

Portfolio optimisation for hydropower producers that balances riverine ecosystem protection and producer needs

X. A Yin, Z. F. Yang and C. L. Liu

{State Key Laboratory of Water Environmental Simulation, School of Environment, Beijing Normal University, Beijing, China}

Correspondence to: Z. F. Yang (zfyang@bnu.edu.cn)

ABSTRACT

In deregulated electricity markets, hydropower portfolio design has become an essential task for producers. The previous research on hydropower portfolio optimisation focused mainly on the maximisation of profits but did not take into account riverine ecosystem protection. Although profit maximisation is the major objective for producers in deregulated markets, protection of riverine ecosystems must be incorporated into the process of hydropower portfolio optimisation, especially against a background of increasing attention to environmental protection and stronger opposition to hydropower generation. This research seeks mainly to remind hydropower producers of the requirement of river protection when they design portfolios and help shift portfolio optimisation from economically oriented to ecologically friendly. We establish a framework to determine the optimal portfolio for a hydropower reservoir, accounting for both economic benefits and ecological needs. In this framework, the degree of natural flow regime alteration is adopted as a constraint on hydropower generation to protect riverine ecosystems, and the maximisation of mean annual revenue is set as the optimisation objective. The electricity volumes assigned in different electricity sub-markets are optimised by the noisy genetic algorithm. The proposed framework is applied to China's Wangkuai Reservoir to test its effectiveness. The results show that the new framework could help to design eco-friendly portfolios that can ensure a planned profit and reduce alteration of the natural flow regime.

1 INTRODUCTION

2 Since the global electricity reform process began in the 1980s (Zelner et al., 2009; Wang and
3 Chen, 2012), and especially after the 1990s, market-oriented reforms in the electric power
4 industry were implemented in many countries to allocate electricity more efficiently through
5 market mechanisms (Cai et al., 2009, 2011; Williams and Dubash, 2004; Tsai, 2011; Wu, 2012).
6 In the process of reform, vertically integrated electricity utilities were restructured and
7 unbundled, and competition has been introduced into generation as well as the wholesale and
8 retail segments of the industry (Pollitt, 2009; Holmberg, 2011; Mulder, 2011). In deregulated
9 markets, hydropower producers usually own generation resources and are allowed to participate
10 in any sub-markets such as bilateral contract and spot markets (Karandikar et al., 2010; Ramos et
11 al., 2010). Maximising profits is usually their sole objective for participating in the market (Liu
12 et al., 2009). To maximise profits, hydropower producers need to devise their own strategies for
13 portfolio design (Shen and Yang, 2012).

14 Extensive research has been performed to optimise hydropower portfolios. Bjørgan et al. (1999)
15 integrated the optimisation of future contract and power scheduling based on risk management in
16 a static mean-variance framework, and the efficient frontier was used as a tool to identify a
17 preferred contract portfolio. Using a continuous-time framework, Keppo (2002) proposed a
18 model for optimal long-term electricity trading strategies and the associated production process
19 by maximising production and terminal water reservoir level in the case of multi-reservoir
20 hydropower systems. Fleten et al. (2002) used a four-stage stochastic programming model with
21 256 scenarios for simultaneous risk management via contracts and hydropower generation
22 planning on a 1.5-year horizon. Shrestha et al. (2005) presented a portfolio management
23 technique to optimise expected revenue for a hydropower producer, a scenario that utilises tree
24 analysis with corrective recourse actions for probable scenarios. The effect of contract position
25 adjustment is also analysed to minimise revenue variation from the expected values for risk-
26 averse producers. Liu et al. (2009) present a stochastic linear programming framework for
27 hydropower portfolio management with uncertainty in market prices and inflows on medium
28 term, in which the uncertainty was modelled as a scenario tree using the Monte Carlo simulation
29 method, to maximise the expected revenue over the entire scenario tree. These approaches could
30 effectively optimise hydropower portfolios and maximise the total profit of hydropower

1 producers. However, none of the previous research on hydropower portfolio optimisation
2 considered the need to protect riverine ecosystems.

3 The determined portfolios could give two important results: 1) the optimal electricity volume
4 that should be generated for each period (day, week, month, etc.); 2) the optimal allocation of the
5 generated hydropower among different electricity sub-markets. The electricity volume
6 determines the water volume that should be released to the downstream rivers, and in turn
7 determines the degree of flow regime alteration. Flow regime alteration is the major cause of
8 riverine ecosystem degradation (Bunn and Arthington, 2002; Babel et al., 2011; Kern et al., 2012;
9 Bhatt and Khanal, 2012). Due to the difference of electricity price among different sub-markets,
10 the electricity allocation among different sub-markets as well as the total generated electricity
11 volume determines the revenue of hydropower producers. Thus, the determination of
12 hydropower portfolio before hydropower generation is essential for both riverine ecosystem
13 protection and producer needs. Although profit maximisation is the major objective for
14 producers in deregulated markets, the need to reduce flow regime alteration must be incorporated
15 into the process of hydropower portfolio optimisation for riverine ecosystem protection,
16 especially with the background of increasing attention to environmental protection and stronger
17 opposition to hydropower generation (Jager and Smith, 2008; Chen et al., 2012).

18 Many new reservoir operating methods have been proposed to better sustain environmental flows
19 (e-flows, the volume of water that should remain in a river and the variation of this provision
20 over time to maintain specific indicators of ecosystem health) in rivers (Richter, 2010; Shiau and
21 Wu, 2010; Brown and King, 2012). These methods are river protection approaches at the
22 hydropower generation stage. Portfolio determination is a task that occurs before hydropower
23 generation. The designed hydropower portfolio can significantly influence reservoir operation
24 through the influence of planned electricity volume and in turn the water volume released to the
25 downstream rivers (Chen et al., 2012; Yin et al., 2011, 2012). Even if the reservoir operating
26 rules are refined, their ecological protection effects may not be as effective as expected under the
27 conditions of improperly designed portfolios. Meanwhile, the effects of portfolio optimisation on
28 river protection need to be displayed by the influence on hydropower operation. Research on the
29 optimal portfolios must be performed with the consideration of both economic benefits and
30 ecological needs, which can provide the basis for developing eco-friendly reservoir operating
31 rules.

1 This research seeks to remind hydropower producers of the requirement of river protection when
2 they design the portfolios and to help the producers design eco-friendly portfolios. In this work,
3 we extend previous research on hydropower portfolio optimisation and establish a framework to
4 determine the optimal portfolio of a hydropower reservoir, accounting for both economic
5 benefits and ecological needs. This framework may help mitigate the impact of hydropower
6 generation on riverine ecosystems, especially for the situation where the tension between river
7 protection and power generation is very severe.

8 9 **2 METHODS**

10 **2.1 Framework for determining optimal hydropower portfolios for both riverine** 11 **ecosystem and producer needs**

12 **2.1.1 Determining the sub-markets for participation**

13 Sub-markets available for hydropower are not the same for each country in the world. Three
14 common markets are bilateral contract (future), day-ahead, and real-time balancing (Alaywan
15 and Wu, 2002; Kranz et al., 2002). Day-ahead and real-time balancing markets are also called
16 spot markets. Participants in the electricity market face the risks of unknown demand and price
17 (Aggarwal et al., 2009; Eichhorn et al., 2009). To avoid revenue risks, hydropower producers
18 and grid companies like to make long-term or mid-term electricity supply contracts, forming the
19 bilateral contract market (Lin and Wu, 2008). In a bilateral contract, the trading power volume
20 and power price are designed by the power producers and grid companies, and will not change
21 during the contract period. In the day-ahead market, participants submit sell/bid offers for
22 electricity for the following day. These offers consist of a quantity of energy to be sold or
23 purchased and a desired price, where sell offers correspond roughly to each producer's marginal
24 cost of energy production. The system operators then rank sell offers from least to most
25 expensive; the last sell offer required to satisfy day-ahead forecast demand clears the market, and
26 the marginal cost of increasing power supply by one additional megawatt determines the market-
27 clearing energy price. Sellers with offers equal to or below this price then generate revenue equal
28 to their respective bid quantities multiplied by the market-clearing price (Rothwell and Gomez,
29 2003). In the real-time balancing market, system managers coordinate an hourly real-time energy

1 market, which is used to meet real-time electricity demand when it varies relative to day-ahead
2 forecasts. An hourly real-time market clearing price is determined in a manner similar to that of
3 the day-ahead market (i.e., via the ranking of bid/sell offers), and transactions are consummated
4 as necessary to meet real-time demand (Lambert, 2001). The price in the spot market is uncertain,
5 and it could be higher than, lower than or equal to the price in the contract market.

6 The hydropower producers choose the submarkets in which they want to participate. The
7 selection depends to some extent on the risk preferences of the producers (Shrestha et al., 2005;
8 Botterud et al., 2010). Risk-taking producers tend to participate in the spot market for possibly
9 higher profit despite higher risk. Risk-averse producers participate in the bilateral contract
10 market that is more reliable, although extensive research supports short-term bidding for
11 potentially higher revenue. Risk-neutral producers tend to participate in both the bilateral
12 contract and spot markets.

13 **2.1.2 Determining the rules for reducing flow regime alteration**

14 Although sustaining the natural flow regime is a basic principle for river protection and e-flow
15 management (Poff et al., 1997, 2010), hydropower generation will inevitably lead to changes. A
16 possible method to reduce flow regime alteration would be to apply a type of e-flow provision
17 strategy (such as sustaining the minimum e-flows and ensuring several high flow pulses, etc.)
18 and optimise the parameters related to the hydropower portfolio to minimise alteration of the
19 natural flow regime or restrict the degree of alteration to a specified threshold. This method has
20 been applied extensively in research (Black et al., 2005; Richter and Thomas, 2007; Jager and
21 Smith, 2008; Yin et al., 2011, 2012).

22 Reservoir operators can use different e-flow provision strategies depending on their attitude
23 toward riverine ecosystems. Sustaining the minimum e-flow is a commonly used strategy for
24 real-world e-flow provisions. This strategy can provide basic protection of the riverine
25 ecosystem, avoiding severe degradation. To sustain ecological functions related to high flows,
26 some research proposes occasional high-flow releases for habitat improvement (Ligon et al.,
27 1995; Gore et al., 2001; Renofalt et al., 2009). To better protect riverine ecosystems, hydropower
28 operators can develop and apply more sophisticated e-flow strategies.

1 **2.1.3 Setting the portfolio optimisation objectives and constraints**

2 Maximising the total profit for a given planning period and reducing the degree of flow regime
3 alteration are two objectives for hydropower portfolio design. However, the two objectives are in
4 conflict and cannot be achieved simultaneously, which is a typical multi-objective problem. To
5 address this problem, the optimisation objectives need to be set first. An optimisation objective
6 can be set as one of two conflicting objectives, i.e., maximising the overall profit for a given
7 planning period or reducing the degree of alteration of the flow regime. The other objective can
8 be set as one constraint by assigning a threshold accepted by the hydropower producers or river
9 protectors. Alternatively, the two objectives could be integrated into one by some mathematical
10 method such as compromise programming or weighted average.

11 Constraints for portfolio optimisation include maximum power generation capacity, water
12 release capacity, reservoir maximum storage capacity, etc. If either of the two objectives is
13 chosen as a single optimisation objective, the constraints also need to include the threshold for
14 the other objective, i.e., the minimum acceptable overall profit or the maximum acceptable
15 degree of flow regime alteration. The water mass balance also needs to be considered (Liu et al.,
16 2009).

17 **2.1.4 Choosing the solution method under uncertainty**

18 In a deregulated market, portfolio optimisation is faced with the uncertainty of reservoir inflows
19 and spot electricity prices (Fleten et al., 2002). A series of methods has been developed to obtain
20 optimal solutions under uncertainty, such as stochastic dynamic programming, stochastic dual
21 dynamic programming, stochastic programming combined with scenario trees, and noisy genetic
22 algorithms (Chang et al., 2005; Chen, 2003; Chen et al., 2007). The optimisation method needs
23 to address these uncertainties.

24 **2.2 Methods used in the case study**

25 **2.2.1 Range of variability approach**

26 The range of variability approach (RVA) (Richter et al., 1996, 1997, 1998) has been widely used
27 for assessing flow regime alteration and directing hydraulic facility operations (Galat and Lipkin,
28 2000; Shiau and Wu, 2004, 2006, 2007; Zhang et al., 2009). According to the RVA, a range of

1 variation for each hydrological indicator was derived from the natural hydrological time series
2 and was set as the flow management target. A range defined by the 75th and 25th percentile
3 flows has been recommended as the management target (Richter et al., 1998). The degree of
4 alteration, D_m , was used to measure the deviation of the impacted flow regime from the natural
5 one for the m^{th} hydrologic indicator, which was defined by

$$6 \quad D_m = \left| \frac{N_{o,m} - N_{e,m}}{N_{e,m}} \right| \times 100\% \quad (1)$$

7 where $N_{o,m}$ was the observed number of post-impact years in which the value of the m^{th}
8 hydrologic indicator fell within its RVA target range, and $N_{e,m}$ was the expected number of post-
9 impact years in which the indicator value fell within the RVA target range. The average degree of
10 alteration of these hydrologic indicators was applied to quantify the river's overall impact, which
11 can be expressed as follows:

$$12 \quad D = \frac{1}{G} \sum_{m=1}^G D_m \quad (2)$$

13 where D was the overall degree of flow regime alteration, and G was the number of hydrological
14 indicators (G is equal to 32 in this research). The degree of flow regime alteration can be
15 categorised further into three levels: low alterations (values of D between 0 and 0.33), moderate
16 alterations (values of D between 0.33 and 0.67), and high alterations (values of D between 0.67
17 and 1.0) (Richter et al., 1998).

18 **2.2.2 Tennant method**

19 To illustrate the applicability of the proposed approach, we use the Tennant method (Tennant,
20 1976), a simple and widely used method, to determine seasonal minimum e-flows. Tennant
21 method was recommended for e-flow assessment in the “technical guidelines for environmental
22 impact assessment for ecological water usage, low temperature water and fish habitat facilities in
23 the hydraulics projects” by the State Environment Protection Administration of China (2006),
24 and was applied by the Haihe Water Commission (2008) for the Hai River basin. Accordingly,
25 the wet season e-flow was set at 30% of average daily flow (ADF), and the dry season e-flow
26 was set at 10% ADF. More sophisticated methods could be used to replace the Tennant method if
27 enough hydrological, biological, and geomorphological data are available.

2.2.3 Optimisation objectives and constraints

In the following case study, the hydropower producer participates in the contract and day-ahead markets according to the hydropower generation planning. The goal for hydropower portfolio optimisation is to maximise the mean annual revenue subject to specified e-flow management requirements. These requirements include the e-flow provision strategy and the specified threshold for the degree of flow regime alteration. The optimisation problem can be expressed by the following equation

$$L = \max \frac{1}{T} \sum_{j=1}^T \sum_{k=1}^{365} (PC_{kj} \square CL_{kj} + PD_{kj} \square DL_{kj}) \quad (3)$$

$$\text{Subject to: } R_{kj} \geq EF_{kj} \quad (4)$$

$$D \leq D_0 \quad (5)$$

where L denotes the overall optimisation objective, PC_{kj} is the designed hydropower price in the hydropower supply contract for day k of year j (constant within one month, RMB/kwh); CL_{kj} is the designed hydropower volume in the hydropower supply contract for day k of year j (constant within one month, kwh); PD_{kj} is the hydropower price in the day-ahead market for day k of year j (RMB/kwh); DL_{kj} is the bidding volume for power in the day-ahead market for day k of year j (kwh); R_{kj} is the actual reservoir water release for day k of year j ; EF_{kj} is the minimum e-flow for day k of year j ; D is the degree of actual flow regime alteration under a certain portfolio; and D_0 is the specified threshold of degree of flow regime alteration.

In the contract market, the producer and electricity grid make an agreement on the contract load for each month and the associated power price. In the day-ahead market, the producers need to determine the bidding volume for power. In this case, we assume that the producers first use inflow and the water in the reservoir to produce electricity to satisfy the contract load, and the producer will buy electricity from the market to satisfy the contract load only when the available electricity is not sufficient. Because the electricity cannot be stored, the bought electricity is set equal to the difference between the contract volume and the available power volume. We use the following equations to determine the bidding volume of power in the day-ahead market.

$$\text{If } AE_{kj} - CL_{kj} > 0, DL_{kj} = \min [k_{kj}(AE_{kj} - CL_{kj})PD_{kj}, ME - CL_{kj}] \quad (6)$$

$$\text{If } AE_{kj} - CL_{kj} \leq 0, DL_{kj} = AE_{kj} - CL_{kj} \quad (7)$$

1 where AE_{kj} is the available electricity volume that the hydropower plant can generate with the
2 water in the reservoir and inflow for day k of year j (kwh); ME is the maximum electricity
3 production capacity for one day (kwh); and k_{kj} is the parameter for day k of year j (kwh/RMB).

4 In Eq. (6), $k_{kj}(AE_{kj} - CL_{kj})PD_{kj}$ means that the higher the available electricity volume, the
5 higher the day-ahead power price, and the higher the bidding volume for power. There may be
6 some alternative and more sophisticated equations to replace $k_{kj}(AE_{kj} - CL_{kj})P_{kj}$. The equation
7 forms may also influence the revenue of hydropower producers and the effects of riverine
8 ecosystem protection. Further research would be valuable to analyse the influence of equation
9 forms and the optimal forms. The parameters k_{kj} and CL_{kj} are two variables that need to be
10 optimised. We assume k_{kj} and CL_{kj} do not change over the period of one month and are the same
11 for each year. Thus, k_{kj} and CL_{kj} both have 12 values.

12 The real electricity produced by a hydropower reservoir is related to many factors such as the
13 turbine release water discharge for power generation, the water head, and the coefficient of
14 hydropower station power generation. The equations for hydropower generation have been
15 presented extensively in the literature (e.g., Cheng et al., 2008; Li et al., 2009; Liu et al., 2011),
16 and thus are not listed in the present paper.

17 **2.2.4 Noisy genetic algorithm**

18 In hydropower portfolio optimisation, the future inflow and spot price are uncertain. The noisy
19 genetic algorithm (NGA) is an effective method to determine the optimal values of parameters
20 under uncertainty (Miller and Goldberg, 1996). The NGA has been applied for stochastic
21 reservoir operation (Yun et al., 2010), ground water remediation (Aly and Peralta, 1999) and
22 groundwater sampling network design (Wu et al., 2005) under uncertainty. In this research, NGA
23 is applied to optimise the hydropower portfolio under uncertainty of flows and spot price.

24 The term *noise* can be defined as any factor that hinders the accurate evaluation of the fitness of
25 a given trial solution. In this study, noise refers to the stochastic nature of the inflows and the
26 power price in the day-ahead market. Most components in the NGA are the same as in a simple
27 genetic algorithm (GA). The main difference between the NGA and GA is in the fitness function.
28 In the NGA, the fitness value cannot be evaluated accurately because of the variability of
29 monthly inflows. To overcome this difficulty, the fitness value is substituted by the expected

1 fitness value. The details of the NGA can be found in Miller and Goldberg (1996) and Yun et al.
2 (2010).

3

4 **3 STUDY SITE**

5 The Wangkuai Reservoir is a key hydraulic facility in the Hai River basin of China. The present
6 effective storage capacity of the Wangkuai Reservoir is $6.52 \times 10^8 \text{ m}^3$, and the dead storage
7 capacity is $0.88 \times 10^8 \text{ m}^3$. The catchment area of the reservoir is 3770 km^2 . The installed
8 hydropower generation capacity of the Wangkuai Reservoir is 21.5 MW. In this research, we
9 focus on the hydropower generation function of the Wangkuai Reservoir. The inflow data from
10 1971 to 1993 and the physical characteristics are used to simulate hydropower generation and
11 optimise the hydropower portfolio. The producer considered in this paper is a price taker. The
12 hydropower price in the day-ahead market is shown in Table 1 (Liu et al., 2009; Liu, 2009). The
13 bilateral contract price between the Wangkuai Reservoir and the grid company is 0.36 RMB/kwh
14 (Hebei Province Municipal Price Bureau [HPMPB], 2009).

15 In this research, we consider two e-flow provision strategies. In the first e-flow strategy, only the
16 minimum e-flows are sustained. This strategy is most commonly used in real-world e-flow
17 provisions. In the second e-flow strategy, in addition to the minimum e-flows, occasional high-
18 flow (flows falling above the 75th percentile of all flows) releases are required to sustain the
19 ecological functions related to high flows. In this research, we also assume for demonstration
20 that after three high-flow events have occurred in a season, no further high flows are released,
21 following the research by Vogel et al. (2007).

22

23 **4 RESULTS**

24 Matlab 6.5 was used to apply NGA to determine the optimal hydropower portfolio. The
25 generation size and evolution times were set at 600 and 1000, respectively. According to the
26 Tennant method (Tennant, 1976), for the dry season (November to April), the seasonal minimum
27 e-flow (10% average daily flow) was $1.8 \text{ m}^3/\text{s}$ and for the wet season (May to October), the
28 seasonal minimum e-flow (30% average daily flow) was $5.4 \text{ m}^3/\text{s}$. The threshold for the degree
29 of flow regime alteration is set at 0.67, the upper value for moderate alteration of the flow regime

1 (Richter et al., 1996, 1997, 1998).

2 The optimised parameters are listed in Tables 2 and 3. These tables show that, during five of the
3 six months in the wet season, the contract load under the second e-flow provision strategy is
4 higher than the contract load under the first strategy because, under the second e-flow strategy,
5 the reservoir is required to maintain several high flow pulses. The releases of greater flows
6 required by the second e-flow strategy make higher contract loads reasonable. In addition, most
7 (9 of 12) of the values for parameter k under the first e-flow strategy are higher than the values of
8 parameter k under the second e-flow strategy, indicating that more water will be released to
9 produce hydropower for the day-ahead market under the first e-flow strategy than under the
10 second strategy.

11 The optimised mean annual revenues are 8.72×10^6 RMB and 7.55×10^6 RMB under the two e-
12 flow provision strategies. The mean annual revenue under the second strategy is lower than the
13 mean annual revenue under the first strategy, possibly because the extra water releases to
14 maintain the high flows under the second e-flow strategy increase the proportion of electricity
15 assigned in the contract market, reducing the proportion of electricity assigned in the spot market,
16 which sometimes has higher prices than the contract price. Thus, the extra requirement to sustain
17 high flows for river ecosystem protection potentially reduces the profits from hydropower
18 generation.

19 **5 DISCUSSION**

20 **5.1 The influence and significance of incorporating environmental policies in** 21 **portfolio management**

22 In previous research on portfolio optimisation, no specific rules were used for e-flow provision.
23 The e-flows are supplied only by the water released for hydropower generation. This strategy is
24 called non e-flow for short. In the following section, we explore the influence of incorporating
25 environmental policies in portfolio management by comparing revenue and flow regime
26 alteration under the three e-flow strategies (i.e., the non e-flow strategy and the two strategies
27 established in the study site section), possibly helping to test the significance of incorporating
28 environmental policies in portfolio optimisation.

29 We first determine the maximum mean annual revenue (without the constraint of the threshold

1 for flow regime alteration degree) and corresponding degree of flow regime alteration under the
2 three e-flow strategies. Under the three strategies, the maximum revenue and the corresponding
3 degree of alteration are 12.38×10^6 RMB and 0.82 (non e-flow strategy), 10.27×10^6 RMB and
4 0.75 (strategy 1), and 9.37×10^6 RMB and 0.68 (strategy 2). In comparison with the maximum
5 annual revenue under the e-flow strategies 1 and 2 (10.27×10^6 RMB and 9.37×10^6 RMB), the
6 non e-flow portfolio optimisation method achieves higher revenue. However, the degree of flow
7 regime alteration corresponding to this high revenue is 0.82, obviously greater than the degree of
8 alteration under the first and second e-flow provision strategies (0.75 and 0.68). Thus, although
9 the non e-flow portfolio optimisation method could yield higher revenue, it would come at the
10 cost of degradation of the river ecosystem. To avoid severe degradation of riverine ecosystems,
11 incorporation of an e-flow provision strategy into the hydropower portfolio optimisation process
12 is necessary, at least with regard to sustaining the minimum e-flows.

13 The minimum degrees of flow regime alteration are also determined under the three e-flow
14 strategies. The lowest degrees of alteration under the non and the first e-flow strategies are the
15 same (0.31) because under the non e-flow strategy, the releases are also greater than the
16 minimum e-flows in each month to achieve the minimum degree of flow regime alteration, and
17 the contract load and k are the same under the two e-flow strategies. Thus, if reducing the degree
18 of flow regime alteration is taken as the key objective, it is not necessary to incorporate the
19 minimum e-flow requirement as a constraint. The degree of flow regime alteration (0.21,
20 corresponding to the revenue of 3.59×10^6 RMB) under the second e-flow strategy is obviously
21 lower than the degree of flow regime alteration under the other two strategies, demonstrating the
22 significance of assigning some high flows in the e-flow provision rules.

23 We further determine the minimum degree of flow regime alteration corresponding to the mean
24 annual revenues of 9.37×10^6 RMB (the maximum mean annual revenue that all the three
25 strategies can achieve), 3.89×10^6 RMB (the minimum mean annual revenue that all three
26 strategies can achieve), and 6.63×10^6 RMB (the median revenue that all the three strategies can
27 achieve) for the three e-flow provision strategies. The results are listed in Table 4. Table 4 shows
28 that the degree of flow regime alteration under the non e-flow strategy is always greater than the
29 degree of flow regime alteration under the other two strategies, and the degree of alteration under
30 the second strategy is always less than the degree of alteration under the other two strategies.
31 Thus, the incorporation of a specific e-flow strategy can result in a lower degree of flow regime

1 alteration with the same annual revenue. It further demonstrates the importance to incorporate e-
2 flow strategy into portfolio optimization process for a specified revenue.

3 **5.2 Determining the optimal e-flow provision strategy**

4 Different e-flow provision strategies will result in different mean annual revenues and different
5 degrees of flow regime alteration. The basic principles for e-flow strategy determination can be
6 stated as follows: if the planned revenue can be achieved by several e-flow strategies, the
7 strategy that results in the lowest flow regime alteration is chosen. If the planned degree of flow
8 regime alteration can be achieved by several e-flow strategies, the strategy that results in the
9 highest revenue should be chosen. On the basis of these principles, we have drawn the curves for
10 mean annual revenue and minimum degree of alteration under the three e-flow provision
11 strategies. The results are shown in Fig. 1.

12 On the basis of Fig. 1, the mean annual revenue can be divided into three types of intervals, i.e.,
13 exclusive intervals (the intervals that only one e-flow strategy can achieve), shared intervals (the
14 intervals that more than one type of e-flow strategy can achieve), and unachievable intervals (the
15 intervals that no available e-flow strategy can achieve). From the planned revenue, we can easily
16 know which intervals the planned revenue is within. If the planned revenue is within an
17 exclusive interval, the e-flow strategy corresponding to that interval can be applied in the
18 portfolio optimisation process. If the planned revenue is within a shared interval, the e-flow
19 strategy that results in the lowest degree of flow regime alteration should be applied to maintain
20 the riverine ecosystem. For planned revenue within an unachievable interval, if the revenue is
21 above the highest value for all e-flow strategies, no strategy can achieve a low degree of flow
22 regime alteration in the contract and day-ahead market. The revenue can possibly be achieved by
23 participating in other electricity sub-markets, such as the real-time balancing market (the price in
24 this sub-market can be higher, but the price is more uncertain). If the revenue is below the lowest
25 value for all e-flow strategies, which indicates a very favourable attitude toward river protection,
26 the hydropower producers can apply a more favourable e-flow strategy that could result in a
27 lower degree of flow regime alteration.

28 On the basis of Fig. 1, the degree of flow regime alteration can also be divided into three
29 categories, i.e., exclusive intervals (an interval that only one e-flow strategy can achieve), shared

1 intervals (intervals that more than one type of e-flow strategy can achieve), and unachievable
2 intervals (intervals that no e-flow strategy can achieve). Like the procedure for the mean annual
3 revenue discussed above, the most suitable e-flow provision strategy for a planned degree of
4 flow regime alteration can be determined. If the planned degree of flow regime alteration is
5 within an exclusive interval, the e-flow strategy corresponding to that interval can be applied in
6 the portfolio optimisation process. If the planned degree of alteration is within a shared interval,
7 the e-flow strategy that results in the highest revenue should be adopted. If the planned degree of
8 alteration is within an unachievable interval and is below the lowest value for all strategies, the
9 hydropower producers should develop and apply more favourable e-flow strategies.

10 Choosing an e-flow provision strategy is a process of compromising between hydropower
11 producers and river protectors. The river protectors usually have the authority to ask the
12 hydropower producers to obey some basic rules for riverine ecosystem protection, such as a
13 minimum e-flow release. If the river protectors would like to improve the health of the riverine
14 ecosystem by changing the hydropower generation scheme, a more ecologically favourable e-
15 flow provision strategy should become a legal requirement, or ecological compensation should
16 be given to the hydropower producers. On the basis of Fig. 1, we can make a preliminary
17 assessment of the compensation criteria. For example, if the present legally required e-flow rules
18 are to sustain the minimum e-flows and the river protectors want hydropower producers to use
19 the second e-flow strategy, the compensation criteria should be approximately 0.9×10^6 RMB,
20 i.e., the difference between the maximum possible mean annual revenue under the first ($10.27 \times$
21 10^6 RMB) and second e-flow strategies (9.37×10^6 RMB).

22

23 **6 CONCLUSIONS**

24 Previous research on hydropower portfolio optimisation focused mainly on the maximisation of
25 profits but neglected the requirement of riverine ecosystem protection. This research seeks
26 mainly to remind hydropower producers of the requirement for river protection when they design
27 portfolios and help make a shift of portfolio optimisation from economically oriented to
28 ecologically friendly. In this study, a new framework has been developed to determine optimal
29 hydropower portfolios considering both economic benefits and ecological needs. Within this
30 framework, the degree of flow regime alteration is adopted as a constraint for e-flow provision

1 and riverine ecosystem protection, and the maximisation of mean annual revenue is set as the
2 optimisation objective. The following objectives are achieved.

- 3 • For the same planned mean annual revenue, the alteration in flow regime is lower for
4 portfolios with e-flow provision strategies than for the portfolio without an e-flow strategy. A
5 lower degree of alteration indicates a lower degree of river degradation. If a planned mean
6 annual revenue can be achieved under either an e-flow strategy or a non-e-flow strategy,
7 incorporating the e-flow strategy into the portfolio optimisation process is both economically
8 and ecologically beneficial.
- 9 • The proper e-flow provision strategy depends on the planned revenue and the planned degree
10 of flow regime alteration. If the planned revenue can be achieved by several e-flow strategies,
11 the strategy that results in the lowest flow regime alteration should be chosen. If the planned
12 degree of flow regime alteration can be achieved by several e-flow strategies, the strategy
13 that results in the highest revenue should be chosen.

14
15 In the case study of Wangkuai Reservoir, the contract and day-ahead markets are participated in
16 according to the planned needs of the reservoir. In future research on portfolio optimisation in
17 other cases that account for both riverine ecosystem and producer needs, the real-time balancing
18 market may also be participated in according to the planning needs of these specific cases and
19 the risk preferences of the hydropower producers. In these cases, the proposed framework for
20 portfolio optimisation can also be used. The difficulties are the precise prediction of hydropower
21 price in the real-time balancing market and the assessment of hydrological alteration at hourly
22 time steps, which require further research.

23 24 **ACKNOWLEDGMENTS**

25 We thank the International Science & Technology Cooperation Program of China (No.
26 2011DFA72420), the National Basic Research Program of China (No. 2013CB430402), the
27 National Science Foundation for Innovative Research Group (No. 51121003), and the National
28 Natural Science Foundation of China (No. 51309012) for their financial support.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28

REFERENCES

Aggarwal, S. K., Saini, L. M., and Kumarv, A.: Electricity price forecasting in deregulated markets: a review and evaluation, *Int. J. Electr. Power Energ. Syst. Eng.*, 31, 13–22, doi:10.1016/j.ijepes.2008.09.003, 2009.

Alaywan, Z. and Wu, T.: Effects of Firm Transmission Rights on Transmission Revenue Allocation in California, available at: <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.200.1503&rep=rep1&type=pdf>, last access: 10 December 2013, 2002

Aly, A. A. and Peralta, R. C.: Optimal design of aquifer cleanup systems under uncertainty using a neural network and a genetic algorithm, *Water Resour. Res.*, 35, 2523–2532, doi:10.1029/98WR02368, 1999.

Babel, M. S., Chien, N. D., Mullick, M. A., and Nanduri, U. V.: Operation of a hydropower system considering environmental flow requirements: a case study in La Nga river basin, Vietnam, *J. Hydro-viron. Res.*, 6, 63–73, doi:10.1016/j.jher.2011.05.006, 2011.

Bhatt, R. P. and Khanal, S. N.: A study on change in flow regime and discharge impacts on water quality of hydropower operation, *International Journal of Ecology & Development (IJED)*, 21, 76–88, 2012.

Bjørgan, R., Liu, C. C., and Lawarree, J.: Financial risk management in a competitive electricity market, *IEEEET Power Syst.*, 14, 1285–1291, doi:10.1109/59.801886, 1999.

Black, A. R., Rowan, J. S., Duck, R. W., Bragg, O. M., and Clelland, B. E.: DHRAM: a method for classifying river flow regime alterations for the EC Water Framework Directive, *Aquat.Conserv.*, 15, 427–446, doi:10.1002/aqc.707, 2005.

Botterud, A., Kristiansen, T., and Ilic, M. D.: The relationship between spot and futures prices in the Nord Pool electricity market, *Energ. Econ.*, 32, 967–978, doi:10.1016/j.eneco.2009.11.009, 2010.

Brown, C. and King, J.: Modifying dam operating rules to deliver environmental flows: experiences from southern Africa, *Int. J. River Basin Manag.*, 10, 13–28, doi:10.1080/15715124.2011.639304, 2012.

1 Bunn, S. E. and Arthington, A. H.: Basic principles and ecological consequences of altered flow
2 regimes for aquatic biodiversity, *Environ. Manag.*, 30, 492–507, doi:10.1007/s00267-002-2737-0,
3 2002.

4 Cai, Y. P., Huang, G. H., Yang, Z. F., Lin Q. G., Tan Q. (2009). Community-scale energy
5 management systems design under uncertainty - An interval chance-constrained programming
6 approach, *Renew. Sustain. Energ. Rev.*, 13(4), 721-735.

7 Cai, Y. P., Huang, G. H., Tan, Q., Yang, Z. F. (2011). An integrated approach for climate-change
8 impact analysis and adaptation planning under multi-level uncertainties. Part I: Methodology,
9 *Renew. Sustain. Energ. Rev.*, 15(6), 2779-2790.

10 Chang, F. J., Chen, L., and Chang, L. C.: Optimizing the reservoir operating rule curves by
11 genetic algorithms, *Hydrol. Process.*, 19, 2277–2289, 2005.

12 Chen, L.: Real-coded genetic algorithm optimization of long-term reservoir operation, *J. Am.*
13 *Water Resour. As.*, 39, 1157–1165, 2003.

14 Chen, L., McPhee, J., and Yeh, W. W.: A diversified multiobjective GA for optimizing reservoir
15 rule curves, *Adv. Water Resour.*, 30, 1082–1093, 2007.

16 Chen, Q. W., Chen, D., Li, R. N., Ma, J. F., and Blanckaert, K.: Adapting the operation of two
17 cascaded reservoirs for ecological flow requirement of a de-watered river channel due to
18 diversion-type hydropower stations, *Ecol. Model.*, 252, 266–272, 2013,
19 doi:10.1016/j.ecolmodel.2012.03.008, 2012.

20 Cheng, C. T., Wang, W. C., Xu, D. M., and Chau, K. W.: Optimizing hydropower reservoir
21 operation using hybrid genetic algorithm and chaos, *Water Resour. Manag.*, 22, 895–909,
22 doi:10.1007/s11269-007-9200-1, 2008.

23 Eichhorn, A., Heitsch, H., and Römisch, W.: Scenario tree approximation and risk aversion
24 strategies for stochastic optimization of electricity production and trading, in: *Optimization in the*
25 *Energy Industry*, Springer Berlin Heidelberg, Berlin, Germany, 321–346, 2009.

26 Fleten, S. E., Wallace, S. W., and Ziemba, W. T.: Hedging electricity portfolios via stochastic
27 programming, *IMA V. Math.*, 128, 71–94, 2002.

28 Galat, D. L. and Lipkin, R.: Restoring ecological integrity of great rivers: historical hydrographs
29 aid in defining reference conditions for the Missouri River, *Hydrobiologia*, 422–423, 29–48,

1 doi:10.1023/A:1017052319056, 2000.

2 Gore, J. A., Layzer, J. B., and Mead, J.: Macroinvertebrate instream flow studies after 20 year: a
3 role in stream management and restoration, *Regul. River.*, 17, 527–542, doi:10.1002/rrr.650,
4 2001.

5 Haihe Water Commission: Comprehensive water resources planning for Hai River basin,
6 Ministry of Water Resources of China, Tianjin, 2008.

7 Hebei Province Municipal Price Bureau (HPMPB): Announce for the adjustment of electricity
8 price in Hebei Province, HPMPB, Shijiazhuang, 2009.

9 Holmberg, P.: Strategic forward contracting in the wholesale electricity market, *Energy J.*, 32,
10 169–202, 2011.

11 Jager, H. I. and Smith, B. T.: Sustainable reservoir operation: can we generate hydropower and
12 preserve ecosystem values?, *River Res. Appl.*, 24, 340–352, doi:10.1002/rra.1069, 2008.

13 Karandikar, R. G., Khaparde, S. A., and Kulkarni, S. V.: Strategic evaluation of bilateral contract
14 for electricity retailer in restructured power market, *Int. J. Elec. Power*, 32, 457–463,
15 doi:10.1016/j.ijepes.2009.09.018, 2010.

16 Keppo, J.: Optimality with hydropower system, *IEEEET Power Syst.*, 17, 583–589,
17 doi:10.1109/TPWRS.2002.800898, 2002.

18 Kern, J. D., Characklis, G. W., Doyle, M. W., Blumsack, S., and Whisnant, R. B.: Influence of
19 deregulated electricity markets on hydropower generation and downstream flow regime, *J. Water*
20 *Res. Pl.-ASCE*, 138, 342–355, doi:10.1061/(ASCE)WR.1943-5452.0000183, 2012.

21 Kranz, B., Pike, R., and Hirst, E.: Integrated electricity markets in New York, *The Electricity*
22 *Journal*, 16, 54–65, doi:10.1016/S1040-6190(03)00014-9, 2002.

23 Lambert, R. A.: Contracting theory and accounting, *J. Account. Econ.*, 32, 3–87,
24 doi:10.1016/S0165-4101(01)00037-4, 2001.

25 Li, Y. P., Huang, G. H., and Chen, X.: Multistage scenario-based interval-stochastic programming
26 for planning water resources allocation, *Stoch. Environ. Res. Risk Assess.*, 23, 781–792,
27 doi:10.1007/s00477-008-0258-y, 2009.

28 Ligon, F. K., Dietrich, W. E., and Trush, W. J.: Downstream ecological effects of dams,

1 BioScience, 45, 183–192, doi:10.2307/1312557, 1995.

2 Lin, M. and Wu, F. L.: Trading strategy of generation companies in electricity market,
3 Proceedings of the CSEE, 28, 111–117, 2008.

4 Liu, H. L.: Research on Optimal Hydroelectric Scheduling and Risk Management in Electricity
5 Market, Ph.D. thesis, Shanghai Jiaotong University, Shanghai, 138 pp., 2009.

6 Liu, H. L., Jiang, C. W., and Zhang, Y.: Portfolio management of hydropower producer via
7 stochastic programming, Energ. Convers. Manag., 50, 2593–2599,
8 doi:10.1016/j.enconman.2009.06.010, 2009.

9 Liu, X. Y., Guo, S. L., Liu, P., Chen, L., and Li, X.: Deriving optimal refill rules for multi-
10 purpose reservoir operation, Water Resour. Manag., 25, 431–448, doi:10.1007/s11269-010-9707-
11 8,
12 2011.

13 Miller, B. L. and Goldberg, D. E.: Optimal sampling for genetic algorithms, in: Proceedings of
14 the Artificial Neural Networks in Engineering (ANNIE'96) Conference, St. Louis, USA, 10–13
15 November 1996, 291–296, 1996.

16 Mulder, M.: Competition and Long-Term Contracts in the Dutch Electricity Market, Competition,
17 Contracts and Electricity Markets: a New Perspective, Edward Elgar Publishing, Northampton,
18 2011.

19 Pollitt, M.: Evaluating the evidence on electricity reform: lessons for the South East Europe
20 (SEE) market, Util. Pol., 17, 13–23, doi:10.1016/j.jup.2008.02.006, 2009.

21 Poff, N. L., Allan, J. D., Bain, M. D., Karr, J. R., Prestegard, K. L., Richter, B. D., Sparks, R. E.,
22 and Stromberg, J. C.: The natural flow regime: a paradigm for river conservation and restoration,
23 BioScience, 47, 769–784, doi:10.2307/1313099, 1997.

24 Poff, N. L., Richter, B., Arthington, A., Bunn, S. E., Naiman, R. J., Kendy, E., Acreman, M.,
25 Apse, C., Bledsoe, B. P., Freeman, M., Henriksen, J., Jacobsen, R. B., Kennen, J.,
26 Merritt, D. M., O'Keefe, J., Olden, J., Rogers, K., Tharme, R. E., and Warner, A.: The ecological
27 limits of hydrologic alteration (ELOHA): a new framework for developing

1 regional environmental flow standards, *Freshwat. Biol.*, 55, 147–170, doi:10.1111/j.1365-
2 2427.2009.02204.x, 2010.

3 Ramos, L., de Sousa, J., Silva, T., Jero nimo, R., and Lima, J. A.: A risk management model for
4 trading electricity in the spot market and through bilateral contracts, in: *Energy Market*
5 (EEM)/2010 7th International Conference on the European, Madrid, Spain, 23–25 June 2010, 1–
6 7, doi:10.1109/EEM.2010.5558701, 2010.

7 Renofalt, B., Jansson, R., and Nilsson, C.: Effects of hydropower generation and opportunities
8 for environmental flow management in Swedish riverine ecosystems, *Freshwat. Biol.*, 55, 49–67,
9 doi:10.1111/j.1365-2427.2009.02241.x, 2009.

10 Richter, B. D.: Re-thinking environmental flows: from allocations and reserves to sustainability
11 boundaries, *River Res. Appl.*, 26, 1052–1063, doi:10.1002/rra.1320, 2010.

12 Richter, B. D. and Thomas, G. A.: Restoring environmental flows by modifying dam operations,
13 *Ecol. Soc.*, 12, 12 pp., 2007.

14 Richter, B. D., Baumgartner, J. V., Powell, J., and Braun, D. P.: A method for assessing
15 hydrologic alteration within ecosystems, *Conservat. Biol.*, 10, 1163–1174,
16 doi:10.1046/j.1523-1739.1996.10041163.x, 1996. Richter, B. D., Baumgartner, J. V., Wigington,
17 R., and Braun, D. P.: How much water does a river
18 need?, *Freshwater Biol.*, 37, 231–249, doi:10.1046/j.1365-2427.1997.00153.x, 1997. Richter, B.
19 D., Baumgartner, J. V., Braun, D. P., and Powell, J.: A spatial assessment of
20 hydrologic alteration within a river network, *Regul. River*, 14, 329–340, 1998. Rothwell, G. S.
21 and Gomez, T.: *Electricity Economics: Regulation and Deregulation*, IEEE Press, New York,
22 2003.

23 Shen, D. and Yang, Q.: Electricity market regulatory reform and competition-case study of the
24 New Zealand electricity market, in: *Energy Market Integration in East Asia: Theories, Electricity*
25 *Sector and Subsidies*, ERIA, Jakarta, Indonesia, 103–139, 2012.

26 Shiau, J. T. and Wu, F. C.: Assessment of hydrologic alterations caused by Chi-Chi diversion
27 weir in Chou-Shui Creek, Taiwan: opportunities for restoring natural flow conditions, *River Res.*
28 *Appl.*, 20, 401–412, doi:10.1002/rra.762, 2004.

1 Shiau, J. T. and Wu, F. C.: Compromise programming methodology for determining instream
2 flow under multiobjective water allocation criteria 1, *J. Am. Water Resour. Assoc.*, 42, 1179–
3 1191, doi:10.1111/j.1752-1688.2006.tb05293.x, 2006.

4 Shiau, J. T. and Wu, F. C.: Pareto-optimal solutions for environmental flow schemes
5 incorporating the intra-annual and interannual variability of the natural flow regime, *Water*
6 *Resour. Res.*, 43, W06433, doi:10.1029/2006WR005523, 2007.

7 Shiau, J. T. and Wu, F. C.: A dual active-restrictive approach to incorporating environmental flow
8 targets into existing reservoir operation rules, *Water Resour. Res.*, 46, W08515,
9 doi:10.1029/2009WR008765, 2010.

10 Shrestha, G. B., Pokharel, B. K., Lie, T. T., and Fleten, S. E.: Medium term power planning with
11 bilateral contracts, *IEEE Trans. Power Syst.*, 20, 627–633, doi:10.1109/TPWRS.2005.846239,
12 2005.

13 State Environment Protection Administration of China: Technical guidelines for environmental
14 impact assessment for ecological water usage, low temperature water and fish habitat facilities in
15 hydraulics projects, report, Beijing, 2006 (in Chinese).

16 Tennant, D. L.: Instream flow regimens for fish, wildlife, recreation and related environmental
17 resources, *Fisheries*, 1, 6–10, doi:10.1577/1548-8446(1976)001<0006:IFRFFW>2.0.CO;2, 1976.

18 Tsai, C. M.: The reform paradox and regulatory dilemma in China's electricity industry, *Asian*
19 *Surv.*, 51, 520–539, 2011.

20 Vogel, R. M., Sieber, J., Archfield, S. A., Smith, M. P., Apse, C. D., and Huber-Lee, A.: Relations
21 among storage, yield, and instream flow, *Water Resour. Res.*, 43, W05403,
22 doi:10.1029/2006WR005226, 2007.

23 Wang, Q. and Chen, X.: China's electricity market-oriented reform: from an absolute to a relative
24 monopoly, *Energ. Pol.*, 51, 143–148, doi:10.1016/j.enpol.2012.08.039, 2012.

25 Williams, J. H. and Dubash, N. K.: Asian electricity reform in historical perspective, *Pac. Aff.*,
26 77, 411–436, 2004.

27 Wu, J., Zheng, C., and Chien, C. C.: Cost-effective sampling network design for contaminant
28 plume monitoring under general hydrogeological conditions, *J. Contam. Hydro.*, 77, 41–65,

1 doi:10.1016/j.jconhyd.2004.11.006, 2005.

2 Wu, Y.: Electricity market integration: global trends and implications for the EAS region, in:
3 Energy Market Integration in East Asia: Theories, Electricity Sector and Subsidies, ERIA, Jakarta,
4 Indonesia, 59–81, 2012.

5 Yin, X. A., Yang, Z. F., and Petts, G. E.: Reservoir operating rules to sustain environmental flows
6 in regulated rivers, *Water Resour. Res.*, 47, W08509, doi:10.1029/2010WR009991, 2011.

7 Yin, X. A., Yang, Z. F., and Petts, G. E.: Optimizing environmental flows below dams, *River Res.*
8 *Appl.*, 28, 703–716, doi:10.1002/rra.1477, 2012.

9 Yun, R., Singh, V. P., and Dong, Z. C.: Long-term stochastic reservoir operation using a noisy
10 genetic algorithm, *Water Resour. Manag.*, 24, 3159–3172, doi:10.1007/s11269-010-9600-5, 2010.

11 Zelner, B. A., Henisz, W. J., and Holburn, G. L. F.: Contentious implementation and retrenchment
12 in neoliberal policy reform: the global electric power industry, 1989–2001, *Admin. Sci. Quart.*,
13 54, 379–412, doi:10.2189/asqu.2009.54.3.379, 2009.

14 Zhang, Q., Xu, C. Y, Chen, Y. D., and Yang, T.: Spatial assessment of hydrologic alteration
15 across the Pearl River Delta, China, and possible underlying causes, *Hydrol. Process.*, 23, 1565–
16 1574, doi:10.1002/hyp.7268, 2009.

17

18

1 Table 1. Details of price variations in the day-ahead market

Month	Mean (RMB/kwh)	Maximum (RMB/kwh)	Minimum (RMB/kwh)	Standard deviation (RMB/kwh)
1	0.29	0.45	0.20	0.03
2	0.28	0.45	0.20	0.03
3	0.27	0.45	0.20	0.03
4	0.29	0.45	0.20	0.04
5	0.33	0.45	0.20	0.03
6	0.37	0.45	0.20	0.04
7	0.43	0.45	0.20	0.02
8	0.40	0.45	0.20	0.04
9	0.41	0.45	0.20	0.03
10	0.38	0.45	0.20	0.05
11	0.36	0.45	0.20	0.05
12	0.32	0.45	0.20	0.04

2

3

Table 2. Optimised monthly volume of hydropower in the contract for the Wangkuai Reservoir ($\times 10^5$ kwh)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
E-flow strategy 1	8.86	7.27	10.35	10.18	14.18	14.91	16.39	18.65	18.21	17.85	7.50	7.78
E-flow strategy 2	9.21	7.86	9.47	9.26	17.69	18.35	19.47	21.11	20.81	17.36	8.75	7.70

Table 3. Optimised value of k for each month for the Wangkuai Reservoir (kwh/RMB)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
E-flow strategy 1	1.13	0.86	0.78	0.72	0.81	0.92	1.03	1.35	1.48	0.78	1.31	0.98
E-flow strategy 2	0.96	0.76	1.32	0.64	0.84	0.68	0.64	1.08	0.72	0.92	0.96	0.88

Table 4. Minimum degree of flow regime alteration under different planned revenues and different e-flow provision strategies

Revenue	9.37×10^6 RMB	6.63×10^6 RMB	3.89×10^6 RMB
Non e-flow strategy	0.78	0.69	0.36
E-flow strategy 1	0.72	0.61	0.31
E-flow strategy 2	0.68	0.57	0.28

Figure 1. Minimum degree of flow regime alteration for different planned mean revenues under three e-flow provision strategies. D is the degree of flow regime alteration; MAR is the mean annual revenue; UI is the unachievable interval; EI is the exclusive interval; SI is the shared interval.

