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TRADE-OFFS MODEL OF MULTI-OBJECTIVE RESERVOIR OPERATION WITH UNCERTAINTIES

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As the increase of water resources management and exploitation goals, it is gaining increasing weights for reservoir operation to seek optimal options for the balance between multiple and contradictory water resources use objectives. This study develops a trade-offs model to quantify the benefits of reservoir operation rules on the downstream water supply yield. Uncertainties of different water use benefits are considered by using the Monte Carlo method as error propagation for the model. The case study is analyzed to evaluate its performance in terms of water use benefits of agriculture, hydropower, flood control and environmental flows requirement in the Yellow River, China. Trade-offs results are obtained among the multiple water resources under reservoir operation. Results indicate that there are magnificent trade-offs between ecological benefits and social economical one under different management policies and scenarios. This study proposes a simple but robust trade-offs model for quantifying the consequence of hydropower management options. The results could also be used by authorities and policy makes as reference of compromised solutions to the ecological and human negotiations in water resources management.

INTRODUCTION

As the increasing of hazard augmentation and river flow depletion, conflicts for water resources supplies have been more concerned than ever [1]. Conflicts and contradictions over water utilization for human activities and ecosystems have received negligible attentions worldwide [2-5]. In this circumstance, an emerging challenge is to utilize water resources to provide sustainable social benefits while minimizing adverse impacts on natural ecosystem [6]. Based on this assumption, operating schemes for hydropower dams are built to maximize economic and social gains while meeting minimal environmental flows requirements [7]. Extensive efforts have been made towards balancing both the human and ecological requirements for water based on the current reservoir operation rules [8-13].

There is growing evidence that water resources management experiments may result in complicated trade-offs among variety objectives [14-17]. Recent research has further emphasized the attempts towards trade-offs analysis between ecological and human requirements for water by negotiating between these two classes of users [18-19]. Rheinheimer applied the bootstrap sampling method with replication to detect the change point for the population quantity of the triangle smelt [20]. Based on the Bayesian analysis method, Beckage

[21] and Thomson [22] built the Bayesian hierarchy model for the change point analysis of the population quantity for multiple species.

Instead of developing a computation method to maximize the outcomes of different water uses considers environmental flows as restrictive conditions. We proposed a scenario-driven approach for environmental flows assessment based on an integrative trade-offs model. Trade-offs between water users of the society and the environment were analyzed under alternative scenarios of multi-objective water resources management. Effects of the temporal variations of river flows and water requirements were identified in the assessment.

METHODS

Reservoir operation simulation model

The reservoir simulation model was established to understand the effects of reservoir operations on river flow alternation based on a simplified Saint-Venant equation to determine the stage-storage and stage-discharge relationships in the reservoir.

$$\frac{dV(Z)}{dt} = \sum_{j=1}^n Q(t)_j - q(Z) \quad (1)$$

$$q(Z)_t = f(V_t) \quad (2)$$

where $V(Z)$ represents the reservoir storage with a variation in water level Z and time t ; $Q(t)_j$ is the river discharge from the above tributary into the reservoir; n is the number of tributaries; $q(Z)$ is the river release from the reservoir with a variation in water level Z and volume V . A fourth-order Runge-Kutta solution technique can be used to solve the simplified Saint-Venant equation. Based on the reservoir simulation model, river regime conditions and operation rules are integrated and reservoir release amount of downstream hydrological conditions are under control.

Trade-offs evaluation model

Benefits for multiple management objectives downstream from the reservoirs are evaluated including not only the environmental flows, but also society water use benefits such as agriculture, flood control, navigation and hydropower generation downstream from the dams. Benefits of water uses for irrigation, hydropower production, flood control, and navigation are calculated as percentage by using the ratio of water usages compared to the annual or daily average level of use amount respectively. Here we apply the rule of taking the mean of multiple water use benefits as the integrated social results, which is one of the advantages by using percentage benefit definitions. Ecological benefits of environmental flows are represented as environmental water supply reliability which is expressed as the ratio of the monthly flow alteration to the monthly average altered flow.

After evaluation of multi-objective benefits, trade-offs curves between social and ecological benefits can be obtained by non-linear curve fitting and then abrupt change points on the curve will be recognized as the optimal location for the trade-offs results where benefits of water resources allocation on social economic development could be maximized, with the security for environmental flows least influenced at the same time. Basic Newton's method [23-24] is applied in this procedure to solve the one-dimensional unconstrained optimization problems.

Uncertainty analysis

The ISO Guide to the Expression of Uncertainty in Measurement (GUM) (International Organization for Standardization, 1995; JCGM 100, 2008) provides a conceptual framework for evaluating and expressing uncertainty, deals with the propagation of distributions, and emphasizes the use of Monte-Carlo Simulation (MCS) for estimating the uncertainty of measurements. Following the ISO Guide, ROV Risk Simulator (Real Options Valuation Inc., 2013) is software very suitable to be used to perform the uncertainty analysis of any measurement, test or analysis, including calibrations (Jalukse et al., 2003; Losinger, 2004).

By applying error propagation analysis of the reservoir operation model, average altered flow was discovered to show a normal distribution with a mean of 1320.9368 m³/s and standard deviation of 169.1288 under 2,000 trials (Figure 1). Under the confidence interval of 95%, the error precision propagated from input river discharge into the reservoir was calculated to be 0.0056.

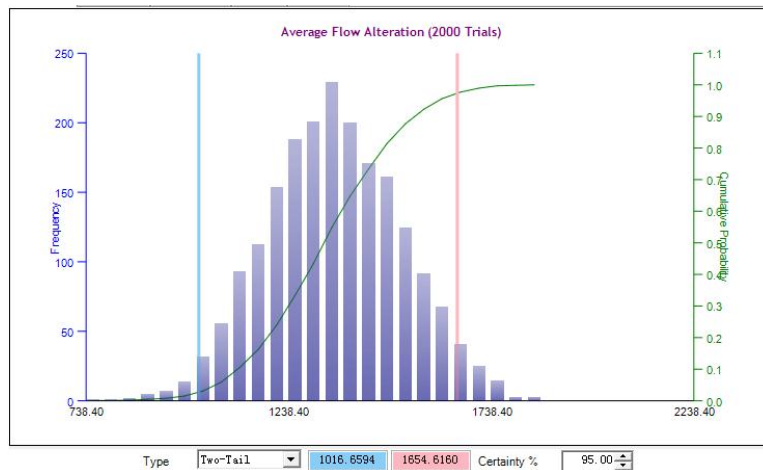


Figure 1. Error propagation analysis of the reservoir operation model

RESULTS AND DISCUSSION

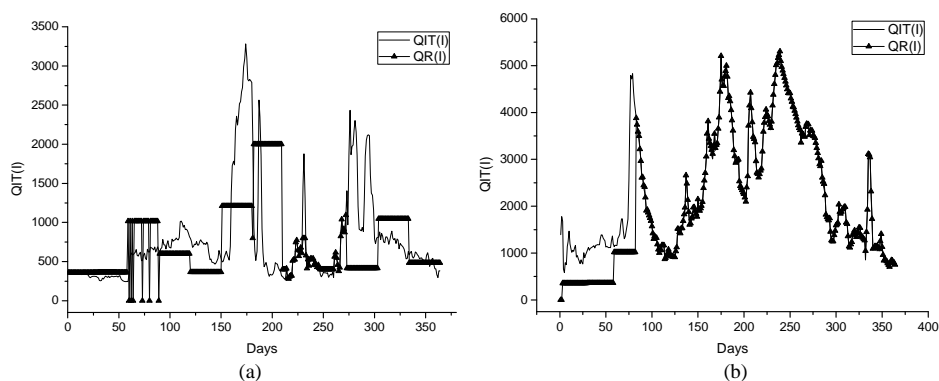


Figure 2. Inflow (QIT) and outflow (QR) amount of dry year 2007(a) and wet year 1963 (b)

The model was applied and calibrated in Yellow River Basin, China, by using the dataset of daily hydrological records covers from 1950 to 2007 which locates above and below the

Xiaolangdi Reservoir. Hydrologic outputs of reservoir release are simulated dynamically through the reservoir operation rules under control (Figure 2). Trade-offs distribution between social and ecological benefits of water is given under certain operation rules (Figure 3). We could see that the environmental flows benefits and social and economic water use benefits are in reciprocal relationship with social and economic benefits stayed above 0.5 and environmental flows benefits began to rise in the late 1980s.

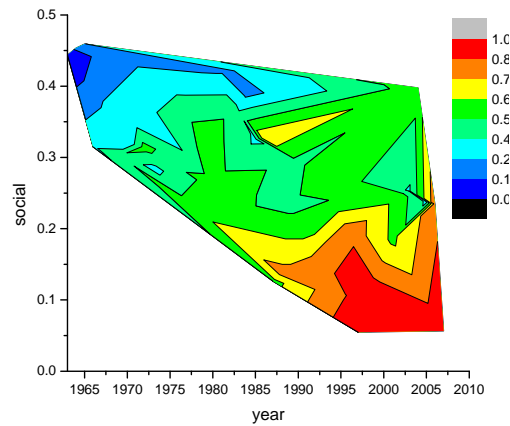


Figure 3. Contour map of the social and environmental water use benefits under the WST operation rule from 1950 to 2007.

Table 1. Trade-offs results of environmental flows and social benefits both optimized

	Annualized Returns	Volatility Risk	Benefits Allocation
Agriculture	10.54%	12.36%	30.01%
Hydropower	11.25%	16.23%	18.58%
flood control	11.84%	15.64%	21.06%
Environmental flows	10.64%	12.35%	30.35%
Social benefits Total			23.22%
Trade-offs results	1.5881		

Table 2. Trade-offs results of optimized social benefits without considering environmental flows

	Annualized Returns	Volatility Risk	Benefits Allocation
Agriculture	10.54%	12.36%	100%
Hydropower	11.25%	16.23%	0%
flood control	11.84%	15.64%	0%
Environmental flows	10.64%	12.35%	0%
Social benefits Total			100%
Trade-offs results	1.0		

By integrating the risk indicator of different water use benefits, optimization results was obtained to be social benefits of 0.2322 and environmental one to be 0.3035 (Table 1).

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