

Article

Piecewise-Linear Hedging Rules for Reservoir Operation with Economic and Ecologic Objectives

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Received: 10 May 2018; Accepted: 25 June 2018; Published: 29 June 2018



Abstract: The construction of dams and operation of reservoirs have a significant impact on the interruption of aquatic and riparian ecological systems, by altering natural stream flows in river courses. Recently, the ecological requirements are included as an additional objective in reservoir operation in order to restore the natural stream flows and reduce the negative impacts of reservoir operations on ecosystems that rely on the natural flows. The key challenge involving ecological requirements is to balance the ecological and economic objectives by operation rules, on the basis of quantitatively identifying the objective of ecological flows required to maintain the natural flow regime for ecosystem. This study develops a piecewise-linear multi-objective hedging rule (PMHR) for reservoir operations, with ecologic flow objectives represented by 33 hydrologic parameters from the indicators of hydrologic alteration (IHA). Variables of the PMHR are obtained through optimization using a vector evaluated genetic algorithm. The results show that the PMHR improves the ecological water releases without reducing economic water supplies in the case river in the context of hydrological uncertainty. It can offer technological references for improving the utility of water resource management under competitive conditions of water resources.

Keywords: natural flow regime; multi-objective model; uncertainty; genetic algorithm

1. Introduction

For decades, dams have been built and operated mostly for economic purposes that require a reliable water supply for human needs, such as hydropower electricity, irrigation, living and industry water supply, and navigation. Water withdrawn for increasing economic demands has led to conflicts between human water use and ecosystem water needs [1–3]. The operation of dams leads to negative effects on aquatic and riparian ecosystem systems [4–6]. The alteration of the flow regime caused by reservoir operation is recognized as a major driving factor that threatens the integrity of the river ecosystem [7–11]. Bunn and Arthington reviewed the studies focused on the relationship between hydrological flow regime and river ecosystems, and illustrate four critical negative impacts of the alteration: (1) alteration of the magnitude of flow as the determinant of physical habitat and biotic composition; (2) alteration of the timing and frequency of peak flow as key factors of the life history of aquatic species; (3) destruction of the patterns of longitudinal and lateral connectivity for riverine species; and (4) the extinguishing of extreme low flow avoidance, meant to prevent the invasion of exotic species [12].

How to balance the trade-off between humans and ecosystems has been discussed for decades regarding integrated river basin management [13–16]. Many investigations have been conducted to address the conflicts between environmental flow release and the economic water supply over the past

decades. To evaluate the ecological objective for aquatic and riparian ecosystems' sustainability, four kinds of approaches are often applied, including (1) estimating the minimum flow requirement for downstream habitats to maintain the survival of specific species [17–19]; (2) determining a flow regime based on fish diversity information [20]; (3) providing a regime-based, prescribed flow duration curve that considers floods and droughts for species and morphological needs [21–23]; and (4) minimizing the degree of flow alterations in order to maintain the stability of river ecosystems and population structures of species [16,24–26]. In these studies, it can be found that the adopted ecological objectives have been shifted from an emphasis on a minimum flow requirement or single species to the development of a regime-based comprehensive approach. With the first two methods mentioned above, the flow fluctuation, which decides the ecological integrity, is generally neglected. Therefore, ecologists currently prefer to recommend the last two methods, in which the ecological integrity can be sustained by accounting for the functional and structural requirements for aquatic and riparian ecosystems.

Suen and Eheart proposed a multi-objective model based on the ecological flow regime paradigm, which incorporates the intermediate disturbance hypothesis to address the ecological and anthropic need [16]. Their study uses parts of the Taiwan Eco-Hydrology Indicators System (TEIS) as the criteria to represent ecosystem objectives. Lane et al. proposed a multi-step re-operation methodology to address environmental flow requirements and human water use objectives [23]. This model summarizes the environmental flow requirements on the basis of empirical streamflow thresholds for the maintenance of an ecosystem with geomorphic functions. Using a one-dimensional water routing model by the Water Evaluation and Planning System (WEAP), the model develops an alternative reservoir rule curve and suggests the new timing of releases to sustain key ecological and geomorphic functions. Generally, these studies have used a monthly-based interval and have therefore failed to reflect important hydrological factors with daily variations, which may play an important role for sustaining the health of an ecosystem [7,27–29]. Chen et al. proposed a time-nested approach, in order to scale down the decision variables from a monthly to a 10-day basis, and further to a daily basis for reservoir operations [30]. They used a daily flow hydrograph as a constraint in the optimization model. However, the model was extremely complex, with 730 decision variables, leading to a high cost of calculation in the optimization process. Considering daily scale indicators in reservoir operations, such as the timing and frequency of peak flow, the rising and falling rates requires a large number of decision variables in the optimization process, and lead to a computing-heavy task.

It has been noted that involving a set of fixed operation rules in reservoir modelling can reduce the number of decision variables as well as the computational costs [31]. Standard operating policy (SOP) and hedging rules (HR) are the most commonly used rules in reservoir operations. SOP, which is the traditional and simplest operating rule, releases water as close to the delivery targets as possible in order to meet the demands of the current stage [32]. By contrast, HR prefers to keep a certain proportion of available water in the reservoir, in order to minimize the possible losses caused by water shortages in the future. Usually, SOP is recommended only if the objective function is linear, while the hedging rules have been proven to be a more efficient way to optimize the reservoir operations when the supply benefits are nonlinear [33,34]. In real operations, the trade-off analysis of multiple objectives is often complicated with nonlinear systems and uncertain inflow conditions [35–37]. Therefore, HR is often used to cope with uncertain future inflows among different nonlinear objectives in practice [38]. Taghian et al. employed HR to achieve the optimal water allocation, in order to reduce the intensity of severe water shortages [39]. A hybrid model was developed to simultaneously optimize both the conventional rule curve and the hedging rule. Shiau developed a parameterization–simulation–optimization approach for optimal hedging for a water supply reservoir by considering the balance between beneficial release and carryover storage value. The proposed methodology was applied to the Shihmen Reservoir in northern Taiwan to illustrate the effects of derived optimal hedging on reservoir performance in terms of shortage-related indices and hedging uncertainty [40]. Yin et al. used a typical approach that uses three limit curves to divide the reservoir storage and the reservoir inflow into several zones [24]. A series of water supply rules

and water releasing rules were derived by the actual reservoir storage and the reservoir inflows to provide the water supply and to satisfy the ecological needs of seasonally variables, such as base flows, dry season flow recessions, high-flow pulses, etc. However, daily interval variations were not exactly considered in the above-mentioned studies.

Accounting for the daily variation of downstream flows, Yang et al. proposed a set of linear rules to generate daily reservoir releases, with the aim of satisfying the needs of ecological assessment [20]. This method can explicitly engage flow regime variation based on real-time inflow information [41], while short-term inflow information becomes crucial for reservoir operation when daily scale ecologic indicators are considered. However, the proposed operation rules were based on traditional operation curves for flood control and ecologic objectives, without further considerations regarding the balance between consumptive water supply and ecological flow needs. Moreover, the ecologic objective in this paper was calculated by seven indicators, including Q_3 and Q_5 , the average discharges in March and May, respectively; $Q_{3day\ min}$ and $Q_{7day\ min}$, which represent the annual minimum average of three- and seven-day discharges; $Q_{3day\ max}$, which is the annual maximum average 3-day flow; and D_{min} , representing the Julian date of the annual minimum daily flow. Further information, such as the changing trends of daily flow and the statistics of daily flow reversals, are required to establish a more comprehensive function for the ecological objective.

The purpose of this study is to develop practical hedging rules for reservoir operation with economic and ecologic objectives, which will be able to reflect daily interval variations and engage the real-time daily inflow forecast and storage information simultaneously into decision-making. In this paper, piecewise-linear hedging rules are proposed in order to generate the daily release for ecological and economic objectives, through which the parameters are optimized based on historical and synthetic streamflow series. In addition, the objective of ecological flow requirements is quantified by 33 hydrologic parameters from Indicators of Hydrologic Alteration (IHA). The proposed methodology is applied to a realistic reservoir as a performance test. The rest of this paper is organized as follows. Section 2 briefly introduces the structure of the model. Section 3 presents a real world case study of Baiguishan reservoir, China. Section 4 compares the proposed HRs with SOP and analyzes the value of forecast information. Finally, conclusions are drawn in Section 5.

2. Methodology

The framework of the method for optimizing the reservoir's target water levels and flows released to the economic and ecological objectives is shown in Figure 1. It is composed of the following three steps: (1) generating daily water release based on daily inflow and pre-defined hedging rules, (2) multi-objective optimization for releasing water to economic and ecologic objectives, (3) Monte Carlo simulation and probability analysis to identify the variations of the optimal water release in various hydrological years.

The aim of this framework is to identify a set of practical operating rules for water release. A set of pre-defined, piecewise-linear hedging rules are used to generate water release under the conditions of various inflow and water levels of the reservoirs. A multi-objective genetic algorithm is then applied to optimize the parameters of the rules' curves iteratively, by balancing the economic and ecological objectives of water release. The statistical characteristics of the parameters are obtained through Monte Carlo simulations, in which the historical and synthetic daily inflows are used as the inputs.

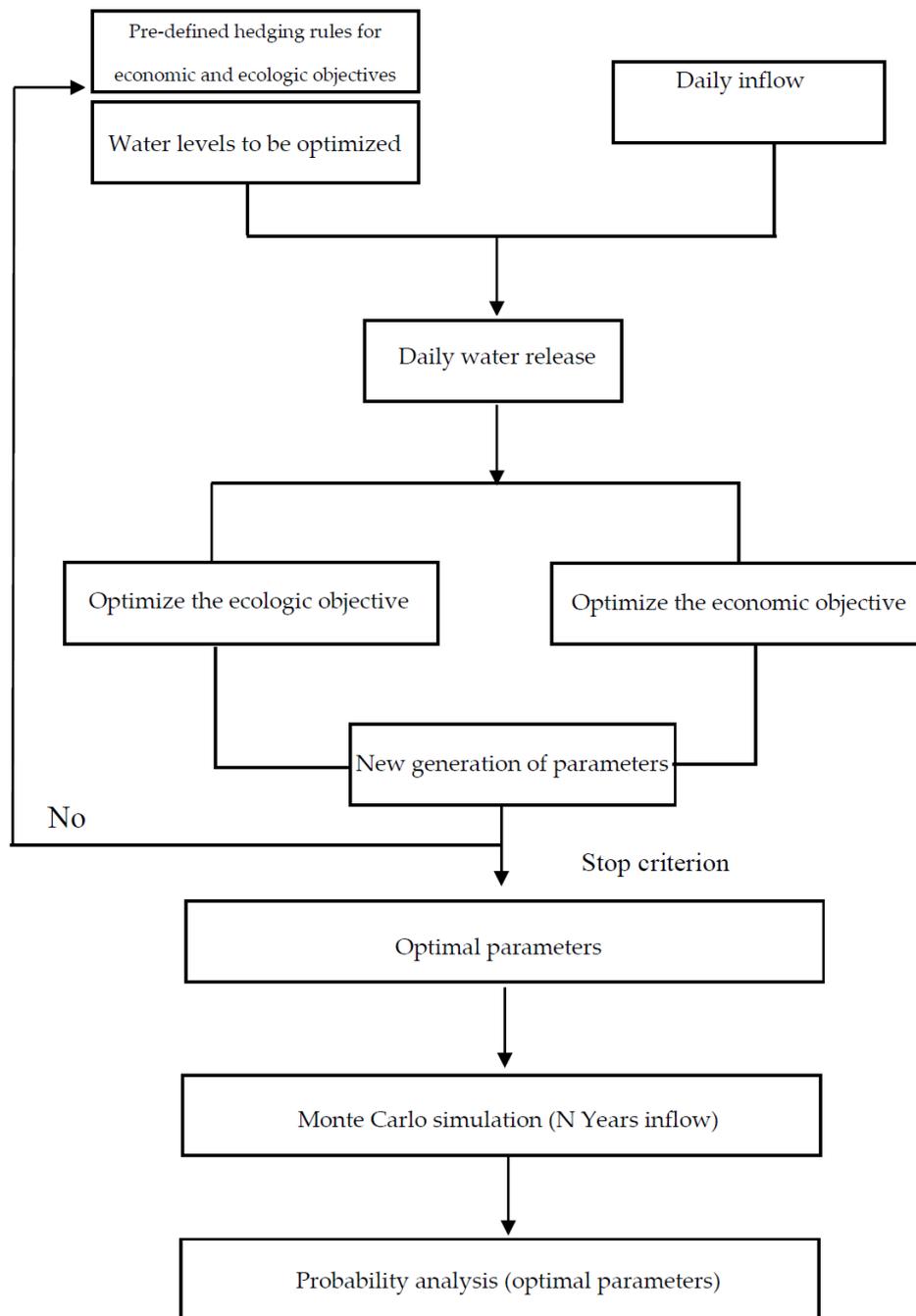


Figure 1. Process diagram for optimizing the operating rules.

2.1. Pre-Defined Piecewise-Linear Hedging Rules

In this paper, piecewise-linear hedging rules considering both economic and ecological objectives are pre-defined for the dry and wet seasons separately. As shown in Figure 2, zones 1–3 represent the rules in the dry season, and zones 4–6 stand for the rules during the wet season. Red lines show the maximum and minimum water level of different periods following the traditional operation rules currently used by the reservoir.

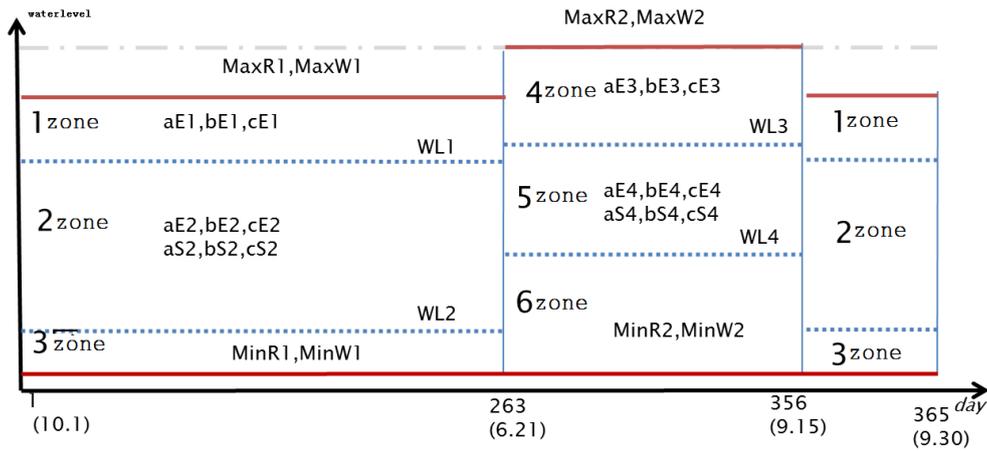


Figure 2. Release functions in different zones characterized by seasons.

For the dry season, daily water release for economic objectives can be defined as a set of piecewise-linear hedging rule functions incorporating actual storage and future inflow while considering the effect of daily inflow forecast [42], as follows:

$$\begin{cases} W_t = D_t & L_t \geq WL_1 \\ W_t = \text{Min}(D_t, \text{Max}(\text{Min}W_1, aS_1 \times I_t + bS_1 \times L_{t-1} + cS_1)) & WL_2 \leq L_t < WL_1 \\ W_t = \text{Min}W_1 & L_t < WL_2 \end{cases} \quad (1)$$

where W_t is the water release for economic objective of day t ; D_t is the target release for economic objective of day t ; I_t is the inflow of day t ; L_t and L_{t-1} are water levels of day t and day $t - 1$, respectively; WL_1 and WL_2 stand for upper and lower limits of the water level, respectively; $\text{Min}W_1$ represents the minimum release for the economic objective of day t ; aS_1 , bS_1 , and cS_1 are the coefficients of the linear functions of hedging rules.

Specifically, when the actual water level (L_t) is higher than the upper limit (WL_1), it implies that the stored water is enough to defend the area from droughts in the future. In this case, the economic water release W_t can be described as the amount of water that is needed (D_t). When the actual water level (L_t) is between the upper limit (WL_1) and the lower limit (WL_2), it means that there is insufficient storage to defend against future droughts, and thus the water release W_t can be described as a linear function related to the forecasted inflow and current water level. When the current water level is lower than the lower limit (WL_2), it means that storage is rare and there is a huge drought risk in future. In this case, W_t is defined as a fixed minimum value, representing the minimum or basic water release to the economic system.

Similar to Equation (1), the daily water release for an ecologic objective is defined as follows:

$$\begin{cases} R_t = \text{Min}(\text{Max}R_1, \text{Max}(\text{Min}R_1, aE_1 \times I_t + bE_1 \times L_{t-1} + cE_1)) & L_t \geq WL_1 \\ R_t = \text{Min}(\text{Max}R_1, \text{Max}(\text{Min}R_1, aE_2 \times I_t + bE_2 \times L_{t-1} + cE_2)) & WL_2 \leq L_t < WL_1 \\ R_t = \text{Min}R_1 & L_t < WL_2 \end{cases} \quad (2)$$

where R_t represents the ecological water release of day t ; aE_1 , bE_1 , cE_1 , aE_2 , bE_2 , and cE_2 are the parameters of the HR, which will be obtained through the optimizations illustrated in Figure 1; $\text{Max}R_1$ and $\text{Min}R_1$ are the maximum and minimum water release that need to be optimized, respectively.

Similarly, economic and ecological water releases in wet seasons can be defined as follows:

$$\begin{cases} W_t = D_t & L_t \geq WL_3 \\ W_t = \text{Min}(D_t, \text{Max}(\text{Min}W_2, aS_2 \times I_t + bS_2 \times L_{t-1} + cS_2)) & WL_4 \leq L_t < WL_3 \\ W_t = \text{Min}W_2 & L_t < WL_4 \end{cases} \quad (3)$$

$$\begin{cases} R_t = \text{Min}(\text{Max}R_2, \text{Max}(\text{Min}R_2, aE_3 \times I_t + bE_3 \times L_{t-1} + cE_3)) & L_t \geq WL_3 \\ R_t = \text{Min}(\text{Max}R_2, \text{Max}(\text{Min}R_2, aE_4 \times I_t + bE_4 \times L_{t-1} + cE_4)) & WL_4 \leq L_t < WL_3 \\ R_t = \text{Min}R_2 & L_t < WL_4 \end{cases} \quad (4)$$

where WL_3 and WL_4 are the upper and lower limit, respectively; $MaxR_2$ and $MinR_2$ are maximum and minimum water release to be optimized, respectively; and $aS2, bS2, cS2, aE3, bE3, cE3, aE4, bE4,$ and $cE4$ are the parameters of the HR during wet seasons.

Consequently, the decision variables consist of the following three parts: (1) water level limits ($WL1$ and $WL2$ in dry seasons and $WL3$ and $WL4$ in wet seasons); (2) ecological and economic hedging coefficients ($aE1, bE1, cE1, aE2, bE2, cE2, aE3, bE3, cE3, aE4, bE4, cE4, aS2, bS2, cS2, aS4, bS4,$ and $cS4$); and (3) maximum and minimum water release ($MinW1, MinW2, MinR1, MinR2, MaxW1, MaxW2, MaxR1, MaxR2$).

2.2. Ecological Objective

The ecological objective is to minimize reservoirs' alterations on rivers' natural flows, which have been adapted to by aquatic and riparian species over thousands years of evolution by maintaining the stability of ecosystems and population structures of species. The Indicators of Hydrologic Alteration (IHA) program, proposed by Richter, has been adopted to represent the ecological objective in this paper [4]. It contains 33 hydrologic parameters involving five groups of characteristics, including (1) the magnitude of monthly stream flow; (2) the magnitude of annual extreme flows at different time durations; (3) the timing of annual extreme flows; (4) the frequency and duration of high and low pulses; (5) the rate of change.

For each eco-hydrological indicator, a spectrum of values could be set as the target range, which could reflect the changes of environmental flow regime that a species can adapt to. If the actual value of an indicator falls in that range, it means that the alteration of the natural flow regime is acceptable by the aquatic or riparian species. Those acceptable ranges of all the indicators have been investigated by many researchers [9], among which the findings by Richter et al. are mostly widely applied through the range of variability approach (RVA) [4]. RVA is an efficient and convenient method to evaluate the degree of flow regime alteration. According to Richter and in this paper, the 25th and 75th percentiles of the historical annual value of the indicators are set as the upper and lower limits of the target range of environmental flow regime, respectively.

Here, let $f_i(r)$ represent the effect function of the i -th indicator of IHA. In addition, $iha_i(r)$ represents the value of the i -th indicator. $f_i(r)$ equals 0 if $iha_i(r)$ falls in the target range, which implies that the ecological release and flow alternation compared to the natural flow regime are acceptable. When the value of the indicator falls outside of the target range, $f_i(r)$ is calculated as the distance from the target range, as follows:

$$f_i(r) = \begin{cases} 0 & iha_{ip75} \leq iha_i(r) \leq iha_{ip25} \\ \left(\frac{iha_i(r) - iha_{ip25}}{iha_{ip25} - iha_{ip75}}\right)^2 & iha_i(r) \geq iha_{ip25} \\ \left(\frac{iha_{ip75} - iha_i(r)}{iha_{ip25} - iha_{ip75}}\right)^2 & iha_i(r) \leq iha_{ip75} \end{cases} \quad (5)$$

where r is the series of ecological water release generated by Equations (2) and (4); iha_{ip25} and iha_{ip75} are the upper and lower limits of the annual values of the indicators, respectively; and $iha_i(r)$ represents the value of the i -th indicator. The ecological objective can be calculated by the sum of the 33 indicators of the IHA, as

$$f_1 = \sum_{i=1}^{33} f_i(r) \quad (6)$$

The value of f_1 , the range of which is greater than zero, represents the ecosystem objective to be minimized in the multi-objective optimization model.

2.3. Economic Objective

The economic objective is represented in a target-hitting form, in which the water demands of agriculture, industry, and domestic water use are considered. For equalizing the water supply shortages across time intervals throughout the year, the economic objective is employed through quantifying the water supply deficits, as follows:

$$f_2 = -g(w) = f(w) = \sum_{i=1}^T \left(\frac{d_i - w_i}{d_i} \right)^2 \quad (7)$$

where T is the total number of time periods; d_i is the economic water demand of the i -th day, including the water demands of agriculture, industry and domestic sectors; and w_i is the water supplied in the i -th day. The value of f_2 , range from 0 to 1, and represents the economic objective to be minimized in the multi-objective optimization model.

2.4. Constraints

Constraints within the optimization model are set as follows.

(1) Water balance constraint:

$$V_i = V_{i-1} + I_i \Delta t - q_i \Delta t - E_i \quad (8)$$

where V_i and V_{i-1} represent the reservoir storage available at the end of the i -th day and $i - 1$ day, respectively; I_i is the inflow of the i -th day; q_i is the total release during the i -th day; and E_i is the evaporation of the reservoir in the i -th day.

(2) Reservoir storage capacity constraint:

$$L_i^{min} \leq L_i \leq L_i^{max} \quad (9)$$

where L_i^{min} and L_i^{max} are the minimum and maximum water level limits at the end of the i -th day, respectively; and L_i is the water level of the i -th day.

(3) Initial and end storage constraint:

Considering the initial water storage of next year, here we set up initial storage and end storage equally as

$$V_0 = V_a \quad (10)$$

where V_0 is the initial storage of the reservoir and V_a is its end storage.

The multiple objectives of the model are set to meet both the ecosystem and human demand, which can be expressed as follows:

$$Obj. \text{ Min}\{f_1(r), f_2(w)\} \quad (11)$$

2.5. Vector Evaluated Genetic Algorithm

This multi-objective model is solved by the vector evaluated genetic algorithm (VEGA). Different from the standard procedure of a genetic algorithm, VEGA focuses on the optimization of several objectives [43]. Through the VEGA, the initial population is divided into a number of objectives, and the elite of each group is selected for the next generation while the others are put in crossover and mutation pools. A population with a higher fitness value has a greater probability of persevering to the next generation. The procedure of VEGA is presented in Figure 3.

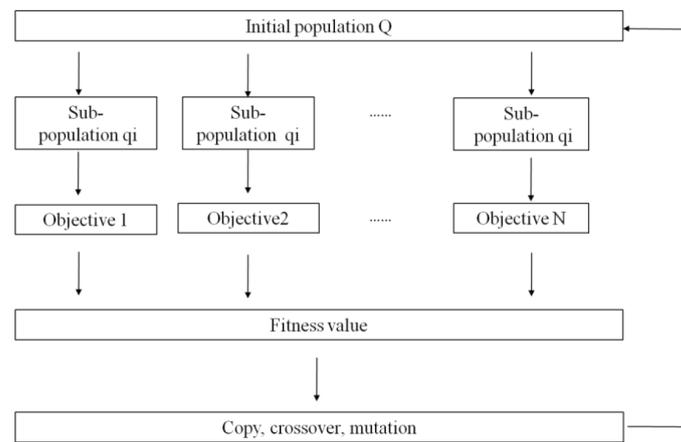


Figure 3. Procedure of the vector evaluated genetic algorithm (VEGA).

3. Results

3.1. Study Site

The Baiguishan Reservoir, which is located on the Shahe River (Figure 4) in the Huaihe River Basin in China, was selected as a case study to test the proposed model. It is a multipurpose reservoir serving as a water supply, flood control, a source of recreation, and ecologic purposes, with a total storage of 0.92 billion m³. Historical daily inflow series from 1976–2005 were used to design the operation rules. Affected by pacific monsoons, 80% of the rainfall to the reservoir occurs in summer, and this divides the year of operation into two seasons, including the dry season (16 September–20 June) and the wet season (21 June–15 September). The maximum water level used in the current operation is 103 m and 105.9 m in the dry and wet seasons, respectively; the minimum water level is limited to 92 m.

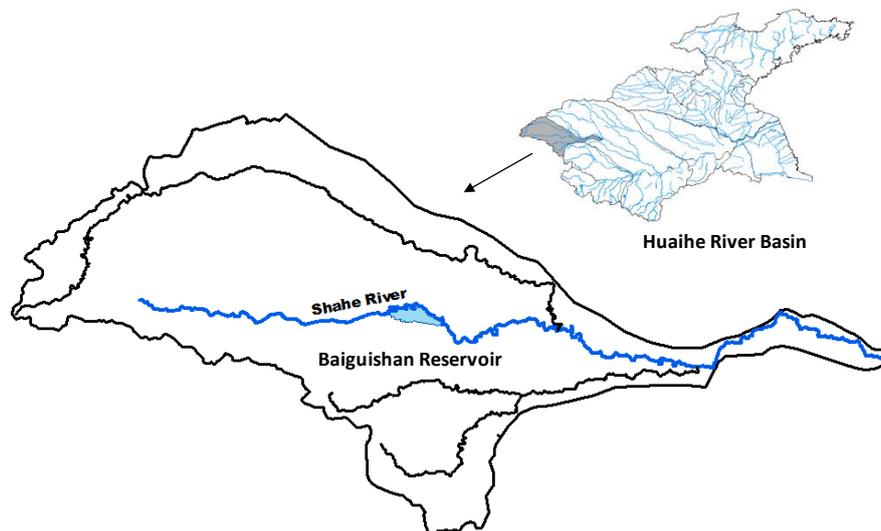


Figure 4. Location of the Baiguishan Reservoir.

3.2. Ecological Management Target Range

Generally, IHA should be calculated based on historically natural flow without intervention. In this paper, the ecological objective is defined based on the historical inflow data of the Baiguishan Reservoir instead, due to the lack of historical daily hydrologic data for the Shahe River before the

1950s—in other words, when the stream flow had not yet been altered by human beings in China. For each eco-hydrological indicator, the target range was calculated by the values of the 25th and 75th percentile of the historical series. Table 1 shows the ecological target ranges calculated by data from 1976–2005. Moreover, the expected value and the standard deviation (SD) are investigated for further discussion.

Table 1. Ecological target ranges and statistical analysis of eco-hydrologic indicators.

No.	Indicator	Unit	Ecological Target Range		Statistical Analysis	
			P25%	P75%	Expected	SD
IHA1	October	m ³ /s	19.81	8.21	17.88	20.91
IHA2	November	m ³ /s	20.52	4.26	12.68	11.3
IHA3	December	m ³ /s	20.71	5.02	11.41	9.03
IHA4	January	m ³ /s	14.59	6.6	9.05	6.33
IHA5	February	m ³ /s	17.25	5.02	11.44	7.62
IHA6	March	m ³ /s	21.48	2.57	13.5	9.11
IHA7	April	m ³ /s	17.81	2.16	11.57	10.8
IHA8	May	m ³ /s	23.1	8.2	17.36	17.06
IHA9	June	m ³ /s	36.65	9.09	24.4	17.86
IHA10	July	m ³ /s	38.91	15.97	36.42	42.28
IHA11	August	m ³ /s	48.18	19.29	39.97	32.7
IHA12	September	m ³ /s	25.75	7.79	21.18	20.34
IHA13	1 day-min	m ³ /s	2.56	0.3	0.63	1.43
IHA14	3 day-min	m ³ /s	3.19	0.24	0.85	1.97
IHA15	7 day-min	m ³ /s	3.56	0.29	1.15	2.21
IHA16	30 day-min	m ³ /s	7.28	0.84	2.84	3.36
IHA17	90 day-min	m ³ /s	10.08	0.91	6.68	5.15
IHA18	1 day-max	m ³ /s	435.98	66.1	286.19	260.18
IHA19	3 day-max	m ³ /s	329.97	55.33	205.25	192.94
IHA20	7 day-max	m ³ /s	219.25	49.42	141.09	133.33
IHA21	30 day-max	m ³ /s	81.72	31.73	67.62	50.98
IHA22	90 day-max	m ³ /s	51.79	23.8	41.1	24
IHA23	Zero days	days	93	6	44.1	63.79
IHA24	Base flow	/	0.24	0.03	0.05	0.1
IHA25	Date of max	/	276.2	122	274.93	61.4
IHA26	Date of min	/	260	159.6	222.9	117.792
IHA27	Low count	/	12	4	4.55	3.25
IHA28	Low duration	days	16	7.22	22.94	23.62
IHA29	High count	/	13	2	7.69	3.6
IHA30	High duration	days	28.75	6	15.77	18.58
IHA31	Fall rate	/	0.52	0.19	0.63	0.39
IHA32	Rise rate	/	−0.11	−0.18	−0.76	0.62
IHA33	Reversal	/	135	81	121.8	32.62

In Table 1, eco-hydrological indicators are ordered from IHA1 to IHA33. IHA1–IHA12 are the annual mean values of monthly flow from January to December. IHA13–IHA22 are the annual mean values of the maximum or minimum t -day ($t = 1, 3, 7, 9, 30, 90$) flows. IHA23 and IHA24 are the number of zero flow days and the base flow, respectively. IHA25 and IHA26 are the Julian date of each annual one-day maximum and minimum, respectively; IHA27 and IHA29 are the number of high or low pulses, respectively, within each year (days); IHA28 and IHA30 are the mean duration of high or low pulses, respectively, within each year; IHA31 and IHA32 are the means of all positive and negative differences between consecutive days, respectively; and IHA33 is the total number of reversals [4].

3.3. Pareto-Optimum Solutions

To deal with the trade-off between economic and ecological objectives, VEGA with a population size of 1000 was adopted to solve the model within one year. With the series of daily inflow from

1976–2005, a Pareto-optimal frontier for every year can be obtained. Using three typical years (frequency = 25%, 50%, 75%) as examples, after running 100 generations, the algorithm is stopped; the result of the Pareto-optimal frontiers of the typical years is shown in Figure 5. Each individual solution represents one possible trade-off between the economic and ecological objectives with different inflow scenarios. Here, a frequency of 75% means the annual runoff for the year will be exceeded in 75 years out of 100. In Figure 5, each frontier solution is calculated by a searching direction in the genetic algorithm, and prioritization between the objectives is decided by the decision-maker. For example, for the scenario of frequency being 75%, the solution at point A represents an emphasis on the ecological objective, while the solution at point D represents an emphasis on the economic objective. Solutions at points B and C are the destinations with two sub-population evolution directions, which represent the trade-offs of the two competitive objectives.

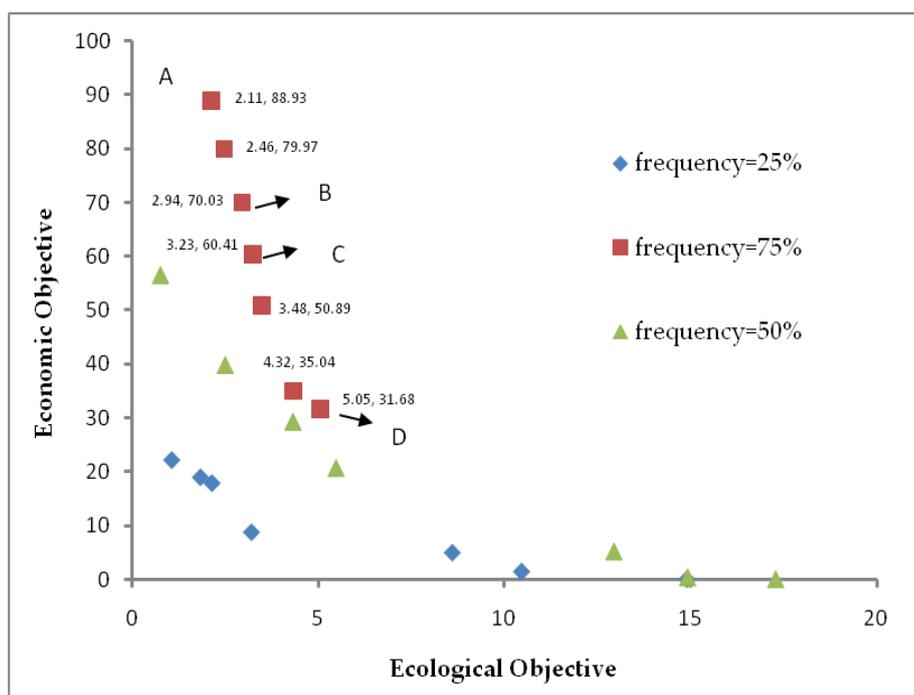


Figure 5. Trade-offs between economic and ecosystem objectives.

The corresponding decision variables of points A, B, C, and D are presented in Table 2.

Table 2. Decision variables of points of A, B, C, and D of the year with 75% frequency.

Pt.	MinW1	MinR1	MaxW1	MaxR1	aE1	bE1	cE1	aS1	bS1	cS1	SL1	MinW2
A	5.14	3.14	8.09	729.09	0.6	0.44	2.89	0.7	−0.95	1.89	102.51	5.13
B	5.9	5.58	8.03	764.83	0.93	−0.35	1.83	0.74	0.99	0.82	102.99	5.33
C	5.48	1.71	8.09	705.23	0.62	−0.8	1.83	0.32	0.05	4.81	102.99	5.66
D	5.35	2.72	8.09	732.35	0.47	0.38	2.32	0.4	−0.07	2.61	102.55	5.4
Pt.	MinR2	MaxW2	MaxR2	aE2	bE2	cE2	aS2	bS2	cS2	SL2	aE3	bE3
A	8.09	8.06	712.42	0.35	0.01	2.5	0.52	−0.95	0.61	97.72	0.2	−0.7
B	6.5	8.09	714.88	0.79	−0.01	2.5	0.63	−0.7	3.09	98.03	0.34	0.83
C	7.6	8.1	776.57	0.82	0	1.08	0.76	0.16	3.69	99.14	0.83	0.1
D	5.53	8.07	737.35	0.63	−0.45	2.55	0.47	0.17	2.45	98.49	0.51	0
Pt.	cE3	aS3	bS3	cS3	SL3	aE4	bE4	cE4	aS4	bS4	cS4	SL4
A	5.06	0.79	0.23	1.03	103.44	0.15	−0.97	3.58	0.05	−0.39	2.19	96.99
B	3.77	0.04	0.38	4.64	102.71	0.71	−0.08	2.77	0.49	−0.05	3.99	98.17
C	1.54	0.66	−0.38	2.65	102.97	0.49	−0.78	2.92	0.77	−0.44	1.26	97.09
D	2.04	0.48	0	2.13	62.4	0.23	−0.18	1.27	0.13	0.22	0.74	97.65

3.4. Monte Carlo Simulation

In the above section, we use the inflow data of a given year to demonstrate the efficiency of the model by generating a set of optimized parameters. However, the obtained optimal parameters for the piecewise-linear multi-objective hedging rule (PMHR) are not applicable for other streamflow conditions. To obtain the optimal PMHR in the context of hydrological uncertainty, a Monte Carlo simulation is applied in this section to deal with different inflow conditions, rather than the inflow of one year.

Based on 29 years of historical hydrological data, a synthetic daily inflow for 100 years was generated, according to the statistical characteristics of the 29-year inflow. To be more specific, the annual mean discharge of these 100 years were obtained by a P-III curve based on samplings from the 29-year historical inflow from 1976–2005. The daily inflow of a synthetic year was decomposed from its annual discharge, according to the historical daily inflow of the year in which the frequency is equal to the synthetic year. The statistical properties of the historical and synthetic flow series is shown in Table 3. Here, the coefficient of variation (C_V) is defined as the ratio of the standard deviation to the mean. It reflects the extent of variability in relation to the mean of inflow. The deviation coefficient (C_S) is measured as the ratio of the difference between the mean and median value of standard deviation. It reflects the skewness of the mean of the inflow.

Table 3. Statistical parameters of the historical inflow series and the synthetic flow series.

	Average Annual Discharge	C_V	C_S
historical inflow series	24.37	0.33	0.83
synthetic flow series	18.70	0.40	0.74

In this paper, the main purposes of synthetic inflow generation are (1) to generate more input scenarios that are close to the historical inflow for the Monte Carlo simulation of the optimal operation model, and (2) to test the effectiveness of the model under the typical frequency of these inflow scenarios. The synthetic flow series can be seen as the input series of a mathematical experiment, while results and discussions are mostly based on the synthetic flow series.

For 100 years of daily inflow data, the optimization model is applied 100 times, and 100 sets of Pareto-optimal frontiers and 100 sets of optimized parameters are calculated correspondingly. In this way, through a Monte Carlo simulation, each set of the optimized parameter forms a possible operation rule for the case reservoir. These 100 groups of parameters represent the optimal operation rules under 100 various inflow scenarios. For each Pareto-optimal frontier, the expected and median values represent the entire probability distribution under different conditions. By using the expected and median values of parameters as the operation rules, optimal economic and ecological water release can be derived under any inflow conditions for decision-makers.

Searching directions used to obtain points B and C in Figure 5 are applied in the model with 100 years' synthetic daily inflow. In this way, 200 groups of optimal decision variables with different searching directions (similar to the method used to obtain points B and C) are obtained. For each searching direction, we calculated the expected and median values of the optimal decision variables ($PMHR_B$ and $PMHR_C$), which represent the optimal operation rules for the case reservoir. Table 4 shows the statistical values of the optimal parameters for 100 years.

Table 4. Statistical Analysis for the Parameters of Counterbalance Solutions.

Parameters		<i>MinW1</i>	<i>MinR1</i>	<i>MaxW1</i>	<i>MaxR1</i>	<i>aE1</i>	<i>bE1</i>	<i>cE1</i>	<i>aS1</i>	<i>bS1</i>	<i>cS1</i>	<i>SL1</i>	<i>MinW2</i>
PMHR _B	Expected	5.43	4.84	8.08	736.31	0.55	0.07	2.37	0.58	0.05	3.2	102.69	5.46
	Median	5.44	5.06	8.08	737.19	0.57	0.24	2.52	0.57	0.1	3.41	102.71	5.43
	SD	0.23	2.13	0.02	19.63	0.25	0.47	1.21	0.17	0.49	1.4	0.44	0.23
	Skew	0.26	−0.16	0.09	0.17	−0.18	−0.38	0.3	0.1	0.15	−0.35	−0.64	0.01
PMHR _C	Expected	5.44	3.84	8.08	743.23	0.54	0.18	2.66	0.52	0.02	2.85	102.68	5.41
	Median	5.44	4.27	8.08	741.9	0.56	0.28	2.78	0.57	0.1	3	102.67	5.43
	SD	0.25	2.05	0.02	18.96	0.27	0.46	1.16	0.24	0.42	1.26	0.43	0.23
	Skew	0.18	0.05	0.01	0.29	−0.36	−0.53	0.25	−0.46	−0.77	0.04	−0.67	0.05
Parameters		<i>MinR2</i>	<i>MaxW2</i>	<i>MaxR2</i>	<i>aE2</i>	<i>bE2</i>	<i>cE2</i>	<i>aS2</i>	<i>bS2</i>	<i>cS2</i>	<i>SL2</i>	<i>aE3</i>	<i>bE3</i>
PMHR _B	Expected	5.21	8.08	739.83	0.55	−0.13	2.69	0.48	0.1	3.22	98.48	0.45	0.02
	Median	5.47	8.08	739.72	0.59	−0.03	2.63	0.44	0.19	3.2	98.55	0.4	−0.01
	SD	2	0.02	19.61	0.24	0.2	1.33	0.24	0.5	1.1	0.35	0.21	0.49
	Skew	−0.32	−0.34	−0.18	−0.25	−1.41	−0.06	−0.01	−0.32	−0.02	−0.43	0.74	0.18
PMHR _C	Expected	4.47	8.08	743.41	0.54	−0.27	2.58	0.46	0.33	2.67	98.45	0.45	0.08
	Median	4.33	8.08	742.96	0.53	−0.2	2.49	0.44	0.39	2.72	98.51	0.45	0.07
	SD	2.07	0.03	16.29	0.25	0.3	1.11	0.21	0.41	1.26	0.38	0.21	0.45
	Skew	0.13	0.23	−0.14	−0.17	−0.61	0.11	−0.08	−1.27	0.09	−0.29	0.65	−0.04
Parameters		<i>cE3</i>	<i>aS3</i>	<i>bS3</i>	<i>cS3</i>	<i>SL3</i>	<i>aE4</i>	<i>bE4</i>	<i>cE4</i>	<i>aS4</i>	<i>bS4</i>	<i>cS4</i>	<i>SL4</i>
PMHR _B	Expected	2.57	0.5	0.03	2.96	102.71	0.4	−0.36	1.87	0.42	0.04	2	97.68
	Median	2.46	0.52	0.02	3.01	102.06	0.32	−0.24	1.82	0.42	0.11	1.96	97.7
	SD	0.98	0.27	0.48	1.29	0.36	0.28	0.37	1.19	0.27	0.43	1.29	0.48
	Skew	0.63	0.23	−0.02	0.1	−0.83	0.5	−0.36	0.63	0.18	−0.07	0.47	−0.36
PMHR _C	Expected	2.76	0.47	0.08	2.82	102.08	0.35	−0.37	2	0.4	0.25	1.93	97.55
	Median	2.65	0.43	0.15	2.99	102.2	0.23	−0.34	1.75	0.37	0.18	1.78	97.65
	SD	0.87	0.24	0.54	1.22	0.36	0.26	0.28	1.34	0.25	0.38	1.31	0.45
	Skew	0.16	0.57	−0.47	0	−0.58	0.72	−0.22	0.55	0.24	−0.4	0.49	−0.53

4. Discussion

To test the effectiveness and the robustness of the proposed model, PMHR_B and PMHR_C in Table 4 were used to generate the economic and ecological water release by which the corresponding objectives were derived. Using the 100 years of synthetic inflows generated in Section 3.4, the economic and ecological water release processes, as well as the corresponding objectives under different inflow scenarios by the two PMHR rules, were calculated. For comparative study, the economic and ecological water release and their objectives were calculated by the traditional and simplest operating rule SOP, which meant releasing water as close to the delivery targets as possible in order to meet the demand.

4.1. Economic Versus Ecological Objectives under Different Inflow Scenarios

To demonstrate the effectiveness of the HR rules comparing with the SOP rule, the values of economic and ecological objectives optimized by the PMHR_B, the PMHR_C, and the SOP are compared in Table 5.

Table 5. Comparison of economic and ecological objectives.

No.	Frequency	Rules	Economic Objective		Ecological Objective	
			Expected	Median	Expected	Median
1	95%	SOP		0.99		238.65
		PMHR _B	0.57	0.58	17.89	20.38
		PMHR _C	0.6	0.64	88.02	229.25
2	90%	SOP		1.00		165.64
		PMHR _B	0.89	0.83	12.86	11.97
		PMHR _C	0.92	0.95	43.29	61.25
3	75%	SOP		1.00		148.68
		PMHR _B	0.90	0.82	7.15	10.1
		PMHR _C	0.95	0.97	13.43	21.36
4	50%	SOP		1.00		114.05
		PMHR _B	0.99	0.99	3.53	7.23
		PMHR _C	1.00	1.00	4.97	18.08
5	25%	SOP		1.00		193.8
		PMHR _B	0.99	0.99	3.77	6.37
		PMHR _C	1.00	1.00	2.66	7.23
6	10%	SOP		1.00		137.92
		PMHR _B	1.00	0.99	5.21	3.81
		PMHR _C	1.00	1.00	28.01	52.21

According to Equations (5) and (6), the range of ecological objectives is greater than or equal to 0, and a greater value means a less satisfied ecologic objective. According to Equation (7), the range of economic objectives is from 0 to 1, where a greater value means a higher water supply deficit. With the annual inflow data ranging from a frequency of 10% to 95%, two objective values are compared, as shown in Table 3.

The SOP can satisfy almost all of the economic water demands under a majority of scenarios, but with a greater alteration to the natural flow regime. For the water supply objective (economic objective), the SOP guarantees meeting 100% of the water demands, except in extremely dry years (frequency = 95%). At the same time, the corresponding ecologic objective is greater than 100, which implies a highly altered flow regime. Meanwhile, PMHR_B and PMHR_C are able to effectively improve the ecological objective by decreasing the ecologic objectives to the range of 2.66–52.21, and satisfy the economic water demands in wet years (frequency < 50%). In dry years, PMHR_B and PMHR_C have to reduce the water supply for human demand in order to meet the demands of the ecosystem. For a typical dry year (when the inflow frequency is 75%), PMHR_B and PMHR_C each reduce nearly 10% of

the water supply for human demands in order to balance the ecological objective. When it comes to the extreme dry year (frequency > 95%), $PMHR_B$ and $PMHR_C$ each reduce about 50% of human water supply to meet the demands of ecosystem.

4.2. Ecological Release

Under the synthetic inflow conditions, the processes of ecological release in a typical dry year (75% frequency), generated by three rules (SOP, $PMHR_B$ and $PMHR_C$), were compared, as shown in Figures 6 and 7. The processes generated by the expected values of $PMHR_B$ and $PMHR_C$ are shown in Figure 6; processes generated by the median values of $PMHR_B$ and $PMHR_C$ are shown in Figure 7. Compared to the SOP, the ecological release processes generated by $PMHR_B$ and $PMHR_C$ are closer to the natural inflow process. The similarity of the ecological water release process to the inflow process can be quantified by the correlation coefficient. The higher the correlation coefficient is, the closer the release is to the inflow of the reservoir. This means that the smaller hydrologic alteration is made through reservoir operations. Using Figure 6 as an example, the correlation coefficient of the inflow and water release under the SOP is 0.54, while the correlation coefficient of inflow and water release under the $PMHR_B$ and $PMHR_C$ are 0.81 and 0.66, respectively.

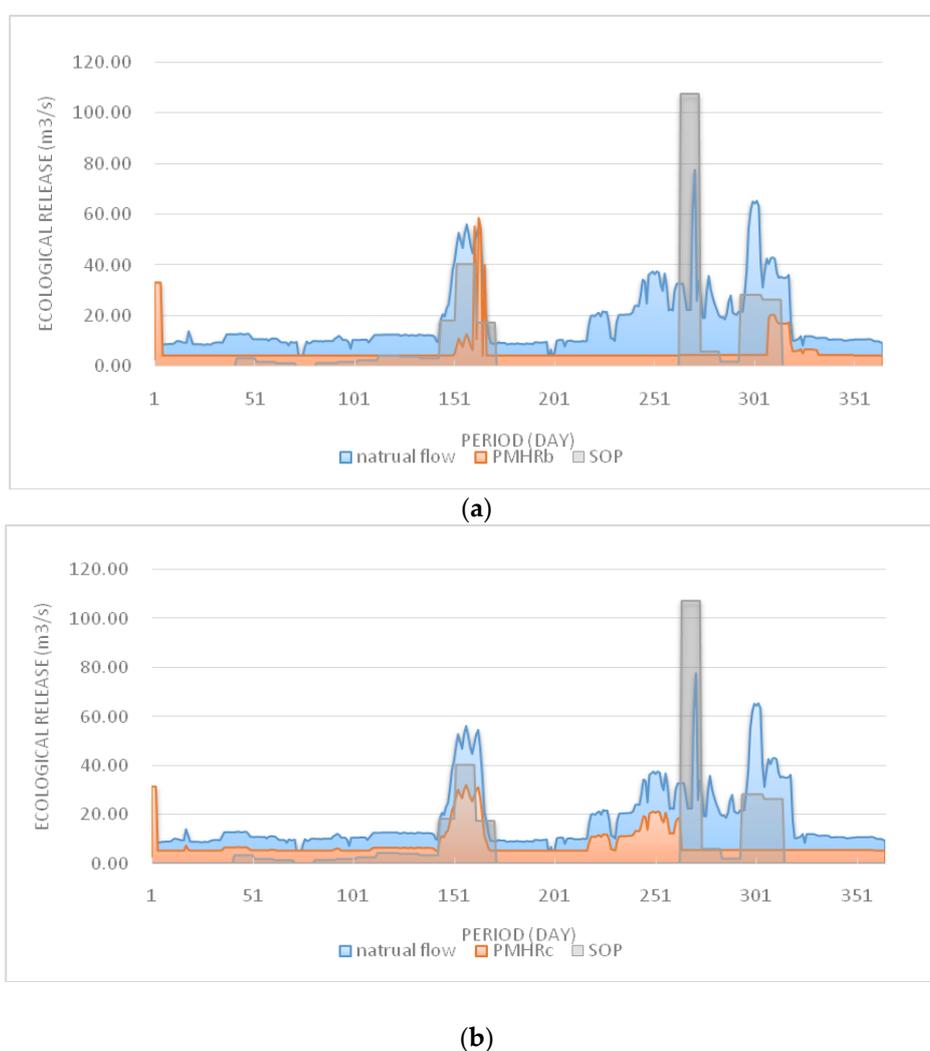


Figure 6. Comparison of release processes between different operating rules, calculated by expectation. (a) Comparison of release process of natural flow, $PMHR_B$ and SOP; (b) Comparison of release process of natural flow, $PMHR_C$ and SOP.

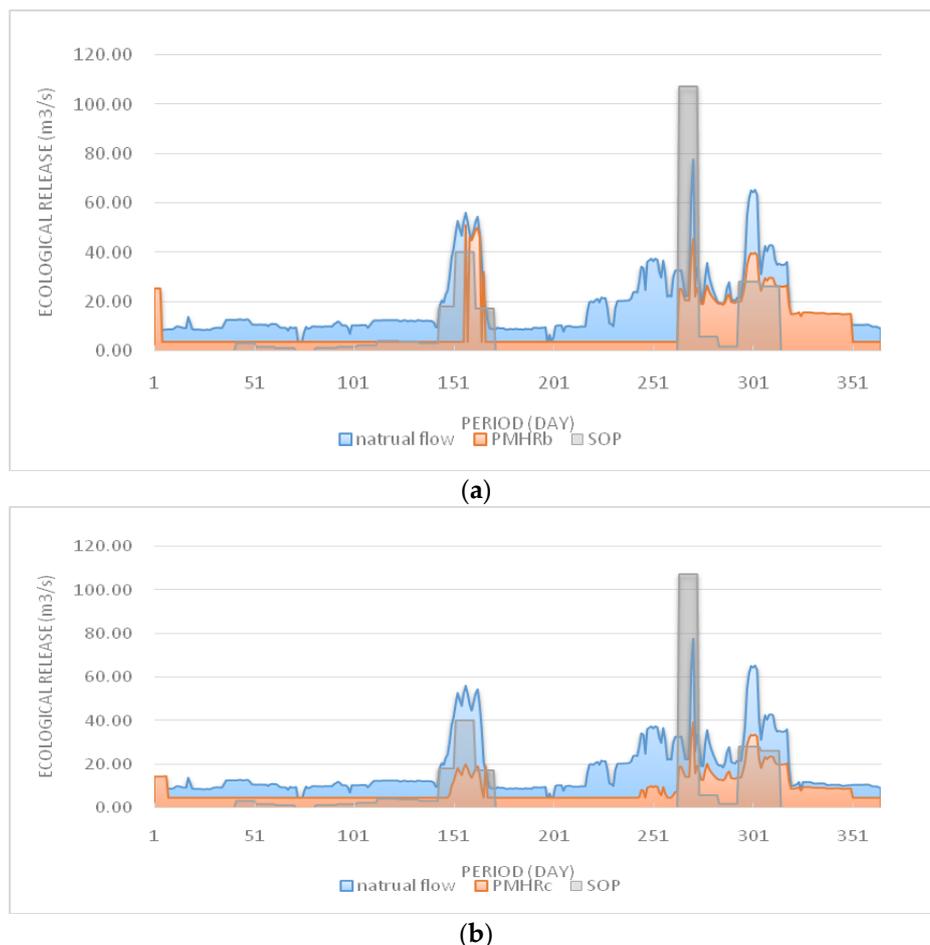


Figure 7. Comparison of release processes between different operating rules, calculated by median values. (a) Comparison of release process of natural flow, PMHR_B and SOP; (b) Comparison of release process of natural flow, PMHR_C and SOP.

4.3. Monte Carlo Simulation Key Indicators Analysis

Figures 6 and 7 demonstrate that reservoir water release alters the flow regime of the river course. This will threaten fish communities and the integrity of river ecosystems downstream. Compared to the operation results under the SOP, the ecological release under the PMHR_B and the PMHR_C can recover the altered flow regime significantly.

The most altered IHA indicators under the SOP are in Table 6, as well as the indicators under PMHR_B and PMHR_C. The upper and lower limits (25% and 75% frequency of natural distribution, respectively) of each indicator are also listed for reference. If the value of indicators falls within the range of the upper and lower limits, it means a more acceptable ecological condition for sustainability (as the bold number in Table 6).

Table 6. Comparison of indicator analysis of standard operating policy (SOP) and the piecewise-linear multi-objective hedging rule (PMHR).

	October	November	December	January	April	May	July	August	September	30 Day-Min	90 Day-Min	Low Duration	Reversal	Rise Rate	Fall Rate
SOP	0	1.69	0.92	2.92	0	0	12.6	8.49	0	0	0	74	5	3.37	−0.57
PMHR _B	7.03	4.84	4.84	4.84	4.84	4.84	18.74	14.8	6.94	4.84	4.84	20.31	68	0.2	− 0.14
PMHR _C	6.65	3.84	3.84	3.84	3.84	3.84	25.03	21.04	9.53	3.84	3.84	21.5	47	0.78	− 0.14
Upper limit	19.81	20.52	20.71	14.59	17.81	23.1	38.91	48.18	25.75	7.28	10.08	28.75	135	0.52	−0.11
Lower limit	8.21	4.26	5.02	6.6	2.16	8.2	15.97	19.29	7.79	0.84	0.91	6	81	0.19	−0.18

4.4. Extended Analysis: Impact of Long-Term Forecast Information

In this section, the impacts of using long-term annual forecast inflows in an operation are discussed preliminarily. We suppose that the annual forecast information, which simply indicates the inflow of the next year and is either larger (wet year) or smaller (dry year) than the average level, is known in advance. Thus, the synthetic inflows used by the Monte Carlo simulation can be divided into two parts: the inflow in wet years and the inflow in dry years. By using the inflow of wet or dry years instead of all the synthetic inflows, the parameters of PMHR can be optimized in two groups: parameters adapted to wet years and parameters adapted to dry years. The expected value of these parameters can be used for wet and dry years, respectively.

Figure 8 shows the environmental flow release using rules in both wet and dry years with long-term forecast information, as well as the release using rules of all possible hydrological years without long-term forecast information. Figure 8a presents the results of a typical wet year (frequency = 25%), in which the correlation coefficient between the water release process and the inflow process is 0.95 with forecast information, but 0.90 without forecast. Figure 8b presents the results of a typical dry year, in which the correlation coefficient is 0.66 with forecast information and 0.61 without forecast information. This indicates that the PMHR combined with forecast information is able to improve the restoration of an ecological flow regime compared to one without the forecast.

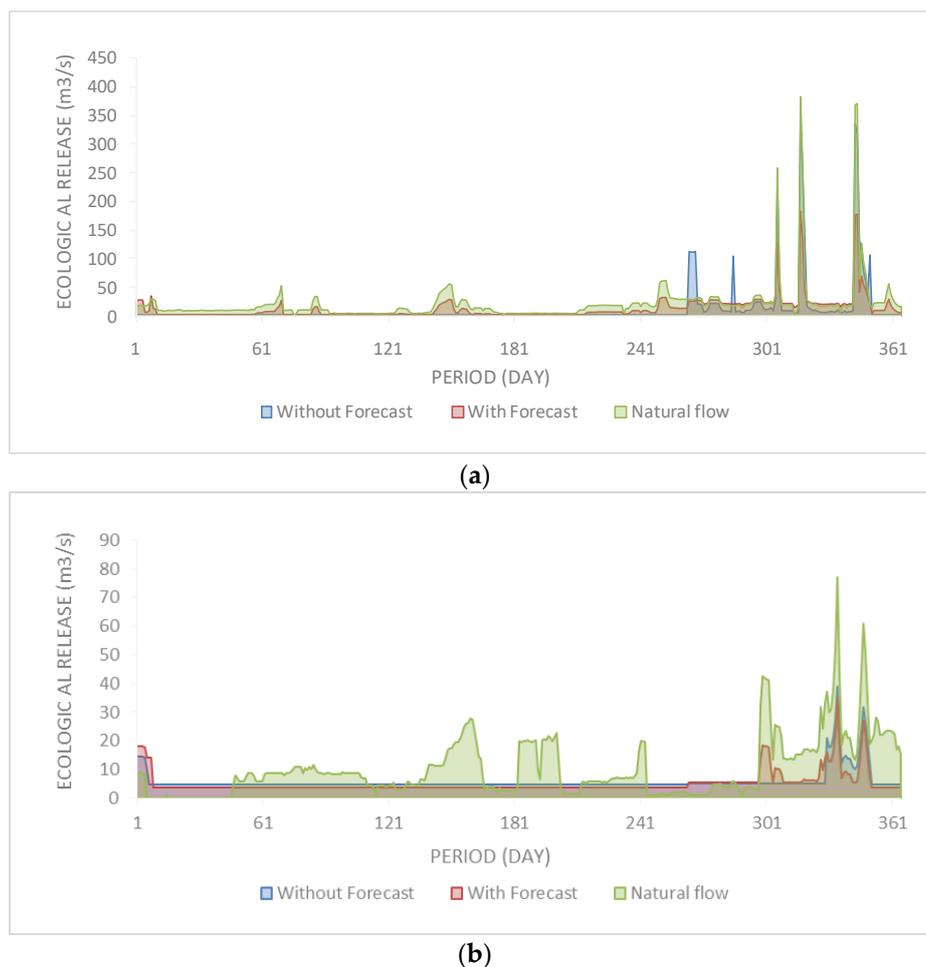


Figure 8. Comparison of ecological releases, between those with and without a long-term forecast. (a) Comparison of wet years; (b) Comparison of dry years.

5. Conclusions

This study adopts the restoration of natural stream flows as an objective of reservoir operation. An optimization model is proposed by using piecewise-linear multi-objective hedging rules (PMHR) to balance the ecological objective of recovering the natural flow regime and the economic objective of satisfying human consumptive water demand. The proposed model can reflect the daily interval variations of the flow by engaging real-time daily inflow forecasts and storage information into decision-making. The parameters of the PMHR were optimized, and Pareto frontiers were discovered by a vector evaluated genetic algorithm. A Monte Carlo simulation was used to deal with inflow uncertainty during real operation.

The results of Baiguishan Reservoir show the balance between ecological and economic objectives. With the consideration of ecological objectives, the ecological release of a reservoir was restored, reflected by the decrease of IHA to different degrees. To deal with inflow uncertainty, synthetic inflow was generated and used in a Monte Carlo simulation under uncertain hydrological conditions. To test the effectiveness of the model, a set of typical frequency inflows was selected for analysis. The model with PMHR has improved the ecological objective and guaranteed the water supply under most of the hydrological conditions in the case reservoir. The alteration degree of the hydrologic indicators, which has been seriously altered, was recovered into the acceptable range. The impact of involving long-term hydrologic forecast information on improving reservoir operation is also demonstrated by the comparisons of two hydrological conditions (wet and dry years) in the case reservoir. The application of forecast inflow information can obviously improve the scheme of ecological water release.

Author Contributions: The conceptualization and framework of this article are derived from J.Z. Model computation and result analysis are completed by Y.L., supervised by J.Z. and H.Z. The article is modified and reviewed by H.Z.

Funding: This research was funded by the National Key Research and Development Program of China (2017YFC0404403 and 2016YFC0401302) and the National Natural Science Foundation of China (91747208 and 51579129).

Acknowledgments: We are grateful to the editors and the three anonymous reviewers for their constructive comments and detailed suggestions, which helped us to substantially improve the paper.

Conflicts of Interest: The authors declare no conflicts of interest.

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