Incorporating ecological adaptation in a multi-objective optimization for the Three Gorges Reservoir

Fang-Fang Li and Jun Qiu

ABSTRACT

Evidence from ecological studies has suggested that alteration of river flows downstream of reservoirs can threaten native aquatic ecosystems. The Three Gorges Reservoir has been controversial since its design and construction stage, and the ecological damage downstream is an important concern. However, protecting long-term health of the river ecosystem has a low priority in reservoir operation compared to other human demands, and is traditionally treated as a constraint of minimum water release. A multi-objective reservoir optimization model incorporating ecological adaption is proposed. Range of variability approach is first used to quantify the hydrological alteration. A satisfying ecological flow scenario is then worked out if it is necessary to take ecological issues into consideration. With the aim of eco-compensation, the reservoir release should be as close to satisfying ecological flow as possible, which is set to be the objective for ecological adaption. Together with other objectives, such as flood control and power generation, a multi-objective optimization model is established, which is optimized by NSGA-II algorithm. Results not only provide the operational references in both wet and dry years, but also illustrate the negative impacts on the river ecosystem by reservoirs can be alleviated with low economic cost. Quantitative relationships among different objectives can also be used for trading markets.

Key words | ecological adaptation, multi-objective optimization, NSGA-II, Three Gorges Reservoir (TGR)

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INTRODUCTION

The accomplishment of reservoirs benefits society with multiple objectives, such as flood control, ice prevention, power generation, water supply, navigation, and many other targets. On the other hand, reservoirs give rise to impact on the environment and ecosystems. It has been well documented that existing river ecosystems have developed long-term to adapt to hydrological patterns (Gorman & Karr 1978; Junk *et al.* 1989; Poff & Ward 1990), which would be changed by large-scale water conservancy constructions. Moreover, a number of environmental factors associated with the runoff would alter, such as sediment load, nutrients, water quality, temperature, and water self-purification capacity. These changes affect the habitats of the biocoen in a river basin, and thus transform its structure, composition, distribution, and productivity. McCartney (2009) demonstrated the significant impacts of hydrological alteration on freshwater ecosystems induced by reservoirs, which are slow, potential, long-term, complex, and usually a result of various superimposed water conservancy projects.

The ecological issues of freshwater ecosystems are complex to formulate, as the ecosystem and the natural environment interact at different spatial and temporal scales (Newson & Large 2006; Vaughan & Ormerod 2010). 'Environmental flow requirement' is often described as 'minimum flow' (arbitrarily 10% of the mean annual runoff) in a river (Akter & Ali 2012). To overcome the problem of attaining optimal conditions for all species at a

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certain time, attention has shifted from a minimum flow approach to an approach that uses the 'natural' regime of the river as a starting point. Various methods have been developed to determine the environmental flow, ranging from relatively simple, low confidence desktop approaches, to resource-intensive, high-confidence approaches. The comprehensive methods usually involve expert discussions and the collection of large amounts of geomorphological and ecological data (Swales & Harris 1995; King & Louw 1998). A key constraint to the application of comprehensive methods, particularly in developing countries, is lack of data linking ecological conditions to specific flows. To compensate for this, several methods based solely on hydrological indices derived from historical flow data have been presented (Richter *et al.* 1996; Yang *et al.* 2008). Among these, indicators of hydrologic alteration (IHA) calculations are commonly used, which consider that hydrological characteristics, such as timing, frequency, or duration of flow events play decisive roles in river ecosystems. Holistic models also have been applied to analyzing the hydrological ecological sustainability, for instance, those of Cai *et al.* (2003) for destination lake ecosystems and Ringler & Cai (2006) for instream ecological water requirements.

When considering environmental flow requirement in reservoir operation, most of the studies quantify ecological flow requirements by simply assigning an extra water quantity constraint to the minimum reservoir water release (Homa *et al.* 2005; Jager & Smith 2008). Such minimal ecological flow meets the minimum living conditions of aquatic organisms, but it is not conducive to maintain stable and healthy ecosystems in the long term. Some attempts on minimizing the degree of hydrologic alteration imposed by system operations have been found recently. Cai & Rosegrant (2004) present a modeling scenario analysis of some water development strategies to harmonize water withdrawal demand and ecological water demand in the Yellow River Basin through water savings and inter-basin water transfers. Yang *et al.* (2012) incorporate a range of variation approach (RVA) to reservoir operation, and apply the model to the Han River in China. Suen & Eheart (2006) considered both ecosystem and human needs to optimize reservoir operation, where the ecosystem needs' objective uses some of the critical indicators of the Taiwan Ecohydrology Indicator System (TEIS) to provide an ecological flow regime. Yin *et al.* (2011) couple three e-flow management strategies for normal, wet, and dry year situations with reservoir operating rule curves to form a reservoir operating approach that optimized e-flow provision under given water supply constraints. More holistic approaches have also been developed for incorporating social, environmental, and economic components of water management. For example, a holistic model embedding water resources and economic components into a consistent mathematical programming model, with the objective of maximizing economic profits from water uses in various sectors was proposed by Cai (2008). In general, although the ecological problems related to water conservancy projects have been drawing attention from both governments and scientists, they are rarely or just simply embedded in reservoir operation routines (Bizzi *et al.* 2012).

The difficulties in optimizing various objectives including eco-compensation simultaneously during reservoir operation mainly lie in: (1) the incommensurability of these objectives, i.e., different objectives are estimated by different criteria; (2) the contradictions between some objectives; and (3) the conditionality among the objectives. For example, maximizing power generation requires maintaining the water level in the reservoir at a high altitude and decreasing the release, while to protect the ecosystem downstream requires water release; meanwhile, the water release should not be too much or too violent to disturb flood control.

In this study, a multi-objective model considering power generation, flood control, and ecological benefits simultaneously is proposed that uses the NSGA-II (non-dominated sorting genetic algorithm) technique. The hydrological variation of the runoff downstream before and after reservoir construction is first analyzed by IHA and RVA. A satisfying ecological flow on the basis of frequency analysis of historical data is then worked out. To alleviate the operation impact on the ecosystem downstream, the release of the reservoir should be as close to the satisfying ecological flow as possible. Meanwhile, the peak flow of the release process needs to be diminished to control flood, and the whole release process should be able to maximize the power generation. Various operational constraints need to be satisfied during the optimization. The proposed methodology is applied to the Three Gorges Reservoir (TGR), which is one of the largest reservoirs in the world. The results not only prove the validity and applicability of the model, but also provide references for the reservoir operation, illustrating that the negative impacts on the river ecosystem by reservoirs can be alleviated at low economic cost.

CASE STUDY

The Yangtze River is the largest river in China, with plenty of water and abundant species resources. The construction of large-scale water conservancy projects, such as the TGR not only affect the river bed evolution and reproduction of the migratory fish directly, but also impact potentially the aquatic biological resources of the lakes, estuaries, and beaches, leading to the possibility of recession, endangerment, and even extinction.

In June 2003, the TGR began impoundment with a water level of 135 m. In the year 2006, the water level of the TGR was raised to 156 m, and the whole project was accomplished in 2009. The region impacted by the TGR (Figure 1) is about 1 million km^2, accounting for 56% of the Yangtze River drainage area. The annual dam site discharge is about 14,300 m^3/s, and the normal water level of the TGR is 175 m, with a total storage capacity of 39.3 billion m^3. The Gezhouba (GZB) runoff hydropower station 38 km downstream is used as the counter reservoir for the TGR with a capacity of 2,715MW.

The primary function of the TGR is flood control. The flood season for the TGR lasts from June to September, when the water level in the reservoir needs to be lowered from the

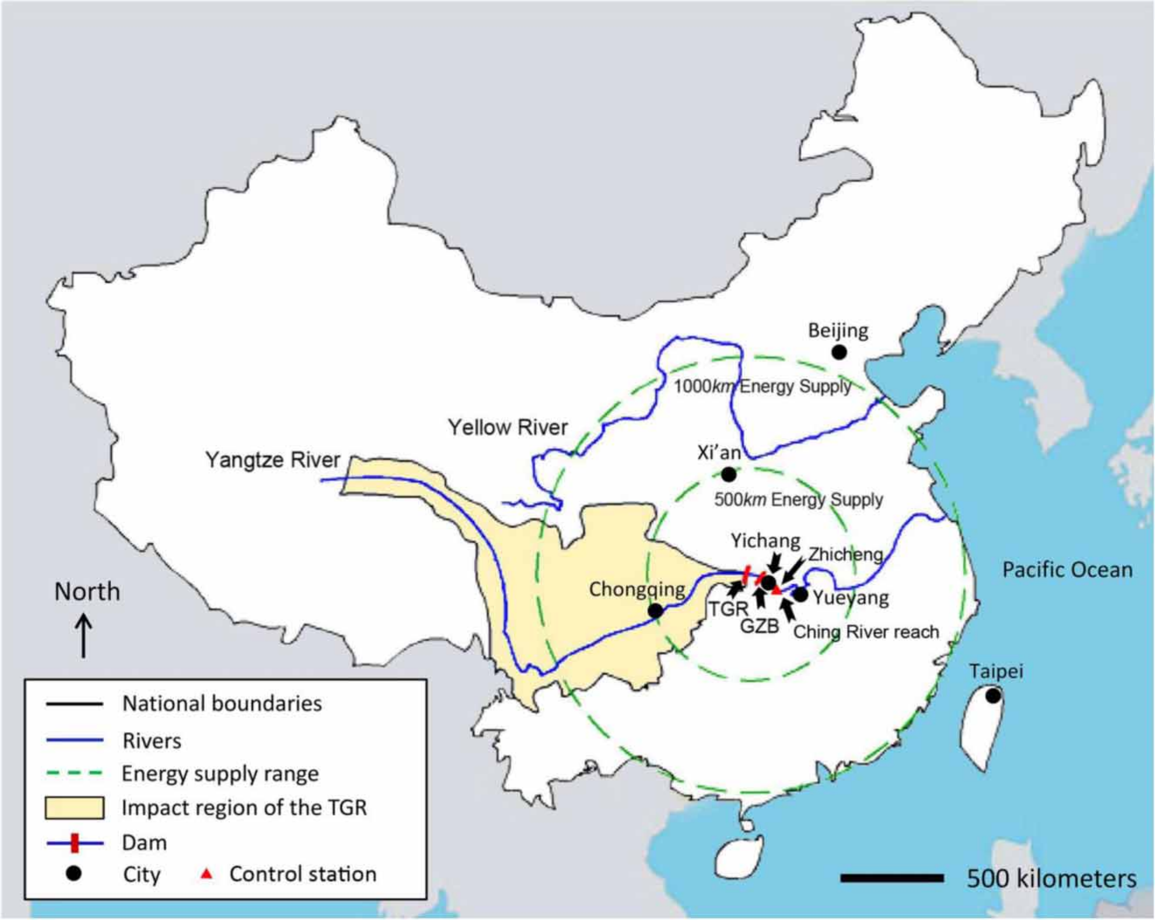

Figure 1 | Location and energy supply range of the TGR in China.

normal storage level of 175 m to the flood control water level of 145 m. The storage between 145 m and 175 m is as large as 22.15×10^9 m^3, equivalent to four times the storage capacity of the flood diversion area of the Ching River. The Ching River is the river reach of the Yangtze River from Zhicheng control station, which is located 60 km downstream of Yichang city, to Yueyang city, with a length of 330 km. The width of the Ching River is about 2,000 m with a small slope, and thus a large amount of sediment is deposited in this reach. This, on the one hand, produces a major grain producing area with fertile land, but, on the other hand, flood control appears significant for this area. There are two levels of flood control for the TGR: (1) the regular flood can be wholly retained by the reservoir; the flood can pass the Ching River reach safely, when it is no more than 56,700 m^3/s, without diversion measures; (2) when encountering catastrophic flood, the TGR is able to schedule it to ensure the flow at Zhicheng control station is less than 77,000 m^3/s. Coordinated with other flood-diversion projects, the devastating consequences to the plain area on the Ching River can be avoided.

Power generation is another important function of the TGR. Together with the GZB, the TGR supplies electric power for about one-third of China, as illustrated in Figure 1. The TGR power plant has a large installed capacity of 22.4 million kW, and the annual power generation approaches 100 billion kWh. With respect to both the installed capacity and the annual power generation, the TGR is now the largest hydropower station in the world.

Besides the benefits to flood control and power generation, the construction of the TGR has altered the river terrain boundary, as well as the hydrological characteristics; as a result, the ecological environment of the Yangtze River is affected detrimentally.

METHODS

The methodology includes three main components: (1) analysis of hydrological alteration from pre-dam to post-dam periods, which is accomplished by IHA and RVA; (2) calculation of satisfying ecological flow on the basis of frequency analysis of historical data; and (3) multi-objective optimization considering ecological protection by NSGA-II as proposed by Deb *et al.* (2002).

The NSGA-II has proven to be capable of improving the original NSGA in preserving diversity and thus saving computational effort without specifying any additional parameter, and applied to multi-objective water-resources problems widely, such as in Reed *et al.* (2003), Kim *et al.* (2006), Yandamuri *et al.* (2006), Shiau & Wu (2007), Malekmohammadi *et al.* (2011), Lerma *et al.* (2014), and Vonk *et al.* (2014).

Long-term hydrometric records before and after the reservoir construction are used first to determine whether the interference of human activity has changed the natural hydrological characteristics severely. A satisfying ecological flow is worked out with different guarantee rates in different seasons. Such a flow scenario is believed to be able to maintain a stable and healthy ecosystem. To minimize the gaps between reservoir release and such a flow scenario is regarded as one of the operational objectives.

Alteration analysis of river runoff pre-and post-dam

Reservoir operation is capable of balancing water supply and demand by adjusting the spatial and temporal distribution of water resources; however, it alters river runoff downstream so that the runoff variation is no longer determined by seasonal precipitation. In this study, RVA is selected to analyze the runoff variations downstream of the TGR before and after its construction.

RVA was originally proposed by Richter *et al.* (1997), and is based on the IHA. The IHA describes hydrological data from the perspectives of runoff volume, time of occurrence, frequency, duration and rate of change, converting the data into hydrological indicators. A certain bound is then set for each indicator according to the data in a pre-impact period, called RVA targets. The indicators in pre- and post-impact periods are compared, so that the extent of changes caused by human beings can be assessed.

The main idea of the RVA is that if the frequency of the post-impact indicators falling into the range of natural variation, i.e., RVA targets, coincides with that in the pre-impact period, the interference of human activity is slight, and the river still has its natural characteristics; whereas if the frequency of the post-impact indices falling into RVA targets diverges, it means human activity has altered the original river characteristics, and has exceeded the affordable range of the natural ecosystem. Furthermore, such alteration might impact the river ecosystem negatively.

IHA indicators

The 32 indicators selected by the IHA are illustrated as follows, divided into five categories.

Group 1: Mean runoff for each month (12 parameters), describing the 'normal' daily conditions for the month and providing a general measure of habitat availability or suitability. They influence the satisfaction degree of the requirements of habitat for aquatic organisms, soil humidity for vegetation, migration of carnivores, as well as the water temperature, oxygen content, photosynthetic, and so on.

Group 2: Magnitude and duration of annual extreme conditions, including annual minimal 1-day, 3-day, 7-day, 30-day, 90-day means, annual maximal 1-day, 3-day, 7-day, 30-day, 90-day means, and the ratio of annual minimal 7-day means to annual means (base flow index), which refers to the stable part of the flow. These indicators provide measures of environmental stress and disturbance during the year. They impact the ecosystem on vegetation expansion, organism balance under extreme conditions, topographic shaping of river bed, nutrient exchanges between river and floodplain, and so on.

Group 3: Timing of annual extreme conditions, including Julian date of each annual 1-day maximum and minimum, which provide another measure of environmental disturbance by describing the seasonal nature of these stresses. These conditions affect the circular breeding, habitat conditions of breeding season, evolutionary needs of species, and fish migration.

Group 4: Frequency and duration of high and low pulses, including number of high and low pulses each year, mean duration of high and low pulses within each year. These indicators describe the pulsing behavior of the environmental variation within a year and provide measures of the shape of the pulses. Such characteristics impact the ecosystem on the frequency and dimension of soil humidity for vegetation, sediment transportation, channel structure, perturbation of bottom water, as well as the habitat for aquatic birds.

Group 5: Rate and frequency of changes in conditions, composed of means of all positive and negative differences between consecutive daily means, and the number of changeover. They describe the abruptness and number of intra-annual cycles of environmental variation and can provide a measure of the rate and frequency of intra-annual environmental change. Their influence on the ecosystem includes the drought stress for vegetation, drying stress for organisms, trapping of organisms, and so on.

RVA targets

The evaluation on whether the IHA indicators have been affected is based on the ecological information. Richter *et al.* (1997) suggested taking the standard deviation on means as the RVA targets, while in practical applications, most research makes frequency calculations, and takes the values with 75 and 25% probability as the bounds of the IHA. RVA targets provide the range of acceptable change of the natural ecosystem. The runoff falling into such ranges can satisfy the requirements of the ecosystem to different extents.

Hydrologic alteration degree

Richter *et al.* (1997) suggested quantifying the alteration of the IHA by hydrologic alteration degree D, which is defined in Equation (1):

$$D = \frac{|N_0 - N_e|}{N_e} \times 100\% \tag{1}$$

where N_e is the count of post-impact years in which the value of the hydrologic parameter fell within the targeted range; N_0 is the count of years for which the value is expected to fall within the targeted range. In this study, N_0 is represented by $r \times N_T$, where r is the ratio that the count of pre-impact years' value is expected to fall within the targeted range, and N_T is the total number of the post-impact years. Hydrologic alteration is equal to zero when the observed frequency of post-impact annual values falling within the RVA target range equals the expected frequency. A positive deviation indicates that annual parameter values fell inside the RVA target window more often than expected; negative values indicate that annual values fell within the RVA target window less often than expected.

The ability of tolerating hydrological alteration is distinct for different species, so that the severity of the alteration degree of a particular IHA index needs to be quantified. The hydrologic alteration degree D is simply classified into three different severity levels, which are: non- or low-grade, moderate, and high grade, as shown in Table 1. The extent of the impact of human activities on the hydrological regime of the river can now be determined by quantitation.

Hydrologic alteration analysis for Yangtze River

Yichang is the release control station of the TGR. Hydrological data from 1980 to 2002 at Yichang station are taken as the references of the pre-impact period, and the period from 2003 to 2010 is post-impact. Table 2 presents the results of the IHA-RVA analysis with the hydrological data at Yichang station.

It can be seen from monthly magnitude variation that the reservoir impoundment exerts an obvious attenuation effect on flow. The release of the TGR in non-flood season is getting larger, while that in flood season decreases. The coefficients of variation increase significantly in the post-impact period, implying that the monthly magnitude of river discharge varies more dispersedly from year to year in the post-impact period. Such changes may affect the habitat of organisms and the soil moisture by vegetation.

For Group 2, the base flow index rises from 0.25 to 0.37. Thus the magnitude and duration of flow at Yichang station is more assured due to the reservoir upstream. Meanwhile, the evident increment of the minimum flow helps to alleviate the water shortage problem in the dry season, but remaining at such a status for a long time also goes against the original ecological balance. The reduction of maximum flow has a strong impact on the nutrients exchange between river and flood retarding basin, and thus on the growth of aquatic organisms and plants.

The Julian date is the continuous count of days since the beginning of the year. The range of the Julian date for February is between 32 and 60 (61 in leap years). Thus the timing of the annual minimal flow at Yichang station is mainly in February with the Julian date of 51.8 before the construction of the TGR, while with the regulation of the reservoir, it is delayed up to March with the Julian date of 70. In addition, the timing of minimal flow also appears unstable with the variance coefficient of 1.87. Such variation seriously impacts the life cycle of aquatic organisms.

Table 1 | Severity description of hydrologic alteration degree

Range of *D*	$0 \leq D \leq 33\%$	$33\% \leq D \leq 97\%$	$67\% \leq D \leq 100\%$
Severity description	Low-grade (L)	Moderate (M)	High grade (H)

Both the frequency and the duration of high and low pulses decrease with the regulation of the TGR, which affects the sediment transportation and the bottom perturbance.

Although the daily fall and daily rise have no significant change after the construction of the reservoir, the frequency of changes grows up with a high grade, which will influence plants, low-speed organisms, and organic matter on flood plains.

Satisfying ecological flow

The criteria of necessarily considering ecologic issues in reservoir operation in this study are set as: (1) the high grade alteration of indicators appears in more than one-third of all the groups; or (2) the total number of high grade and moderate alterations of the indicators is larger than one-third of the total amount of indicators, as shown in Equation (2):

$$\begin{aligned} & n(N_{\mathrm{H}}^{k} > 0) \geq \frac{1}{3} \times n_{\mathrm{total\_groups}} = \frac{1}{3} \times 5 \\ & \sum_{k=1}^{5} (N_{\mathrm{H}}^{k} + N_{\mathrm{M}}^{k}) \geq \frac{1}{3} \times \sum_{k=1}^{5} (N_{\mathrm{H}}^{k} + N_{\mathrm{M}}^{k} + N_{\mathrm{L}}^{k}) = \frac{1}{3} \times 32 \end{aligned} \tag{2}$$

According to the analysis results in Table 2 and the criteria in Equation (2), the ecological issues have to be taken into account in the operation of the TGR.

Minimum ecological water requirement is believed to be the natural drought extremes that can be tolerated (Yu *et al.* 2004). Nevertheless, it is unfavorable hydrological conditions and long-term sustainability of such flow that are not conducive to healthy development of the ecosystem. A satisfying ecological flow is determined as below, which is believed to be a favorable hydrological process allowing

Table 2 | Summary statistics for IHA Group 1–5 parameters for the unimpaired hydrologic conditions (1980–2002) at Yichang control station and 2003–2010 post-dam outflow of the TGR

	Mean		**Coefficient of variance (Cv)**		**RVA target**					
IHA group	**Pre-impact**	**Post-impact**	**Pre-impact**	**Post-impact**	**Low-bound**	**High-bound**	N_o	N_e	***D***	**Severity**
Group 1: Monthly magnitude of stream flows (m^3/s)										
January	4,396	5,037	0.09	0.41	4,080	4,730	2	4	0.5	M
February	3,991	5,092	0.11	0.42	3,690	4,260	0	4	1	H
March	4,533	5,668	0.17	0.41	4,000	5,170	1	4	0.75	H
April	6,777	7,313	0.24	0.44	5,510	7,830	5	4	0.25	L
May	11,049	11,737	0.21	0.43	9,160	12,400	5	4	0.25	L
June	18,309	16,740	0.15	0.44	16,700	20,800	7	4	0.75	H
July	31,065	25,412	0.22	0.45	26,100	35,300	3	4	0.25	L
August	27,274	24,561	0.30	0.53	22,400	32,800	4	4	0	L
September	24,622	21,507	0.24	0.49	20,000	29,400	5	4	0.25	L
October	17,630	12,404	0.19	0.51	15,500	20,000	2	4	0.5	M
November	9,706	9,094	0.18	0.50	8,230	11,000	2	4	0.5	M
December	5,890	5,780	0.12	0.41	5,250	6,540	6	4	0.5	M
Group 2: Magnitude and duration of annual extreme flows (m^3/s)										
1-day minimum	3,388	4,560	0.10	0.19	3,140	3,585	0	3.67	1	H
1-day maximum	50,967	41,729	0.17	0.13	44,350	57,850	2	3.67	0.45	M
3-day minimum	3,432	4,580	0.09	0.19	3,177	3,612	0	3.67	1	H
3-day maximum	49,179	40,729	0.17	0.12	43,033	55,217	2	3.67	0.45	M
7-day minimum	3,494	4,620	0.09	0.18	3,217	3,671	0	3.67	1	H
7-day maximum	44,499	38,088	0.17	0.08	40,293	49,164	3	3.67	0.18	L
30-day minimum	3,715	4,869	0.09	0.18	3,488	4,005	0	3.67	1	H
30-day maximum	35,809	30,339	0.17	0.07	31,958	38,568	3	3.67	0.18	L
90-day minimum	4,237	5,266	0.10	0.19	3,963	4,573	0	3.67	1	H
90-day maximum	28,829	24,379	0.17	0.19	26,203	31,152	3	4.00	0.25	L
Base flow index (dimensionless)	0.25	0.37	0.13	0.19	0.23	0.28	0	3.67	1	H
Group 3: Timing of annual extremes										
Julian date of annual minimum	51.8	70.0	0.28	1.87	44	65	1	4	0.75	H
Julian date of annual maximum	208.9	214.6	0.10	0.10	193.5	227.5	3	3.67	0.18	L
Group 4: Frequency and duration of high and low pulses										
Low pulse count	87.3	52.7	0.53	0.86	43.5	125.5	1	3.67	0.73	H
High pulse count	86.1	60.7	0.44	0.63	52.5	125.5	3	3.67	0.18	L
Low pulse duration (day)	6.4	4.1	0.45	0.35	3.6	8.7	4	3.67	0.09	L
High pulse duration (day)	6.3	4.5	0.37	0.37	4.2	8.1	3	3.67	0.18	L
Group 5: Rate and frequency of change in conditions										
Daily fall (m^3/s)	463	407	0.15	0.22	393	504	4	3.67	0.09	L
Daily rise (m^3/s)	– 464	−407	−0.15	−0.22	−504	−396	4	3.67	0.09	L
Changeover count	55.8	71.1	0.10	0.07	52.0	60.5	0	4	1	H

the ecosystem to achieve stability and health, and can be maintained for the long term. First, a year is divided into wet, median, and dry season according to the historical data. Second, different guaranteed rates are selected for different seasons. In this study, 50%, 70%, and 90% are set to be the guaranteed rate for wet, median, and dry seasons, respectively, as in Chen's study (Chen 2002). Then, the flows of each month in different years are ranked respectively according to the frequency, which is also taken as the guaranteed rate. Finally, the flow with the corresponding guaranteed rate of 50, 70, or 90% is selected for each month separately, and they compose a flow scenario, called satisfying ecological flow, as shown in Figure 2.

Multi-objective optimization model

To increase the benefits from flood control and power generation, more water should be blocked in the reservoir, which will lead to a shortage of water downstream and the destruction of the ecological environment. Besides, stable discharge is preferred to: (1) protect floodwalls downstream; (2) prolong water supply time downstream; and (3) help navigation. At the same time, some flow pulse is necessary for ecosystems, as analyzed above. Not only such conflictions but also the incommensurability among different objectives contributes to the difficulty to optimize the operation.

In this study, the three main operational objectives of the TGR are considered simultaneously to provide optimal scheduling plans with stationary release series, maximal power generation, and as close to the satisfying ecological flow as possible.

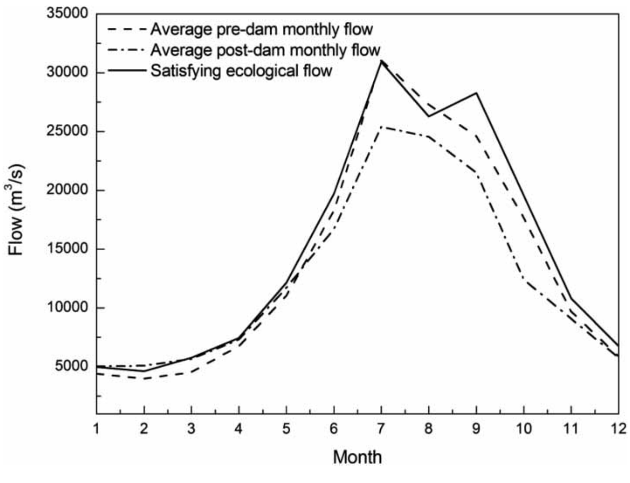

Figure 2 | Monthly flow in pre-dam and post-dam periods, and satisfying ecological flow.

Objective function

Objective 1: Flood control

Flood control is the primary function of the TGR, which is accomplished by retaining or shifting the peak flood.

To protect the downstream area and prolong water utilization, the TGR needs to retain some surplus water by its huge impoundment capacity instead of releasing all the floods at once even if the flood threshold is not reached. After the flood peak passes, the retained flood is released successively to prepare for another flood peak. Thus, minimizing the annual maximum peak flow is one term in the objective function that accounts for flood control, as shown in Equation (3):

$$Z_1 = \mathrm{Min}\{\mathrm{Max}[Q^t]\} \tag{3}$$

where Z is the objective function; Q is the reservoir release (m^3/s); and t is the index of months ($t = 1,2,\ldots,12$).

Objective 2: Power generation

Hydropower uses water power to run hydraulic turbines, thus transforming the gravitational potential energy of water into power energy by generators. The higher the water level of the reservoir is, the more power can be generated. The basic function to calculate the hydropower output P (kW) is $P = KqH$, where K is the output coefficient; q is the turbine flow (m^3/s); and H is the water head (m). Due to the important role of the TGP and the national development strategy of clean energies, the TGP is used for basic load in the power grid. Thus the objective of power generation is set as maximizing annual power generation E of the cascade reservoir system without consideration of the load demand, as in Equation (4):

$$Z_2 = \mathrm{Max}\ E(\vec{q}) = \mathrm{Max}\sum_{t=1}^{T} Kq^t H^t \times \Delta t \tag{4}$$

It needs to be illustrated that most of the time the turbine discharge equals to the reservoir release without abandoned water. When encountering great flood and the reservoir release exceeds the capacity of the turbine, there is surplus water spilled through spillways, which does not contribute to power generation.

Objective 3: Ecological protection

As the satisfying ecological flow has been determined, the objective function for ecological protection is set as minimizing the offset between the release and the satisfying ecological flow, as shown in Equation (5):

$$Z_3 = \mathrm{Min}\sqrt{\sum_{t=1}^{T}(Q^t - Q_{\mathrm{E}}^t)^2} \tag{5}$$

Decision variables

Since the reservoir release Q appears in all three objective terms from Equations (3) to (5), this variable has been chosen to be the decision variable, as shown in Equation (6):

$$u = \{\vec{Q}\} = \{Q^1, Q^2, \ldots, Q^t, \ldots, Q^T\} \tag{6}$$

Constraints

Mathematically, the reservoir operation needs to satisfy various equality and inequality constraints, including: water balance equality, water level-storage curves of the reservoirs, tail water elevation curves at reservoirs, high and low water level limits of reservoirs, and high and low release limits of reservoirs, as shown from Equations (7) to (12):

$$V^{t+1} = V^t + I^t \times \Delta t - Q^t \times \Delta t \tag{7}$$

$$Q^t = q^t + S^t \tag{8}$$

$$L^t = f(V^t) \tag{9}$$

$$T^t = g(Q^t) \tag{10}$$

$$L_{\min} \le L^t \le L_{\max} \tag{11}$$

$$0 \le q^t \le q_{\max} \tag{12}$$

where V is the reservoir storage (m^3); I is the inflow (m^3/s); S is the surplus flow exceeding the capacity of turbine (m^3/s); Δt is the time length of each period (s); L represents the reservoir water level (m); and T is the tail water elevation (m).

All the constraints are handled by either of two ways: one is to set certain limit conditions when producing the initial population and evolving a new generation; the other is to check whether they are satisfied after the calculation and the unfeasible solutions are filtered out automatically by adding penalty functions to the constraints.

Implementation of optimization

A vector composed of the monthly reservoir release, as shown in Equation (6), is called an individual in genetic algorithms. These individuals are generated randomly at the beginning of the NSGA-II with a population of size A. The objectives from Equations (3) to (5) are evaluated for each individual respectively. In order to calculate the objective function term of ecology in Equation (5), a satisfying ecological flow has to be worked out based on the IHA and RVA analysis. If either of the two criteria in Equation (2) is met, the ecological issue is deemed to be so severe that the operation of the reservoir has to consider the ecological protection in Equation (5). Otherwise, the ecological flow can be only considered in the constraints. On the basis of the non-dominated level, the individuals in such parent populations are ranked. Another offspring population of the equal size A is also generated by selection, crossover, and mutation. Then, the parent and offspring compose a new population of size 2A, in which the elitisms are selected for successive generations. There are two significant selective sorting procedures in NSGA-II besides the ordinary GA selection: non-dominated sorting and crowding distance sorting. The mathematical definition of the dominance is shown in Equation (13):

$$\begin{aligned}&X = \{x_1, x_2, \ldots, x_M\}\\&Y = \{y_1, y_2, \ldots, y_M\}\\&X \text{ Dom } Y \Leftrightarrow \forall i{:}x_i \leq y_i \text{ and } \exists j{:}x_j \leq y_j\end{aligned} \tag{13}$$

where X and Y are two individuals of population; x_i and y_i are objective functions that should be minimized; and B is number of objectives. The non-dominated sorting is a fast and simple approach requiring $O(BA^2)$ computations. The crowding distance representing the density of individuals is used to keep the population diverse and a consistently spread-out Pareto-optimal front. For two individuals in the same rank of dominance, the one with a greater crowding distance, as defined in Equation (14), is better:

$$d(k) = \sum_{j=1}^{M} \frac{|f_j^{k+1} - f_j^{k-1}|}{f_j^{\max} - f_j^{\min}} \tag{14}$$

where $d(k)$ is crowding distance of individual k; f_j^k is the j-th objective function value of k-th individual; $f_j^{\max}$ and $f_j^{\min}$ are the maximum and minimum values for the j-th objective function, respectively. The procedure is repeated until a certain number of generations have been evaluated.

A scheme of the proposed optimization model is given in Figure 3.

RESULTS

To apply the NGSA-II algorithm, the following parameters are used. The initial population was set to 300; simulated binary crossover (SBX) (Deb & Agrawal 1995) with a probability of 0.90 and polynomial mutation (Deb & Goyal 1996) with a probability of 0.10 were carried out. The year 2011 is the driest year in the past 50 years, and is selected as the study case. Another wet year, 2012, is also analyzed for comparison.

To avoid the premature convergence of GA resulting from the high dimension of decision variables and large feasible domain of each variable, the search space is constrained within a certain range. As suggested by Li *et al.* (2012), taking the historical average monthly flow as the benchmark, the half range width of 500 m^3/s is believed to be large enough to provide an efficient optimized result without waste of computation and low efficiency in the whole search space. Nevertheless, the reservoir release is over 20,000 m^3/s in flood season, and a search space with the range of 1,000 m^3/s appears too small to generate various candidate solutions. So to give attention to both the diversity of the solutions and the computational efficiency, the optional releases of the TGR vary from 0.9 to 1.1 times of the historical releases, i.e., the search space is set as [−10%, +10%] of the historical data.

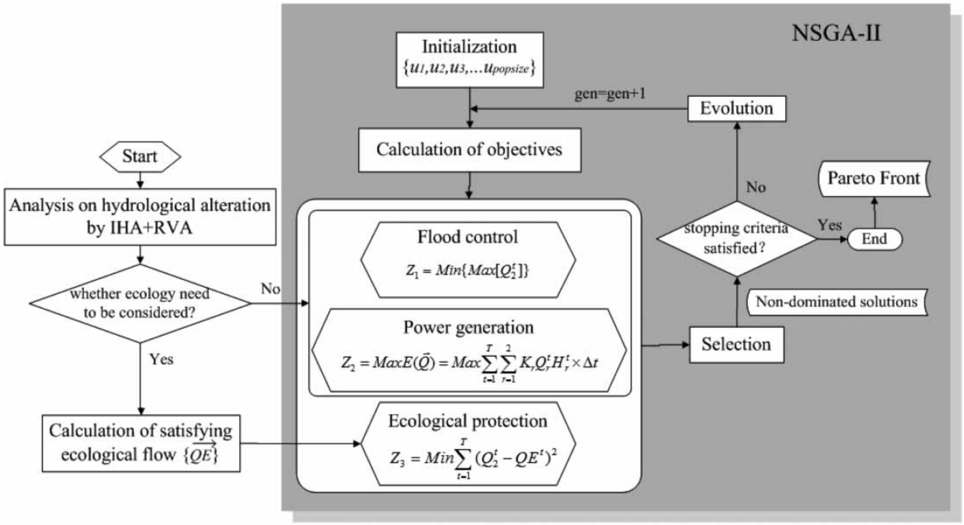

Figure 3 | Multi-objective reservoir optimization incorporating ecological adaptation.

Figures 4 and 5 show the optimized results for the year 2011 and 2012, respectively, as well as their projective figures. The hollow, grey and black bubbles represent the optimized results after 100, 500, and 1,000 generations, respectively. For the flood control and ecological protection objectives, the ideal value was minimum value, and reversely for the power generation objective the ideal point was maximum value. The optimal trade-off satisfying all three objectives is indicated by an arrow. Such a trade-off is on the basis that the importance of the three objectives is equal. To inspect the relationships among the three objective functions, the projective figures onto three normal planes are also presented in Figures 4(d)–4(f) and 5(d)–5(f), respectively.

Table 3 presents the statistics of optimized results after 1,000 generations, including the mean, the best, the worst,

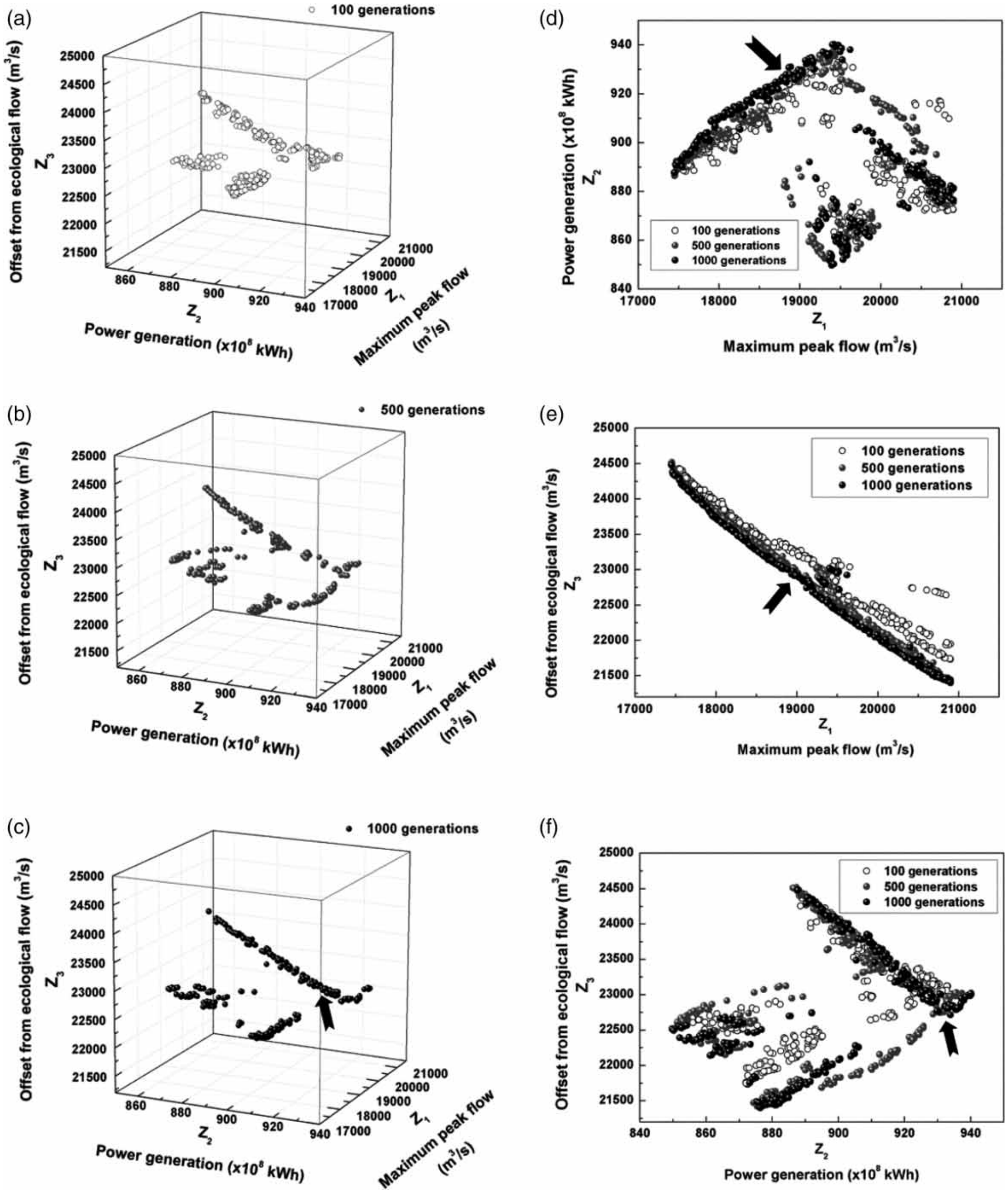

Figure 4 | Optimized results of the year 2011 after (a) 100 generations, (b) 500 generations, (c) 1,000 generations, and the projective figures onto three normal planes in (d) to (f). The arrow in (c), (d), (e), and (f) indicates the optimal trade-off satisfying all three objectives.

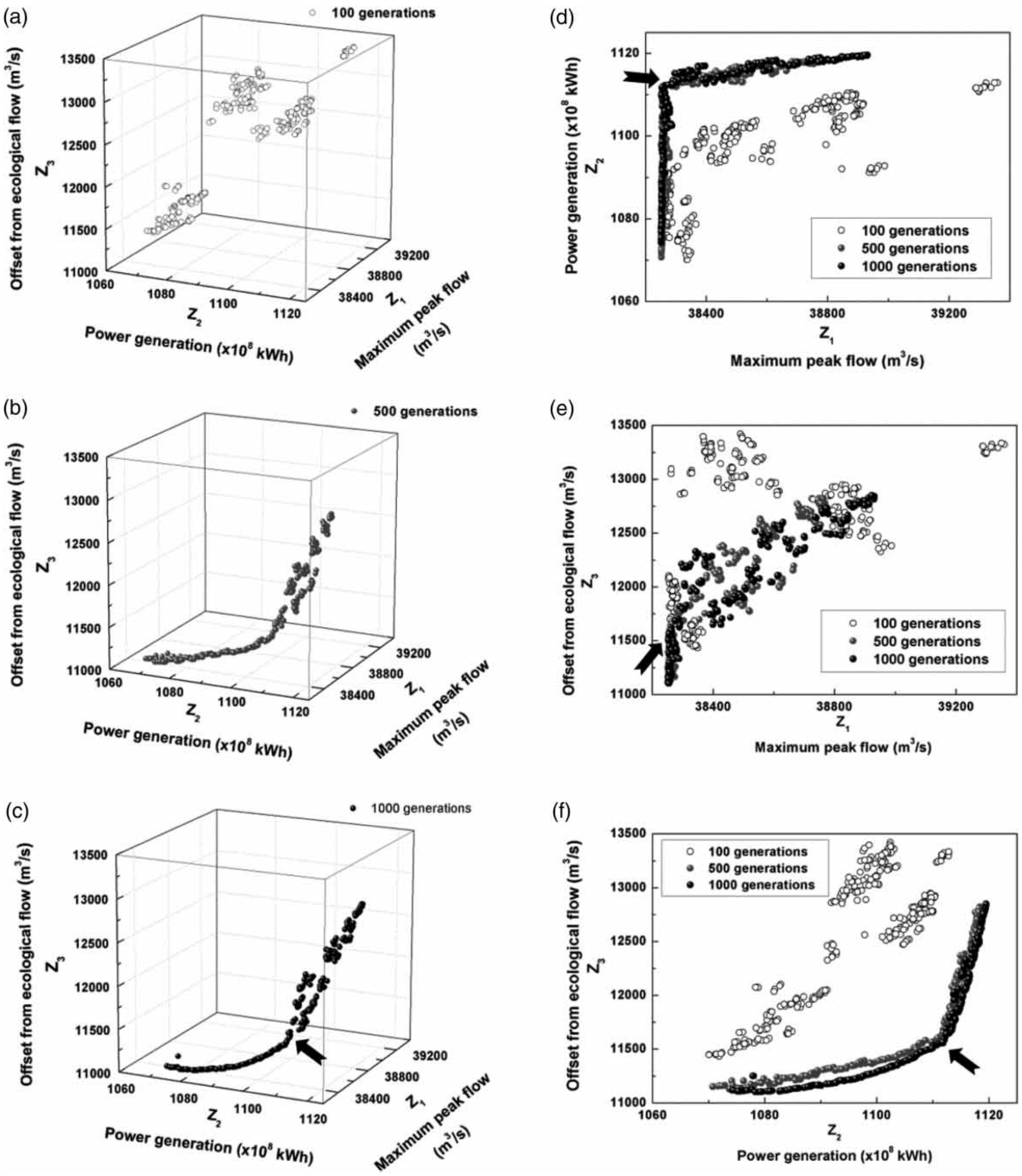

Figure 5 | Optimized results of the year 2012 after (a) 100 generations, (b) 500 generations, (c) 1,000 generations, and the projective figures onto three normal planes in (d) to (f). The arrow in (c), (d), (e), and (f) indicates the optimal trade-off satisfying all three objectives.

and the standard deviation (SD). SD is a measure to quantify the amount of variation or dispersion of a set of data values. A SD close to 0 indicates that the data points tend to be very close to the mean of the set, while a high standard deviation indicates that the data points are spread out over a wider range of values.

The optimal operation scheme corresponding to the optimal trade-off which satisfies all three objectives, as indicated by the arrows in Figures 4 and 5, is shown in Figure 6.

DISCUSSION

It can be seen clearly that the optimized results improve as the iterations went on, while the convergence rate decreases in both Figures 4 and 5. Generally, after 500 generations, optimal solutions with high quality can be obtained.

In Figures 4(d) and 5(d), the best solution should be in the upper left corner. Flood control and power generation present competitive relationships for both dry and wet

Table 3 | Statistics of optimized results after 1,000 generations

	Solutions after 1,000 generations						
Objectives	**Mean**	**Max**	**Min**	**SD**	**Historical data**	**Corresponding to the optimal trade-off**	**Optimized by**
2011							
Z_1(m^3/s)	19,116	20,900	17,449	995	19,000	19,120	−0.63%
Z_2(×10^{8}kWh)	897.7	940.2	849.8	23.7	906.1	892.0	−1.56%
Z_3(m^3/s)	22,827	24,484	21,397	850	23,928	22,741	+4.96%
2012							
Z_1(m^3/s)	38,448	38,931	38,252	216	38,474	38,867	−1.02%
Z_2(×10^{8}kWh)	1,108.1	1,119.5	1,074.3	12.6	1,131.4	1,119.1	−1.09%
Z_3(m^3/s)	11,871	12,848	11,101	566	13,336	12,752	+4.38%

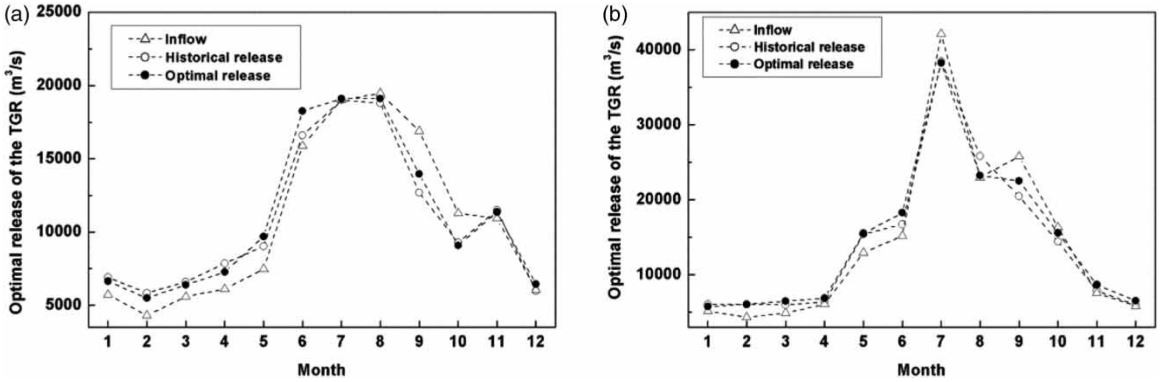

Figure 6 | Operation scheme of the year (a) 2011 and (b) 2012 for the optimal trade-off satisfying all three objectives, which is indicated by the arrows in Figures 4 and 5.

years. In the dry year of 2011, such competition appears more prominent, as the improvement of one objective brings about recession of the other objective; while in the wet year, the ligature of the solutions is almost rectangular, and it is easy to find a solution satisfying both the flood control and power generation simultaneously. Figures 4(e) and 5(e) show the objective function values of flood control and eco-compensation, and the optimum should be in the bottom left corner. An interesting phenomenon is that these two objectives appear as distinct competitive relationships in the dry year, while in the wet year they seem to be harmonious. Consideration could be given to either of them in wet years, but in dry years the trade-off between these two objectives has to be paid attention to. In Figures 4(f) and 5(f) the objective function values of power generation and eco-compensation are shown with the best solution in the bottom right corner. In the wet year of 2012 in Figure 5(f), there is a turning point balancing the rates of improvement of the two objectives, which is selected as the optimal trade-off.

For the operation scheme of the dry year satisfying all the three objectives, more water is reserved before the flood season to maintain a high level, which benefits power generation. In flood season, the flood control plays a leading role for optimization, and more water should be released compared with the historical operation. The timing of impoundment is delayed by the optimization, which also helps the power generation. Weighing the three objectives with the same weights, concession of 0.63% of the flood control, and 1.56% of the power generation can produce 4.96% improvement of eco-compensation. Such results can also be used for trading markets for quantification.

To operate the reservoir in the wet year with all the three objectives satisfied, less water should be released after the flood season, and the water release process should be as stable as possible. Generally, the optimized scheme in the wet year is less different from the historical operation than in the dry year. About 1% of the concession of both the flood control and power generation gives rise to 4.38% improvement of the eco-compensation. The results of both the years 2011 and 2012 indicate that the ecological issue did not raise too much concern in reality, and there is plenty of room for improvement of eco-compensation with the relatively low cost of power generation.

The results not only provide operational references for regional water managers in both dry and wet years, but also present the quantitative relationships among different objectives, which can be used for trading markets. Other objectives can also been chosen for this method than those selected here. Multi-objective optimization of reservoirs considering ecological adaption with a comprehensive ecological model such as habitat models can be expected in the future.

CONCLUSIONS

To incorporate ecological consideration into the reservoir system, this study proposed a multi-objective optimization model with respect to flood control, power generation, and ecological protection simultaneously for a multi-reservoir system. The ecological issue is first evaluated by the IHA and RVA methods. Based on a certain criterion about the severity of the ecological damage by reservoir construction, whether to take the ecological protection as one of the optimization objectives or simply just put it into the constraints, is determined. If the ecological issue is serious so that the ordinary method, i.e., taking a certain amount of water requirement as the lower bound of the reservoir release, is not appropriate any longer, a satisfying ecological flow is calculated on the basis of hydrological frequency. To minimize the offset between the reservoir releases to this satisfying ecological flow is taken as the objective for ecological protection. Together with maximizing power generation and minimizing the peak flow, a multi-objective optimization model is established. NSGA-II is selected to optimize the proposed model, and the methodology is applied to the TGR–GZB cascade system. The results not only provide the operational references for water managers in both wet years and dry years, but also illustrate that the negative impacts on the river ecosystem by reservoirs can be alleviated with low economic cost. The quantitative relationships among different objectives can also be used for trading markets.

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