

A framework for incorporating ecological releases in single reservoir operation



Hui Wang^{a,*}, Earl D. Brill^b, Ranji S. Ranjithan^b, A. Sankarasubramanian^b

^a Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas at Austin, Austin, TX 78758, USA

^b Dept. of Civil, Construction and Environmental Engineering, North Carolina State University, Raleigh, NC 27695-7908, USA

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ABSTRACT

Most reservoir operation practices consider downstream environmental flow as a constraint to meet a minimum release. The resulting flow regime may not necessarily provide downstream aquatic conditions to support healthy ecosystems. These effects can be quantified in terms of changes in values of parameters that represent the flow regimes. Numerous studies have focused on determining the ecological response to hydrological alteration caused by reservoir operation. To mitigate hydrological alteration and restore the natural flow regime as much as possible, a reservoir operation framework is proposed to explicitly incorporate ecological flow requirements. A general optimization-based decision model is presented to consider simultaneously the multiple anthropogenic uses of the reservoir and desirable ecological releases represented by parameters that capture the flow regime. Multiple uses of the reservoir, including water supply, hydropower generation, etc., are modeled as a mixed integer programming problem. Hydropower generation, which is represented by a nonlinear function that usually depends on head and water flow, is linearized using a two-dimensional function. Investigations using a reservoir in Virginia, located in the southeastern United States, demonstrate that compared to standard releases based on current operation practice, releases simulated using this framework perform better in mimicking pre-development flows. The tradeoff between anthropogenic use and ecological releases is investigated. The framework is first demonstrated for instances with perfect stream flow information. To examine the flexibility of this framework in reservoir release management, monthly flow forecasts and disaggregated daily flow conditions are incorporated. Retrospective monthly flow forecasts are obtained through regression models that use gridded precipitation forecasts and gridded soil moisture estimates as predictors. A nonparametric method is chosen to disaggregate monthly flow forecasts to daily flow conditions. Compared with daily flow climatology, forecasted monthly and daily flow better preserves flow variability and result in lower changes of flow parameters under the proposed framework.

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1. Introduction

Reservoirs play an important role in ensuring water for multiple uses (e.g., water supply, hydropower generation) by reducing the temporal variability in inflows through regulated outflows. It is well recognized that such controlled releases from reservoirs have detrimental effects on the downstream ecosystem health [17,19]. One common effect of regulated releases from a reservoir is the induced change in the hydrologic flow regime that potentially impairs the aquatic environment by altering the natural flow condition to which the aquatic and riparian system is well adapted [12,14]. Various flow conditions, e.g., the magnitude and timing

of flows, are critical to some species at specific periods in the year [1]. Mandated release requirements inevitably introduce adverse alterations in the natural flow regime [17,19]. Though the relationship between impaired ecological environment and hydrological flow regime alteration may be determined on a case-by-case basis [18], maintaining or mimicking the natural flow pattern is in general important for preserving the ecosystem health [22]. The primary focus of this study is to develop a reservoir operation framework that explicitly considers both anthropogenic water demands and ecological flow requirements to minimize impacts on downstream ecosystem health.

Explicit consideration of ecological flow regimes is not commonly included in current reservoir operation rules (e.g., [8,32] that generally specify a minimum release, which is usually determined based on long-term flow conditions (e.g., 7-day average

* Corresponding author. Tel.: +1 512 471 9299.

E-mail address: watersystemresearch@gmail.com (H. Wang).

Notations

J	total days in the decision horizon	r	water supply satisfaction ratio
s_j	end storage on day j	st_k	breakpoints on the storage axis in the linearization of storage-head curve
I_j	reservoir inflow on day j	$\alpha_{k,j}$	a real number between 0 and 1 associated with each breakpoint
x_j	downstream release on day j , assumed to be flowing through turbines	$b_{k,j}$	a binary variable associated with each interval on storage axis
ws_j	water supply release on day j	$b_{0,j}, b_{K_1,j}$	two dummy binary variables associated with the two end points, both are 0
sp_j	spillage on day j	he_j	estimated monthly mean water elevation in the reservoir
R_j	release for other purposes on day j	E_j	approximated daily hydropower generation
s_{\min}	minimum allowable storage	$f(st_k)$	the water head corresponds to a certain storage, st_k , is provided to piecewise linearize the storage-head curve.
s_{\max}	maximum allowable storage	q_k	break points on the release axis
P_1	monthly mean downstream flow	$\beta_{i,j}$	a binary variable associated with each interval on the elevation axis
P_2	1-day minimum flow	\bar{y}_l	mid points of each interval on the elevation axis
P_3	3-day minimum flow	M	a large positive number
P_4	7-day minimum flow	K_1	the number of breaking points (including two end points) in linearization of Storage–Elevation curve
P_5	3-day maximum flow	K_2	the number of breaking points (including two end points) in modeling of Energy–Elevation–Storage–Release relationship
P_6	7-day maximum flow	g	allowable number of mis-hits
h_j^i	a binary variable associated with the i th ecological flow parameter on day j	$E_{\text{firm yield}}$	monthly firm energy requirement
C	a large positive number	$f(q_k, \bar{y}_l)$	daily hydropower generation corresponds to a break point q_k on the release axis and midpoint \bar{y}_l for the intervals on elevation axis
C^*	a large positive number		
q_1^i	a binary variable associated with the i th ecological flow parameter, it is 1 if the i th ecological flow parameter is less than its low boundary, $target_{\min}^i$		
q_2^i	a binary variable associated with the i th ecological flow parameter, it is 1 if the i th ecological flow parameter is larger than its upper boundary, $target_{\max}^i$		
$\}ws_j$	releases for water supply on day j		
wd_j	daily domestic (industrial) water demand		
\bar{s}_j	estimated average storage for day j		

10 year return period flows) and anthropogenic demands. On one hand, due to the competing needs, outflow from the reservoir might not be able to sustain ecological health of the river since minimum environmental flow is usually determined based on agreement among stakeholders, especially downstream communities. On the other hand, water releases for hydropower generation are usually not in conflict with ecological requirements since tail-water from turbines typically is returned to the river. Too much water released after hydropower generation from stored water, however, would also alter the flow regime, leading to ecological damage. Therefore, it is challenging to explicitly consider ecological flow amount and variation requirements in multi-purpose reservoir operation planning [7].

Interest in modifying current reservoir operation practice is getting more attention with the aim of improving downstream ecosystem health. When there is no upstream storage and little water extraction for anthropogenic needs, “Run-Of-the-River” (ROR) operation is a good solution for waterways to generate hydropower and preserve the ecosystem at the same time. Recently, it has been reported that some hydropower projects have been changed from peaking to ROR operation with the main consideration of protecting downstream aquatic biota [7]. This operation mode is not feasible, however, for a large reservoir that serves multiple purposes, such as flood control, domestic water supply, irrigation supply, and hydropower generation. Thus, modified operational rules are needed to meet these anthropogenic demands while minimizing the potential damage to the downstream ecological system.

Hydrology-based ecological considerations in multi-purpose reservoir operation has drawn much attention in the research community (e.g., [2,21,24,29]). Cardwell et al. [2] proposed a multi-objective optimization model for monthly reservoir operation that considers anthropogenic water demands as well as fish habitats. Jager [7] suggested three steps to conceptually bring

multi-objective reservoir operation closer to meeting the goal of ecological sustainability. Identification of features of flow variation that are essential for river health and quantification of the relationships between flow variation and river health could provide a comprehensive understanding of the river ecosystem. Richter and Thomas [24] described a descriptive framework for modifying reservoir operation to restore ecological flow regime.

Shiau and Wu [27] simulated various combinations of in-stream flow releases and diversions for a projected diversion weir, and optimized the operation by minimizing the alteration in the distribution of several parameters. Suan and Eheart [28] proposed a paradigm to incorporate ecological flow regime into reservoir operations. A multi-objective optimization model was set up to incorporate hydropower generation and ecological requirements. Reservoir operation was assumed to be the same in each historical year. This approach, however, cannot be easily applied directly for future operations since historical flows are not necessarily representative of future daily flows. Also, reservoir inflow forecast information is generally not available or reliable beyond a certain time, e.g., one month or one season depending on the inflow forecast model. Recently, Yang and Cai [31] investigated a multi-objective optimization model that minimizes flood damage and maximizes fish diversity by generating synthetic daily inflow data that preserve the statistical characteristics of historical data. Very recently, Stei [29] investigated preserving ecological flow requirements, by minimizing deviation between flows from reservoir operation model and pre-estimated natural flow for each day. Its flexibility and applicability has been successfully demonstrated for Connecticut River. Its application, however, may be limited for areas where natural flow conditions for each day during the simulation period cannot be easily estimated.

The objectives of the study reported in this paper are to: (1) develop a reservoir operation framework for restoring the flow

regime to pre-impact conditions; (2) implement and test the framework using a daily reservoir operation model considering anthropogenic water needs and ecological flow releases; and (3) investigate the tradeoff between meeting anthropogenic water needs and ecological flow requirements.

2. Methodology

2.1. Framework description

A three-step framework for multi-purpose reservoir operation to restore natural flow regime is proposed.

The first step is to identify appropriate flow parameters that represent the flow regime and have significant impact on the ecological system. Numerous hydrological metrics have been proposed [15] to characterize flow regime. It is challenging to select a few parameters for any specific river system of interest. Olden and Poff [15] investigated the overlap present in all hydrological metrics reported in the literature, and presented a framework to identify hydrological flow indices as Indicators of Hydrological Alteration (IHA) that adequately characterize flow regimes. Gao et al. [4] studied the presence of any potential redundancy in existing IHA parameters and suggested that only a few parameters based on ecodeficit and ecosurplus can sufficiently represent the flow variability; however, IHA parameters are meant to capture flow variability as well as many other factors that affect the health of ecological habitats.

The collection of IHA parameters reflects the magnitude, duration and timing of hydrological variables. Five groups of hydrological variables were proposed by Richter et al. [22], and each group corresponds to its own ecological influence. For example, the magnitude of monthly mean flow reflects the habitat availability for aquatic organisms, soil moisture availability for plants and availability of water for terrestrial animals [22]. To determine the relation between hydrological parameters and their possible ecological impacts on a river system requires additional site-specific knowledge and cooperation from river managers and ecologists. For example, some species are usually sensitive to low flow and high flow conditions. Mean flow in specific months may influence fish spawning.

The second step is to determine a target range for each identified flow parameter. For naturally flowing rivers, long term distribution of each hydrological flow parameter reflects the characteristics of the ecological system to which the aquatic and riparian system has been adapted. RVA [23] is employed to evaluate hydrological flow alterations induced by a disturbance, such as reservoir operation, to the natural flow conditions. The 33rd and 67th percentiles of a flow parameter distribution in the pre-impact years are used as the critical values to divide the distribution into three categories, namely, low, medium and high categories. Let $N_{i,pre}$ and $N_{i,post}$ represent the number of pre-impact and post-impact years, respectively, for which the value of a hydrological parameter falls within the category i . Then D_i is the difference between $N_{i,pre}$ and $N_{i,post}$. The absolute value of D_i is M_i , which represents the degree of alteration, as represented in Eq. (1).

$$M_i = |D_i| = |N_{i,post} - N_{i,pre}| \quad i = 1, 2, 3 \quad (1)$$

Though D_i is not directly used in RVA analysis, it usually reflects the flow impact of reservoir operation. For example, when a large portion of outflow is needed to meet anthropogenic demand in some months, there will be many years when the monthly average flow parameter falls in the low category for those months. RVA analysis is done for all three categories and for all ecological flow parameters under consideration. Summation of M_i over the three categories of all flow parameters is the total number of mis-hits; its magnitude reflects the degree of flow alteration. Ideally,

hydrological alteration over all three categories for all parameters should be zero, indicating that the reservoir operation has no impact on the hydrological flow regime.

To determine the daily release, one must know into which category should the next value of each flow parameter fall to best mimic the pre-impact flow pattern. Richter and Thomas [24] suggested that if the parameter value in post-impact years falls within a certain range of the parameter value distribution in pre-impact years, the ecosystem can be assumed to be similar to that in the pre-impact years. Two approaches, a parametric and a non-parametric approach, for setting a fixed target range for each parameter based on historic flow data were suggested [23,27]. Setting a fixed target range, e.g., 25th–75th percentile of flow conditions in the pre-development years, neglects future inflow conditions and reduces the flow variability.

To better preserve the flow regime variability, a new approach based on inflow conditions is proposed in this study to determine the target range for a flow parameter, which considers all three categories of the a flow parameter in pre-impact years. Given a well-calibrated inflow forecasts, the proposed approach could be employed to suggest releases conditional on the forecasts. For instance, if the inflow forecasts suggest above-normal inflow conditions over the decision horizon, e.g., one month, then the high category of the flow parameter in the pre-impact years is chosen as the target range for the selected parameter. If the forecasted inflow is below normal, the low category of the flow parameter in the pre-impact years is chosen as the target range.

The third step is to formulate a daily reservoir operation optimization model to determine daily releases that meet different water demands effectively. Various components, such as flow balance, ecological constraints, water supply, and hydropower generation, of this optimization model are described in Section 2.2. A key input to this model is the inflows that are based on streamflow forecasts. Hence, the releases are determined contingent on the forecasted inflow instead of a static release policy.

The length of the planning horizon is critical when using the proposed framework. If the horizon is relatively long, e.g., six months to a year, reliable streamflow forecasts are usually not available. On the other hand, if the horizon is shorter, e.g., one week, the forecasts are usually reliable but are not sufficient to predict seasonal drought conditions. Also, it is hard to estimate ecological parameters such as monthly mean flow if the planning horizon is less than a month. Considering these factors, a one-month planning horizon and the following six flow parameters were chosen to reflect the downstream ecosystem [16] for the reservoir considered in this study: average monthly flow; 1-day minimum flow; 3-day minimum flow; 7-day minimum flow; 3-day maximum flow; and 7-day maximum flow during one month. It would be possible to select other flow parameters for specific locations and these identified flow parameters are not definitive. The following section presents a daily reservoir operation optimization model to explicitly consider ecological flow requirement and other anthropogenic water demands.

2.2. Mathematical formulation of reservoir operation

A multi-purpose reservoir operation optimization model was developed to estimate water releases for the different human demands and ecological flow needs. The sets of constraints and necessary expressions for defining the objective function are described below.

2.2.1. Flow balance

Eq. (2) describes the reservoir flow balance, where s_j is the end-storage on day j , J is total number of days in the decision horizon, J_j is net inflow to the reservoir on day j after the evaporation

discounted from inflow, x_j is ecological release on day j including potential spillage to the downstream and R_j is the non-ecological release (e.g., irrigation withdrawn) on day j , ws_j is water supply release. Reservoir storage is constrained by Eq. (3), where s_{\min} is the user-defined acceptable minimum storage and s_{\max} is the user-defined acceptable maximum storage.

$$s_j = s_{j-1} + I_j - R_j - x_j - ws_j \quad \forall j \in \{1, 2, \dots, J\} \quad (2)$$

$$s_{\min} \leq s_j \leq s_{\max} \quad \forall j \in \{1, 2, \dots, J\} \quad (3)$$

2.2.2. Mis-hits in ecological flows

This section shows how to mathematically represent six ecological flow parameters considered in this study, and how they are used to calculate the number of mis-hits, i.e., frequency of falling outside of the target range for each parameter. The considered six ecological flow parameters are monthly mean flow, 1-day minimum, 3-day minimum, 7-day minimum, 3-day maximum and 7-day maximum flow conditions during one month.

Monthly mean flow, P_1 , can be easily represented in Eq. (4).

$$P_1 = \frac{\sum_{j=1}^J x_j}{J} \quad (4)$$

where J denotes the total number of days in one month; x_j represents daily outflow from reservoir at day j ($j = 1, 2, \dots, J$); and P_1 is monthly mean flow.

Ecological flow parameter P_2 , monthly 3-day minimum flow, can be represented as following:

$$P_2 \leq x_j \quad \forall j \in \{1, 2, \dots, J\} \quad (5)$$

$$\frac{x_j - P_2}{C} \leq h_j^2 \quad \forall j \in \{1, 2, \dots, J-2\} \quad (6)$$

$$\sum_{j=1}^J (1 - h_j^i) \geq 1 \quad i = 2 \quad (7)$$

where C is a large positive number; the superscript 2 in h_j^2 denotes a binary variable introduced for the second ecological flow parameters. Note that the left hand side of Eq. (6) is often a fraction less than 1 and this will force the binary variable h_j^2 being 1. Only when P_2 is equal to the 1-day minimum flow, the left hand side of Eq. (6) is zero. Under such condition, the binary variable h_j^2 would be either 0 or 1. Eq. (7), however, ensures that at least h_j^2 is zero for at least one time and this occurs only if the left hand side of Eq. (6) is zero.

Similarly, monthly 3-day minimum flow can be represented in Eqs. (12)–(14).

$$P_3 \leq \frac{\sum_{t=0}^2 x_{j+t}}{3} \quad \forall j \in \{1, 2, \dots, J-2\} \quad (8)$$

$$\frac{\sum_{t=0}^2 \frac{x_{j+t}}{3} - P_3}{C} \leq h_j^3 \quad \forall j \in \{1, 2, \dots, J-2\} \quad (9)$$

$$\sum_{j=1}^{J-2} (1 - h_j^i) \geq 1 \quad i = 3 \quad (10)$$

where x_{j+t} for j from 0 to 2 denotes reservoir outflow for three consecutive days and h_j^3 is an introduced binary variable.

Eqs. (11)–(13) are used to represent constraints for 7-day minimum flow.

$$P_4 \leq \frac{\sum_{t=0}^6 x_{j+t}}{7} \quad \forall j \in \{1, 2, \dots, J-6\} \quad (11)$$

$$\frac{\sum_{t=0}^6 \frac{x_{j+t}}{7} - P_4}{C} \leq h_j^4 \quad \forall j \in \{1, 2, \dots, J-6\} \quad (12)$$

$$\sum_{j=1}^{J-6} (1 - h_j^i) \geq 1 \quad i = 4 \quad (13)$$

Similarly, Eqs. (14)–(16) are employed to represent constraints for 3-day maximum flow P_5 .

$$P_5 \geq \frac{\sum_{t=0}^2 x_{j+t}}{3} \quad \forall j \in \{1, 2, \dots, J-2\} \quad (14)$$

$$\frac{P_5 - \sum_{t=0}^2 \frac{x_{j+t}}{3}}{C} \geq h_j^5 \quad \forall j \in \{1, 2, \dots, J-2\} \quad (15)$$

$$\sum_{j=1}^{J-2} (1 - h_j^i) \geq 1 \quad i = 5 \quad (16)$$

Additionally, Eqs. (17)–(19) are used to represent constraints for 3-day maximum flow P_6 .

$$P_6 \leq \frac{\sum_{t=0}^6 x_{j+t}}{7} \quad \forall j \in \{1, 2, \dots, J-6\} \quad (17)$$

$$\frac{P_6 - \sum_{t=0}^6 \frac{x_{j+t}}{7}}{C} \leq h_j^6 \quad \forall j \in \{1, 2, \dots, J-6\} \quad (18)$$

$$\sum_{j=1}^{J-6} (1 - h_j^i) \geq 1 \quad i = 6 \quad (19)$$

As described in the methodology section, it is ideal to determine daily releases such that the each flow parameter falls into its target range which is determined based on monthly flow conditions. The target range for each flow parameter can be represented as $[T \arg et_{\min}^i, T \arg et_{\max}^i]$. The superscript i denotes one of the six flow parameters under consideration. Two binary variables, q_1^i and q_2^i are introduced to represent if the flow parameter is higher than upper boundary of the target $T \arg et_{\min}^i$ (when $q_1^i = 1$) or if it is lower than lower boundary of $T \arg et_{\min}^i$ (when $q_2^i = 1$), as described in Eqs. (20)–(23):

$$P_i - t \arg et_{\max}^i \leq q_1^i \times C^* \quad \forall i = 1, 2, \dots, 6 \quad (20)$$

$$t \arg et_{\max}^i - P_i \leq (1 - q_1^i) \times C^* \quad \forall i = 1, 2, \dots, 6 \quad (21)$$

$$t \arg et_{\min}^i - P_i \leq q_2^i \times C^* \quad \forall i = 1, 2, \dots, 6 \quad (22)$$

$$P_i - t \arg et_{\min}^i \leq (1 - q_2^i) \times C^* \quad \forall i = 1, 2, \dots, 6 \quad (23)$$

where C^* is a large positive number.

Take one flow parameter, monthly mean flow, as an example. Both q_1^1 and q_2^1 are zeros if the monthly mean flow falls within its pre-defined target range for a specific month. Either q_1^1 or q_2^1 can be 1 if monthly mean flow falls outside the range. Under no circumstance can both binary variables be 1. Hence, summation of the two binary variables can be used to represent the number of mis-hits of monthly mean flow. Similarly, mis-hits can be calculated for the remaining five flow parameters.

The total number of mis-hits, M_{total} , is calculated as follows:

$$M_{total} = \sum_{i=1}^6 (q_1^i + q_2^i) \quad (24)$$

The total count of mis-hits, M_{total} , is then used either as an objective function in scenarios focused on minimizing ecological flow alteration, or as a constraint (Eq. (25)) in scenarios where

the flow alteration is limited by some target number (g) of deviations from pre-impact conditions. Reichold et al. also minimized mis-hits to preserve ecological flows in their watershed management study, although their work focused on managing land use changes, not reservoir operations.

$$M_{total} \leq g. \tag{25}$$

2.2.3. Water supply

Eqs. (26) and (27) are included to ensure that at least fraction r , defined as water supply ratio, of water demand is satisfied, where ws_j is the release for water supply on day j , and wd_j is the daily water demand.

$$\sum_{j=1}^J ws_j \geq r \times \sum_{j=1}^J wd_j \tag{26}$$

$$ws_j \leq wd_j \quad \forall j \in \{1, 2, \dots, J\} \tag{27}$$

Table 1
Objectives that are optimized and constrained in each scenario.

	Ecological flow	Water supply	Hydropower generation
A		• Optimized	× Constrained
B	• Optimized		
C	• Optimized	× Constrained	
D	• Optimized	× Constrained	× Constrained
E		× Constrained	• Optimized
F	× Constrained	× Constrained	• Optimized

2.2.4. Hydropower generation

Hydropower generation is represented usually as a function of water released to turbines and elevation difference between turbines and water level in the reservoir. This relationship depends on the bathymetry of the reservoir and is characterized by the storage-elevation curve, which is unique for each reservoir (see an example in Fig. 8a). For large reservoirs where elevation fluctuation is not a critical factor in hydropower generation or where hydropower generation is mainly flow-dependent, an alternative approach is to assume a constant reservoir water elevation [10,11], but this is not generally the case. The typical nonlinear relation between storage and elevation can be explicitly modeled by using a piece-wise linearization approach [3,6]. See Appendix A for details. Summation of daily hydropower generation E_j is constrained to be greater than or equal to firm hydropower requirement, as shown in Eq. (28).

$$\sum_{j=1}^J E_j \geq E_{firm \ yield} \tag{28}$$

2.2.5. Optimization models

In this study, four Scenarios A–D listed in Table 1 were first investigated. In each scenario, a different objective was optimized while other objectives were formulated as target constraints. To explore the tradeoff among different objectives, we analyze two additional scenarios, namely scenario E and F. The combinations of objectives that were optimized and constrained in the six scenarios are tabulated in Table 1. The structure of optimization model for each scenario is presented in Fig. 1.

A:

$$\text{Maximize } \sum_{j=1}^J ws_j \text{ (water supply)}$$

- s.t. Flow balance Eqns. 2-3
- Water supply Eqn. 27
- Hydropower Eqn. 28

C:

$$\text{Minimize } \sum_{i=1}^N (q_1^i + q_2^i) \text{ (mis-hits)}$$

- s.t. Flow balance Eqns. 2-3
- Mis-hit formulation, Eqns. 4-23
- Water supply Eqns. 26-27

E:

$$\text{Maximize } \sum_{j=1}^J E_j \text{ (hydropower)}$$

- s.t. Flow balance Eqns. 2-3
- Water supply Eqns. 26-27
- Hydropower Eqns. A.1-A.15

B:

$$\text{Minimize } \sum_{i=1}^N (q_1^i + q_2^i) \text{ (mis-hits)}$$

- s.t. Flow balance, Eqns. 2-3
- Mis-hits formulation, Eqns. 4-23

D:

$$\text{Minimize } \sum_{i=1}^N (q_1^i + q_2^i) \text{ (mis-hits)}$$

- s.t. Flow balance, Eqns. 2-3
- Mis-hit formulation, Eqns. 4-23
- Water supply Eqns. 26-27
- Hydropower Eqn. 28

F:

$$\text{Maximize } \sum_{j=1}^J E_j \text{ (hydropower)}$$

- s.t. Flow balance, Eqns. 2-3
- Water supply Eqns. 26-27
- Hydropower Eqns. A.1-A.15
- s-hit Formulation, Eqns. 4-23
- Allowable mis-hits, $\sum_{i=1}^6 (q_1^i + q_2^i) \leq 3$

Fig. 1. Optimization models of different scenarios investigated in this study.

2.3. Retrospective monthly and daily flow forecasts

Climate-information based flow forecasting has increasing application in water resources management (e.g., [25,26]). In this study, lag-1 month flow condition, gridded precipitation forecasts from climate models and estimated soil moisture estimates in the prior month at neighboring grids are used as potential predictors for monthly flow. Gridded precipitation forecasts at spatial resolution of 2.5 degree latitude by 2.5 degree longitude from ECHAM4.5 and estimated monthly soil moisture at the same spatial resolution are downloaded from International Research Institute for Climate and Society (<http://iridl.ldeo.columbia.edu/>). Forecasted precipitation or estimated soil moisture that is statistically significantly correlated with reservoir inflows is selected as a predictor. Monthly inflow regression model is constructed for each of the 12 months between inflow and identified predictors. Principal component analysis of predictors is used to reduce the dimension of the regression model [26]. Each regression model is based on data in the period 1960–2011 under leave-one-out cross-validation mode.

Obtained monthly inflow was disaggregated to daily reservoir inflow based on a non-parametric approach [20,30]. The disaggregation of monthly flow forecasts into daily flow forecasts was performed in a leave-one out cross-validation mode by leaving out the conditioning year from the training dataset. For the given monthly flow forecasts over the year 1960–2011, we identify ‘K’ neighbors on the observed monthly flow by computing the Euclidean distance from the conditioning variable (i.e., monthly flow forecasts) to the monthly flow observations in the remaining years. The observed daily flow for the respective neighbors is resampled to constitute ‘N’ ensembles of daily disaggregated forecasts. The number of ensembles ($w(k)*N$) that each identified neighbor represents in the conditional PDF (i.e., represented by ‘N’ ensembles) is estimated by the kernel weighting function (Eq. (29)) suggested by Lall and Sharma [9].

$$w(k) = \frac{1}{k \sum_{k=1}^K \frac{1}{k}} \quad (29)$$

where $w(k)$ represents the kernel weights of the k th neighbor, and k is the rank of the neighbor out of the total selected ‘K’ neighbors. Thus, temporal disaggregation from monthly flow condition to daily flow is carried out independently for each month to generate 100 ensemble members by selecting ‘K = 10’ neighbors under leave-one out cross-validation.

3. Illustrative study

3.1. Site description

Philpott dam, which was built during 1948–1952, is located 44 river miles (about 71 km) above the mouth of Smith River in the Roanoke River basin (Fig. 2). The top of the reservoir’s active conservation elevation is 974 feet (296.9 m) above mean sea level and corresponding surface area is 2880 acres (1.165×10^7 square meters). Its main purposes are flood control, recreation and hydropower generation; the powerhouse was built in 1953 with three turbines located at 813 feet (247.9 m) above mean sea level. It is operated by USACE.

Hydrological alteration in the river downstream of the reservoir due to current reservoir operation was evaluated first using USGS gage data and historical operation data. Then, four scenarios were investigated to examine whether the ecological flow requirements and anthropogenic water use can be met in a more effective manner using the optimization model formulations.

3.2. Scenarios

Scenarios A–D listed in Table 1 are first examined. In Scenario A, the water supply ratio is optimized while monthly hydropower

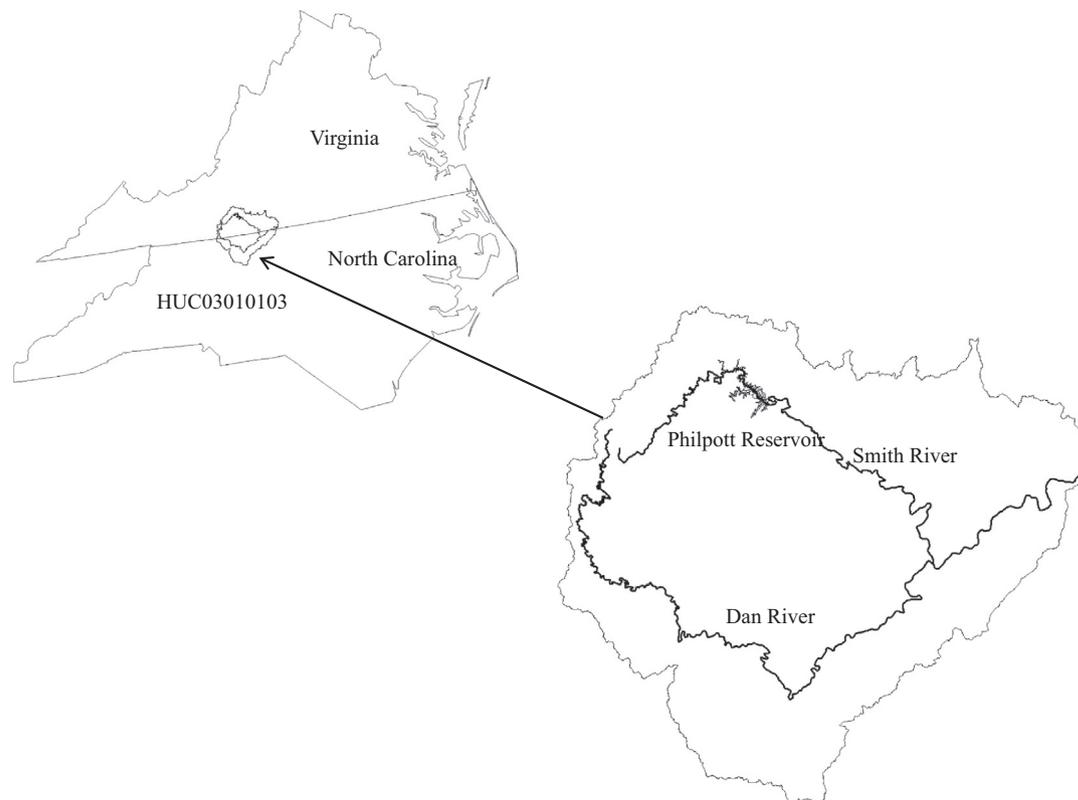


Fig. 2. Philpott reservoir, residing at upper Smith River, is located at watershed. HUC03010103, which crosses North Carolina and Virginia.

generation is constrained to meet the firm energy requirement. Ecological flow requirements are not explicitly considered in this scenario; this scenario represents closely the current reservoir operation. In the other three scenarios, the total number of mis-hits is minimized to improve ecological flow conditions. Scenario B represents a hypothetical instance where ecological flow is the only consideration; this scenario is used to set a benchmark (or bound) for the most ecologically friendly operation condition for comparison purposes. Scenario C represents a case that considers ecological flow conditions in conjunction with the current operation; water supply is constrained to be no less than 90% of the demand. Scenario D is built upon Scenario C by adding hydropower generation requirement. The pre-impact duration is based on flows in years 1930–1950. The optimization model for each scenario was constructed and optimized one month at a time for the post-impact period of October 1950–1980. The optimization model, a mixed integer linear programming (MILP) model, was implemented using

A Mathematical Programming Language (AMPL) and was solved using CPLEX 12.2.

Scenarios E and F are used for tradeoff analysis to examine possible tradeoff between human needs and ecological flow requirements.

4. Result analysis

4.1. Evaluation of current operation

Fig. 3a shows the comparison of October mean flow values between pre-impact period and post-impact period. The two dashed lines correspond to the 33rd percentile and the 67th percentile of the time series in the pre-impact period; there are seven years within each of the three categories (low is the first 33rd percentile, medium is the second 33rd percentile, and high is the third 33rd percentile) defined by the two critical values (the dashed

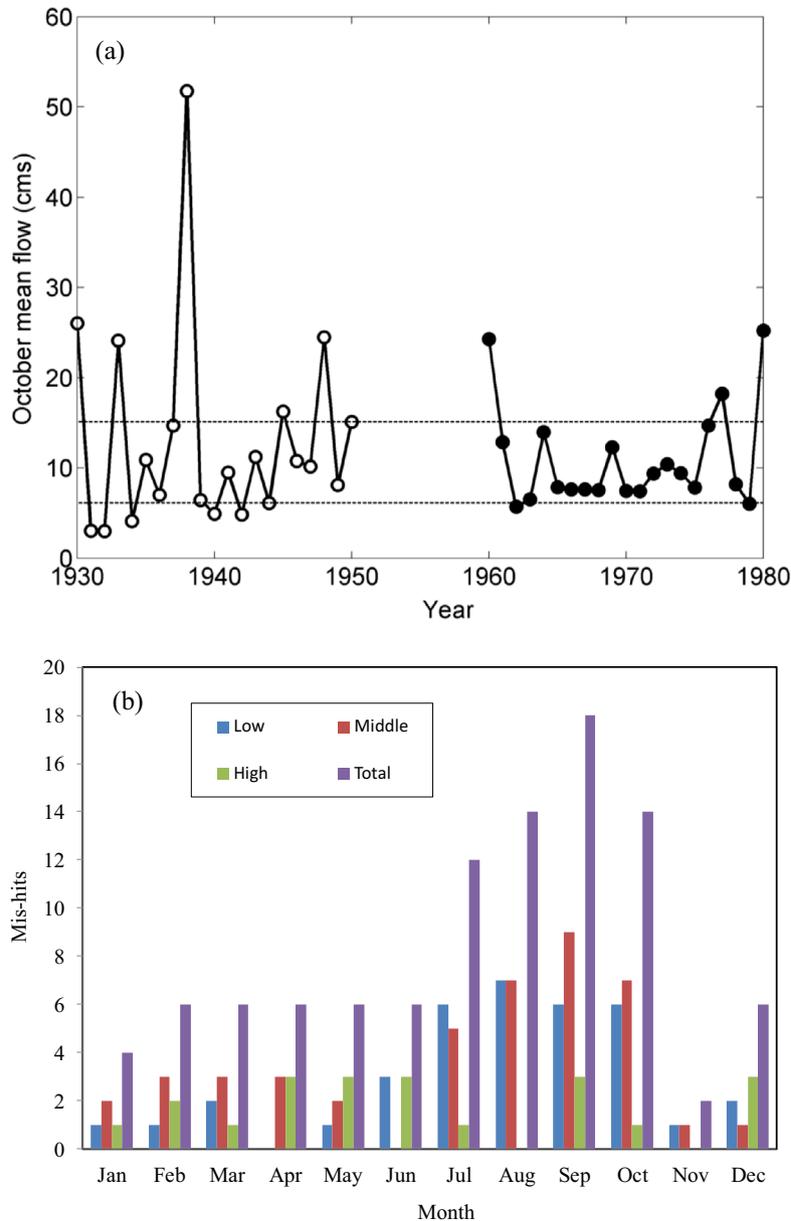


Fig. 3. Alterations in monthly mean flow under current operation for Philpott Reservoir indicating: (a) the shift in October mean flow between pre-impact and post-impact years; (b) presents the number of mis-hits in the three categories (low, medium, and high) for mean flow in each month.

horizontal lines). The distribution by categories is different in the post-impact period. For example, the flow is in the low category in only one year, and is in the high category for six years, resulting in increased number of occurrences (14) in the medium category. The differences in this distribution are represented in terms of mis-hits that reflect the total alteration as a consequence of reservoir operation. Fig. 3b shows the number of mis-hits in each category for the monthly mean flow in each month. The number of mis-hits in the July–August–September (JAS) summer season is relatively high compared to the other months. This result is reflective of the current operations where more water is released in the summer months to meet increased energy demand. Since the Philpott reservoir is used primarily for hydropower, the deviation in the summer months and the increased flow alterations are consistent with current operation.

The number of mis-hits for each of the six flow parameters corresponding to the current operations are analyzed (results not shown). Compared to monthly average flow, the minimum and maximum flow parameters have higher numbers of mis-hits. The mis-hits for 1-day minimum flow in January–February–March (JFM) season, for example, are all higher than 20, whereas the mis-hits for the monthly average flow parameter are lower than 10. The total number of mis-hits of all six parameters ranges from 50 to 90, with more mis-hits in the summer (JAS) months.

4.2. Comparison of Scenarios A, B, C and D

Scenario A aims to maximize water supply ratio while meeting the hydropower generation requirement. Daily water demand was set at 40 cfs and monthly firm energy yield was set at 300 MKWH, based on the water control plan for Philpott dam. This scenario is similar to the current reservoir operation in that ecological flow alteration is not explicitly considered. The total number of mis-hits in each month is shown in Fig. 4. Compared to the number of mis-hits for the current operation, Scenario A has more mis-hits as expected since the water supply deficiency is minimized, resulting in no deficits even though the real operation may have had some. Among the six parameters, mis-hits for minimum and maximum flow parameters are higher than that for monthly average flow.

Since ecological flow requirements are not explicitly considered in this scenario, the number of mis-hits increased as expected.

Scenario B is a hypothetical (or ecologically ideal) case where only ecological flow requirements are optimized and no anthropogenic water demand is considered. The total number of mis-hits in each month is included in Fig. 4 to enable a comparison with other scenarios, as discussed below, where the ecological flow is explicitly optimized.

The total number of mis-hits for Scenario C is significantly lower than that of current operation and Scenario A (Fig. 4). The water supply satisfaction ratio was 0.9 for Scenario C, which is slightly less than 100% demand satisfaction in Scenario A. Compared to Scenario B (the ecologically ideal case), Scenario C performs similarly in terms of preserving ecological flow conditions while meeting the target water supply satisfaction ratio.

Scenario D captures all anthropogenic uses as well as ecological flow considerations. As shown in Fig. 4, the total number of mis-hits for Scenario D is still much lower than that of current operation, although all anthropogenic uses are considered in this scenario. Although hydropower generation is considered in both Scenarios A and D, Fig. 5 shows a difference in the monthly hydropower generation, suggesting different downstream releases between the two scenarios. In Section 4.3, we provide a tradeoff analysis that examines possible tradeoff between hydropower generation and ecological flow requirements.

By modeling and solving these different scenarios, the applicability of the reservoir operation framework was demonstrated for a realistic case study. Using mis-hits as a surrogate for flow alterations, the results that compare the new scenarios and the current operation indicate that an improvement in ecological flow impact can be achieved while still meeting the different anthropogenic water demands.

4.3. Tradeoff analysis

To study the tradeoff between hydropower generation and water supply, two additional scenarios were developed. Scenario E helps to generate the tradeoff when ecological flow alterations are not considered at all, i.e., the anthropogenic uses are the only objectives optimized. By constraining monthly water supply ratio

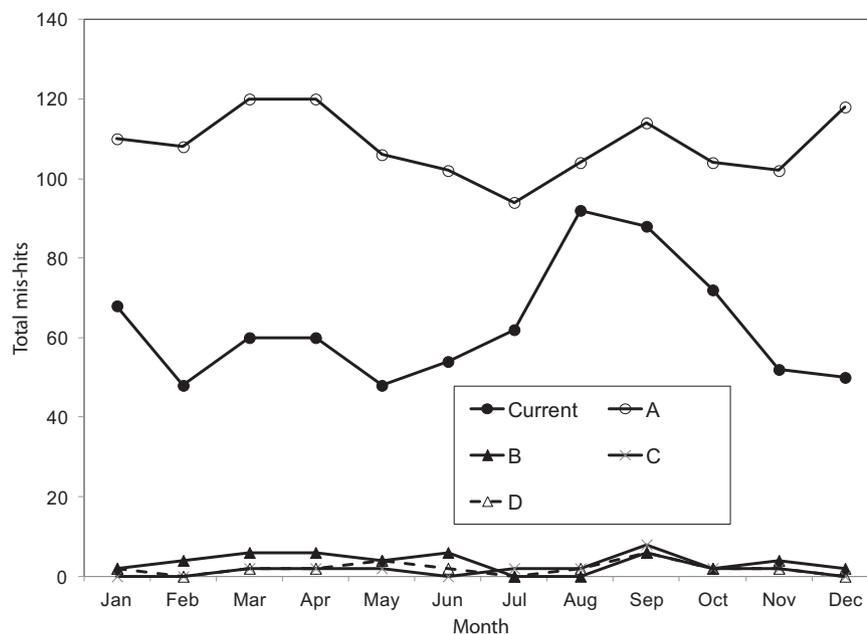


Fig. 4. Total number of mis-hits for the four Scenarios (A–D) and current operation.

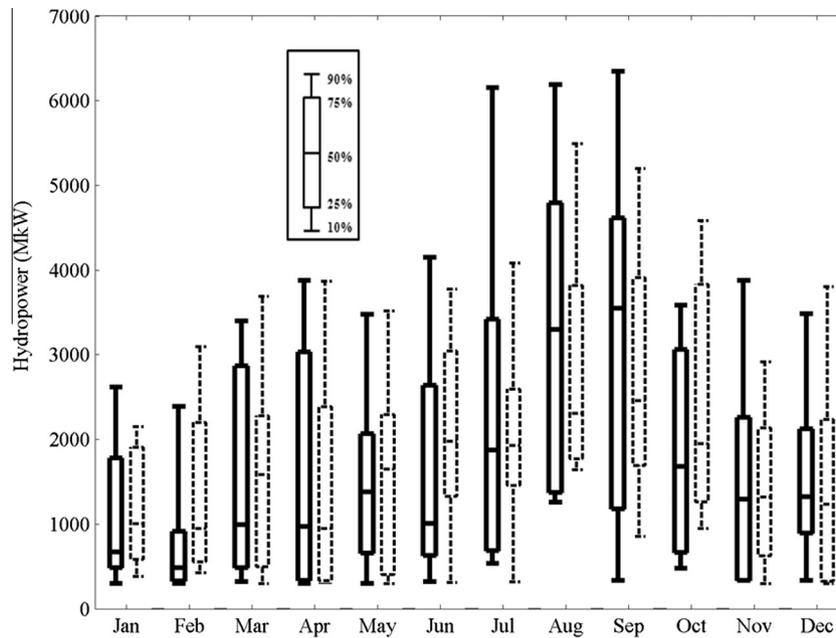


Fig. 5. Monthly hydropower generation for Scenarios A (solid box-plots) and D (dashed boxplots).

at discrete values and optimizing for hydropower generation, an approximation of the non-inferior tradeoff was generated (Fig. 6). To study the effect of ecological flow considerations on the tradeoff, Scenario F is defined in which a constraint on the total number of mis-hits is included. The mis-hit limit was set to be no more than 3, which corresponds to the maximum number of mis-hits for Scenario D. This is to ensure that the resulting number of mis-hits is no worse than those of the solutions obtained using Scenario D, which represents consideration of all anthropogenic uses and the ecological flow objective. The resulting tradeoff is also plotted in Fig. 6(a). These plots imply that explicit consideration of ecological flow consideration has little effect (less than 0.2% reduction) on meeting the hydropower and water supply objectives if the releases are accordingly optimized. Fig. 6(b) shows the box-plots of monthly hydropower generation, for Scenario E, over the months during the period 1961–1990. The dashed line represents the monthly average inflow.

4.4. Application of the framework in reservoir releases management

To further explore the applicability of the framework in reservoir releases management, retrospective flow forecasts during the period 1960–1980 are incorporated to allocate water for different users, herein called “retrospective case”. This is compared to reservoir operation simulation under long-term average of daily flow (herein called “climatology case”), as well as reservoir operation under perfect flow information, which is historical observation, shown in the previous section (herein called “perfect flow case”). Comparison of reservoir objectives among the three cases aims to examine the utility of operational flow forecasts. Scenario D described in Table 1 is selected as the reservoir operation scenario since it considers multiple users at the same time.

As for retrospective daily flow forecasts, although variance of daily flow is not well preserved, the long-term average of forecasts is 267 cfs, which is close to that of historical observations (269 cfs).

Comparison of reservoir operation simulation under different flow information shows that difference in hydropower generation is less than 5%. For instance, monthly average hydropower generation for the retrospective case is 1920 Mkw and it is

1858 Mkw for the climatology case. There is, however, striking difference for the number of mis-hits among the three cases. As expected, the number of mis-hits for the perfect case is the minimum (Fig. 7). Reservoir operation under the retrospective case has less mis-hits than the climatology case. The difference of mis-hits difference between the two is largely due to that fact that forecasted inflow has a better performance in preserving the variability of reservoir flow conditions. This also demonstrates the applicability of the framework in adaptive reservoir operation using monthly and daily flow forecasts.

5. Discussions

One implicit assumption behind restoring a natural flow pattern is that the natural (or pre-impact) flow pattern is the best for maintaining a healthy downstream ecological system. This assumption is based on the reasoning that aquatic systems in the river downstream of a reservoir are adapted to the pre-impact flow regime. One argument against this assumption is that aquatic systems could adapt to the altered flow regime in the post-impact period. Most flow control constructions, e.g., weirs and reservoirs, were constructed within the last 100 years, which is short compared to geological and evolutionary time scale. Hence it is reasonable to assume that natural flow regimes are good for sustaining a healthy ecosystem. But whether aquatic systems can partially or well adapt to altered flow regimes remains a research question [7]. Systematic study of the altered flow regime and the ecosystems based on field monitoring is required to test such scientific hypotheses.

Richter and Thomas [24] suggested using the 25th and 75th percentile of the flow parameter values in pre-impact years as the lower and upper bounds for the target range. One limitation of using such a fixed target range approach is that the flow variability cannot be well preserved because only a very limited number of flow values fall below the 25th percentile or above the 75th percentile. Preliminary investigation of the correlation between monthly average flow and the other five ecological flow parameters reveal significant correlation (p value < 0.05). The correlation between monthly average flow and 1-day minimum flow in

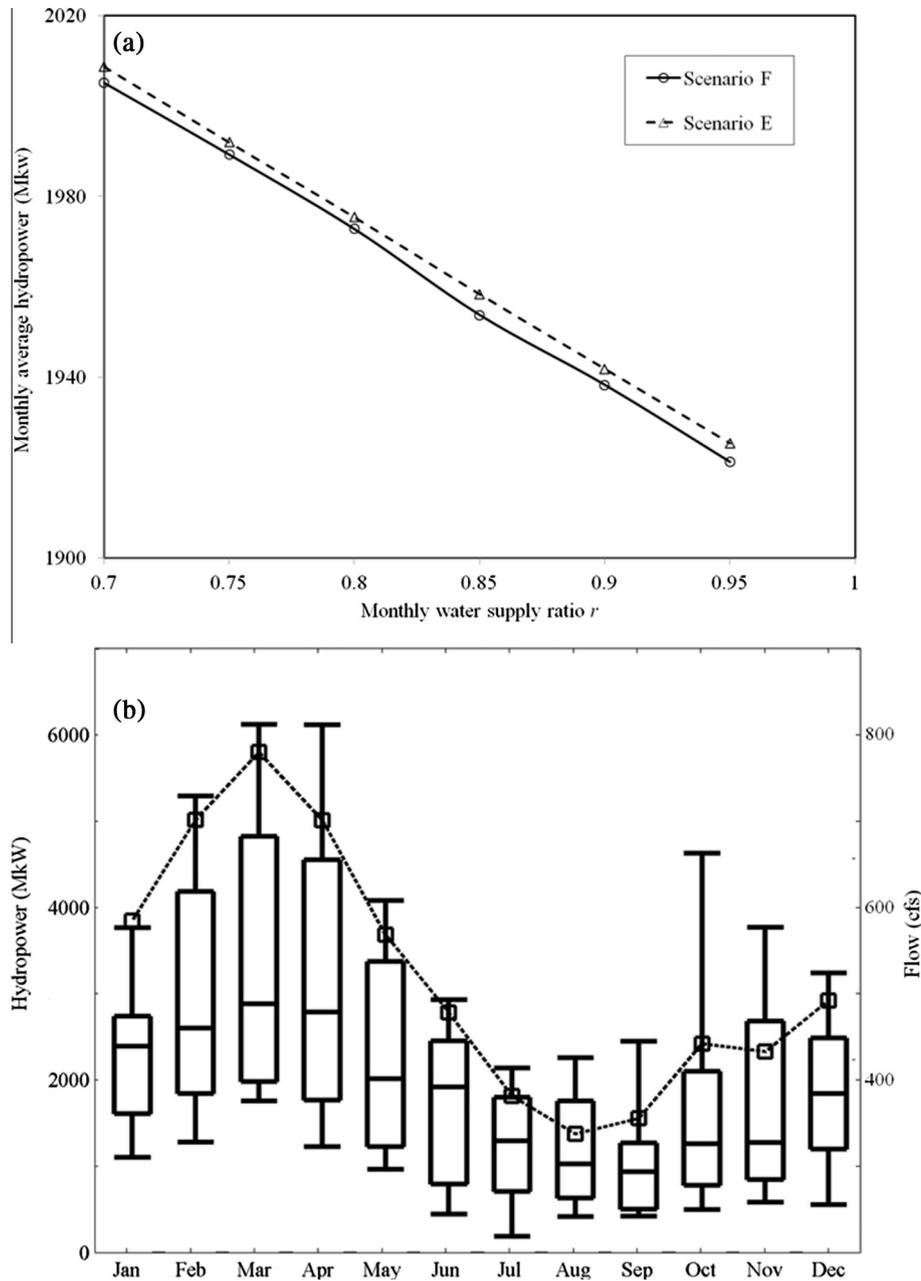


Fig. 6. (a) The tradeoff between hydropower generation and monthly water supply ratio for Scenarios E and F. (b) Monthly hydropower generation for Scenario E.

the pre-impact period (252 months) is 0.63. Hence, it is reasonable to assign the target range for the other flow parameters to be the same as that of the monthly average flow.

The framework was tested for different cases of reservoir inflow conditions, namely the perfect case, climatology case and retrospective. Flow forecast information is usually given in one of the following forms: deterministic, probabilistic or Ensemble Streamflow Forecasts (ESP). Deterministic flow information is used in daily reservoir operation model to compare with and demonstrate the effectiveness of the proposed framework. This framework does not preclude the use of other forms of flow information. Many studies reported in the literature (e.g., [5,13]) have examined ways to incorporate flow information and uncertainty into optimization of water resources systems. Different forms of flow information could be incorporated in future studies to examine the value of using streamflow forecasts within the proposed framework.

The daily reservoir operation optimization model under the different scenarios was tested by considering different combinations

of mis-hits, monthly water supply and monthly hydropower generation requirements. In addition to monthly anthropogenic water demands, daily requirements can also be modeled. This model also shares the capacity for considering other constraints, such as a maximum number of days to allow violation of water demand requirement or hydropower requirement. Since daily water supply and hydropower were simulated and demonstrated successfully in the current formulation, considering daily requirements would be a trivial extension. One limitation of the current model formulation is that it is not ready to be applied for multi-reservoir systems.

6. Summary and observations

RVA analysis was applied to evaluate the shift in several flow parameter distributions from pre-impact years to post-impact years. The number of mis-hits was used to quantify the difference between the two distributions over three discretized categories,

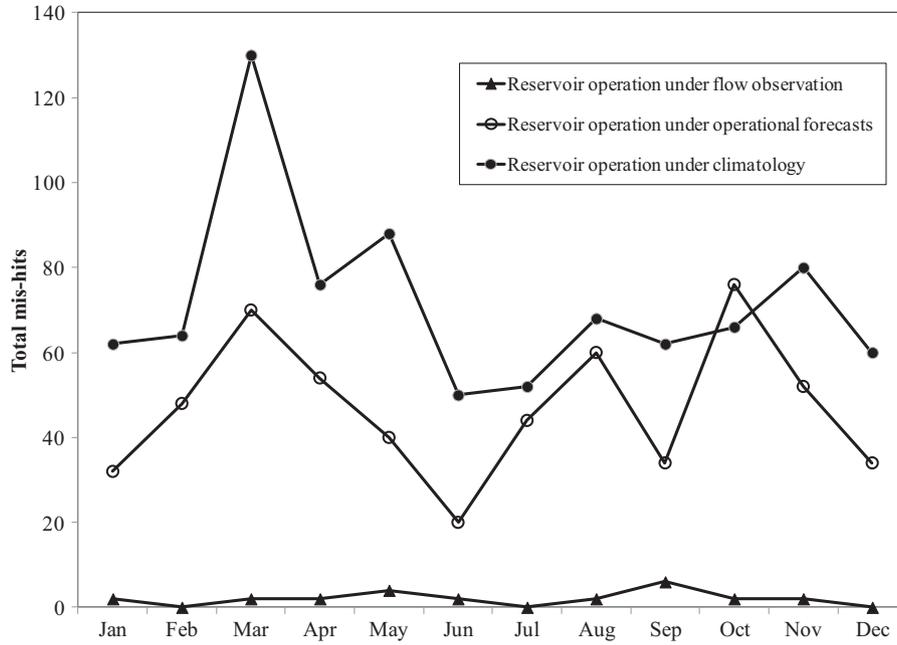


Fig. 7. Comparison of the number of total mis-hits for reservoir operation simulation under different inflow conditions.

namely, low, medium and high ranges. The key challenge to matching the release to the natural flow pattern is the determination of the releases that mimic the natural flow pattern in the short-term. While the natural flow pattern may not be restored in a short time period, e.g., one or several years; this approach can minimize alteration in the flow regime over longer periods (e.g., 10–20 years).

An MILP optimization model was formulated to explicitly incorporate ecological flow requirements. Four scenarios of the mathematical model were investigated. The results demonstrate the effectiveness in simultaneously satisfying anthropogenic water demands and ecological releases. Comparisons among these different scenarios show that there is a clear tradeoff between anthropogenic demands and ecological flow requirements. The results based on the scenarios analyzed show that flow alterations can be minimized, almost to zero occurrences, by optimizing the daily releases and still meet the anthropogenic requirements. Although these observations are specific to the reservoir modeled in this study, the framework is generally applicable and holds promise to enable consideration of ecological flow regime alteration explicitly without sacrificing other benefits through reservoir reoperation using such an approach. A general reoperation rule cannot be identified based on the current limited study, but additional studies and results using the proposed framework could shed more light on potential general approaches for different types of reservoir operations. This study demonstrates the framework of incorporating ecological flow requirements using perfect inflow information and retrospective flow forecasts. The applicability of this framework incorporating ecological flow requirements for multi-reservoir systems would require additional research efforts and the authors are currently conducting such study and will report this later.

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Appendix A

For day j , the daily average storage, \bar{S}_j , is calculated as the average of the daily initial storage s_{j-1} and end-of-day storage s_j , as shown in Eq. (A.1). The storage axis is divided into $K-1$ intervals with $K-1$ break points (Fig. 8a), and b_{kj} is a binary variable associated with interval k . At the boundary break points, b_{0j} is associated with the first break point and $b_{K-1,j}$ is associated with the last break point. α_{kj} is a coefficient in the range of [0, 1], and it represents a weight for day j associated with break point k . To find an estimate of elevation corresponding to \bar{S}_j , first the pair of break points adjacent to \bar{S}_j in the storage axis is determined; then the elevation for these break points are weighted to estimate the elevation. The weights are determined based on the relative location of \bar{S}_j compared to the two adjacent break points. Eqs. (27–30) are used to find the two adjacent break points. The weights (α_{kj}) corresponding to these two adjacent break points are used to relate (Eqs. (A.2) and (A.3)) the storage (st_k) at these break points to \bar{S}_j . Then the elevations associated with these adjacent break points are combined using the corresponding weights (Eq. (A.8)) to estimate the elevation h_j^e in day j . These equations are shown below.

$$\bar{S}_j = (s_{j-1} + s_j)/2 \quad \forall j \in \{1, 2, \dots, J\} \tag{A.1}$$

$$\bar{S}_j = \sum_{k=1}^K \alpha_{kj} st_k \quad \forall j \in \{1, 2, \dots, J\} \tag{A.2}$$

$$\sum_{k=1}^K \alpha_{kj} = 1 \quad \forall j \in \{1, 2, \dots, J\} \tag{A.3}$$

$$\sum_{k=1}^{K-1} b_{kj} = 1 \quad \forall j \in \{1, 2, \dots, J\} \quad \forall k \in \{1, 2, \dots, K\} \tag{A.4}$$

$$\alpha_{kj} \leq b_{k-1,j} + b_{k,j} \quad \forall j \in \{1, 2, \dots, J\} \quad \forall k \in \{1, 2, \dots, K\} \tag{A.5}$$

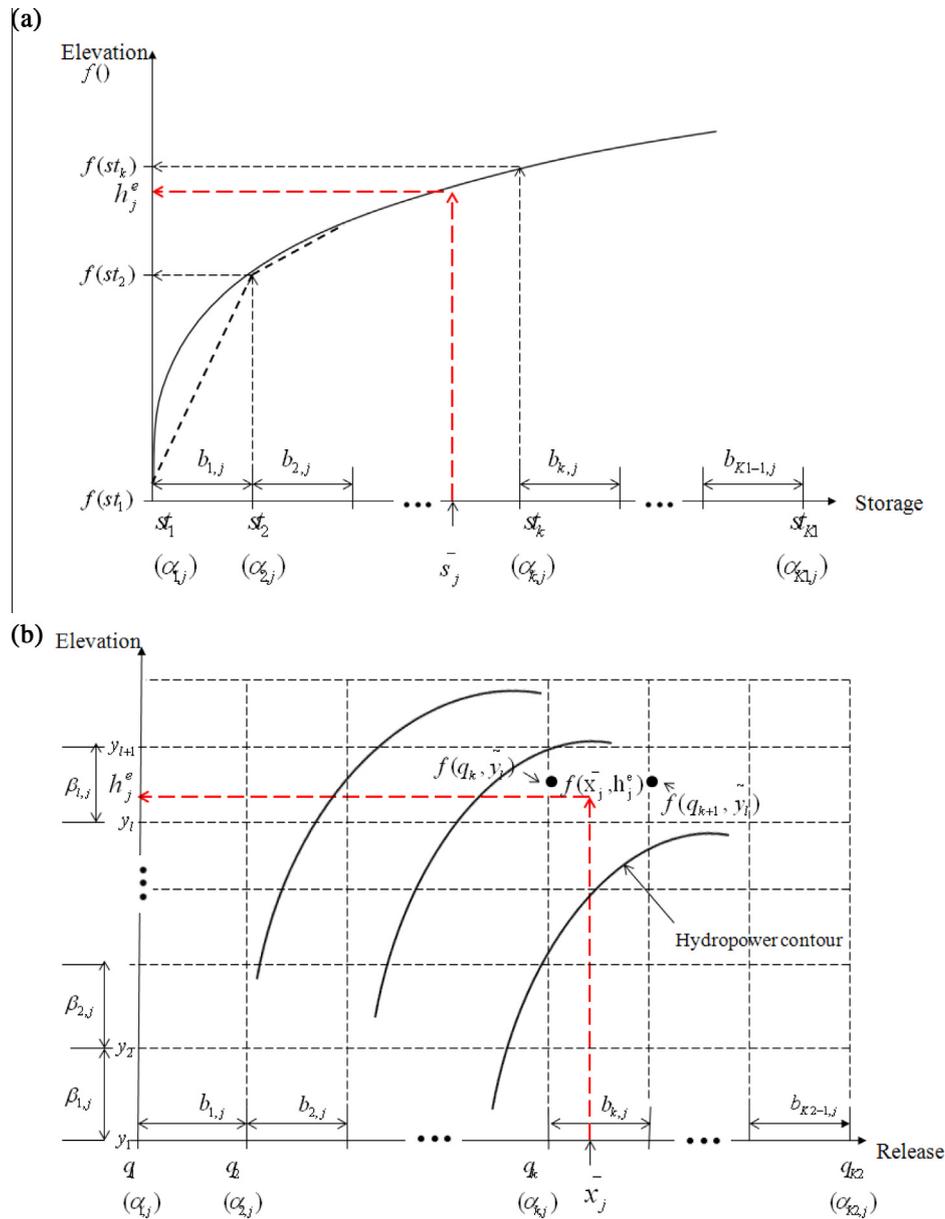


Fig. 8. (a) Linearization for the storage-elevation curve; (b) Two-dimensional linearization for hydropower generation.

$$b_{0j} = 0 \quad \forall j \in \{1, 2, \dots, J\} \quad (\text{A.6})$$

$$b_{Kj} = 0 \quad \forall j \in \{1, 2, \dots, J\} \quad \forall k \in \{1, 2, \dots, K\} \quad (\text{A.7})$$

$$he_j = \sum_{k=1}^K \alpha_{k,j} f(st_k) \quad \forall j \in \{1, 2, \dots, J\} \quad (\text{A.8})$$

The estimated elevation (he_j) corresponding to average daily storage \bar{S}_j on day j and daily release \bar{x}_j are combined to estimate the hydropower generated on day j , expressed as energy E_j produced on day j . The Energy–Elevation–Storage–Release relationship, which is non-linear, is discretized and is represented, as before, using a piece-wise-linear approximation. The elevation axis is discretized into L intervals with $(L + 1)$ break points (Fig. 8). The variable y_l represents the elevation at break point l . A set of binary variables ($\beta_{l,j}; l = 1, 2, \dots, L; j = 1, 2, \dots, J$) is used to indicate the interval in the elevation axis, and is used to determine the break point closest to h_j^e on day j (Eqs. (A.8)–(A.12)). The release axis is discretized into $K2$ intervals with $(K2 + 1)$ break points. $\alpha_{k,j}$ represents the

weight on day j for break point k ; the $\alpha_{k,j}$ weights at the two break points adjacent to \bar{x}_j must be such that the weighted average of the releases q_k at these adjacent break points is equal to \bar{x}_j . Eqs. (A.13) and (A.14) are used to find the energy generated (E_j) on day j as the weighted average (using $\alpha_{k,j}$ weights as corresponding to \bar{x}_j) of energy associated with the midpoint \tilde{y}_l for the interval in which h_j^e falls. These constraints are shown below.

$$he_j \leq \sum_{l=1}^{L-1} \beta_{l,j} y_{l+1} \quad \forall j \in \{1, 2, \dots, J\} \quad (\text{A.9})$$

$$he_j \geq \sum_{l=1}^{L-1} \beta_{l,j} y_l \quad \forall j \in \{1, 2, \dots, J\} \quad (\text{A.10})$$

$$\beta_{l,j} \in [0, 1] \quad \forall j \in \{1, 2, \dots, J\} \quad \forall l \in \{1, 2, \dots, L-1\} \quad (\text{A.11})$$

$$\sum_{l=1}^{L-1} \beta_{l,j} = 1 \quad \forall j \in \{1, 2, \dots, J\} \quad (\text{A.12})$$

$$E_j \leq \sum_{k=1}^{K2} \alpha_{k,j} f(q_k, \tilde{y}_l) + M(1 - \beta_{l,j}) \quad \forall l \in \{1, 2, \dots, L-1\} \quad (\text{A.13})$$

$$E_j \geq \sum_{k=1}^{K2} \alpha_{k,j} f(q_k, \tilde{y}_l) - M(1 - \beta_{l,j}) \quad \forall l \in \{1, 2, \dots, L-1\} \quad (\text{A.14})$$

$$\sum_{j=1}^J E_j \geq E_{\text{firm yield}} \quad (\text{A.15})$$

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