Front. Earth Sci. 2015, 9(3): 546–554
DOI 10.1007/s11707-014-0470-7

RESEARCH ARTICLE

An optimal hydropower contract load determination method considering both human and riverine ecosystem needs

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Abstract In this research, a new method is developed to determine the optimal contract load for a hydropower reservoir, which is achieved by incorporating environmental flows into the determination process to increase hydropower revenues, while mitigating the negative impacts of hydropower generation on riverine ecosystems. In this method, the degree of natural flow regime alteration is adopted as a constraint of hydropower generation to protect riverine ecosystems, and the maximization of mean annual revenue is set as the optimization objective. The contract load in each month and the associated reservoir operating parameters were simultaneously optimized by a genetic algorithm. The proposed method was applied to China's Wangkuai Reservoir to test its effectiveness. The new method offers two advantages over traditional studies. First, it takes into account both the economic benefits and the ecological needs of riverine systems, rather than only the economic benefits, as in previous methods. Second, although many measures have been established to mitigate the negative ecological impacts of hydropower generation, few have been applied to the hydropower planning stage. Thus, since the contract load is an important planning parameter for hydropower generation, influencing both economic benefits and riverine ecosystem protection, this new method could provide guidelines for the establishment of river protection measures at the hydropower planning stage.

Keywords hydropower, electricity supply load, reservoir operation, river protection

1 Introduction

More than one quarter of the world's population (about 1.6 billion people) have no access to electricity in their homes, and about 2.4 billion people still rely on traditional biomass fuels for their daily energy needs (Rehfuess et al., 2006). If the poverty-reduction target in the United Nations Millennium Development Goal is to be met, modern energy services will need to be provided to an additional 700 million people by 2015 (IEA, 2003). At the same time, concerns about the detrimental effects of fossil-fuel use require looking to renewable sources to fill this shortfall. Hydropower is by far the most important type of renewable energy, as it generates approximately 17% of global electricity (Yüksel, 2007; Cai et al., 2009, 2011). Moreover, with the reduction of coal use, hydropower will maintain, or even extend, its significance in future electricity production. Hence, a number of studies have been conducted on how to increase the generation of hydropower (Li et al., 2009; Liu et al., 2011; Ferreira and Teegavarapu, 2012; Hänggi and Weingartner, 2012).

Alternatively, hydropower generation can lead to many adverse ecological impacts on riverine ecosystems, in many cases extending for hundreds of kilometers below a dam (Richter and Thomas, 2007). One major reason for these negative impacts is the alteration of the natural flow regime, which is considered the major driver of ecological processes in rivers (Walker and Thoms, 1993; Kingsford, 2000; Poff et al., 2010). Natural flow regime alteration can cause a sequence of ecological consequences, including 1) habitat loss from river channels and floodplains; 2) desynchronization of natural flow variability and life-cycle strategies of aquatic species; 3) loss of lateral and longitudinal hydrological connectivity, especially seasonal linkages within the drainage network and channel-floodplain systems; and 4) invasion of exotic and introduced species into river systems (Bunn and Arthington, 2002).

Hydropower generation will inevitably lead to changes in the natural flow regime. The concept of environmental flows (e-flows) has been advanced as a way to balance human and ecosystem needs. E-flows are defined as the volume of water that should remain in a river to maintain

Received November 28, 2013; accepted May 3, 2014

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specific indicators of ecosystem health (King et al., 2003). Sustaining e-flows has become one key approach to mitigating the negative impacts of reservoirs and hydropower generation (Renöfält et al., 2010).

A range of methods has been proposed to better sustain e-flows in rivers. Some research has focused on sustaining e-flows by assigning an extra constraint on minimum reservoir releases (Jager and Smith, 2008; Chang et al., 2010). Other research has sought to make more radical changes to reservoir operating rules. Suen and Eheart (2006) set the minimization of natural hydrological alteration as one optimization objective and applied the non-dominated-sorting genetic algorithm to determine the Pareto-optimal set of operating rules. Yin et al. (2010, 2011, 2012) proposed basic, acceptable, preferred, and combined e-flow management strategies to better satisfy the e-flow requirements of rivers. While all of these methods are valuable approaches for satisfying e-flow requirements, they focus mainly on hydropower generation. The hydropower planning stage, however, can also influence the water supply for e-flows, yet few methods have been established to better manage e-flows at the planning stage.

Contract load is one of the most important planning parameters for hydropower generation. In the electricity market, producers are faced with the risk of unknown electricity demand and prices. To avoid revenue risks, hydropower producers and grid companies prefer to make long-term or mid-term (usually one-year) electricity supply contracts, while much of the previous research has been based on adopting short-term bidding for potentially higher revenues. The electricity supply load is a major factor in these contracts. The contract load determines the monthly water releases from reservoirs, which in turn influences the health of riverine ecosystems. In academic research, many methods have been developed to determine the contract and bidding loads by adopting a range of mathematical methods or theories, such as stochastic programming, stochastic dual dynamic programming, and portfolio selection theory (Rotting and Gjelsvik, 1992; Carrion et al., 2007; Feng et al., 2007). These studies emphasized the division between contract and bidding loads to maximize total revenue, yet did not take into consideration the ecological protection requirements. In practice, many hydropower producers tend to assign all the produced electricity into contracts with grid companies to avoid risk. They use the flow data of a long time series or a typical year to perform electricity generation simulation for determining the guaranteed load under a specified reliability. However, these methods have only considered the power generation, without taking into account the e-flow requirements or the needs of riverine ecosystem protection. The contract load is such a key factor for influencing reservoir operating rules, that even if the rules are refined at the hydropower generation stage, their ecological protection results may not be effective if the contract loads are improperly designed. Research on the optimal contract load of a hydropower reservoir must be conducted in such a manner that both economic benefits and ecological needs are taken into consideration. In other words, environmentally friendly reservoir operating rules should direct the establishment of proper electricity supply contracts.

Thus, e-flow management methods need to be advanced from the hydropower generation stage to the planning stage to improve the effects of e-flow supply and riverine ecosystem protection. The contract load, as an important planning parameter, needs to be determined with consideration of the e-flow supply. In this research, we tried to establish a new method of determining the optimal contract load of a hydropower reservoir, considering both economic benefits and ecological needs, by incorporating e-flows into the planning process. Since reservoir operating rules and riverine ecosystem protection objectives can influence the optimal contract load, these are enumerated in Section 2. The proposed method was applied to the Wangkuai Reservoir in China to test its effectiveness.

2 Methods

2.1 Reservoir operating rules

Reservoir operating rule curves (RORCs) are commonly used to direct mid- or long-term hydropower generation in the real world, especially in China, where an official document — the "*Specifications for reservoir operation for large- and medium-scale hydropower stations*", issued by the State Bureau of Quality and Technical Supervision in 1998, clearly required hydropower reservoirs to draw up RORCs, including flow regulations, and to design operating rules based on the relationship between the reservoir water level and the RORCs. The specifications also require the RORCs to divide the reservoir space into zones, such as load-guaranteed, load-increased, load-decreased, etc. (SBQTS, 1998). Therefore, in this research, we adopted the RORC guidelines as the basis for designing reservoir operating rules for hydropower generation.

We adopted the M-5 type of RORC for this research since it is one of the most widely used (Chen, 2003; Chang et al., 2005; Chen et al., 2007; Yin et al., 2010). The RORCs include three types of curves (Fig. 1): upper-, lower-, and critical-limit (Yin and Yang, 2011). Each curve can be described by six variables: two that describe the high and low storage level zones (X_1 and X_2 for the lower-limit curve, and X_3 and X_4 for the critical-limit curve), and four that describe the initial and final times of the linear transition zones between the high and low storage levels (T_1, T_2, T_3, and T_4 for the lower-limit curve, and T_5, T_6, T_7, and T_8 for the critical-limit curve). To maintain the flood control function of a hydropower reservoir, the upper limit curve, already determined during the reservoir design stage

by means of simulations, was not changed in the present study (Chen, 2003; Chen et al., 2007), while the parameters X_i (i = 1, 2, 3, 4) and T_j (j = 1, 2, …, 8) for the lower- and critical-limit curves were to be optimized (Yin et al., 2010).

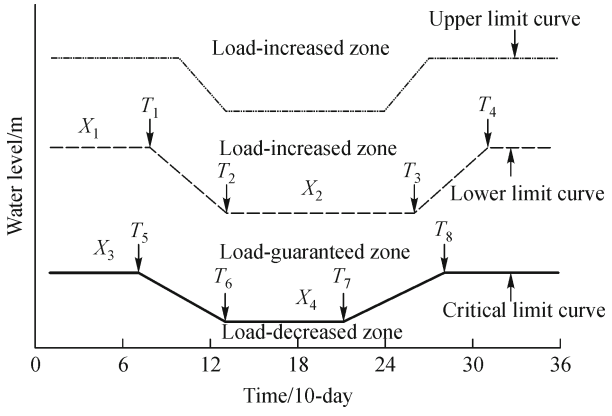

Fig. 1 Reservoir operating rule curves for hydropower generation.

Based on the RORCs, the principle guiding the development of reservoir operating rules is to decrease or increase power generation by some specified ratebased on the relationship between the existing water level and the rule curves (Chen, 2003; Chang et al., 2005; Chen et al., 2007; Tu et al., 2008). Although it is widely acknowledged that flow magnitude, frequency, timing, duration, and rate of change are all significant in controlling riverine ecosystems, it is very difficult to maintain the characteristics of these parameters in real-world reservoir operations because of the complexity of reservoir operating rules, the conflict between human and ecosystem needs, and the uncertainty of the relationship between these parameters and riverine ecosystem health (Arthington et al., 2006; Chang et al., 2010). A more practical method for e-flow management is the provision of seasonal or monthly minimum e-flows (Chang et al., 2010). In the previous work by Yin et al. (2010), a regulated minimum e-flow release (RMEFR) policy was designed for e-flow provision, prescribing the minimum flow that must be released into the downstream river to provide the necessary e-flow each month. The RMEFR was required to be no less than the minimum e-flow for each month. A variety of approaches can be used to assess the minimum monthly e-flows, such as the Tennant method, the wet perimeter method, and the PHABSIM method (Tennant, 1976; Gippel and Stewardson, 1998; Spence and Hickley, 2000). Operating rules suitable for the reservoirs whose functions include flood control and power generation were then established as follows::

• When the water level reaches its maximum limit, water is released, and the actual power load should be increased to the maximum possible. If the actual flow released into the downstream river is less than the RMEFR, additional water is released to meet the RMEFR requirement.

• When the water level is between the maximum and minimum limits, the actual power load can be increased by α percent over the contract load, subject to the maximum possible load. If the actual flow release into the downstream river is less than the RMEFR, additional water needs to be released to satisfy the RMEFR requirement.

• When the water level is between minimum and critical limits, the contract load needs be maintained. If the actual flow release into the downstream river is less than the RMEFR, additional water releases will be required.

• When the water level is between the critical limit and the dead storage level, the actual load is reduced by β percent. Water is also released to meet the RMEFR requirements.

• When the water level is below the dead storage level, all water releases are stopped.

The rates, α and β percent ($0 < \alpha < 100$, $0 < \beta < 100$), are empirically determined by the reservoir managers.

2.2 Ecosystem needs

The instream flow regime is a key driving force for river ecosystems. The more serious the hydrological alteration of the natural flow regime, the worse the condition of the riverine ecosystem (Poff et al., 1997, 2010). In addition to satisfying RMEFR requirements, hydropower generation should also reduce the alteration of the natural flow regime.

The annual proportional flow deviation (APFD) was found to be correlated with fish species diversity in four regulated rivers of the Murray-Darling Basin (Gehrke et al., 1995). Greater flow modification was associated with reduced diversity of fish species. Thus, this index could be used to indirectly reflect the change in fish diversity by the measurement of flow regime alteration. Due to the computational instability of APFD when the natural flow for a month approached zero, the authors developed an amended indicator, AAPFD (Ladson and White, 1999):

$$\mathrm{AAPFD} = \frac{1}{m}\sum_{j=1}^{m}\left[\sum_{k=1}^{12}\left(\frac{C_{kj}-N_{kj}}{\overline{N_j}}\right)^2\right]^{0.5}, \qquad (1)$$

where m is the year number of the flow time series; C_{kj} is the actual flow for month k of year j; N_{kj} is the natural flow for month k of year j; and $\overline{N_j}$ is the average monthly flow for year j.

AAPFD has high sensitivity to significant alteration in the flow regime and an ecological basis; thus, Australia's Department of Natural Resources and Environment uses it as a major indicator for stream conditions (Ladson and White, 1999). In this study, AAPFD was also adopted to reflect the degree of hydrological alteration. The lower the value of AAPFD, the less serious the hydrological alteration and the better the condition of the river

ecosystem. An AAPFD greater than 5 indicates serious impacts on the river ecosystem (Ladson and White, 1999). In order to maintain an acceptably healthy condition of a river ecosystem, reservoir releases should ensure that the AAPFD remains below 5.

In addition to AAPFD, many other methods have been developed to measure the degree of flow regime alteration, such as the Range of Variability Approach (RVA), which is based on daily discharges (Richter et al., 1996, 1997, 1998). The daily-discharge-based methods can be more precise than the AAPFD in measuring the alteration of the flow regime. However, in this research, RVA, as well as other daily-discharge-based methods, was not adopted because it is difficult to explain, and because the scientific relationship between the ecological degradation degree and the flow regime alteration degree measured by RVA has not been adequately proven (Poff and Zimmerman, 2009).

2.3 Overall objective functions

The actual electricity produced by a hydropower reservoir is related to many factors, such as the turbine release water discharge for power generation, the water head, and the coefficient of power generation from the hydropower station. The equations for hydropower generation have been given in much of the published literature (e.g., Cheng et al., 2008; Li et al., 2009; Liu et al., 2011), and thus are not listed in the present study.

The hydropower producers would like to supply electricity at or above the contract load. If extra loads could be produced, the excess electricity could be sold in the market; whereas if the produced load is less than the contract load, the producer must either compensate the grid company or buy electricity in the market to fulfill the contract. The goal for reservoir operation is to maximize the mean annual revenue of hydropower generation, subject to the specified degree of flow regime alteration.

$$L = \max\left\{\frac{1}{m}\sum_{j=1}^{m}\sum_{k=1}^{12}[PC_{kj}EC_{kj} + f(ER_{kj} - EC_{kj})]T_{kj}\right\}, \tag{2}$$

$$f(ER_{kj} - EC_{kj}) = \begin{cases} PR_{kj}(ER_{kj} - EC_{kj}), \text{ if } ER_{kj} > EC_{kj} \\ PM_{kj}(ER_{kj} - EC_{kj}), \text{ if } ER_{kj} < EC_{kj} \end{cases}, \tag{3}$$

subject to

$$\text{AAPFD} \leqslant \text{AAPFD}_0, \tag{4}$$

where L denotes the overall optimization objective; PC_{kj} is the contract on-grid power tariff for month k of year j; EC_{kj} is the contract load for month k of year j; ER_{kj} is the real load produced by a reservoir for month k of year j; T_{kj} is the number of hours for month k of year j; PR_{kj} is the price of over-produced electricity for month k of year j, which is assumed to be the lowest on-grid power tariff in the electricity system, to ensure that the over-produced electricity of a reservoir can be sold in the market defined in this research; and PM_{kj} is the electricity penalty for not fulfilling a contract, or the retail electricity price for month k of year j, which is assumed to be the highest retail electricity price in the electricity system, to ensure that enough electricity can be bought in the market to compensate for the unfulfilled load. AAPFD is the actual flow regime alteration degree under the given contract load and reservoir operating parameters; and AAPFD_0 is the specified threshold of flow regime alteration degree.

2.4 Constraints

In this study, the decision variables were EC_k (k = 1, 2, …, 12), the contract load in each month; X_i (i = 1, 2, 3, 4), T_j (j = 1, 2, … , 8), the parameters of reservoir operating rule curves in Fig. 1; and E_k (k = 1, 2, …, 12), the RMEFR from the reservoir in each month. The constraints for X_i and T_j were as follows (Chen, 2003):

$$\text{MAX}_{\text{level}} > X_1 > X_2, \tag{5}$$

$$\text{MAX}_{\text{level}} > X_1 > X_3, \tag{6}$$

$$X_2 > X_4 > \text{MIN}_{\text{level}}, \tag{7}$$

$$X_3 > X_4 > \text{MIN}_{\text{level}}, \tag{8}$$

$$1 \leqslant T_1 < T_2 < T_3 < T_4 < 36, \tag{9}$$

$$1 \leqslant T_5 < T_6 < T_7 < T_8 \leqslant 36. \tag{10}$$

The constraint for E_k (Yin et al., 2010) is

$$E_k \geqslant \text{MEFR}_k. \tag{11}$$

The constraint for EC_k is

$$0 \leqslant EC_k \leqslant \text{MAX}_{\text{load}}, \tag{12}$$

where $\text{MAX}_{\text{level}}$ is the maximum allowable storage level; $\text{MIN}_{\text{level}}$ is the minimum admissible storage level; MEFR_k is the minimum e-flow requirement for month k; and MAX_{load} is the maximum possible load of a hydropower reservoir.

2.5 Solution method

The Adaptive Genetic Algorithm (AGA) is an efficient method for identifying the optimal values of variables (Srinivas and Patnaik, 1994). In AGA, the probabilities of crossover and mutation are changed based on the fitness values of the solutions. Solutions with below-average

fitness are totally eliminated, while solutions with high fitness are protected. For most nontrivial multimodal functions, the AGA converges to the global optimum more quickly than the standard genetic algorithm does, and is less likely to converge to an optimum that is only local. AGA is effective at maintaining diversity in the population of solutions, can search the entire space, and sustains the convergence capacity of the genetic algorithm. Thus, AGA was used in this research to find the optimal values of variables X_i (i = 1, 2, 3, 4), T_j (j = 1, 2, … , 8), E_k (k = 1, 2, …, 12) and EC_k (k = 1, 2, …, 12). The population form in this study is [X_1,…,X_4, T_1,…,T_8, E_1,…,E_{12}, EC_1,…,EC_{12}]. Details of AGA can be found in Srinivas and Patnaik (1994).

3 Study site

The Wangkuai Reservoir is a major hydraulic facility located on the Sha River in the Hai River basin of China (Fig. 2). Its present effective storage capacity is 6.52×10^8 m^3, and its dead storage capacity is 0.88×10^8 m^3. The reservoir's catchment area is 3,770 km^2. In this research, we focused on the Wangkuai Reservoir's functions of hydropower generation and flood control, and did not consider the water supply function. The inflow data from 1971 to 1993 and the reservoir's physical characteristics data were used to simulate the hydropower generation and optimize the contract loads and reservoir operating parameters. The standard deviation, and coefficients of variation and of skewness of annual inflows were 43.07 m^3/s, 2.39, and 7.08, respectively. The reservoir's installed hydropower generation capacity is 21.5 MW. There are over 200 phytoplankton species in the Sha River, with Bacillariophyceae as the key phylum, over 90 zooplankton species, and approximaely 20 benthos species. Over 20 fish species, with the smaller-sized as the dominant species, can be found in this river. *Pseudorasbora parva* is the dominant fish species in the sand-bed river segment, while loaches are dominant in the silt-bed river segment.

Electricity is a necessity of life. In China, its on-grid tariff and retail price are largely determined by the government. The producer on-grid power tariff differs depending on the electricity type, amount, etc. In addition, the consumer retail price index for electricity varies depending on the consumer type, time of use, etc. According to the formal document by the Hebei Province Municipal Price Bureau, the on-grid power tariff of the Wangkuai Reservoir is 0.36 CNY/kWh (HPMPB, 2009). To ensure that the excess electricity produced by the reservoir can be sold in the market, its price was assumed to be the lowest on-grid power tariff in the electrical system, as determined by HPMPB, i.e., 0.31 CNY/kWh. Furthermore, to ensure the reservoir can buy enough electricity to compensate for the unfulfilled load, the price is set at the highest approved retail price in the system, i.e., 1.19 CNY/kWh.

The Tennant method (Tennant, 1976) is most commonly recommended for e-flow assessment in the "technical guidelines for environmental impact assessment for ecological water usage, low-temperature water, and fish habitat facilities in the hydraulics projects" by the State Environmental Protection Administration of China (2006), and was applied by the Haihe Water Commission (2008) for the Hai River basin. Thus, the Tennant method was also adopted in this research for a preliminary determination of e-flows. Accordingly, the wet season e-flow was set at 30% of average daily flow (ADF), and the dry season e-flow was set at 10% ADF. In this research, AAPFD was adopted to measure the degree of flow regime alteration. However, due to the limitation of insufficient long-term ecological data, we have been unable to test the suitability of the AAFPD method for flow regime alteration assessment in this case.

4 Results and discussion

Here, we assumed that $\alpha = 20$ and $\beta = 10$ (Chang et al., 2005; Chen et al., 2007). According to the Tennant method (Tennant, 1976), the base flow (10% average daily flow) for the dry season (from November to April) was 1.8 m^3/s, whereas for the wet season (from May to October, 30% average daily flow), it was 5.4 m^3/s.

Matlab 6.5 was used to apply AGA to determine the optimal parameters in reservoir operating rule curves, the RMEFR, and the contract load in each month. The AAPFD was set to no more than 5. The generation size and evolution times were set at 600 and 800, respectively. The optimization objective value became constant after about 600 iterations, indicating that the approximate optimal values had been achieved (Fig. 3). The optimized mean annual revenue was 9.76×10^6 CNY. The optimized reservoir operating rule curves are shown in Fig. 4. These show that the optimized critical limit curve was very low, close to the reservoir dead storage level (178 m), while the lower-limit curve was high, approaching the upper-limit curve. As a result, the load-guaranteed zone (see Fig. 1) covers the majority of the reservoir space, ensuring that the planned hydropower load could be maintained for a high proportion of the operating periods.

It was interesting to note that the optimized RMEFR in each month was the same as the minimum e-flow determined by the Tennant method, even though the RMEFR was allowed to be greater than the minimum e-flow in this research. When we set the AAPFD threshold to 5 and tried to maximize the mean annual revenue, the actual AAPFD value was only 3.9. These results meant that setting the RMEFR at the minimum e-flow could already guarantee the overall alteration of the flow regime

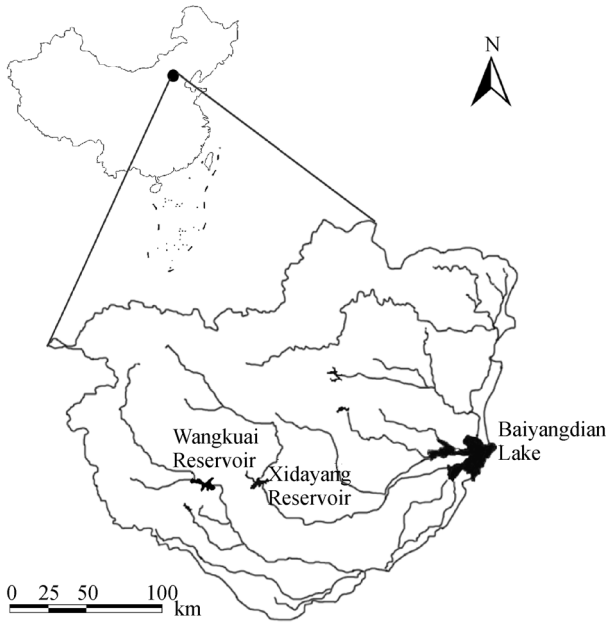

Fig. 2 Location of the Wangkuai Reservoir.

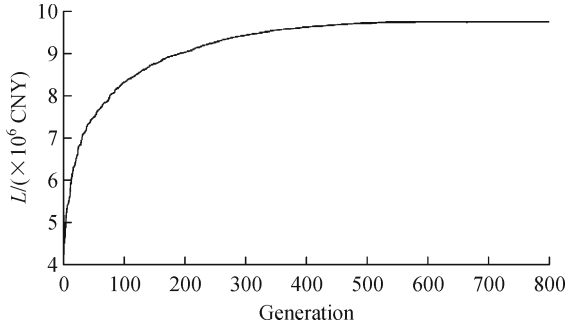

Fig. 3 Optimal results of each generation in the adaptive genetic algorithm.

within the acceptable threshold and thus avoid severe degradation of riverine ecosystems.

The optimized contract load for each month is listed in Table 1. Obviously, the optimized loads in the wet season are greater than those in the dry season, because the inflows in the wet season are greater than those in the dry season, while the on-grid power tariff was the same every month. Even so, an uneven monthly electricity production would lead to an electricity shortage in the dry seasons. Many countries and regions are currently in the process of designing different on-grid power tariffs for the dry, normal, and wet seasons; the tariff is lowest during the wet season and highest during the dry season. This measure will help to decrease electricity production in the wet season and increase it in the dry season, thus mitigating seasonal electricity shortages.

The current releases from Wangkuai Reservoir are determined by administrative orders from the government rather than by optimized operating rules. Here, the historical flow releases to downstream rivers were considered as the benchmark scenario, with all releases assumed to be used for power generation. Based on the contract tariff between the Wangkuai Reservoir and the grid company, the on-grid power tariff was set at 0.36 CNY/kwh. Under the benchmark scenario, mean annual revenue is 6.76×10^6 CNY, and the corresponding AAPFD value is 5.78. Thus, the performances of both revenue (9.76×10^6 CNY) and e-flow provision (AAPFD = 3.9) under the proposed method are better than those under the benchmark scenario. The poor performance under the benchmark scenario can be attributed to the following: 1) The historical reservoir releases cannot always meet the requirements of minimum e-flows; and 2) the previous water release scheme considered the needs of water supply, irrigation, etc., in addition to power generation.

4.1 The influence of a specified flow regime alteration degree on hydropower generation

In this research, the AAPFD value of 5 was set as the threshold for the flow regime alteration degree, following the prescription of Australia's Department of Natural Resources (Ladson and White, 1999). However, in real-world hydropower generation, hydropower producers may set the AAPFD threshold at other values depending on the ecological significance of particular rivers. It is therefore necessary to examine the influence of a specified flow regime alteration degree on hydropower generation.

We used MATLAB 6.5 to run AGA to determine the minimum and maximum degrees of flow regime alteration, which turned out to be 1.46 and 6.62, respectively. We further determined the maximum mean annual revenues obtained under the different AAPFD thresholds, as shown in Fig. 4. It can be seen here that while the specified threshold for AAPFD increased from 3.9 to 6.62, the mean annual revenue did not actually change. As it turns out, the actual AAPFD value remained constant at 3.9, even though the flow regime alteration varied. Furthermore, even though the mean annual revenue increased while the specified threshold for AAPFD rose from 1.46 to 3.9, the margin of revenue increase fell. For example, as the AAPFD threshold increased from 1.49 to 2, the mean annual revenue increase was 3.96×10^6 CNY (from 2.08 to 6.04×10^6 CNY), while as the AAPFD threshold increased from 3.5 to 3.9, the increase of the mean annual revenue was only 0.35×10^6 CNY (from 9.43 to 9.78×10^6 CNY). These results indicate that when the flow regime alteration is relatively high (e.g., AAPFD = 3.9), reducing the hydrological alteration degree in order to promote better riverine ecosystem conditions will lead to little revenue loss, making river protection economically feasible and compatible with hydropower production. Conversely, if the flow regime alteration degree is already low (e.g., AAPFD = 2), an attempt to further reduce the flow regime

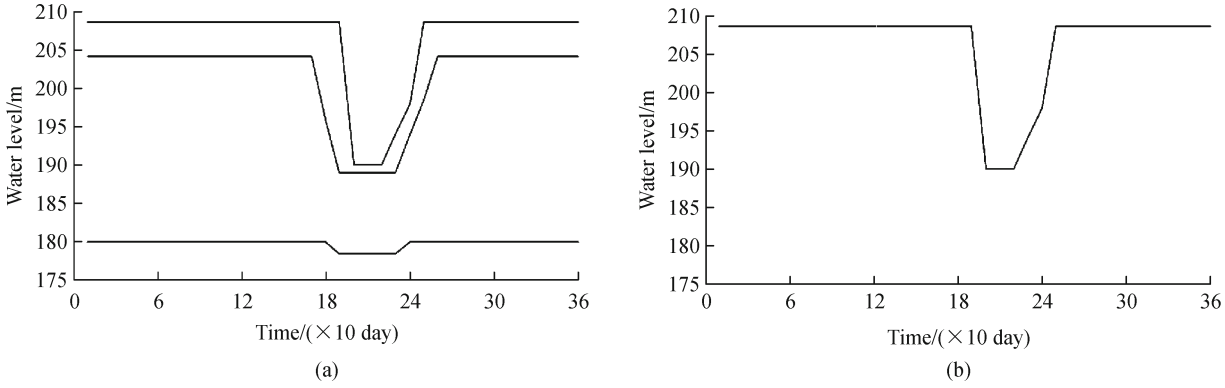

Fig. 4 Optimal and conventional reservoir operating rule curves of the Wangkuai Reservoir: (a) optimal reservoir operating rule curves; (b) conventional reservoir operating rule curves.

Table 1 Optimized load for the Wangkuai reservoir in each month

Month	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Load/MW	0.44	0.32	0.57	0.57	1.09	1.15	1.38	1.50	1.48	1.11	0.32	0.34

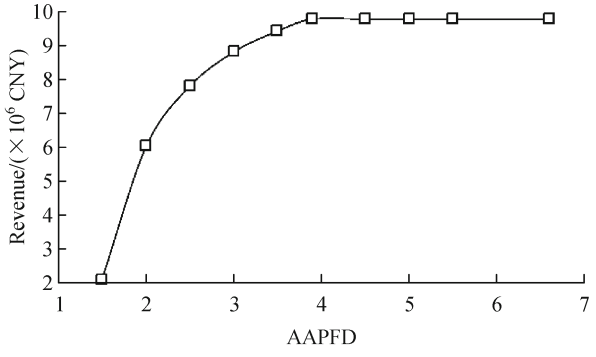

Fig. 5 Mean annual revenues under different AAPFD threshold values.

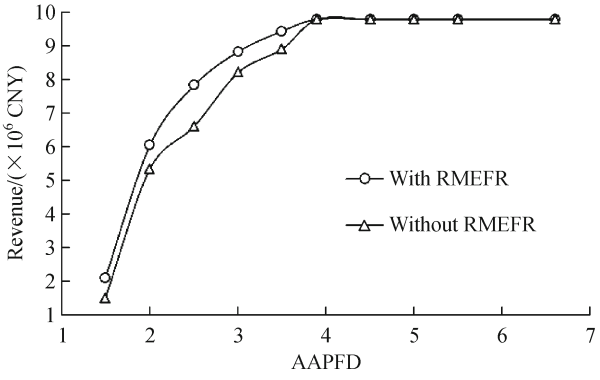

Fig. 6 Mean annual revenues with and without RMEFR policy.

alteration may be economically unacceptable due to the high economic loss.

4.2 The effect of RMEFR policy on hydropower generation

In this research, we proposed that the regulatory minimum e-flow release should be no less than the minimum e-flow (RMEFR policy), while in many similar studies, RMEFR was set equal to the minimum e-flow (Jager and Smith, 2008). Here, we further examined the significance of the RMEFR policy by comparing the mean annual revenues with and without the RMEFR policy under different specified AAPFD threshold values. Again, the AGA was used. The results are shown in Fig. 6.

When the specified AAPFD threshold was relatively high (i.e., $\geqslant 3.9$), the mean annual revenue with the RMEFR policy was the same as that without the policy, because in these situations, the RMEFR values were equal to the minimum e-flows under the two policy scenarios. Alternatively, when the specified AAPFD threshold was low (i.e., < 3.9), the mean annual revenue with the RMEFR policy was better than without the policy. Overall, the mean annual revenue with the RMEFR policy was at least equal to the revenue without the RMEFR policy. Intuitively, we might expect that greater e-flows will lead to lower revenues. In fact, in this research, hydropower generation was restricted only by the degree of flow regime alteration, and the target flow regime alteration degree would be easier to achieve with the help of the RMEFR policy than it would by simply modifying the planned power loads and RORCs. Thus, we suggest that the RMEFR not be tied to the minimum e-flow, but rather be modified based on the specified flow regime alteration degree and planned loads, even though the specified degree of flow regime alteration can be achieved by modifying the planned power loads and RORCs.

5 Conclusions

In this research, a new method was developed to determine the optimal contract load for a hydropower reservoir to

increase hydropower revenues and mitigate the negative impacts of hydropower generation on riverine ecosystems. The following conclusions were reached.

• This method considered both the economic benefits and the ecological needs by incorporating environmental flows into the contract load determination process rather than looking at only the economic benefits, as previous methods have done. Also, the research focused on river protection measures at the hydropower planning stage, an approach seldom used before.

• It would be better to determine the mean annual revenues under several different flow regime alteration degrees rather than only under the maximum acceptable alteration degree. Based on the curve of revenue-alteration degree, the hydropower producers and the river protectors may find a proper hydrological alteration degree that will lead to insignificant revenue loss, but much lower hydrological alteration degree. The method developed in this research offers a tool for making this analysis in order to better balance human and ecosystem needs. In addition, we have suggested that the regulatory minimum e-flows be set higher than the minimum e-flow requirement which could possibly achieve the specified flow regime maintenance target and even increase revenues.

• The method proposed in this research is only suitable for a reservoir with the major functions of power generation and flood control. Other reservoir functions, such as water supply, irrigation, and navigation, were not considered. Methods of simultaneously dealing with these additional requirements are subjects for future research.

Acknowledgements We thank the International Science & Technology Cooperation Program of China (No. 2011DFA72420), the National Basic Research Program of China (No. 2013CB430402), Huoyingdong Education Fund (No. 142023), and the National Natural Science Foundation of China (Grant No. 51309012) and the Fundamental Research Funds for their financial support.

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