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Optimizing environmental flow operations based on explicit quantification of IHA parameters

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ABSTRACT

Reservoir operations are increasingly being asked to consider environmental flow, which is needed to sustain a healthy river ecosystem. The Indicators of Hydrologic Alteration (IHA) is a tool that is used widely to describe environmental flow regimes, but few studies have explicitly included its parameters in multi-objective reservoir operation models. With the goal of incorporating detailed environmental flow requirements into reservoir operations, this study proposes a two-objective reservoir operation model that includes explicit IHA constraints. A series of formulae is developed to calculate IHA parameters without using a loop or conditional statement, which allows operators to manage environmental flow directly. An experimental operation of the Jinghong reservoir in the upstream portion of the Mekong Basin is conducted to apply the method. The economic objective is defined by hydropower production (HP), while the environmental flow objective is represented by a weighted aggregate eco-index (EI) based on IHA parameters. Five scenarios with different objective functions and constraints are compared, and the results show that the scenario with "HP–EI" as its objective achieved optimal benefits for both indices. Hard EI and explicit IHA constraints led to significant loss of HP that can be attributed to variations of inflow. To make this model more convenient for practical use, operation rule curves are regressed from the optimized results of the model. Finally, policy implications of the operation with economic and environmental objectives and some limitations are discussed. The quantification method of IHA parameters provides significant reference value for reservoir environmental operation issues.

1. Introduction

Reservoirs, especially those with large storage capacities, have the flexibility to regulate water in space and time (Tilmant and Muyunda, 2010). They serve a wide variety of purposes such as hydropower production, flood control, water supply, recreation, and meeting environmental demands. Many studies have explored the effects of reservoir operation considering ecological objectives (Harman and Stewardson, 2005; Suen and Eheart, 2006; Tilmant and Muyunda, 2010; Yang and Cai, 2010). In each of these studies, environmental flow plays a significant role. Generally, there are three methods for obtaining environmental flow: (1) estimate flow requirements to restore or maintain fish habitat, (2) mimic the natural flow regime, and (3) determine a suitable flow regime based on existing data on aquatic organisms (Jager and Smith, 2008).

However, conflicts often exist between ecological and other objectives in reservoir operation. For example, hydropower production is determined by the water level difference between upstream and downstream (i.e., water head). When environmental flow is not included, the best way to maximize hydropower output is to impound as much water as possible and then release it with a high water head (Zhao et al., 2015). However, this hydropower-oriented operation would change the downstream flow regime overwhelmingly, thus causing detrimental effects (Acreman and Dunbar, 2004). Many studies have examined the balance between ecological objectives and economic objectives. For instance, Cardwell et al. (1996) introduced monthly minimum flow scenarios to explore the trade-offs between fish population capacity and water shortage levels. Shiau and Wu (2004) focused on the trade-offs between changes in hydrological indicators and human water needs and connected flow variability to natural stream biota. The two major methods for solving a multi-objective model are the weighted sum method and taking one objective as a single objective while treating the others as constraints (Wang et al., 2015).

Optimization models are often used to explore Pareto optimal solutions (Yeh, 1985; Labadie et al., 2004; Zhao and Zhao, 2014). Operation rules (or rule curves), which are commonly employed by operators in practice, can be derived based on the results of these optimization models (Huang and Yang, 1999; Tu and Yeh, 2003; Wan

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et al., 2016). For both optimization models and rule curves, recreating the natural flow regime is a promising and effective way to meet ecological objectives (Poff et al., 1997; Richter et al., 1996). The Indicators of Hydrologic Alteration (IHA) (Richter et al., 1996, 1997) is a popular tool for capturing the majority of the natural flow regime. IHA consists of a suite of 33 hydrologic parameters, including magnitude, duration time, timing of extreme flow, and frequency, that can be used to analyze flow regimes. However, the complexities of these 33 parameters make it difficult to apply them explicitly to objective or constraint equations when establishing an optimization model. Therefore, the IHA parameters are generally used to evaluate the resulting water release, and then produce statistics and a set of operation rules (Harman and Stewardson, 2005; Hughes et al., 1997). Another method is to find intermediate variables to represent IHA parameters and use these in reservoir optimization models. The weakness in these two methods, however, is that operators cannot directly apply IHA parameters to guide practice. Recently, Wang et al. (2015) introduced a mixed linear programming model to constrain some of the IHA parameters (e.g., monthly flows and magnitude of extreme flow), thus demonstrating a new approach applying IHA to reservoir operation. Nonetheless, many IHA parameters still cannot be considered explicitly in the objectives or constraints in an optimization model, due to difficulties in formulating them quantitatively. These facts make it difficult for operators to manage environmental flow directly according to IHA parameters.

This study aims to address the problem by quantitatively formulating all 33 hydrologic parameters of IHA into the objectives or constraints of a reservoir operation optimization model, while making practical operation rules for environmental flow release. This study has two related major objectives: (a) explicitly quantify IHA parameters that provide a mathematical basis for environmental flow operation issues; (b) develop an optimization model for hydropower production and environmental flow operation based on all 33 IHA parameters, and then derive simplified operational rule curves that incorporate environmental flow release based on the optimization model.

2. Two-objective reservoir operation model considering environmental flow

2.1. Model framework

The framework for the two-objective reservoir operation model considering environmental flow, presented in Fig. 1, includes the following steps: (1) generate synthetic daily inflows, (2) set up the optimization model with appropriate objectives and constraints, (3) generate daily release using the optimization model, and (4) derive operation rule curves.

With a focus on the trade-off between hydropower operation and environmental flow, a schematic sketch of the alteration of streamflow due to reservoir operation is shown in Fig. 2. Water release from the reservoir can be divided conceptually into two parts (Fig. 2(a)), i.e., beneficial water release, for uses such as hydropower generation, and water spill. Both of these parts are released downstream. Because water withdrawal for municipal, industrial, or agriculture use and water diversion are not considered in this model, the total volume of water does not change after reservoir operation. Compared with natural streamflow, the downstream flow regime after reservoir operation may be changed substantially, leading to ecological alteration (Fig. 2(b)).

To reflect the effect of inter-annual climate variability on the robustness of the streamflow series, synthetic monthly inflows were first generated for 100 years and then downscaled to daily scale. The economic and ecological objectives considered in the model are hydropower production (HP), defined as the annual output of hydroelectric energy, and the eco-index (EI), defined as a weighted average value of the key parameters selected from the 33 IHA parameters. The Principal Component Analysis (PCA) method was used to select the key IHA parameters (Gao et al., 2012). Five scenarios were designed to demonstrate the trade-offs between the economic and ecological objectives. The optimization model was written in GAMS 23.3. Finally, reservoir operation rule curves were derived by analyzing the obtained optimal release patterns.

2.2. Synthetic daily reservoir inflows

The time interval used to calculate reservoir operations affects the accuracy of the objectives, especially those related to ecology. Conventional operations use mostly one-month or ten-day intervals (Bednarek and Hart, 2005; Cardwell et al., 1996; Sale et al., 1982; Suen et al., 2009), but these are too coarse to represent environmental characteristics. A daily interval is essential for studies that consider ecological demand because IHA parameters must be calculated using daily-scale data. This paper employs a robust, simple, and parsimonious approach for space–time streamflow disaggregation that can capture the features of historical data (Prairie et al., 2007; Zhao et al., 2013).

The Markov model is recognized as a good tool for simulating stochastic hydrological processes (Thomas and Fiering, 1962). The linear stationary autoregressive (or Markov) model can simulate stationary time series at an annual scale, which means that reservoir inflows can be described by a time-invariant probability density function. Monthly streamflow changes periodically within a year; thus, a periodic autoregressive Markov model can be used to generate monthly streamflow. Assuming that the monthly streamflow satisfies the first-order Markov process and fits a Pearson type III frequency distribution (P-III), we obtained the following equation:

$$X_{i,j} = \overline{X_j} + b_j(X_{i,j-1}-\overline{X_j}) + F_{i,j}S_j\sqrt{1-r_j^2} \tag{1}$$

where $X_{i,j}$ is the simulated streamflow in the jth month of the ith year, $\overline{X_j}$ is the mean streamflow value of the jth month in the observed series, b_j is the regression coefficient of the jth month in the observed series, $F_{i,j}$ is the standardized P-III coefficient generated from a pseudo-random number 0–1, S_j is the mean squared deviation of the jth month in the observed series, and r_j^2 is the correlation coefficient of the jth month and $j + 1$th month in the observed series.

Generated monthly inflows were then disaggregated to daily reservoir inflows based on a non-parametric approach (Prairie et al., 2007; Tarboton et al., 1998; Wang et al., 2013). The disaggregated (daily) flow was resampled from the fitted historical monthly (nearest neighbor) flow data using the nearest-neighbor bootstrap method (K-NN). K-nearest neighbors were computed using the Euclidean distance between simulated monthly flow and fitted historical monthly flow. The neighbor of the ith year was weighted as follows:

$$\mathrm{W(i)} = \frac{1/i}{\sum_{i=1}^{K} 1/i} \tag{2}$$

where $K = \sqrt{number\ of\ sample\ data\ points}$. The nearest neighbor (the "kth" month in the historical series) has the Euclidean distance with the lowest weight.

2.3. Objectives functions of optimization model

The primary economic objective was set as the benefit of hydropower generation, defined as follows:

$$HP = \eta g \sum_{i=1}^{365} RG_i(\overline{h_{up,i}}-h_{down,i}) \tag{3}$$

where HP is total hydropower production, η is the coefficient of efficiency, RG_i is the water release for hydropower generation on the ith day, g is gravitational acceleration, $\overline{h_{up,i}}$ is the average reservoir water level on the ith day, and $h_{down,i}$ is the downstream tailwater level of the hydropower plant.

Incorporating ecological objectives into reservoir operation has been the goal of many studies (Jager and Smith, 2008), and the IHA