Water **2014**, *6*, 796-812; doi:10.3390/w6040796

OPEN ACCESS

water

ISSN 2073-4441

www.mdpi.com/journal/water

Article

Optimal Reoperation of Multi-Reservoirs for Integrated Watershed Management with Multiple Benefits

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Received: 12 February 2014; in revised form: 18 March 2014 / Accepted: 21 March 2014 / Published: 2 April 2014

Abstract: Constructing reservoirs can make more efficient use of water resources for human society. However, the negative impacts of these projects on the environment are often ignored. Optimal reoperation of reservoirs, which considers not only in socio-economic values but also environmental benefits, is increasingly important. A model of optimal reoperation of multi-reservoirs for integrated watershed management with multiple benefits was proposed to alleviate the conflict between water use and environmental deterioration. The social, economic, water quality and ecological benefits were respectively taken into account as the scheduling objectives and quantified according to economic models. River minimum ecological flows and reservoir water levels based on flood control were taken as key constraint conditions. Feasible search discrete differential dynamic programming (FS-DDDP) was used to run the model. The proposed model was used in the upstream of the Nanpan River, to quantitatively evaluate the difference between optimal reoperation and routine operation. The results indicated that the reoperation could significantly increase the water quality benefit and have a minor effect on the benefits of power generation and irrigation under different hydrological years. The model can be readily adapted to other multi-reservoir systems for water resources management.

Keywords: eco-environment; multi-reservoirs; model; optimal reoperation; benefit

1. Introduction

Reservoirs and dams are the most serious anthropogenic effects on riverine ecosystems [1]. Currently, many of the world's major rivers have become ladder-type river systems, whose flows are punctuated by reservoirs. Water construction projects make the management and utilization of water resources more effective. On the one hand, the construction of reservoirs is the primary way that humans manage water resources for water supply, power generation, flood control and irrigation and to alleviate the increasing disparity between water supply and demand. On the other hand, constructing a reservoir significantly changes the natural river runoff process and destroys the dynamic equilibrium of the river ecosystem, resulting in problems of eutrophication in reservoirs, increased soil salinity downstream from dams, sediment deposition in dams, shrinking of the delta, deteriorating water quality and other adverse effects [2].

The efficient management of reservoirs has been the subject of a great deal of research over the years. The current research on the impact of water projects on river flow and the surrounding environment tends to focus on multiple reservoirs. Muñoz [3] investigated the environmental role of the reservoir in the river network and proposed many approaches to integrate water quality with quantity requirements for reservoir operation. Moreover, some mathematical models were built and widely used to assess the impact of reservoirs on water quality and quantity [4–6]. In Campbell's paper, the water environment in Klamath River was evaluated from the perspective of fish habitat and populations. In the reservoir ecological scheduling model, the ecological water demand and ecological flow runoff allocation were generally assigned as scheduling goals [7–10]. Yang [11] realized the goal that minimizes flood damage and maximizes fish diversity by setting up an optimization model with adding an ecological objective. In areas with serious water pollution, water quality improvements have been realized through the reasonable allocation of river discharge to achieve the greatest dilution for river pollutants [12–14].

Currently, there are several multi-faceted studies under joint operation. The multi-objective reservoir ecological operation model was built to solve the environmental and ecological problems caused by improper operation and alleviate the impact of the dams on the natural environment [15]. In the joint scheduling model, water uses, such as water supply, irrigation and power generation, were usually set as targets, while ecological flow or water quality was considered as a constraint [16,17]. Eco-environmental and socio-economic objectives are taken into account in all these models, but only one or two aspects of the goals were evaluated or tested. In eco-environmental scheduling, direct economic benefits were quantitatively computed, but the evaluation of eco-environmental effects was conducted from a different angle. In benefit maximization, on the other hand, the scheduling model took economic benefit as the dominant goal, and eco-environmental factors were only considered as constraints; so, their effectiveness was not included in the range of scheduling targets [18].

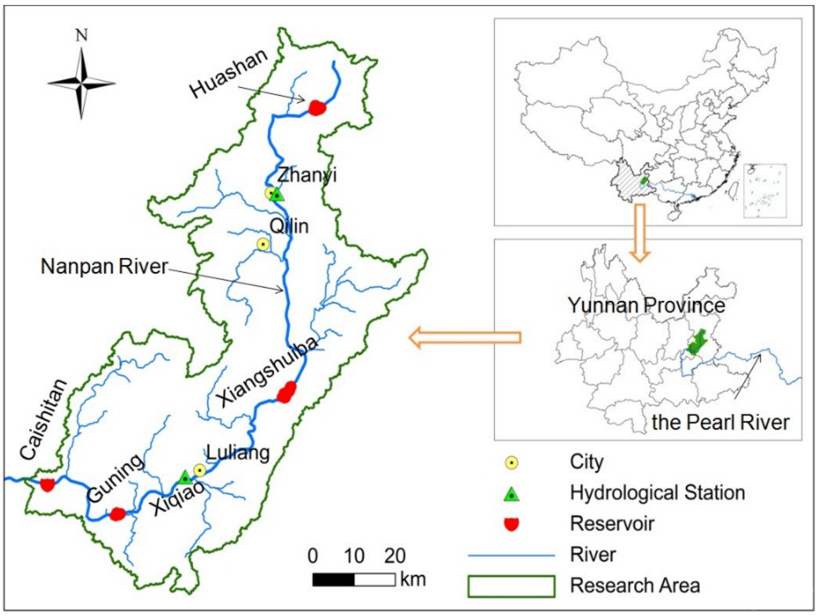
China contains more dams than any other country. In north China, reservoirs provide the opportunity to develop irrigation and control the water supply. However, because of large amounts of water diverted for irrigation, the Yellow River became dried-up downstream in the 1990s. The excessive reservoir and dam construction and their unreasonable operation have also led to serious water pollution in many river basins [2]. To ensure irrigation and water supply, most reservoirs are closed during the dry season, when industrial wastewater and domestic sewage are discharged into the river in high concentrations. In flood season, these high concentrations of centralized sewage can cause sudden pollution accidents [19]. Such incidents have occurred in large areas along the Huai River, interrupting the urban water supply and killing many fish in Hongze Lake in the early years of the 21st century [14].

With respect to integrated dispatching, how to coordinate different operation benefits is a new focus, currently. In this paper, we developed a reservoir optimal reoperation and evaluation framework for multiple reservoirs, which takes into account economic, social and eco-environmental benefits with overall planning ideas on the basin scale. In this model, all of the benefits of the operation objectives were calculated in monetary terms, to comprehensively evaluate scheduling benefits. The model was designed to be assembled modules, and users in different basins and areas can choose the appropriate benefits as operational objectives. The methods of benefit calculation were also flexible. The purpose of this paper was to explore an optimal operation method, improving eco-environmental benefits without sacrificing other benefits. The optimal reoperation frame was further used by a case study at the upper reach of Nanpan River, China.

2. Study Area

The research area (103°17′–104°09′ E and 24°46′–26°57′ N), shown in Figure 1, with a drainage area of 4656 km^2 and 200 km of mainstream, is located in eastern Yunnan Province, mainly in the upper reaches of the Nanpan River watershed, above the Caishitan Reservoir. The Nanpan River is the main source of the Pearl River. Although the annual mean precipitation and water resource of the watershed are 978.4 mm and 1.527 billion m^3, respectively, water resources per capita and per unit area are less than half of the national average. What is more, up to 41% of the water resources are overexploited, which greatly exceeds the recommended rate for international inland rivers (30%). Agricultural irrigation is the main water use, which accounts for more than 75% of the total water consumption within the region. Again, this level is much higher than the national average of 62%.

Figure 1. Location of the research area.



There are four reservoirs (Huashan, Xiangshuiba, Guning and Caishitan) and two hydrological stations (Zhanyi and Xiqiao) in the upstream of Nanpan River (Figure 1). Huashan and Xiangshuiba were built for irrigation; Guning and Caishitan for power generation. The construction of these reservoirs has to block the river's natural system, and each reservoir only tends to take into account its own benefit, rather than the integrated function from the viewpoint of the watershed system. The research area is facing increasingly serious water quality problems. The river water was very dirty, especially the Luliang lower reaches, with poor water quality throughout the year. Currently, these water projects almost close in the dry season, reducing the discharge and the ability of the river to naturally purify pollutants. When flood season comes, all the runoff with sewage spills down, resulting in the deterioration of water quality and the death of aquatic life in rivers and reservoirs. All of these environmental problems, which are caused by the reservoirs routine operation of only working for irrigation and power generation, ignoring the environmental and ecological functions, present a great challenge for water management. It is difficult to know how to solve the contradiction between water use and environmental water demand.

3. Methods

3.1. Model Structure

Socio-economic water use is the main goal of reservoir routine operation. The reservoir's optimal reoperation is to regulate the reservoir discharge to meet the demand of water use, reducing disparity between water supply and demand, alleviating environmental problems, such as deterioration, or maintaining the ecological and social function of rivers. The main objective of the model is to meet the demand of water use by reoperation while maximizing the comprehensive benefits. Water use can be divided into four major functions: environmental, ecological, social and economic, which correspond to the four sectors of the model. Environmental water, indicated by environmental flows, is used to dilute and degrade wastewater, realizing water quality benefits. Ecological water is used to maintain the healthy function of the river system, including the major indicators of ecological flows and flood peaks. Aesthetics and flood control are the major social benefits of reservoirs. As for the economic benefits, navigation, irrigation, urban water supply, industrial water supply and fisheries water are included. With respect to the model's input variables, water use inside and outside the river should be taken into account. A model sector is a system that is formally defined as Equation (1):

$$MS_i = (Iwi, Iwo, t) \rightarrow O_t(q,t) \rightarrow B\left(B_{WAQ}, B_{ECL}, B_{SOC}, B_{ECN}\right) \tag{1}$$

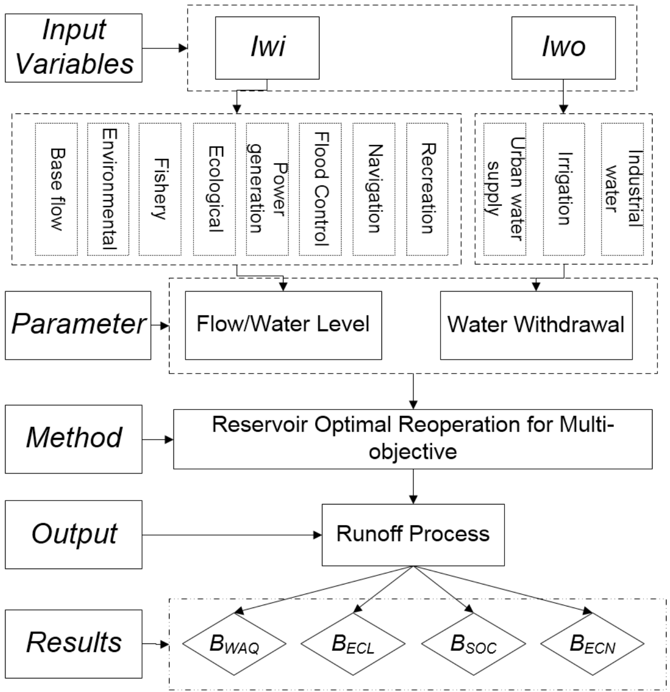
where MS is the model sector, i is the model sector number (i = 1, 2, 3, 4), Iwi is the instream water use variable, Iwo is the water use variable outside the river, t is time domain, O is output, q is the river runoff distribution and B_{WAQ}, B_{ECL}, B_{SOC}, B_{ECN} represent the benefits to the water quality, ecology, society and economy, respectively.

The overall model structure is illustrated in Figure 2.

3.2. Selection of Variables

A large number of variables were involved in the different model sectors. Figure 2 lists all the input variables and the corresponding indexes (river flow and water level) to the model. Some of the variables were not explicitly indices of water use, but may influence the decision-making process, such as flood control. Theoretically, all of these input variables should be considered during model development. However, in the actual model application, appropriate variables can be selected as targets or constraint conditions as required.

Figure 2. Overall model structure. *Iwi*, instream water use variable; *Iwo*, water use variable outside the river; *t*, time domain; B_{WAQ}, water quality benefits; B_{ECL}, ecological benefits; B_{SOC}, social benefits; B_{ECN}, economic benefits.



3.3. Objective

The management objective of this model is to meet the water demands in these four sectors, while realizing maximum economic benefits. A quantitative objective for watershed comprehensive benefits (WCB) was determined for the operation; the objective function was established in Equation (2).

$$WCB=max\{B_{WAQ} + B_{ECL} + B_{SOC} + B_{ECN}\} \quad (2)$$

where *WCB* is the watershed comprehensive benefits and B_{WAQ}, B_{ECL}, B_{SOC} and B_{ECN} are the benefits for the four sectors of the model. For the case study on multi-reservoir joint operation, *WCB* was the sum of benefits provided by reservoirs and control sections. In addition, the benefits were influenced by both human and natural aspects; therefore, the evaluation of benefits should be carried out in different hydrological years. In this case, the objective of the multi-reservoirs optimal reoperation is to maximize the benefits of water quality and economy, since water environment improvement and water resource shortages are currently the two greatest demands in the research area.

3.3.1. Water Quality Benefits

The water quality benefits of the reservoir were increased by increasing discharge and the aquatic environmental capacity of river. To achieve water quality benefits, the reservoir discharge was increased, which, in turn, raised the river's environmental capacity. As a result, the sewage disposal cost necessary to achieve water quality standards was lower, so that the cost reduction was a consequence of the water quality benefits of the management practice. To properly calculate cost/benefit analyses, the outlets of rivers between reservoirs should be combined and the benefit calculated for the entire outlet section. Before reservoir operation, the river itself must have some ability to improve water quality. Therefore, in this study, only the increase in reservoir dispatch was used in the benefit evaluation. How should the original environmental capacity of the river be defined? We selected the baseline value as that of the driest month, because the reservoir is then being operated without considering the water quality benefits. Accordingly, the minimum flow for each month was chosen as the reference flow. The water quality benefits were calculated by the dilution ratio proposed by Zhang [20]. The dilution ratio (b) can be expressed as follows:

$$b = \frac{Q_D}{Q_R}\frac{C_R}{C_I}\frac{C_D}{C_I} \tag{3}$$

where Q_D and Q_R are the discharge of sewage and the river discharge; C_D and C_R are pollutant concentrations in the sewage and river water and C_I is the same pollutant concentration in highest standard class water.

The computing approach is: (1) select the runoff of a typical hydrological year; (2) find the average sewage discharge and pollutant drainage over a period of time; (3) set the environmental benefits to 0 for extreme cases of minimal mean monthly flow; (4) the dilution ratios were then calculated for the extreme case (b_0) and typical year (b_1). When the dilution ratio was reduced from b_0 to b_1, the sewage should be diluted to a certain concentration (C_f) before discharge. Finally, (5), the cost of treating sewage to the appropriate concentration was used as the environmental benefit provided by regulating the reservoir.

3.3.2. Ecological Benefits

Ecological benefits appear in the compensation for the river base flow of reservoir discharge. However, ecological benefits achieved by the growth of river runoff are too complicated to quantize. In this paper, a simple and rough calculation formula was proposed by the ratio of river flow to the average monthly flow and multiplied by an ecological benefit coefficient. The sum of benefits over 12 months is the total ecological benefit of the cross-section. This was calculated according to Equation (4):

$$B_{ECL} = \sum_{1}^{12} K_{ECL}\frac{Q_i}{\overline{Q}} \tag{4}$$

where Q_i is flow in month i; $\overline{Q}$ is the average flow in month i and K_{ECL} is the ecological benefit coefficient, which was inspired by the method proposed by Zheng [21]. In his paper, the Tennant method for ecological flow calculation was referred to for the benefit evaluation. The Tennant method considered that 10% of the average flow provided minimum protection and that 30% of the average flow was satisfactory for aquatic life [22]. Specialists in biology were invited to rate the assignment to the potential value of the river flow in different periods and magnitudes. In other words, every river discharge will achieve a time score and a level score. The time score was determined by the season when the river discharge was estimated. The level score was decided by the ratio of the average annual discharge, while the potential ecological benefits were the product of scores and river discharge. The ecological benefit coefficient in this paper can be obtained by the same expert assignment method. In the research area, the most critical problem is to improve the water quality. Once the water quality scheduling succeeds, river discharge can meet the ecological flow in dry seasons, with the additional benefit of water quality improvement. Therefore, ecological benefits were not set as the objective in the research area, but as a constraint condition for minimum ecological flow demand.

3.3.3. Social Benefits

The social functions of reservoirs and rivers, such as aesthetic value, recreation and flood control, have the potential to make important contributions to local and state economies. However, these economic contributions are often underestimated. Social benefits are complex to estimate and were computed according to Equation (5):

$$B_{SOC} = B_R + B_{F1} \tag{5}$$

where B_{SOC} is the social benefit; B_R is the reaction benefit and B_{F1} is the flood benefit.

Landscape/recreation benefits were available for both urban rivers and reservoirs. Efforts to place quantitative measures on recreation values have been common, because this function was recognized as a public responsibility. Two principal methods of estimating values for recreation are currently in use to evaluate multipurpose reservoir developments [23]. One is based on expenditures by the users of the recreation facilities, while the other is based on the costs of providing recreation facilities. The expenditure approach assumes that dollars spent for recreation are appropriate measures of recreational benefit. The second method is usually associated with multipurpose reservoir projects and may be described as the cost method. A third estimate, based on willingness-to-pay (WTP) for landscape and recreation values, is also an effective evaluation method [24–27]. Water level fluctuations can have harmful impacts on recreation. The recreational benefits of the reservoirs may be estimated by surveying people's awareness.

Flood benefits were expressed by the reduced direct economic loss through reservoir regulation in the flood control system. First, the basin area was divided into calculation units based on the reservoir and region, then the whole flood benefits were added for each unit. The total flood benefit was calculated using Equations (6) and (7):

$$B_{F1} = \sum b_i \tag{6}$$

$$b = (A_0 - A_1) \times E \times \eta \tag{7}$$

where B_{F1} is the total flood benefit and b_i is the flood benefit in *i* units; A_0 is the flooded area restored to the parallel state without a reservoir; A_1 is the actual inundation area; *E* is the property value per unit area and η is the comprehensive property loss due to floods.

3.3.4. Economic Benefits

The economic benefits are revenue and can be obtained directly, being compromised of irrigation benefits, navigation benefits, power generation, water supply and fishing revenue (Equation (8)).

$$B_{ECN} = B_I + B_N + B_P + B_W + B_{F2} \tag{8}$$

where B_I is the irrigation benefits, B_N is the navigation benefits, B_P is the power generation benefits, B_W is the water supply benefits and B_{F2} is the fishing revenue.

Irrigation benefits can be evaluated by the profit obtained by grain yield increase under the various irrigation conditions [28]; it can be expressed as follows:

$$B_I = K_C \times Y_C \times P_C \times A \tag{9}$$

where K_C is the degree coefficient of crop yield growth, Y_C is the average yield of the rice crop in the natural state, P_C is the income from the crop and A is the irrigation area. In this paper, Huashan Reservoir and Xiangshuiba Reservoir have a total irrigation area of 13,400 hectares. The average and maximum rice yield of this area were 9000 and 13,500 kilograms per hectare. Therefore, 0.5 is the peak value of K_C.

The navigation benefits can be calculated by an equivalent alternative method. The additional passengers and freight that were shipped under reservoir management would be shipped to their destinations by other means without management, and these paths can be called the equivalent alternative program. The minimum cost transportation program was set as the optimal equivalent transport program. The cost difference between the optimal equivalent alternative method and waterway transport were the net shipping benefits (Equation (10)). In addition, navigation benefits can be obtained by improving navigation conditions. The benefits from navigation improvements were expressed by a reduction in shipping costs [29]. In this method, changes in transportation costs and the impacts of sedimentation are also considered (Equation (11)). The navigation benefits were not calculated in this case, because there is no river shipping conditions in the study area.

$$B_N = C_0 - C_S \tag{10}$$

where B_N is the benefits from the reduction in shipping costs; C_0 is the costs of the optimal equivalent alternatives and C_S is the costs of waterway transport.

$$\begin{gathered} B_N = [S_C \times (1 - c \times t)]e \times TR_t \text{ for } t \geq T_S \\ TR_t = TR_0, \text{ for } t = 0; \\ TR_t = (1+g)TR_t - 1, \text{ for } t > 0 \end{gathered} \tag{11}$$

where B_N is the benefit from navigation improvement (it starts functioning in T_S); S_C is the annual shipping capacity; e is the annual rate of reduction in shipping costs; c is the annual rate of decline in the navigation control benefit as a result of sedimentation; TR_t is the shipping costs in Yuan/ton; T_S is the time when hydropower starts operating; TR_0 is the shipping costs at $t = 0$ in Yuan/ton and g is annual rate of change in transportation costs.

Power generation can be computed based on the installed capacity and the water used for power generation from the reservoir after runoff is allocated. The power generated was simply multiplied by the online price of electricity to calculate the economic income, which is the power generation benefit of the reservoir's regulation.

$$B_P = N \times P_G \tag{12}$$

where N is power generation and P_G is the feed-in tariff. Gulong reservoir and Caishitan reservoir were designed for power generation, and the other two have no power generation capacities.

Water supply benefits were derived from the supply quantity for urban use and industry, multiplied by the unit price of water.

$$B_W = B_{WU} + B_{WI} = V_{WU} \times P_{WU} + V_{WI} \times P_{WI} \tag{13}$$

where B_{WU} and B_{WI} are urban and industrial water supply benefits; V_{WU} and V_{WI} are the supply quantities for urban use and industry and P_{WU} and P_{WI} are the unit price of the water supplied to urban and industrial users.

The fishing benefit was calculated in a manner similar to the irrigation benefits, by simply quantifying the increase in fish yield under the different water level conditions.

$$B_{F2} = K_F \times Y_F \times P_F \tag{14}$$

where K_F is the coefficient of fish growth; Y_F is the average yield of fish in the natural state and P_F is the purchase price. When the reservoir discharge increases, river levels rise and available water areas expand, which is beneficial for river fishing.

3.4. Constraint Conditions

Once the objective is determined, some constraints must be set according to actual conditions to reach the optimal solution. These conditions are considerations that must be met in the process of solving for optimal reservoir regulation. The constraint conditions were as follows:

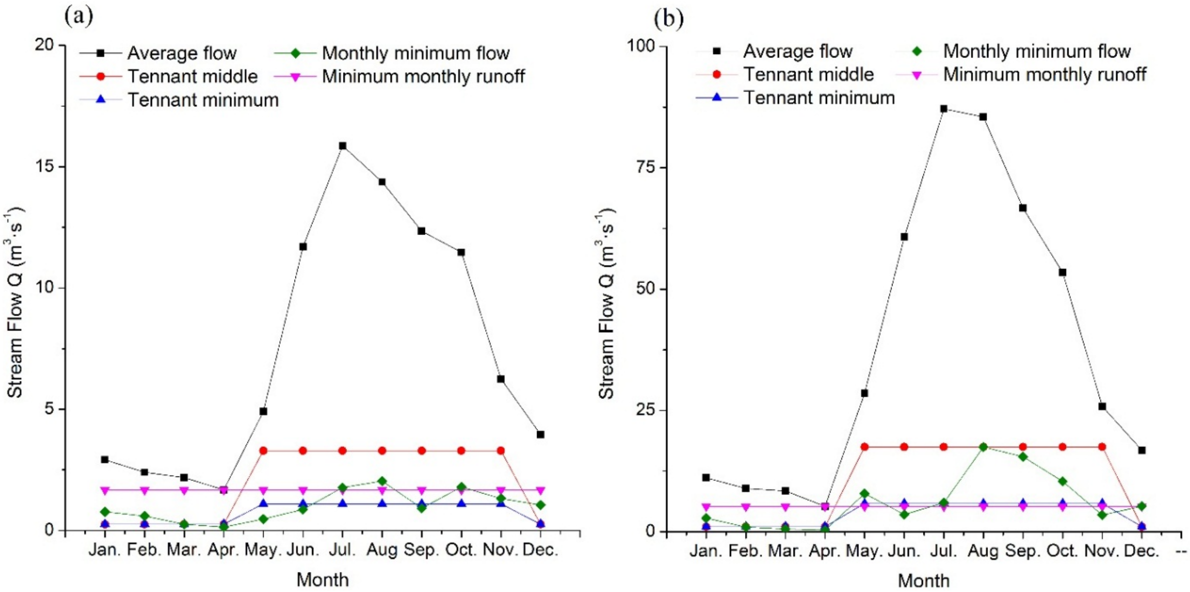
Flow constraint. Firstly, the minimum ecological flow is the basic requirement of dispatch, and therefore, river flows cannot be ignored to obtain the maximum benefit without extreme ecological deterioration. Secondly, to maintain minimum water quality standards, river discharge should be larger than the environmental flow. The minimum flow was set according to Equation (15):

$$Q_i > \max\{Q_{Ei}, Q_{Wi}\} \tag{15}$$

where Q_i is the flow in month i and Q_{Wi} and Q_{Ei} are the minimum environmental flow and ecological flows in month i.

While the objective and constraint conditions were determined, minimum ecological flow should be calculated to limit the minimum outflow for reservoir reoperation. The calculation methods to determine the ecological demand for water can be divided into four categories: historic flow methods, hydraulics methods, habitat methods and overall analysis methods [30]. As data are limited, historic flow methods (the Tennant method, minimum monthly flow and monthly minimum flow) were used to calculate the ecological flow in this paper (Figure 3). Tennant considered that 10% of the average flow throughout the year (Tennant minimum) provided minimum protection and that 10% in dry seasons and 30% in wet seasons of average flow (Tennant middle) were satisfactory for aquatic life [22]. The minimum monthly runoff was the averaged value of minimum observed discharge for many years. The monthly minimum flow was the minimum value of each month in history. In the case study, 55-year flow data from the two hydrological stations were used to draw an average monthly flow curve (Figure 3). There is a large difference in discharge between the wet season (May to November) and the dry season (December to April). Wet season runoff accounted for 85% of the annual average runoff in Zhanyi Station and 89% in Xiqiao Station. In order to meet the demand that river ecosystems are highly adapted to natural, dynamic variation in flows, the outsourcing line of the four ecological flow curve was used as the minimum flow constraints (Figure 3).

Figure 3. The average flow and ecological flows calculated by 4 methods in Zhanyi (**a**) and Xiqiao (**b**) hydrological station.



Water level and reservoir capacity constraints. To maintain the normal operation of the reservoirs, the water level and storage capacity constraints must be considered.

$$Z_d \le Z_i \le Z_n \tag{16}$$

$$V_{\min} \le V_i \le V_{\max} \tag{17}$$

where Z_d and Z_n are the dead storage level and normal water level, V_i is the reservoir capacity and $V_{\min}$ and $V_{\max}$ are the dead and usable capacities.

Flood control constraint. Flood control is the primary consideration in scheduling. A guaranteed rate was set according to the watershed scale and location, as well as the protection goal.

$$Z_i \le Z_l \tag{18}$$

$$Q_{i,\min} \le Q_i \le \alpha Q_{\max} \tag{19}$$

where Z_l is the limiting level during flood season; $Q_{i,min}$ is the minimum discharge; Q_{max} is the highest river flow under natural circumstances and α is a peak to average flow factor to limit the maximum discharge.

3.5. Model Solution Methods

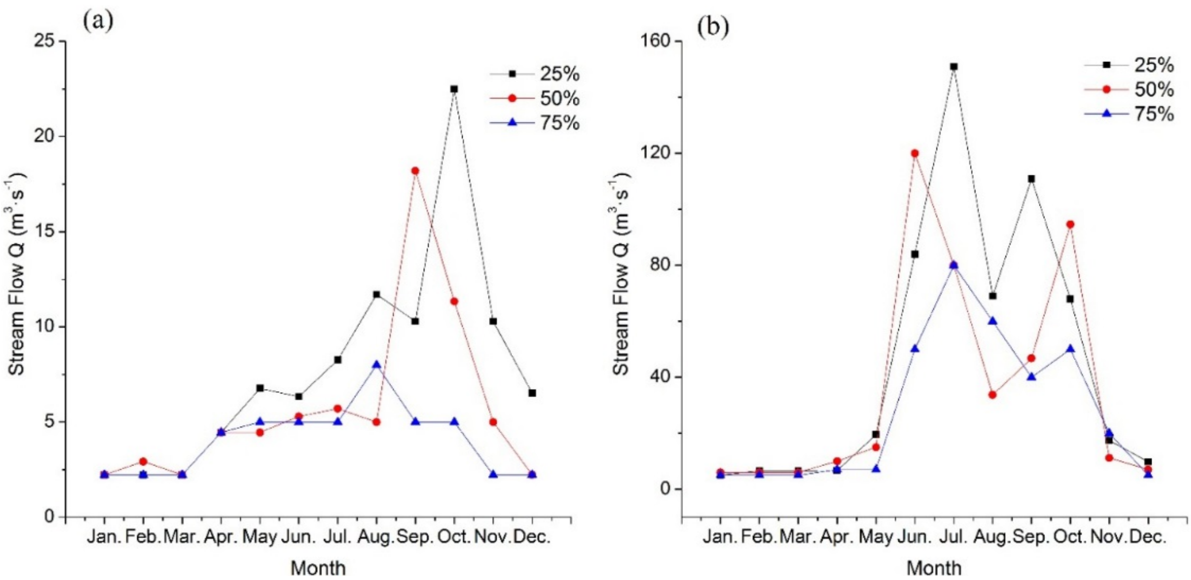
Reservoir reoperation is a multi-objective scheduling model with complex constraints and presents difficulties in multi-objective optimization. Generally, dynamic programming (DP) and its extension, genetic algorithms (GAs), or system decomposition coordination algorithms are used to model the solutions [31]. In this paper, a multi-objective optimization model is simplified into a single-objective optimization model, and then, feasible search discrete differential dynamic programming (FS-DDDP) is used for solving [32]. A feasibility search algorithm was used to find good viable strategies, processes that correspond to the initial trajectory, and then DDDP was used by iterative calculation to reduce dimensionality and achieve a locally optimal solution. In the model application for research area, the runoff distribution under different year types was simulated. Then, the benefits under different inflow hydrological years with 25%, 50% and 75% guarantee rates were calculated with the method of FS-DDDP.

4. Results

4.1. Runoff Distribution

The runoff distribution results in three hydrological years with various inflow conditions were derived according to the objectives and constraint conditions (Figure 4). Because flow in the upstream station is much smaller in natural conditions and to meet the rigid demand of the regulation goal, the change of the upstream flow rate is larger than the downstream one.

Figure 4. Runoff distribution results for three inflow hydrological years of Zhanyi Station (**a**) and Xiqiao Station (**b**).



4.2. Benefits Calculation

According to the runoff distribution results, the total benefits of reoperation were calculated, including water quality benefits, irrigation benefits and power generation benefits.

4.2.1. Water Quality Benefits

Sewage and pollutant data were connected and generalized based on the spatial and temporal distribution. The value of C_f was derived by keeping river discharge unchanged, reducing b_0 to b_1. If the obtained C_f value was larger than the pollutant discharge concentration, sewage for that month did not require treatment, and the sewage charge is zero. Otherwise, the sewage charge is 0.1 Yuan per ton to decrease the concentration to one milligram per liter. Thus, the water quality benefits were achieved (Table 1).

Table 1. Water quality benefits from optimal reoperation (B_{EO}) and routine operation (B_{ER}) in two stations. C_f is in milligrams per liter; c is Yuan per ton; B_E is millions of Yuan. Freq. is the abbreviation of frequency.

Station	Freq.	Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug	Sep.	Oct.	Nov.	Dec.	B_{EO}	B_{ER}
Zhanyi	25%	C_f	57	51	41	22	14	75	37	30	20	20	21	26		
		c	1.08	1.14	1.24	1.41	1.49	0.97	1.35	1.42	1.52	1.52	1.44	1.39		
		B_E	1.29	1.36	1.48	2.27	2.39	1.56	2.17	2.28	2.44	2.44	1.71	1.65	23.05	20.04
	50%	C_f	57	39	41	22	22	90	53	70	20	27	44	77		
		c	1.08	1.26	1.24	1.41	1.41	0.82	1.19	1.02	1.52	1.45	1.21	0.88		
		B_E	1.29	1.5	1.48	2.27	2.27	1.32	1.91	1.64	2.44	2.33	1.45	1.04	20.93	17.64
	75%	C_f	57	51	41	22	19	95	61	44	32	62	98	77		
		c	1.08	1.14	1.24	1.41	1.44	0.77	1.11	1.28	1.4	1.1	0.67	0.88		
		B_E	1.29	1.36	1.48	2.27	2.31	1.23	1.79	2.06	2.26	1.77	0.8	1.04	19.66	14.29
Xiqiao	25%	C_f	155	109	119	2	72	20	20	49	27	30	45	122		
		c	0.73	1.19	1.09	1.78	1.08	1.74	1.74	1.45	1.67	1.65	1.83	1.06		
		B_E	1.56	2.56	2.35	5.68	3.43	5.56	5.56	4.63	5.33	5.25	3.94	2.27	48.12	26.00
	50%	C_f	129	121	131	58	94	20	20	101	64	21	70	171		
		c	0.99	1.07	0.97	1.22	0.86	1.74	1.74	0.94	1.3	1.73	1.58	0.57		
		B_E	2.12	2.31	2.09	3.88	2.74	5.56	5.56	2.99	4.15	5.52	3.4	1.23	41.53	26.28
	75%	C_f	155	145	157	83	180	20	20	57	75	40	39	228		
		c	0.73	0.83	0.71	0.97	0	1.74	1.74	1.38	1.19	1.54	1.89	0		
		B_E	1.56	1.79	1.52	3.08	0	5.56	5.56	4.39	3.8	4.91	4.06	0	36.24	25.94

4.2.2. Irrigation Benefits

In this paper, the irrigation benefits were the revenues obtained by grain yield increases under the different condition of irrigation. Huashan Reservoir and Xiangshuiba Reservoir have a total irrigation area of 13,400 hectares. The average rice yield of this area was 9000 kilogram per hectare. According to information released by the National Development and Reform Commission website, the rice purchase price was 2.5 Yuan per kilogram. The best condition for irrigation in these areas was provided through reservoir scheduling, and the maximum rice yield was reached by 13,500 kilogram per hectare. In view of this, 0.5 is the maximum value of the degree coefficient of crop yield growth in a 25% frequency year. In 50% and 75% years, the K_c was reduced to 0.4. Due to the fact that irrigation was the primary goal in routine operation, the benefits from reoperation will not be reduced. Irrigation benefits were computed in Table 2.

Table 2. Irrigation benefits calculation, where K_c is the degree coefficient of crop yield growth and B_I is the benefits of irrigation.

Freq.	K_c	Irrigation Area (ha)	Rice Price(Yuan/kg)	Average Product (kg/ha)	B_I (million RMB)
25%	0.5	13,400	2.5	9,000	150.75
50%	0.45	13,400	2.5	9,000	135.68
75%	0.4	13,400	2.5	9,000	120.60

4.2.3. Power Generation Benefits

Upstream discharge was confirmed through the runoff distribution, and then, the power generation was computed based on the installed capacity and water used for power generation from the Guning Reservoir and Caishitan Reservoir. Power generation multiplied by the online electricity price is the economic income, which is the power generation benefit from the reservoirs' regulation. The results are shown in Table 3.

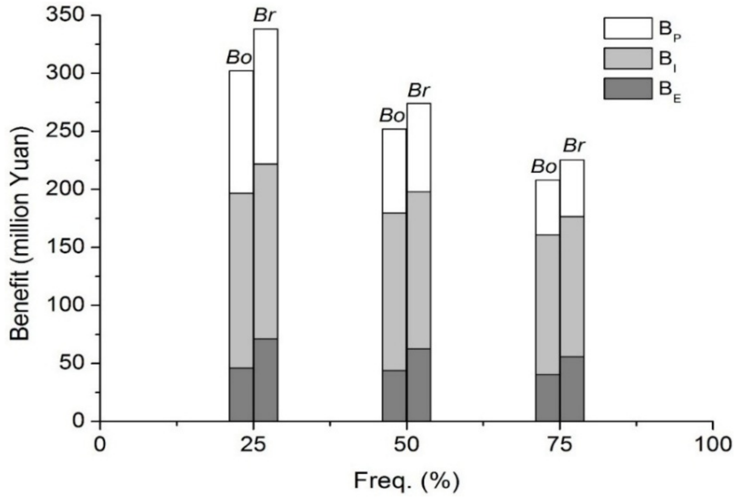
Table 3. Power generation benefits from optimal reoperation (B_{PO}) and routine operation (B_{PR}). The unit of water used is 10^8 m^3; the energy output is MKW (million kilowatt), and benefit is a million Yuan.

Freq.	Guning Reservoir				Caishitan Reservoir				B_{PO}	B_{PR}
	Water used	Energy output	Unit price	B_P	Water used	Energy output	Unit price	B_P		
25%	12.39	217.19	0.25	54.30	14.12	247.59	0.25	61.90	116.19	105.17
50%	9.17	152.35	0.25	38.09	8.65	151.73	0.25	37.93	76.02	72.30
75%	6.14	89.70	0.25	22.42	6.03	105.75	0.25	26.44	48.86	46.98

4.2.4. Benefits from Reservoir Optimal Reoperation and Routine Operation

The watershed comprehensive benefits of reservoir operation can be considered as the sum of water quality benefits, irrigation benefits and the benefits of power generation. Figure 5 exhibits the results of the benefits from reservoir routine operation (Bo) with eco-environmental benefits and reservoir optimal reoperation (Br) with overall planning ideas in the Nanpan River watershed.

Figure 5. The contrast in benefits between the reservoir routine operation (Bo) and optimal reoperation (Br). B_P, B_I and B_E, respectively, refer to the benefits of power generation, irrigation and water quality.



As for reservoir optimal reoperation, the total benefits of rainy years (25%) was 50% greater than that of drought years (75%). This result is consistent with the fact that water resources were affected by climate conditions. More rain runoff retained and stored by multi-reservoirs provide enough water resources for irrigation, power generation and even river flows, which further produced greater economic and environmental benefits in rainy years than those in drought years.

In fact, in the research area, the water eco-environmental problems were mainly caused by the inappropriate operation of reservoirs. The total benefits of routine operation were 301.97 million RMB in rainy years with 25% guarantee rates and 251.9 million RMB and 207.81 million RMB in average years (50%) and dry years (75%), respectively. The optimal reoperation increased the benefits by 12%, 9% and 8% from the routine operation in rainy years, average years and drought years, respectively. Additionally, the corresponding benefits grew approximately from 20 to 40 million Yuan. Compared with the routine operation mode, the optimal reoperation led to a 4% to 10% increase in the power generation benefits and hardly any change to the irrigation benefits. The increased benefits of the optimal reoperation mainly resulted from the increasing environmental benefits. The optimal reoperation significantly increased the environmental benefits, which increased by 55% in a wet year and 39% in a dry year, because of the river discharge rising the in dry season, the eco-environmental function of rivers was taken into account and the states of rivers dried-up in the dry season were changed. Therefore, the optimal reoperation mode should be paid have more attention paid to it in the upstream of the Nanpan River basin. Not only can ecological and environmental problems be solved, but a better economic benefit may also be achieved.

5. Conclusions

In the paper, a reservoir dynamic optimization model for comprehensive watershed benefits was introduced for watershed management. The model is presented via a case study, and the results are credible in application. It integrates various operation objectives with constraint conditions and maintains optimal water efficiency values by: (1) the model structure; (2) the selection of input variables;

(3) the determination of objectives; and (4) the dynamic simulation and optimization. The model results can provide operation feedback to decision-makers in various water sectors, so that they can quickly determine the pros and cons. Furthermore, the modelers can adjust the objectives and constraints in accordance with the results of scheduling and the actual situation to adapt to natural or socio-economic changes and requirements. This means the model is flexible and adaptable. The model provides guidance for developing countries that must rely on water resources to achieve social development and protects the environment and ecological functions at the same time.

However, the model still faces difficulty in meeting the criteria under certain constraints. The optimization will be increasingly challenging, because of aggravated water conflicts, as the scheduling objectives increase. In actual operation, the optimal value was obtained under the target trade-offs, but the absolute maximum benefits were only under conditions that do not exist. In addition, changes of environment, climate and socio-economic conditions were important factors affecting water resources. To the reservoir operation model of the future, the climate forecast module should be joined, in order to provide support for management decisions.

Acknowledgments

This study was supported by the National Key Technology R&D Program (Grant No. 2013BAB05B04). Thanks go to Ximing Cai for his helpful comments during the formation of this paper and we are grateful for the anonymous reviewers' helpful comments.

Author Contributions

Xinyi Xu, Lingling Bin and Chengzhong Pan conceived of and designed the study. Lingling Bin and Chengzhong Pan wrote the paper. Aizhong Ding and Desheng Chen provided data and modified the manuscripts. All authors read and approved the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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