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Sustainable reservoir operations to balance upstream human needs and downstream lake ecosystem targets

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Abstract

Reservoirs improve human health by providing a steady water supply, alleviate poverty by producing cheap electricity and strengthen regional economies by providing job opportunities. However, present modes of reservoir operation, without environmental flow targets, have caused ecosystem degradation while satisfying human needs. The degraded aquatic ecosystem conditions caused by tremendous dam construction in China propel a shift from an emphasis on human needs to sustainable modes of reservoir operation. In this paper, an optimizing reservoir operation model was developed to assist the decision making process of balancing human needs and ecological targets. The environmental flow regime paradigm and water shortage ratio of social water supply were respectively used to establish downstream lake ecosystem targets and upstream human needs. An Interactive Dynamic Programming (IDP) was developed to optimize the conflicts of human needs and ecosystem targets. A set of scenarios were designed for reservoir operations in the Baiyangdian basin in a normal year (50\% percentage), a wet year (25\% percentage) and a dry year (75\% percentage), which provided a very useful tool for reservoir operations to balance human needs and ecosystem targets.

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1. Introduction

China has constructed almost half of the world’s large dams resulting in the most strongly affected rivers with both upstream and downstream effects stemming from inundation, flow manipulation, and

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fragmentation caused by dams [1]. By the end of 2009, there are over 87,000 large and small scale reservoirs with a total storage capacity of 700 billion cubic meters that accounts for more than a quarter of China’s annual runoff, in which 5340 dams completed or under construction are higher than 30m. In 2004, China overtook the United States as the world’s largest hydropower capacity. China's hydropower installed capacity has exceeded 200 million kilowatts in 2010 and aims to 430 million kilowatts in 2020, which means double rivers or river sections will be fragmented. The hydraulic structures built mainly focus on the functions of irrigation, electricity, navigation and flood prevention and so on, with ignoring their impacts on ecological health of downstream within their areas [2].

Alleviating the environmental impacts caused by hydraulic structures and facilities has become an essential component in water resources planning and management [3]. The reservoir management aimed at electricity and flood proofing should add ecological response monitoring to this management. Scheduling a framework of optimizing reservoir release from hydrologic alteration analysis caused by different types of reservoir, such as flood-prevention, power-producing and water-supplying, provide a tool for reservoir operations [4].

Sustainable reservoir operations originate from the hydrologic assessment of reservoir operations [5]. Fishes in each life stage, such as salmon, are target species to be protected from negative effects of reservoir operations [6]. Flow processes, including low flows and high flows etc., should be guaranteed to provide species with suitable habitat [7]. Reservoir operation rules of launching natural flow processes with seasonal change characteristics can satisfy the ecological water base flow and flood pulse demands, and put forward allocation plans for sustainable utilization of water and ecosystem recovery.

When balancing human needs and ecosystem requirements, human needs are adjusted to meet basic environmental flows, which is normally regarded as either a limited condition or single object ignoring the basic water requirements of humans [8]. In dry areas, such as Northern China, rules of priority for basic environmental flows can’t provide an efficient way to assist decision making for managers, as it’s difficult to identify the interaction relationship between economic and ecological benefit. Homaet al. (2005) established an evaluation framework to weigh the conflict between human water demands and ecological water requirement. They defined the difference between natural runoff process and that are affected by human as "ecological deficit", which is the goal for optimization reservoir operation. Suen and Eheart (2006) used Taiwan ecological hydrological index systems (TEIS) to characterizing ecological flow process, figured out a set of Parato optimality reservoir operation rules adopting the dominant sorting genetic algorithm, so as to balance the water demanded by human and ecosystem. Most of researches, in order to balance human water requirements and ecosystem requirements, use some kind of ecological benefit to solve the contradiction of humans and the ecosystem [9, 10].

In this paper, we provide a multi-object reservoir operation model, in which there are two objects, ecological and economical. An approach to solve multi-objects optimization, which cannot show the clear interaction relationship between social and economic objects or ecological objects, is transformed into one object model, with dynamic programming to get a series of optimal results. The relationship between human benefit and ecological benefit can be simulated and provides a useful tool for water resources management agencies.

2. Materials and methods

2.1. Study area

The Baiyangdian wetland (Fig. 1), located between 115°45'E-116°06'E longitude and 38°43'N-39°02'N latitude, covers a area of 366 km², is the largest semi-closed wetland in the Hai River basin. Nine Rivers, with a catchment area of 31200 km², join the Baiyangdian wetland and then flow into the Bohai
Gulf. The elevations of the wetland range from 5.2 to 7.8 m. In the upstream river basin, the average annual precipitation is 590 mm and the average annual runoff is $3.1 \times 10^9$ m$^3$. The Baiyangdian wetland supports significant biodiversity of regional and global significance within the Hai River Basin. The open water and aquatic beds of the wetland are spawning grounds and feeding habitats for a diverse array of fish and other animal species including up to 192 bird species.

In the most recent 60 years, the function and value of the basin as well as the wetland have been eroded, with adverse impacts on its ecosystem. Construction of large reservoirs in the upstream has led to a dramatic decline in water inflows into the wetland, from an average of $1.7 \times 10^9$ m$^3$ of water discharging into the wetland in the 1960s down to $0.1 \times 10^9$ m$^3$ in 2000s. Xidang reservoir (with a capacity of 1.26 billion m$^3$) and Wangkuai reservoir (with a capacity of 1.39 billion m$^3$) are the biggest two reservoirs in the Baiyangdian basin. The sustainable reservoir operation in the study relies on Wangkuai–Xidang comprehensive reservoir project, in which the Wangkuai reservoir will convey part of its water to Xidang reservoir except supporting the original water users. The water needed by the Baiyangdian Lake will be only allocated by Xidang reservoir. Decreasing environmental flows in Baiyangdian Lake have become more acute, especially during dry years, thus contributing to more incidences of low water levels in the wetland (Fig. 2). The size of the wetland has decreased by almost half because of controlled water flows, continuous droughts, and soil erosion. The wetland has dried up several times. Moreover, rising population, expanded agricultural and industrial activities, with limited solid and wastewater disposal measures in the upstream and within the wetland area, have transformed the wetland into a major depository of wastewater discharges, pollutant substances, and sediments [11].

![Baiyangdian Drainage Basin](image)

Fig. 1. The location of reservoirs and the Baiyangdian Lake
2.2. Methods

The goal of the study is to indicate the interaction relationships between social and economic benefits and ecological benefits in different cases, on which managers make their decisions. So the methods are made up of two parts: (a) the calculation of environmental flow; (b) The optimizing reservoir operations model we formulated to consist of objects and restraint conditions, where the objects are either made up of social and economic objects or ecological objects.

2.2.1. Environmental flow assessment

A lowest ecological water level should be defined, below which part of the lake will dry up and the ecosystem function will be badly damaged.

The water area of the wetland is decided by its hydraulic and topographical condition. There is a close relationship between ecosystem health and water area. According to the curve of water level and water area, the peak change rate can be calculated, which indicates the key water level for the change of water area. Using the water level, seven scenarios were designed by scattering the initial ecological water level into two directions, and H1、H2、…、H12 is the water level from January to December (Table 1).

Table 1. Ecological water level scenarios
AAPFD (Amended annual proportional flow deviation) was used to assess each scenario, which is defined as

$$AAPFD = \frac{1}{n} \sum_{i=1}^{n} \left[ \sum_{j=1}^{12} \left( \frac{H_i - h_{ij}}{h_{ij}} \right)^2 \right]^{\frac{1}{2}} (i=1,2,\ldots,12; j=1,2,\ldots,n)$$  \hspace{1cm} (1)$$

Where $n$ is the year number, $H_i$ is the ecological water level of month $i$, $h_{ij}$ is the water level of month $i$ in the year $j$, $h_{ij}$ is the average water level in the year $j$.

Based on the relationship between AAPFD and ecological index (Table 2), if the hydrological index is above 0, it means the condition of the ecosystem is acceptable, while the bigger the hydrological index, the better the ecosystem.

Table 2. Ecological water level scenarios

<table>
<thead>
<tr>
<th>APPFD</th>
<th>Ecological index</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;0.1</td>
<td>10</td>
</tr>
<tr>
<td>0.1-0.2</td>
<td>9</td>
</tr>
<tr>
<td>0.2-0.3</td>
<td>8</td>
</tr>
<tr>
<td>0.3-0.5</td>
<td>7</td>
</tr>
<tr>
<td>0.5-1</td>
<td>6</td>
</tr>
<tr>
<td>1-1.5</td>
<td>5</td>
</tr>
<tr>
<td>1.5-2</td>
<td>4</td>
</tr>
<tr>
<td>2-3</td>
<td>3</td>
</tr>
<tr>
<td>3-4</td>
<td>2</td>
</tr>
<tr>
<td>4-5</td>
<td>1</td>
</tr>
<tr>
<td>&gt;5</td>
<td>0</td>
</tr>
</tbody>
</table>

Each of the above scenarios is assessed by AAPFD, and the Mann-Kendall (MK) method is used to calculate the natural water level by testing the changing trends of water levels. The rank-based Mann-Kendall method is a nonparametric and commonly used method to assess the significance of monotonic
trends in hydrological time series. This test has the advantage of not assuming any distribution form for the data and has the similar power as its parametric competitors. The Mann–Kendall test considers only the relative values of all terms in the series \( x_1, x_2, \ldots, x_n \) to be analyzed. For each term \( m_i \) was computed as the number of later terms in the series whose values exceed \( x_i \). Then the MK rank statistic \( d_k \) was given by:

\[
d_k = \sum_{i=1}^{k} m_i \quad (2 \leq k \leq n)
\]

\[
m_i = \begin{cases} 
+1 & \text{if } x_i > x_j \quad (j = 1, 2, \ldots, i) \\
0 & \text{otherwise}
\end{cases}
\]

Under the null hypothesis of no trend, the statistic \( a_k \) is distributed as a normal distribution with the expected value of \( E(d_k) \) and the variance \( Var(d_k) \) as follows:

\[
E(d_k) = \frac{k(k-1)}{4}
\]

\[
Var(d_k) = \frac{k(k-1)(2k+5)}{72}
\]

Under the above assumption, the definition of the statistic index \( C_k \) is calculated as:

\[
C_k = \frac{d_k - E(d_k)}{\sqrt{Var(d_k)}} \quad (k = 1, 2, 3, \ldots, n)
\]

\( C_k \) follows the standard normal distribution (here, we call it \( C_1 \), and later we will get another \( C_2 \)). In a two-sided test for trends, the null hypothesis is rejected at the significance level of \( \alpha \) if \( |C| > C_{1-\alpha/2} \), where \( C_{1-\alpha/2} \) is the critical value of the standard normal distribution with a probability exceeding \( \alpha/2 \). A positive \( C \) value denotes a positive trend and a negative \( C \) value denotes a negative trend. In this paper, the significance level of \( \alpha = 5\% \) is used. After this, \( C_k \) will be computed again based on the adverse course, which means that the original time series will be \( x_n, x_{n-1}, \ldots, x_1 \) and \( d_k, E(d_k) \), \( Var(d_k) \) and \( C_k \) will be computed again following the procedure showed in Eqs. (1), (2), (3) and (4), and then \( C_2 \) is obtained. The two lines, \( C_1 \) and \( C_2 \) (\( k = 1, 2, \ldots, n \)) will make an intersection point during a certain time interval. If the intersection point is significant at 95% level, we say that the critical point occurred in the analyzed time series at that time.

Environmental flows of the Baiyangdian Lake consist of two parts: one part is the net loss from water loss by evapotranspiration and leakage minus precipitation; the other part is the water volume between initial and objective water level. The equation to calculate the environmental flow is defined as:

\[
Q_i = 2f(h_i) - f(h_i - hh_i) - f(h_{0i})
\]

Where, \( Q_i \) is the environmental flow in month \( i \), \( h_i \) is the ecological water level in month \( i \), \( hh_i \) is the consumption depth of water in month \( i \), \( h_{0i} \) is the initial water level in month \( i \), \( f \) is the function of water level and amount.

2.2.2. Optimization model of reservoir operations

The total object function is the maximum of social and economy benefit and ecological benefit.

\[
\max W(X) = [E_1(X), E_2(X)]
\]
Where, $W$ is the synthetic benefit, $E_1$ is the social and economy benefit, $E_2$ is the ecological benefit. $X$ is decision vector.

To calculate the total object function, individual social and economic benefit functions (SEB) and ecological benefit functions (EBF) should be developed.

The social and economy benefit function is used to indicate the maximum benefit the reservoir supports. Generally, reservoirs play an important role in flood prevention, electricity production, water supply, and so on.

$$E_1 = \min \text{SRW} = \min \sum_{t=1}^{T} \frac{Q_{pt} - Q_{at}}{Q_{pt}} \times 100\% \quad (9)$$

Where, $Q_{pt}$ is supply quantity planned in time $T$, $Q_{at}$ is actual supply quantity in time $T$. $T$ is the total operation time. When the $\text{SRW}$ is not 0, it is required to satisfy the household water first, if that is still insufficient, water will be reduced from the the industry and agriculture water supply.

Based on the aim of reservoir ecological operation to have the let-down flow rate meet the requirement of ecological water in the downstream area, the distance between let-down flow rate of the reservoir (used for ecology) is calculated according to Lance distance.

$$D_t = \text{distance between actual water used for ecology and target ecological water requirement, the smaller the } D_t \text{ is, the more ecological benefit the reservoir operation brings.} \quad (10)$$

All of the above functions should be restrained to the following conditions.

1. Water balance
   $$V_{t+1} = V_t + I_t - Q_t - K_t \quad (11)$$
   Where, $V_{t+1}$ is reservoir pondage at the time $t+1$, $V_t$ is the reservoir pondage at the time $t$, $I_t$ is the reservoir inflow in time $t$, $K_t$ is the quantity of water intake from the reservoir at time $t$.

2. Reservoir release rate
   $$Q_t \leq Q_{max} \quad (12)$$
   Where, $Q_{max}$ is the maximum release rate.

3. Limiting water level of reservoirs
   $$Z_d \leq Z_{min} \quad (13)$$
   $$Z_{max} \leq Z_s \quad (14)$$
   Where, $Z_d$ is the dead water level below which no water can be released, $Z_{min}$ and $Z_{max}$ are the lowest and highest storage levels during time $t$, respectively, $Z_s$ is the safe water level.

4. Minimal environmental flow
   $$Q_{te} \geq Q_{e\min} \quad (15)$$
   Where, $Q_{e\min}$ is the minimal environmental flow.
3. Results and discussion

3.1. Environmental flows in the Baiyangdian Lake

The elevation of Baiyangdian Lake ranges from 5.2m in the east part to 6.5m in the west part. When the water level is below 6.54m, part of the Baiyangdian Lake will dry up and ecosystem function will be badly damaged. Then 6.5m is set as the lowest ecological water level, above which the Baiyangdian Lake can avoid drying up.

As shown in Fig.3, change rate of the water area peak when water level is 7.5m and 8.3m separately, which are the key water levels for the Baiyangdian Lake.

![Fig. 3. (a) Water level and water area; (b) Water level and change rate of water area](image)

In this paper, we made a mutation analysis for the average water level from 1950 to 2000, and the results indicate from 1960 to 1968, there was a mutation in Baiyangdian Lake. So the year before the mutation is treated as the natural state from which to evaluate the ecological level programs (Figure 4).

![Fig. 4. Mann-Kendall analysis of water level series](image)

Based on a screening of the most popular hydrological indices, an amended hydrological index method, AAPFD, was used to assess the environmental flow of the range of scenarios (Table 3). AAPFD can be
used as an indicator of hydrological alteration. We combined monthly percentile curve and an ecological index to develop a dynamic method. Then AAPFD was used to evaluate every scenario, and each scenario was linked with AAPFD. The value of AAPFD was relevant to ecosystem status, and then each scenario was linked with ecosystems. The ecological index is bigger than 6 in scenario 3 and scenario 4, in which ecological states and the corresponding environmental flows are suitable for the Baiyangdian Lake.

Table 3 AAPFD and ecological index
In different years, the water loss by evapotranspiration and leakage is different, and so is the amount of precipitation. In this paper, field data from 1956 to 2000 were used to calculate the net loss in water depth. As shown in Table 4, the minimum and suitable environmental flows in the Baiyangdian Lake were calculated.

Table 4 Environmental flows in the Baiyangdian Lake

<table>
<thead>
<tr>
<th>Month</th>
<th>Ecological level (m)</th>
<th>Water loss (mm)</th>
<th>Environmental flow (10^8m^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum</td>
<td>Suitable</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>6.50</td>
<td>7.51~9.60</td>
<td>85.40</td>
</tr>
<tr>
<td>2</td>
<td>6.50</td>
<td>7.51~9.60</td>
<td>36.30</td>
</tr>
<tr>
<td>3</td>
<td>6.50</td>
<td>7.51~9.60</td>
<td>35.20</td>
</tr>
<tr>
<td>4</td>
<td>6.50</td>
<td>7.51~9.60</td>
<td>16.70</td>
</tr>
<tr>
<td>5</td>
<td>6.50</td>
<td>7.51~9.60</td>
<td>75.50</td>
</tr>
<tr>
<td>6</td>
<td>6.50</td>
<td>8.31~10.62</td>
<td>82.00</td>
</tr>
<tr>
<td>7</td>
<td>6.50</td>
<td>8.31~10.62</td>
<td>221.10</td>
</tr>
<tr>
<td>8</td>
<td>6.50</td>
<td>8.31~10.62</td>
<td>250.30</td>
</tr>
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<td>9</td>
<td>6.50</td>
<td>8.31~10.62</td>
<td>318.90</td>
</tr>
<tr>
<td>10</td>
<td>6.50</td>
<td>7.51~9.60</td>
<td>83.90</td>
</tr>
<tr>
<td>11</td>
<td>6.50</td>
<td>7.51~9.60</td>
<td>150.00</td>
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<tr>
<td>12</td>
<td>6.50</td>
<td>7.51~9.60</td>
<td>196.30</td>
</tr>
<tr>
<td>Total</td>
<td>1551.60</td>
<td></td>
<td>1.00</td>
</tr>
</tbody>
</table>

3.2. Sustainable reservoir operations
The optimized reservoir operation model for the Xidayang reservoir is solved by assuming the reservoir is at dead water level at the beginning. According to the needs of the managers, suitable reservoir operation is made according to the solutions.

As shown in Fig. 5, $D_t$ are negative linear correlatives with water shortage rate, which obviously indicate the conflict of human needs and ecosystem requirements. In normal and dry years, the slope the curve is much bigger than that in wet years when $D_t$ keeps stable between 0.3~0.4.

![Graphs showing the relationship between water shortage rates and $D_t$.](image)

Fig. 5. The relationship between water shortage rates and $D_t$

With more than two objects, the optimized reservoir operation model has to deal with multidimensional data to balance human needs and lake ecosystem targets. All of the objects were transformed into non-dimensional data and multi-objects problem was transformed into a single object problem. Using dynamic programming, the single object optimization model can be solved by the following steps and Table 4 shows the reservoir operation plan in three scenarios:

1. Water shortage rate was used to transform human needs into a non-dimensional object;
2. Month was set to the time variable;
3. Set state variable;
4. Set decision variable;
5. Develop a water balance equation;
6. Set benefit equation;
7. Get an optimal solution;
8. Repeat the steps from (2) to (7) for different water shortage rates.

Table 4 Reservoir operation plans in three scenarios
<table>
<thead>
<tr>
<th>Month</th>
<th>Wet year</th>
<th>Normal year</th>
<th>Dry year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Outflow from reservoir (m³/s)</td>
<td>Flow into Baiyangdian Lake (m³/s)</td>
<td>Water level (m)</td>
</tr>
<tr>
<td>1</td>
<td>7.54</td>
<td>5.91</td>
<td>7.6</td>
</tr>
<tr>
<td>2</td>
<td>3.09</td>
<td>2.69</td>
<td>7.6</td>
</tr>
<tr>
<td>3</td>
<td>2.99</td>
<td>2.35</td>
<td>7.61</td>
</tr>
<tr>
<td>4</td>
<td>22.87</td>
<td>1.07</td>
<td>7.61</td>
</tr>
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<td>5</td>
<td>28.19</td>
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<td>7.63</td>
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<td>65.2</td>
<td>52.81</td>
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<td>66.64</td>
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<td>8</td>
<td>87.12</td>
<td>68.29</td>
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<td>9</td>
<td>111.58</td>
<td>72.93</td>
<td>9.26</td>
</tr>
<tr>
<td>10</td>
<td>28.95</td>
<td>5.8</td>
<td>9.24</td>
</tr>
<tr>
<td>11</td>
<td>13.38</td>
<td>10.84</td>
<td>7.54</td>
</tr>
<tr>
<td>12</td>
<td>17.57</td>
<td>13.78</td>
<td>7.58</td>
</tr>
</tbody>
</table>
4. Conclusions

This paper outlines the development of an effective model for sustainable reservoir operations to balance upstream human needs and downstream lake ecosystem targets. Hydrological data, such as water level and water area, can be used to model ecosystem dynamics, which provide ecosystem targets for reservoir optimization models.

The environmental flow assessment model could be developed using only hydrological data, especially in China where limitations on the resources available for monitoring prevent the development or use of more sophisticated models relying on ecosystem data.

Dams constructed in China have brought about the most strongly affected rivers and wetlands with both upstream and downstream effects stemming from inundation, flow manipulation, and fragmentation. Sustainable reservoir operations to balance upstream human needs and downstream lake ecosystem targets are needed. We transformed the multi-objects of reservoir operation into single object and used dynamic programming to optimize reservoir operation rules, which provide water resources management agency with a useful tool.

Future research should investigate whether the environmental assessment model can express ecosystem needs in different time periods that will provide stronger insights into the seasonal changes of the lake. Public participation, the most important step to design feasible reservoir operation rules, should be involved in sustainable reservoir operations.

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