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ECOENG-2970; No. of Pages 8
ARTICLE IN PRESS

Ecological Engineering xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Ecological Engineering

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

Suitable range of reservoir storage capacities for environmental flow provision

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ARTICLE INFO

Article history:
Received 20 December 2013
Received in revised form 2 March 2014
Accepted 2 April 2014
Available online xxx

Keywords:
Environmental flow
Reservoir storage capacity
Reservoir design
Water supply

ABSTRACT

Environmental flow (e-flow) provision is a basic measure to mitigate the negative impacts of reservoirs on riverine ecosystems, and it is significantly influenced by reservoir storage capacity (RSC). Prior research has focused on the establishment of new reservoir operating rules for better e-flow provision and water supply. However, even if the reservoir operating rules are refined, their effects of ecological protection and water supply may not be as effective as expected under the conditions of improperly designed RSC. In response, this paper explores the influence of RSC on e-flows and determines a suitable range of RSCs from the perspectives of both e-flow provision and water supply. First, new reservoir operating rules were adopted to direct e-flow and human water provision, in which the e-flows were allowed to be less than the regulated e-flows following natural flow recession. Then, the index of amended annual proportional flow deviation was employed to assess the degree of flow regime alteration under different RSCs, and the genetic algorithm was applied to determine the suitable range of RSCs for e-flow provision under planned human water supply levels. The Wangkuai Reservoir in China was adopted as a case study. This research shows that such methods can lead to better tradeoffs between human and ecosystem needs by providing a suitable range of RSCs rather than only a minimum value.

1. Introduction

Reservoirs are important for controlling and managing river flows. By capturing river flows and releasing them in accordance with human purposes, reservoirs contribute greatly to society in terms of hydroelectric power generation, water supply assurance, and flood control (Cai et al., 2009, 2011; Shen and Xie, 2004). However, reservoirs are criticised for their negative effects on riverine ecosystems, such as impounding river habitats, blocking fish migration, deteriorating water quality, and interrupting geomorphological processes (Bunn and Arthington, 2002; Li et al., 2010; Petts, 1984, 2009).

Research has sought to establish new reservoir operation methods by incorporating environmental flows (e-flows) to mitigate the negative impacts of reservoirs. Most of these methods place an extra constraint on minimum reservoir releases, which are normally equal to the seasonal or monthly minimum e-flows (Jager and Smith, 2008; Chang et al., 2010). A few researchers attempted to satisfy e-flow requirements by maintaining natural flow regimes, aiming to protect biodiversity in rivers. Homa et al. (2005) developed the concept of an *ecodeficit* as the area between unregulated and regulated flow duration curves, and used it to quantify the alteration of a natural flow regime. Then, they took the minimisation of the ecodeficit as one indicator to compare the effectiveness of three hypothetical reservoir operating schemes. Suen and Eheart (2006) took the minimisation of natural flow regime alteration as one optimisation objective and used the non-dominated-sorting genetic algorithm to find the pareto-optimal set of operating rules. Yin et al. (2010, 2011, 2012) also proposed three e-flow management strategies and suggested triggering different strategies according to the water storage in a reservoir. These reservoir operation methods reduce the detrimental effects of reservoirs on ecosystems.

However, these methods only mitigate reservoirs' negative ecological impacts after construction. New measures are necessary at the reservoir design stage to better protect the health of

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http://dx.doi.org/10.1016/j.ecoleng.2014.04.002
0925-8574/

Please cite this article in press as: Yin, X.-A., et al., Suitable range of reservoir storage capacities for environmental flow provision. Ecol. Eng. (2014), http://dx.doi.org/10.1016/j.ecoleng.2014.04.002

riverine ecosystems. The reservoir storage capacity (RSC) is one major design parameter for a reservoir that influences water supply and e-flow provision (Vogel et al., 2007). Thus, it is important to determine an RSC that can satisfy both human and ecosystem needs. Effective methods have been developed to determine the required RSC for a planned water supply, such as the Rippl mass curve method, sequent peak algorithm, modified sequent peak algorithm, extended deficit analysis, behaviour analysis, and Vogel and Stedinger empirical method (Adeloye et al., 2001, 2010; McMahon and Adeloye, 2005; McMahon et al., 2007). These methods generally consider human demands for water without consideration of e-flow requirements. In addition, these methods focus on determining the minimum RSC required to deliver the planned water supply, and a larger RSC is not considered because larger RSC can lead to many problems such as greater reservoir construction cost and possible greater earthquake risk. Other capacities, greater than the minimum required value, may be more effective for reducing the negative ecological impacts of reservoirs. Thus, it is necessary to offer reservoir designers a range of RSCs rather than just the minimum value, for better trade-offs between human and ecosystem needs.

It is commonly thought that larger reservoirs impose more severe negative effects on riverine ecosystems. This argument may stem from the fact that reservoirs with larger storage capacities have a greater ability to store water and sediment, block fish migration, and produce greenhouse gas, etc. Indeed, no existing reservoir meets optimum conditions for river protection. As a result of increasing water pressure worldwide, reservoirs with large storage capacity must be constructed. Some measures can mitigate reservoirs' negative effects, such as eco-friendly reservoir operation schemes and construction of fish ladders. Increasing RSCs not only increase the possibility of more severe negative effects, but also offer greater ability to manipulate flows. Increased flow manipulation may improve the effectiveness of e-flow provision, because flow regime is the key driver of riverine ecosystems. Improving e-flow provision effectiveness can be beneficial for river protection, especially for rivers with low sediment loads and without migratory species or obvious greenhouse gas emission. The premise of this research is that e-flow provision effectiveness may be improved by carefully adjusting reservoir content and operating schemes.

In this paper, we explore the existence of a RSC that is greater than the minimum value required to deliver the planned water supplies and the prescribed e-flows and meanwhile is more effective to manipulate the e-flows. Then, we determine a suitable range of RSCs for e-flow provision under the constraints of planned water supplies. The minimum value in the range is the minimum required RSC that can deliver the planned water supply and the prescribed e-flows, while the maximum value is the capacity that reduces negative impacts to the lowest extent under the planned water supply. To demonstrate the effectiveness of the proposed methods, we present a case study of the Wangkuai Reservoir in China's Hai river basin.

2. Methodology

RSCs are expected to satisfy both human and riverine ecosystem needs. Meeting the planned water supply reliability is one major goal for reservoir construction and operation. However, meeting the planned reliability may alter the flow regime beyond the specified threshold. If the water supply reliability or the flow regime alteration degree is not properly planned, the two objectives may not be satisfied simultaneously no matter what RSCs are set. Thus, the determination of the maximum possible water supply

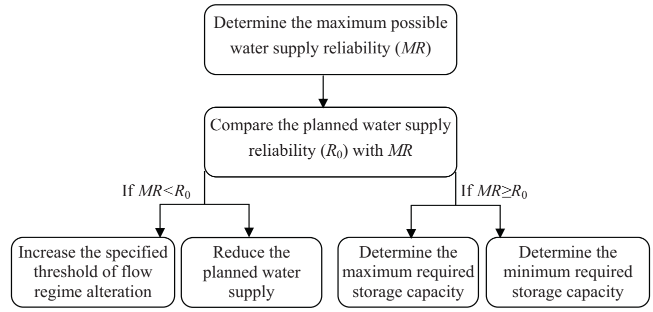

Fig. 1. The procedure for determining the suitable range of reservoir storage capacity.

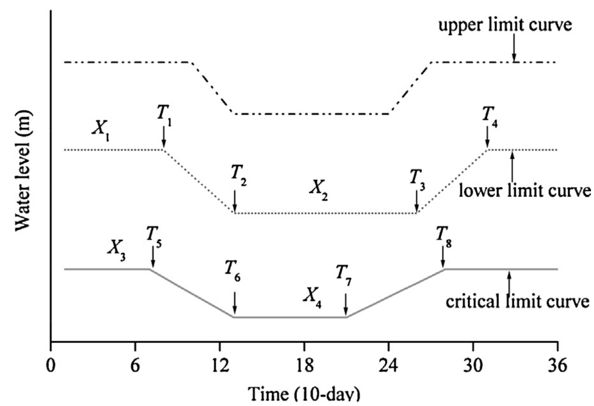

Fig. 2. Typical reservoir operating rule curves.

reliability for a planned yield is a basic step to test the possibility of satisfying the planned reliability subject to a specified flow regime alteration degree. If the maximum reliability is less than the planned reliability, the planned reliability and flow regime alteration degree are not achievable simultaneously. If the maximum reliability meets the planned reliability, the two goals are achievable and we can further determine a suitable RSC to satisfy both human and e-flow requirements.

Reservoir designers are concerned about construction costs. For them the minimum required RSC must deliver the planned water supply and meet the specified river protection objective. In contrast, river protectors are concerned about the riverine ecosystem. For them other possible RSCs must be considered, to protect the riverine ecosystem subject to the planned water supply. Thus, if the planned water supply is possible, both of the two capacities must be determined (Fig. 1).

Reservoir operating rules and assessment of flow regime alterations are the basis of determining suitable RSC, and will be described first.

2.1. Reservoir operating policy

Reservoir operating rule curves (RORCs) are widely used to direct reservoir operations due to their simplicity and effectiveness in providing high water supply reliability (Chang and Chang, 2001; Chang et al., 2005; Chen, 2003; Chen et al., 2007). Fig. 2 illustrates typical RORCs: the upper limit curve, the lower limit curve, and the critical limit curve. The main function of the upper limit curve, which is determined by simulation, is flood control. In this research, we focus on the reservoir functions of e-flow and human water provision. These functions are determined by the lower and critical limit curves. For simplicity, we assume the upper limit curve is a line, coinciding with the upper limit of the reservoir active