in real-world reservoir operating. The use of six groups of RORCs will significantly increase the complexity of reservoir operation.

2.4. Sediment transport model

In this research, we applied the Schoklitsch transport model to calculate the sediment released from reservoirs, based on its widespread use in research on sedimentation control (Schoklitsch, 1934; Nicklow and Mays, 2001), but more sophisticated models (Parker, 2008) can be used instead if sufficient data are available.

The Schoklitsch transport formula is expressed as

$$G = \frac{S^{3/2}}{d^{1/2}}\left(15.4Q - \frac{0.02dW}{S^{4/3}}\right) \tag{1}$$

where G is the mass rate of sediment transport (kg/s); d is the mean grain size diameter (m); Q is the water discharge at a cross-section (m³/s); and W is the channel width (m), S is the energy slope (m/m). The parameters W and S vary during the process of reservoir operation. Many published papers have given their determination methods (Atkinson, 1996; Chang et al., 2003; Kawashima et al.,

2003; Khan and Tingsanchali, 2009). Readers can refer to Khan and Tingsanchali (2009) for details.

2.5. Method for measuring riverine ecosystem needs

Reducing the alteration of natural flow regime is a key principle for river protection and e-flow provision (Poff et al., 1997, 2010). In this study the minimization of natural flow regime alteration degree was set as one ecosystem protection objective for optimizing reservoir operations. The Range of Variability approach (RVA) (Richter et al., 1996, 1997, 1998) has been widely used for assessing flow regime alteration (Galat and Lipkin, 2000; Shiau and Wu, 2004, 2006, 2007, 2008; Zhang et al., 2009), and is also employed in this research with a small modification. The selected hydrological indicators (Table 1) do not include the mean flow for each calendar month which has been related to habitat availability (Richter et al., 1996), because the proposed e-flow management method is effective to maintain this ecological function and the exclusion of these indicators could highlight the alteration of other indicators (Yin et al., 2011, 2012).

As mentioned in the introduction, a natural sediment regime is required for river ecosystem protection. At present there are no widely accepted models to quantitatively measure the degree of sediment regime alteration that could reflect the relationship between the alteration degree and riverine ecosystem degradation. In this research, we simply develop a metric to reflect the sediment regime alteration according to the annual sediment trapping efficiency. The metric is shown as follows.

$$DS_k = min\left(1, \left|\frac{SI_k - SO_k}{SI_k}\right|\right) \qquad (2)$$

$$DS = \frac{1}{T}\sum_{k=1}^{T} DS_k \qquad (3)$$

where DS_k is the alteration of sediment transfer for year k; SI_k is the sediment inflow for year k; SO_k is the sediment outflow for year k; T is the year number of the time series; DS is the degree of sediment regime alteration.

Table 1
Flow regime alteration under the specified water supply and sediment control objectives. The value in each row represents the alteration degree for each hydrologic indicator when the water supply and reliability are set at 15 m^3/s and 80%.

Group	Indicator	Value
Group 1	1-Day minimum flow	0.1
	1-Day maximum flow	0.3
	3-Day minimum flow	0.3
	3-Day maximum flow	0.3
	7-Day minimum flow	0.3
	7-Day maximum flow	0.3
	30-Day minimum flow	0.7
	30-Day maximum flow	0.7
	90-Day minimum flow	1
	90-Day maximum flow	1
Group 2	Date of 1-day minimum flow	0.2
	Date of 1-day maximum flow	0.3
Group 3	High pulse number	0.8
	Low pulses number	0.4
	High pulse duration	0.8
	Low pulse duration	0.4
Group 4	Flow rise rate	1
	Flow fall rate	0.9
	Number of flow rise	1
	Number of flow fall	1
Overall alteration		0.59

For riverine ecosystem protection, it is required to minimize the alteration of both the flow and sediment regimes. The two metrics for the alteration of flow and sediment regimes are combined into one to represent the overall requirement of the riverine ecosystems. The weighted-average method is applied as follows.

$$D = wDF + (1 - w)DS \qquad (4)$$

where D is the overall alteration degree of flow and sediment regimes; DF is the alteration degree of flow regime; w is the weighting factor. D, DF and DS are all between 0 and 1. In this research, we simply consider the maintenance of flow and sediment regimes to have equal significance, and set w at 0.5. More sophisticated metrics could be developed after the advance of quantitative relationships among ecological degradation and sediment and flow regime alterations.

2.6. Reservoir operation objective, constraints and methods of solution

In this paper, the reservoir operation objective (L) is set to minimize the overall alteration degree of flow and sediment regimes (D) subject to the planned water supply reliability and specified ratio of reservoir storage occupied by sediment. The optimization problem can be described by the following equations.

$$L = min(D) \qquad (5)$$

$$Subject \ to: \ R \geqslant R_0 \qquad (6)$$

$$RC \leqslant RC_0 \qquad (7)$$

where R is the actual water supply reliability (volume-based in this study); R_0 is the planned water supply reliability (volume-based); RC is the actual ratio of deposited reservoir storage space (in this research, the reservoir space is set equal to the sum of the dead and effective storage spaces) over a planned period; RC_0 is the planned ratio of deposited reservoir storage space over a planned period. The evaporation loss is not considered in this paper.

The values of D, R and RC were influenced by the parameters I_k ($k = 1, 2, 3$), M_a ($a = 1, 2, \ldots, 12$), X_i ($i = 1, 2, \ldots, 10$), T_j ($j = 1, 2, \ldots, 20$), H_i ($i = 1, 2$), H_f, $R_{f,1}$, $R_{f,2}$ and RR_f. Following the previous research, I_1, I_2 and I_3 were set equal to the sum of the bankfull discharge and the planned water abstraction, the sum of the seasonal baseflow and the planned water supply, and the seasonal baseflow, respectively (Yin et al., 2011, 2012).

In the previous research, the parameters of the reservoir operating rules X_i ($i = 1, 2, \ldots, 10$) and T_j ($j = 1, 2, \ldots, 20$) were optimized by genetic algorithm (Chang and Chang, 2001; Chen, 2003; Chen et al., 2007; Tu et al., 2008; Yin et al., 2010, 2011, 2012). To reduce the optimization variable number, we introduce the following simplification. T_j ($j = 1, 3, 5, 7, 9$) are set at the beginning of the wet season; parameters T_j ($j = 2, 4, 6, 8, 10$) are set at the end of the wet season; X_8 is set equal to the water level of the upper limit curve in the dry season of the non-sediment flushing year with X_9 equal to X_1 and X_{10} equal to X_3, which could also avoid the sudden change of water release at the beginning/end of a year. The parameters X_i ($i = 1, 2, \ldots, 7$) and T_j ($j = 11, 12, \ldots, 20$) are to be optimized. They subject to the following constraints.

The constraints for X_i and T_j are as follows (Chen, 2003):

$$MAXlevel > X_1 > X_2 \qquad (8)$$

$$MAXlevel > X_1 > X_3 \qquad (9)$$

$$X_2 > X_4 > MINlevel \qquad (10)$$

$$X_3 > X_4 > MINlevel \qquad (11)$$

MAXlevel $> X_8 > X_5$ (12)

MAXlevel $> X_9 > X_6$ (13)

MAXlevel $> X_{10} > X_7$ (14)

$X_5 > X_6 > X_7 >$ MINlevel   (15)

where MAXlevel is the maximum allowable storage level; MINlevel is the minimum admissible storage level. Parameters Xi are closely related to the effects of sedimentation control. In this paper, their constraints follow previous published papers (Chang and Chang, 2001; Chen, 2003; Yin et al., 2010, 2011, 2012), and no more specific and strict constraints are established according to the requirement of sedimentation control. It is because the requirement of sedimentation control needs to be balanced with the requirements of water supply and e-flow provisions. These relatively loose constraints for X_i allow the reservoir operators to balance different requirements more flexibly.

We define the constraints for T_j ($j = 11,12,\ldots,20$) as follows:

WetBeg $< T_{11} < T_{12} <$ WetEnd   (16)

WetBeg $< T_{13} < T_{14} <$ WetEnd   (17)

WetBeg $< T_{15} < T_{16} <$ WetEnd   (18)

WetBeg $< T_{17} < T_{18} <$ WetEnd   (19)

WetBeg $< T_{19} < T_{20} <$ WetEnd   (20)

where WetBeg is the beginning time of the wet season; WetEnd is the end time of the wet season.

The constraints for H_f, $R_{f,1}$, $R_{f,2}$, RR_f and H_i ($i = 1,2$) are as follows:

MAXlevel $\geqslant H_f \geqslant$ MINlevel   (21)

$1 \geqslant R_{f,2} \geqslant R_{f,1} \geqslant 0$ (22)

$1 \geqslant RR_f \geqslant 0$ (23)

MAXlevel $\geqslant H_1 \geqslant H_2 \geqslant$ MINlevel   (24)

To illustrate the method we used a simple set of three e-flow values. Two baseflows (minimum e-flows) for the wet and dry seasons are determined by the widely used Montana method (Tennant, 1976). While the Montana method is crude and fails to account for ecological differences among rivers, it is easy to apply (requiring only average flow data) and widely used for this reason. Future refinements of reservoir optimizations should be based on baseflow values determined from physical and ecological information for the river under study, but for our initial application of the approach, we used the Montana method flows of 30% of average daily flow for the wet season e-flow and 10% for the dry season e-flow. The third e-flow value was the bankfull discharge, and here we used the flow with average return period of 1.5 years ($Q_{1.5}$) (Wu et al., 2008), but it is clear from the literature that assumptions about the $Q_{1.5}$ being the 'channel-forming discharge' are simplistic in some climatic regions (Wolman and Gerson, 1978; Williams, 1978), and thus a geomorphically-significant bankfull discharge for a given river should be based on real information for the system under study. The adaptive genetic algorithm (AGA) was used to determine the optimal variable values (Srinivas and Patnaik, 1994).

3. Study site

To demonstrate the use of the new method, we apply it to the Wangkuai Reservoir on the Hai River in northern China with historical data from 1974 to 1993. The Wangkuai Reservoir has an effective storage capacity of 6.52×10^8 m^3, and a dead storage capacity of 0.88×10^8 m^3. The reservoir is a major hydraulic facility in the basin and supplies water to 13 counties. The flow and hypothetical sediment data are as follows. Annual inflow averages 18.05 m^3 s^{-1}, with standard deviation, coefficient of variation, and coefficient of skewness of 43.07 m^3 s^{-1}, 2.39 and 7.08, respectively. The average sediment concentration is 17 kg/m^3 and the mean grain size diameter is 0.03 mm; 80% of the sediment inflow occurs in the flood season (July, August and September), and the sediment load has an approximately positive linear relation with the reservoir inflow. The computation time interval of the optimization model is one day.

4. Results

The $Q_{1.5}$ of the Hai River at Wangkuai Reservoir was 122 m^3 s^{-1}. According to the Montana method, the seasonal baseflows for the dry (from November to April) and wet (from May to October) seasons are 1.8 m^3 s^{-1} (10% average daily flow) and 5.4 m^3 s^{-1} (30% average daily flow), respectively. Coefficients α and β are assumed to be equal to 20 and 30, respectively (Chang et al., 2005; Chen et al., 2007; Yin et al., 2011, 2012).

In our application of MATLAB 6.5 to determine the optimal parameter values of M_a, X_i, T_j, H_i, H_f, $R_{f,1}$, $R_{f,2}$ and RR_f via the AGA (Srinivas and Patnaik, 1994), and the corresponding water supply reliability, flow regime alteration and sediment deposition in the reservoir, the water supply yield and reliability were set at 15 m^3 s^{-1} and 80%, respectively. The sediment-occupied ratio of reservoir space is required to be no more than 10% over the planning horizon, and the population size and maximum generation number in the AGA were set at 500 and 2000, respectively.

The optimized H_f, $R_{f,1}$, $R_{f,2}$ and RR_f were equal to 183.2 m, 0.015, 0.07 and 0.0076, respectively. These parameters set the conditions for performing drawdown flushing. The two groups of optimized RORCs are shown in Fig. 2, indicating that the upper limit curve for the sediment-flushing year (Fig. 2a) is obviously lower than the original one designed for water supply (Fig. 2b), which can induce the sediment flushing.

Under these optimized reservoir operating parameters, the optimized sediment-occupied ratio of reservoir space in each year during the period of 1974–1993 is shown in Fig. 3. Over the planning horizon of 20 years, sediment flushing was implemented only 4 times, and during the remaining 16 years operating rules were adopted without consideration of sediment flushing. The deposited ratios during the 4th, 10th, 13th and 17th years are less than those during the previous year, reflecting the success of drawdown sediment flushing in these years and delivering sediment to the downstream river.

Under these optimized reservoir operating parameters, the overall degree of flow and sediment regime alteration D was 0.7, and the corresponding alteration degrees for flow and sediment regimes were 0.59 and 0.81, respectively. Table 1 listed the alteration degree for each hydrological indicator. In indicator group 1, the alterations of 6 of the 10 indicators were within the low alteration category (between 0 and 0.33) (Richter et al., 1996, 1997, 1998). It indicated that under the planned water supply and sediment delivery situation, the operating model could effectively maintain the characteristics of extreme flow magnitude. In group 2, the alteration for the dates of the annual 1-day minimum and maximum flows were also within low alteration category, reflecting the method's ability to sustain the timing of extreme flows. In indicator group 3, the number and duration of low pulses had moderate levels of alteration, while the number and duration of high pulses experienced very high alteration. This is mainly because most of
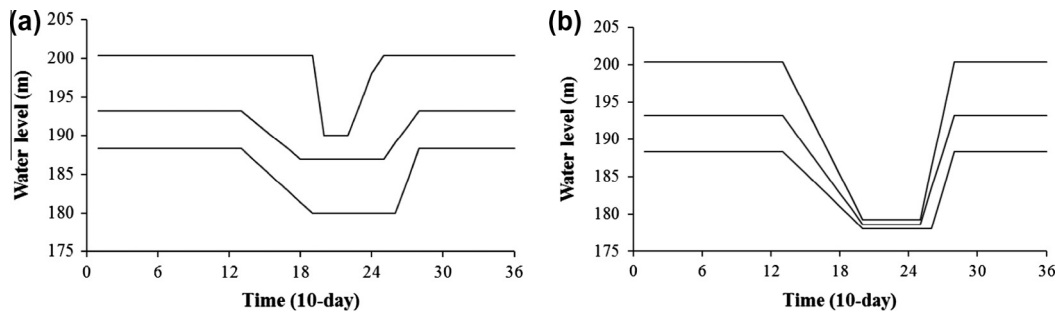
Fig. 2. Optimized reservoir operating rule curves in the (a) non-sediment-flushing and (b) sediment-flushing years. The planned water supply and reliability are set at 15 m³/s and 80%, respectively.

the high flows were stored by the reservoir for future water supply and the low flows were released to the downstream river as their natural magnitude. In the indicators of group 4, the rates of flow rise and fall, and the number of flow reversals were within the category of high alterations (between 0.67 and 1.0), because the flows on most operating days are fixed to the baseflows.

5. Discussion

5.1. Satisfaction of riverine ecosystem needs under different reservoir operating methods

We compare the effectiveness of the proposed method with five other possible reservoir operating methods in terms of water supply, sediment control and riverine ecosystem protection. The five methods include: (1) one group of RORCs is used. The upper limit curve is fixed as designed at the reservoir design stage, while the lower and critical limit curves are changed (Fig. 1a) according to the sedimentation control, water supply and river protection targets (method 1); (2) one group of RORCs are used. The upper limit curve as well as the lower and critical limit curve is to be optimized (method 2), i.e., one fixed group of sediment flushing rule curves (Fig. 1b) are always used; (3) two groups of RORCs (Fig. 1a and b) are used, and the reservoir water level is adopted as the sole trigger of sediment flushing (method 3); (4) two groups of RORCs (Fig. 1a and b) are used, and the sediment-occupied ratio of reservoir space is adopted as the sole trigger of sediment flushing (method 4); (5) two groups of RORCs (Fig. 1a and b) are used, and the increase of sediment-occupied ratio of reservoir space during one previous year is adopted as the sole trigger of sediment flushing (method 5). In these five methods, the e-flow management rules are the same as those proposed above.

The planned water supply was set at from 11 to 15 m³ s⁻¹ with a step of 1 m³ s⁻¹. The planned water supply was not set at a low value (such as 1 m³ s⁻¹) because very small planned water supply

significantly reduces the significance of reservoirs and seldom occurs in real-world water resources planning. The water supply reliability was also set at 80% and the sediment-occupied ratio of reservoir space was required to be no more than 10%. The water supply reliability, flow and sediment regime alteration and sediment deposition in the reservoir were also determined by MATLAB 6.5 using a genetic algorithm under the five methods as well as the proposed method. The results show that under method 1 the sediment-occupied ratio of reservoir space would exceed the allowed value of 10% over the planning horizon if the planned water supply was satisfied. Thus, method 1 is not effective for sedimentation control, and the upper limit curve has to be modified to counter sedimentation. Under methods 2, 3, 4 and 5 and the proposed method, the specified water supply and sedimentation control targets could be achieved. Their resulting minimum overall alteration of flow and sediment regimes is shown in Fig. 4. The more serious the overall alteration of the natural flow and sediment regimes, the worse the condition of the riverine ecosystem (Poff et al., 1997, 2010). Fig. 4 shows that the overall flow and sediment regime alteration under method 2 is always no less than that under the other three methods, and under the proposed method the alteration is always no greater than that under the other four methods. Actually, method 2 is a commonly used method for sedimentation control and water supply in reservoir operation (Chang et al., 2003; Khan and Tingsanchali, 2009). Thus, it is reasonable to use two groups of RORCs for sediment-flushing and non-sediment-flushing years and adopt reservoir water level, sediment-occupied ratio of reservoir space and its increase rate as the triggers of sediment flushing. The use of two RORC groups and three triggers improves the flexibility for the reservoir operators to balance the needs of water supply, sediment control and ecosystem protection.
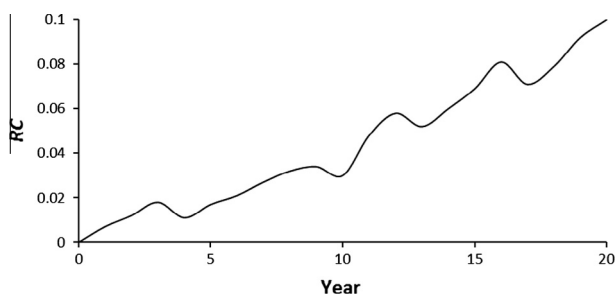

Fig. 3. The sediment-occupied ratio of reservoir space (RC) for each year during the period of 1974–1993 under the optimized reservoir operating parameters. The planned water supply and reliability are set at 15 m³/s and 80%, respectively.
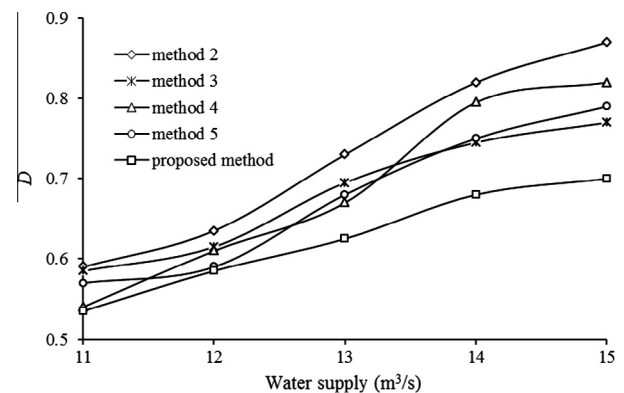

Fig. 4. The overall alteration of the natural flow and sediment regimes (D) for different sediment management methods. The planned water supply reliability is set at 80%.
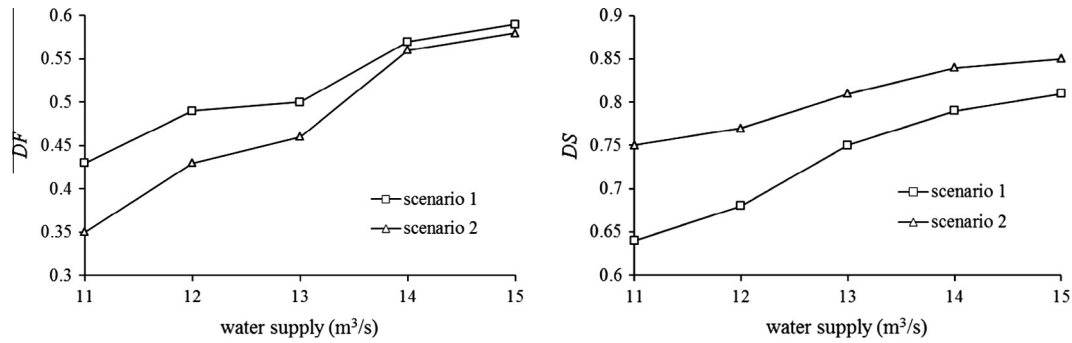
Fig. 5. The alteration degree of flow regime (DF) and sediment regime (DS) with different optimization objectives. Under scenario 1, the objective is to minimize the overall degree of flow and sediment regime alteration; Under scenario 2, the objective is to minimize only the degree of flow regime alteration (scenario 2). The planned water supply reliability is set at 80%.

Table 2
Flow and sediment regime alterations under different scenarios of optimization objectives. The planned water supply reliability is set at 80%.

Indicator	WS = 11 m³/s		WS = 12 m³/s		WS = 13 m³/s		WS = 14 m³/s		WS = 15 m³/s	
	S 1	S 2	S 1	S 2	S 1	S 2	S 1	S 2	S 1	S 2
D	0.54	0.55	0.59	0.6	0.63	0.64	0.68	0.7	0.7	0.72
DF	0.43	0.35	0.49	0.43	0.5	0.46	0.57	0.56	0.59	0.58
DS	0.64	0.75	0.68	0.77	0.75	0.81	0.79	0.84	0.81	0.85
1-Day minimum flow	0.1	0.1	0.2	0.2	0.1	0.2	0.1	0.1	0.1	0.1
1-Day maximum flow	0.3	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.3	0.2
3-Day minimum flow	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.3	0.2
3-Day maximum flow	0.1	0.2	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.2
7-Day minimum flow	0.3	0.1	0.2	0.1	0.3	0.1	0.2	0.2	0.3	0.3
7-Day maximum flow	0.1	0.1	0.2	0.1	0.2	0.2	0.3	0.2	0.3	0.3
30-Day minimum flow	0.1	0.2	0.4	0.2	0.4	0.3	0.4	0.4	0.7	0.5
30-Day maximum flow	0.2	0.1	0.6	0.4	0.5	0.5	0.6	0.5	0.7	0.8
90-Day minimum flow	1	0.6	1	1	1	1	1	1	1	1
90-Day maximum flow	1	0.7	1	1	1	1	1	1	1	1
Date of 1-day minimum flow	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.2	0.2
Date of 1-day maximum flow	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.3	0.2
High pulse number	0.2	0.1	0.4	0.3	0.6	0.4	0.7	0.9	0.8	0.7
Low pulses number	0.2	0.1	0.4	0.3	0.4	0.3	0.6	0.5	0.4	0.6
High pulse duration	0.5	0.3	0.5	0.4	0.6	0.4	0.9	0.9	0.8	0.8
Low pulse duration	0.3	0.2	0.5	0.2	0.4	0.3	0.8	0.8	0.4	0.6
Flow rise rate	0.9	0.9	1	1	1	1	1	1	1	1
Flow fall rate	1	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Number of flow rise	1	1	1	1	1	1	1	1	1	1
Number of flow fall	1	1	1	1	1	1	1	1	1	1

Note: WS is the planned water supply; S1 is scenario 1; S2 is scenario 2.

5.2. Comparison of flow and sediment regime alteration with and without considering sediment regime maintenance

In this research, the maintenance of natural sediment regime is set as one reservoir operation objective for riverine ecosystem protection. It is different from traditional research on eco-friendly reservoir operation schemes in which the maintenance of natural flow regime is usually considered as the sole ecological objective (Yin et al., 2011, 2012; Suen and Eheart, 2006; Shiau and Wu, 2013). Here, we further explore the effects of setting the maintenance of the sediment regime as one objective.

The water supply was set at from 11 to 15 m³ s⁻¹ with a step of 1 m³ s⁻¹; the water supply reliability was set at 80%, and the sediment-occupied ratio of reservoir space was required to be no more than 10%. The optimization objective was set to minimize the overall degree of flow and sediment regime alteration (scenario 1) and only to minimize the degree of flow regime alteration (scenario 2). The degrees of flow and sediment regime alteration are shown in Fig. 5 and Table 2 under the two optimization objective scenarios. This indicates that setting sediment regime maintenance as one objective can reduce the alteration of sediment regime (i.e.

improvement of the sediment regime maintenance effect), but it will lead to the increase of the degree of flow regime alteration (i.e. degradation of the flow regime maintenance effect). As the planned water supply increases, the difference in the degree of flow/sediment regime alteration decreases under the two objective scenarios. When the water supply is high, with the constraint of specified sediment-occupied ratio of reservoir space the reservoir schemes do not differ greatly under the two optimization objective scenarios. In contrast, when the water supply is low, more water is available for e-flow provision and sediment delivery, leading to greater difference in the degree of flow/sediment regime alteration under the two objective scenarios.

5.3. Constraints of the downstream sediment concentration

Drawdown flushing is effective in reducing reservoir sedimentation and delivering sediments to the downstream river, but research has also demonstrated the ecological impacts of drawdown flushing. For example, aquatic life may be damaged, fishes may be killed and spawning areas clogged (Melis et al., 2012). One major cause of the negative ecological impacts is that

sediments with too high and uncontrolled concentrations are sent to the downstream rivers. Too high concentration of sediments for several hours or even several minutes could lead to dramatic ecological impacts.

In this research, due to the absence of results of ecologically acceptable sediment concentration, the sediment concentration constraints are not considered. To reduce the ecological impacts of drawdown flushing, it is necessary to perform research on ecologically acceptable sediment concentrations, in which several sediment concentration thresholds together with acceptable durations (minutes, hours, days) could be determined. These thresholds could be incorporated into the reservoir operating scheme to constrain sediment flushing. Real-time measurement of sediment concentrations could be performed by Gamma Ray devices and other complementary methods (such as Picnometre and Pan Cake method) (Fruchart and Camenen, 2012).

6. Conclusions

Riverine ecosystem protection requires the maintenance of natural flow and sediment regimes but this must be balanced by provision for water-supply needs and the protection of reservoir storage. Traditional research on eco-friendly reservoir operating methods has usually only considered the riverine ecosystem's needs for a natural flow regime and the needs for natural sediment regime have been neglected. It is difficult to balance the three competing water requirements in reservoir operation due to water storage limitations. In this research, a reservoir operating method is proposed to account for the twin needs of river ecosystems (natural flow and sediment regimes) that deals with the three requirements (riverine ecosystem protection, water supply and reservoir storage capacity protection) simultaneously. The following conclusions are reached.

- The new method is a promising approach to address the needs of water supply, sedimentation control and riverine ecosystem provision. Compared with other methods, this method results in a lower degree of flow and sediment regime alteration, subject to specified water supply and sediment control targets. Less flow and sediment regime alteration will lead to less degradation of the riverine ecosystem.
- This method proposes to develop two different groups of reservoir operating rule curves (RORCs) for the sediment-flushing and non-sediment flushing years, respectively. The reservoir water level, sediment-occupied ratio of reservoir space at the beginning of the wet season and the ratio's increase rate are adopted as three triggers of different RORCs to change the "static" RORCs to "dynamic" ones, allowing the reservoir operators more flexibility to satisfy the needs of water supply, sediment control, and flow and sediment regime maintenance.

Despite the advantages of the proposed method, many aspects can be considered for further improvement of the method. The ideal year for drawdown flushing is the year when the reservoir water level is low at the beginning of the wet season (so less water supply is lost when the reservoir is drawn down) and in a wet year when there will be sufficient water inflow to refill the reservoir. However, to date the inflow forecast can only predict the inflow on the short term; the kind of long-term forecast needed for these reservoir management decisions is not sufficiently precise. Thus, the long-term forecasted inflow is not adopted as a trigger of sediment flushing in this proposed approach. However, if the long-term inflow forecasting improves, it can be adopted as another trigger.

In addition, another important factor is that cohesive sediments can 'set' over time, so it becomes more difficult to flush them the longer they remain in the reservoir, or mechanical disturbance may be needed to make the sediment more mobile. Thus, a sediment transport model should ideally take this effect into account, which encourages more frequent flushing.

References

Atkinson, E., 1996. The Feasibility of Flushing Sediment from Reservoirs. HR Wallingford, Oxon.

Bunn, S.E., Arthington, A.H., 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environ. Manage. 30, 492–507. http://dx.doi.org/10.1007/s00267-002-2737-0.

Chang, L.C., Chang, F.J., 2001. Intelligent control for modelling of real-time reservoir operation. Hydrol. Process. 15, 1621–1634.

Chang, F.J., Lai, J.S., Kao, L.S., 2003. Optimization of operation rule curves and flushing schedule in a reservoir. Hydrol. Process. 17 (8), 1623–1640.

Chang, F.J., Chen, L., Chang, L.C., 2005. Optimizing the reservoir operating rule curves by genetic algorithms. Hydrol. Process. 19 (11), 2277–2289.

Chen, L., 2003. Real coded genetic algorithm optimization of long term reservoir operation. J. Am. Water Resour. Assoc. 39 (5), 1157–1165. http://dx.doi.org/10.1111/j.1752-1688.2003.tb03699.x.

Chen, L., McPhee, J., Yeh, W.W.G., 2007. A diversified multiobjective GA for optimizing reservoir rule curves. Adv. Water Resour. 30 (5), 1082–1093. http://dx.doi.org/10.1016/j.advwatres.2006.10.001.

Fruchart, F., Camenen, B., 2012. Reservoir Sedimentation Different Type of Flushing - Friendly Flushing: Example of Genissiat Dam Flushing. ICOLD International Symposium on Dams for a Changing World, Kyoto, Japan.

Galat, G.L., Lipkin, R., 2000. Restoring ecological integrity of great rivers: historical hydrographs aid in defining reference conditions for the Missouri River. Hydrobiologia 422 (423), 29–48. http://dx.doi.org/10.1023/A:1017052319056.

Homa, E.S., Vogel, R.M., 2005. An optimization approach for balancing human and ecological flow needs. In: Proceedings of the EWRI 2005 World Water and Environmental Resources Congress. ASCE, Anchorage, Alaska.

Jager, H.I., Smith, B.T., 2008. Sustainable reservoir operation: can we generate hydropower and preserve ecosystem values. River Res. Appl. 24, 340–352.

Kawashima, S., Johndrow, T.B., Annandale, G.W., Shah, F., 2003. Reservoir Conservation Vol II: Rescon Model and UserManual. The World Bank, Washington, DC.

Khan, N.M., Tingsanchali, T., 2009. Optimization and simulation of reservoir operation with sediment evacuation: a case study of the Tarbela Dam, Pakistan. Hydrol. Process. 23, 730–747.

Kondolf, G.M., 1997. Hungry water: effects of dams and gravel mining on river channels. Environ. Manage. 21 (4), 533–551.

Melis, T.S., Korman, J., Kennedy, T.A., 2012. Abiotic & biotic responses of the Colorado River to controlled floods at Glen Canyon Dam, Arizona, USA. River Res. Appl. 28, 764–776. http://dx.doi.org/10.1002/rra.1503.

Nicklow, J.W., Mays, L.W., 2001. Optimal control of reservoir releases to minimize sedimentation in rivers and reservoirs. J. Am. Water Resour. Assoc. 37, 197–211.

Nilsson, C., Reidy, C.A., Dynesius, M., et al., 2005. Fragmentation and flow regulation of the world's large river systems. Science 308, 405–408.

Parker, G., 2008. Transport of Gravel and Sediment Mixtures. Sedimentation Engineering: Theory, Measurements, Modeling and Practice (ASCE Manuals and Reports on Engineering, Practice. No. 110), pp. 165–251.

Petts, G.E., Gurnell, A., 2013. Hydrogeomorphic effects of reservoirs, dams, and diversions. In: Shroder, J. (Ed.), Treatise on Geomorphology. Elsevier Science & Technology, New York, pp. 13:96–114.

Poff, N.L., Allan, J.D., Bain, M.B., et al., 1997. The natural flow regime: a paradigm for river conservation and restoration. Bioscience 47, 769–784.

Poff, N.L., Richter, B.D., Arthington, A.H., 2010. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. Freshwater Biol. 5 (1), 147–170. http://dx.doi.org/10.1111/j.1365-2427.2009.02204.x.

Richter, B.D., Baumgartner, J.V., Powell, J., et al., 1996. A method for assessing hydrologic alteration within ecosystems. Conserv. Biol. 10, 1163–1174.

Richter, B.D., Baumgartner, J.V., Wigington, R., et al., 1997. How much water does a river need. Freshwater Biol. 37, 231–249.

Richter, B.D., Baumgartner, J.V., Braun, D.P., et al., 1998. A spatial assessment of hydrologic alteration within a river network. Reg. Rivers Res. Manage. 14 (4), 329–340.

Schoklitsch, A., 1934. Der eeschiebetrieb und die geschiebefracht. Wasserkraft Wasserwirtschujl. 29 (4), 37–43.

Shen, H.W., Lai, J.S., 1996. Sustain reservoir useful life by flushing sediment. Int. J. Sed. Res. 11 (3), 10–17.

Shiau, J.T., Wu, F.C., 2004. Feasible diversion and instream flow release using range of variability approach. J. Water Resour. Plann. Manage. 130 (5), 395–404. http://dx.doi.org/10.1061/(ASCE)0733-9496(2004) 130:5(395.

Shiau, J.T., Wu, F.C., 2006. Compromise programming methodology for determining instream flow under multiobjective water allocation criteria. J. Am. Water Resour. Assoc. 42 (5), 1179–1191. http://dx.doi.org/10.1111/j.1752-1688.2006.tb05293.x.

Shiau, J.T., Wu, F.C., 2007. Pareto-optimal solutions for environmental flow schemes incorporating the intra-annual and interannual variability of the natural flow regime. Water Resour. Res. 43, W06433. http://dx.doi.org/10.1029/2006WR005523.

Shiau, J.T., Wu, F.C., 2008. A histogram matching approach for assessment of flow regime alteration: application to environmental flow optimization. River Res. Appl. 24, 914–928. http://dx.doi.org/10.1002/rra.1102.

Shiau, J.T., Wu, F.C., 2013. Optimizing environmental flows for multiple reaches affected by a multipurpose reservoir system in Taiwan: restoring natural flow regimes at multiple temporal scales. Water Resour. Res. 49, 565–584.

Srinivas, M., Patnaik, L.M., 1994. Adaptive probabilities of crossover and mutation in genetic algorithms. IEEE Trans. Syst. Man Cyber. 24, 656–667.

Suen, J.P., Eheart, J.W., 2006. Reservoir management to balance ecosystem and human needs: incorporating the paradigm of the ecological flow regime. Water Resour. Res. 42, W03417.

Tennant, D.L., 1976. Instream flow regimens for fish, wildlife, recreation and related environmental resources. Fisheries 1 (4), 6–10.

Tu, M.Y., Hsu, N.S., Tsai, F.T.C., et al., 2008. Optimization of hedging rules for reservoir operations. J. Water Resour. Plann. Manage. 134 (1), 3–13. http://dx.doi.org/10.1061/(Asce)0733-9496(2008) 134:1(3.

Wang, Z.Y., Hu, C., 2009. Strategies for managing reservoir sedimentation. Int. J. Sed. Res. 24 (4), 369–384.

Williams, G.P., 1978. Bankfull discharge of rivers. Water Resour. Res. 14 (6), 1141–1154.

Wolman, M., Gerson, R., 1978. Relative scales of time and effectiveness of climate in watershed geomorphology. Earth Surf. Proc. Land. 3 (2), 189–208.

Wu, B.S., Xia, J.Q., Fu, X.D., et al., 2008. Effect of altered flow regime on bankfull area of the Lower Yellow River, China. Earth Surf. Proc. Land. 33, 1585–1601.

Yin, X.A., Yang, Z.F., Yang, W., et al., 2010. Optimized reservoir operation to balance human and riverine ecosystem needs: model development, and a case study for the Tanghe reservoir, Tang river basin, China. Hydrol. Process. 24, 461–471. http://dx.doi.org/10.1002/Hyp.7498.

Yin, X.A., Yang, Z.F., Petts, G.E., 2011. Reservoir operating rules to sustain environmental flows in regulated rivers. Water Resour. Res. 47, W08509.

Yin, X.A., Yang, Z.F., Petts, G.E., 2012. Optimizing environmental flows below dams. River Res. Appl. 28, 703–716. http://dx.doi.org/10.1002/rra.1477.

Zhang, Q., Xu, C.Y., Chen, Y.Q., et al., 2009. Spatial assessment of hydrologic alteration across the Pearl River Delta, China, and possible underlying causes. Hydrol. Process. 23 (11), 1565–1574. http://dx.doi.org/10.1002/hyp.7268.