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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.

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