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A shorter time step for eco-friendly reservoir operation does not always produce better water availability and ecosystem benefits

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ABSTRACT

The time step used in the operation of eco-friendly reservoirs has decreased from monthly to daily, and even sub-daily. The shorter time step is considered a better choice for satisfying downstream environmental requirements because it more closely resembles the natural flow regime. However, little consideration has been given to the influence of different time steps on the ability to simultaneously meet human and environmental flow requirements. To analyze this influence, we used an optimization model to explore the relationships among the time step, environmental flow (e-flow) requirements, and human water needs for a wide range of time steps and e-flow scenarios. We used the degree of hydrologic alteration to evaluate the regime's ability to satisfy the e-flow requirements of riverine ecosystems, and used water supply reliability to evaluate the ability to satisfy human needs. We then applied the model to a case study of China's Tanghe Reservoir. We found four efficient time steps (2, 3, 4, and 5 days), with a remarkably high water supply reliability (around 80%) and a low alteration of the flow regime (<35%). Our analysis of the hydrologic alteration revealed the smallest alteration at time steps ranging from 1 to 7 days. However, longer time steps led to higher water supply reliability to meet human needs under several e-flow scenarios. Our results show that adjusting the time step is a simple way to improve reservoir operation performance to balance human and e-flow needs.

1. Introduction

Eco-friendly reservoir operation aims to sustain ecosystem health for a regulated river, while sustaining socioeconomic interests (Harman and Stewardson, 2005; Suen, 2011; Large, 2012; Zhou and Guo, 2013; Chen et al., 2014). Due to the contrasting objectives of maximizing human interests and minimizing hydrologic alterations to protect riverine ecosystems, reservoir operating schedules need to be carefully considered (Tharme, 2003; Suen and Eheart, 2006; Richter and Thomas, 2007; Petts, 2009; Tsai et al., 2015). An increasing number of studies suggest that to achieve a suitable compromise between these objectives, managers should incorporate different environmental flow (e-flow) release scenarios and water supply plans in their efforts to optimize reservoir operation (Shiau and Wu, 2004, 2013; Suen and Eheart, 2006; Vogel et al., 2007; Jager and Smith, 2008; Yin et al., 2012; Ai et al., 2015; Konrad et al., 2011; Lane et al., 2015; Morrison and Stone, 2015). The similarity among these studies is that they all employed a certain e-flow scenario (e.g., minimum flow, fraction of inflow) to sustain river ecosystems while maximizing human benefits, and used different time steps (multi-daily, daily, and sub-daily) to achieve their desired objectives.

Based on literature review, the major reasons for using multiples time steps in reservoir operation can be divided into three categories according to their difference in implementation. The first and most common reason is that the data of river flow have been widely available until recently. The unit of river flow is usually daily (monthly or seasonally) rather than subdaily (Zimmerman et al., 2010). As a consequence, methods and software, which are developed to calculate the flow regime alteration in regulated river, are usually based on the daily flow (Richter et al., 1996, 1997). The commonly used approach cannot be used to detect hydrologic alterations of different time scales. For example, the range of variability approach (RVA) cannot be used to detect subdaily impacts of hydrologic alteration (Haas et al., 2014). The second category is the reservoir operation goals for different human interests. Operation goals for hydropower, water supply, and flood control can be attained based on different time steps. Finer (shorter) time steps (e.g., hour) are usually required for hydropeaking operations and real-time flood control of reservoir (Wei and Hsu, 2009). Olivares et al. (2015) has established a framework to identify Pareto-efficient subdaily environmental flow constraints on hydropower reservoirs using a grid-wide power dispatch

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model. The third category is the different environmental flow (e-flow) requirements. For the sake of simplicity, one or a few minimum e-flow events are usually used in eco-friendly reservoir operation under multi-daily time steps (e.g. 10 days or monthly) (Chaves et al., 2003; Alemu et al., 2010; Tilmant et al., 2010; Han et al., 2012; Cai et al., 2013). For example, Cardwell et al. (1996) considered 12 different monthly minimum-flow values to study the tradeoffs between environmental and human needs on a monthly basis. Gradually, however, river researchers have realized that basing operations on only one or several minimum e-flow events could lead to degradation of downstream river ecosystems, and that maintaining a regime that resembles the natural flow variability offers a more scientific way to protect or even restore these ecosystems (Poff et al., 1997; Richter and Thomas, 2007; Yin et al., 2011). Under the assumption that the natural flow regime provides better protection for the river ecosystem, the time steps in eco-friendly reservoir operating schemes have progressively decreased towards multi-daily, daily, or even sub-daily releases (Homa et al., 2005; Zimmerman et al., 2010; Olivares et al., 2015; Porse et al., 2015; Wu et al., 2015).

Among the existing studies, it has been widely accepted that shorter time steps will always be better. This is because the natural variability (in terms of magnitude, frequency, duration, timing, and rate of change) of river flows can be more closely emulated using a daily or sub-daily time step (Hughes and Mallory, 2008; Gao et al., 2009; Yin et al., 2012; Shiau and Wu, 2013). However, reservoir operation with short time steps (e.g., daily and sub-daily) is a computationally complex task and cannot be performed easily in practical applications. Many reservoir mangers therefore face a dilemma: should they use long time steps that are easier to model and implement, or shorter time steps that provide better ecosystem protection but that are complex to model and difficult to implement?

Interestingly, few of the studies on eco-friendly reservoir operation have accounted for the problem of whether different time steps have different effects on the ability to simultaneously satisfy both human water needs and e-flow requirements. It is clear from the theory of eco-friendly reservoir operation that human needs and downstream e-flow requirements depend primarily upon inflows and actual storage levels in the reservoir (Vogel et al., 2007; Yin et al., 2015). Both factors trigger different operation rules, and will lead to different abilities to satisfy human and ecological needs. Similarly, the time steps used in reservoir operation directly influence inflows and actual storage levels. For example, under a daily time step, the actual reservoir storage might change daily, and would be determined by the relationship between inflows and releases; in contrast, under a monthly time step, the actual reservoir storage might remain roughly constant for a month. In general, different time steps correspond to different inflows and storage levels, and produce different degrees of satisfaction of human and ecological needs. A suitable time step can be defined as one that is simple to implement through reservoir operation, with simple computational needs, and that also achieves a high degree of satisfaction of human and ecological needs. Thus, the influence of different time steps in eco-friendly reservoir operation on human and ecological needs is an important research topic.

To provide more information on this topic, we designed a study to analyze the influence of different time steps on the ability to satisfy human needs and e-flow requirements during reservoir operation. To achieve this goal, we developed indicators that represented the satisfaction of human and e-flow needs, then compared the effects of 30 time steps and four scenarios on these indicators. The objective of reservoir optimization is designed to maximize the human water supply reliability as practice. We used the results to quantify the influence of the time steps on water supply reliability and flow regime alteration.

2. Methods

In this section, we develop a reservoir optimization model that accounts for the effects of different time steps while balancing human water needs with e-flow requirements. We used water supply reliability and the degree of flow regime alteration as indicators to reflect the ability of a given operating regime to satisfy both human and ecosystem needs. We performed the optimization using genetic algorithms (GA) to analyze the tradeoffs among the time steps (ΔT), water supply reliability (R), and the flow regime alteration (D) for a variety of reservoir operation rules. To capture a wide range of reservoir operating schemes, we considered 30 commonly used time steps ranging from 1 to 30 days, where 30 represents the average number of days per month.

For each time step, we designed the optimization to obtain the maximum R (the objective of actual reservoir operation) under a range of e-flow release scenarios that captured different abilities to satisfy e-flow requirements. We used reservoir operating rule curves (RORCs) to define the reservoir's operation (Chang et al., 2005; Taghian et al., 2013). Although our reservoir operation model only considers a single-purpose reservoir (i.e., water supply), our optimization results should be applicable to reservoir systems that include other functions such as irrigation and generation of hydroelectric power, and that conserve water during the wet season and consume the water during the dry season.

2.1. Environmental flow allocation

2.1.1. Scenarios

We considered four commonly used e-flow allocation scenarios in this study. These four scenarios were chosen because they represent a range of possible policies suggested in the existing literatures. Each scenario is designed to protect and restore different functions of riverine ecosystem. We defined e-flows as water released immediately downstream of the reservoir and that consisted of required releases intended for protection of the downstream flow regime, accidental or unplanned spills, or both. In practice, it is only possible to access the previous day's reservoir inflow, so our optimization assumes that inflows averaged over the previous m days from initially available daily data can be used to determine the e-flows in the following m days.

Table 1
Indicators of hydrological alterations (IHAs) in the range of variability approach.

IHA group	Hydrological indicators
Group 1: Magnitude of monthly water conditions	Mean value for each calendar month
Group 2: Magnitude and duration of annual extreme water conditions	Annual minima and maxima for 1-, 3-, 7-, 30-, and 90-day means
Group 3: Timing of annual extreme water conditions	Day of year for each annual 1-day maximum Day of year for each annual l- day minimum
Group 4: Frequency and duration of high and low pulses	No. of high pulses each year No. of low pulses each year Mean duration of high pulses within each year Mean duration of low pulses within each year
Group 5: Rate and frequency of water condition changes	Means of all positive differences between consecutive daily means Means of all negative differences between consecutive daily values No. of rises No. of falls

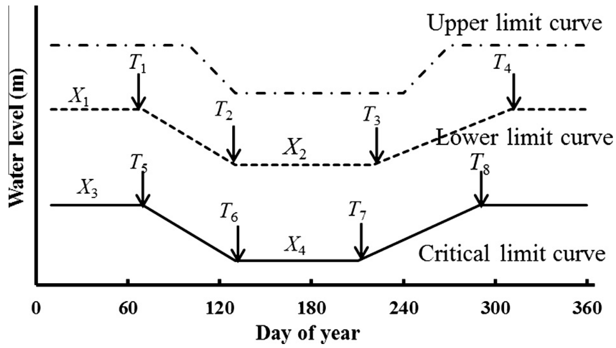

Fig. 1. Typical reservoir operating rule curves. *X* values represent storage water levels; *T* values represent the timing of the transitions between different parts of the curves.

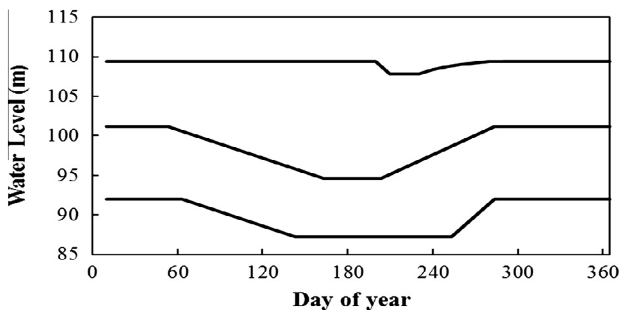

Fig. 2. One of the optimal reservoir operating rule curves under conditions of maximum water supply reliability.

Scenario 1. Fraction of Inflow (FOI)

It attempts to mimic the natural fluctuations of reservoir inflow for ecosystem. In this scenario, a fraction of the reservoir inflow is released as e-flows (Vogel et al., 2007). The fraction ranges from 0.1 to 0.9, so this scenario includes nine operating policies (from FOI = 0.1 to FOI = 0.9).

Scenario 2. Fixed Minimum Flow (FMF)

It attempts to maintain certain specified ecological condition (Tharme, 2003). In this scenario, we chose the widely used Tennant method (Tennant, 1976) to determine the minimum flow. According to this method, 10% of the average daily flow (ADF) is the minimum instantaneous flow recommended to sustain short-term habitat survival for most aquatic species. However, 30% of ADF is recommended as a base flow to sustain good habitat quality. During the dry season, we try to 'sustain short-term survival habitat for most aquatic species'. During the wet season, we try to 'sustain good habitat' (Yin et al., 2012; Rheinheimer et al., 2015). We used FMF values of 10%, 15%, 20%, and 25% of ADF for the e-flow requirements during the dry season, and 30% of ADF during the wet season. This scenario therefore includes four policies.

Scenario 3. Flow Components (FC)

It attempts to provide occasional high-flow releases for habitat improvement (Vogel et al., 2007). This scenario follows one of the FMF policies (10% of ADF for the dry season and 30% of ADF for the wet season), with one exception: it also attempts to provide

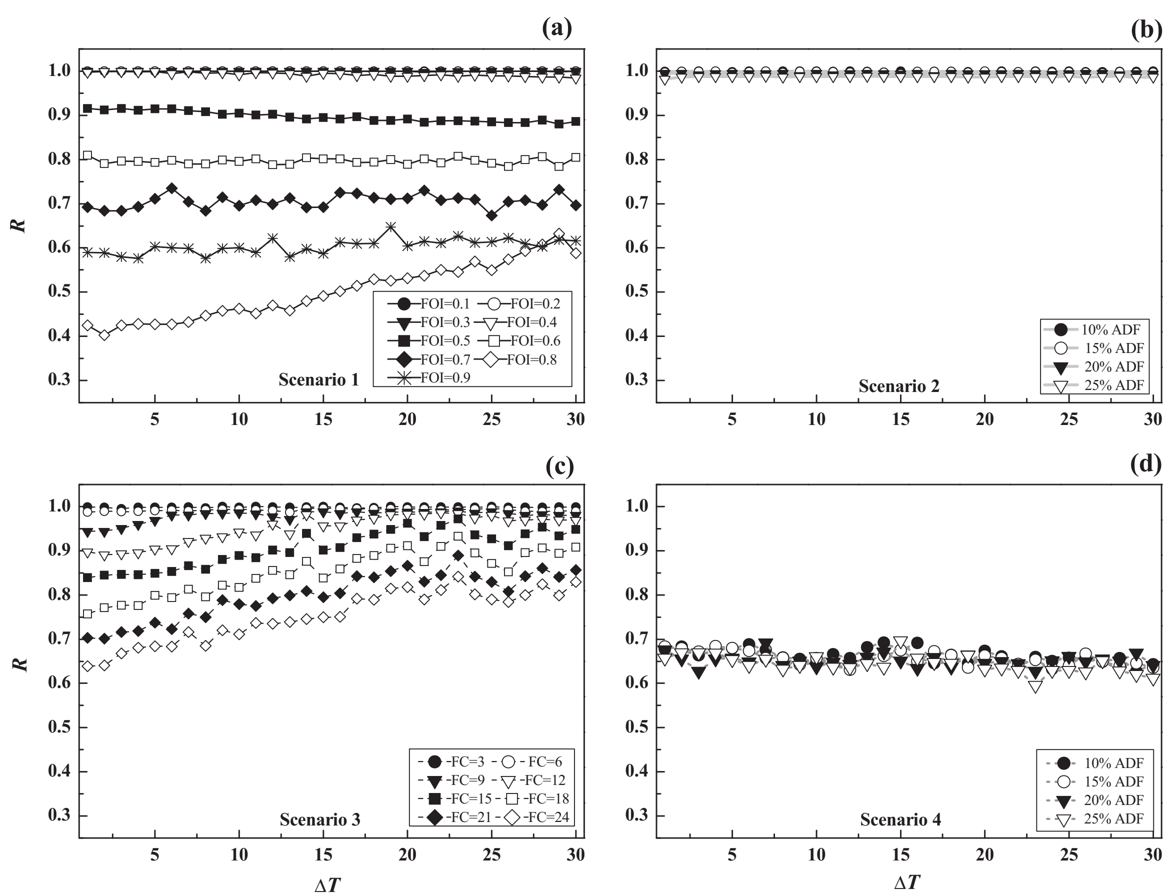

Fig. 3. The relationship between the time step (ΔT) and water supply reliability (R) for the four e-flow release scenarios. FOI, fraction of inflow; ADF, average daily flow; FC = flow components.

occasional high-flow releases. Herein, we considered flows to be a high flow if they were greater than the 75th percentile for all flows. After several high-flow events have occurred in a given year, no further high-flow releases are required. There are at least three high-flow events in each policy (Vogel et al., 2007). And the each policy will add other three high flow events. That is the first policy includes three high-flow events, the second policy includes six high-flow events, and so on. The maximum number of high-flow events in this scenario equals to the total number of high-flow events in the driest year. The dry year is defined as $0 < F(x) \leqslant 0.35$ (F(x) is the probability distribution of an annual precipitation and annual runoff, normal year ($0.35 < F(x) \leqslant 0.65$) and wet year ($0.65 < F(x) \leqslant 1.00$)) (Pinkayan, 1966). This scenario therefore includes policies equaling to a third of high-flow events of the driest year in the historic period under unimpaired conditions.

Scenario 4. Four-period release approach (FP)

It attempts to maintain generic ecological functions provided by different flows at different times of the year. In this scenario, we used the four-period release approach proposed by Yin et al. (2012). The reservoir operation is divided into four basic flow periods, with different e-flows during each of these periods: (i) Floods (flows equal to or greater than bankfull discharges, bd): The 1.5-year flood is used as an estimate of the bd and an amount equivalent to bd is released as the e-flow during a flood period. (ii) Low flows (baseflows in different months): This period is the same as in Scenario 2 (Fixed Minimum Flow), and uses values of 10%, 15%, 20%, and 25% of ADF for the base flow in the dry season, and 30% of ADF for the base flow in wet season. (iii) Extreme low flows (flows equal to or less than 95th percentile flow): The inflow of the reservoir is released as the e-flow. (iv) High-flow pulses (flows less than bd but greater than seasonal base flows): All high-flow events are released. There are therefore four policies in this scenario.

2.1.2. Alteration of the flow regime

One of the most commonly used approaches for assessing the degree of alteration of the hydrologic flow regime is the range of variability approach (RVA; Richter et al., 1996). In this approach, indicators are categorized into five groups that address the magnitude, timing, frequency, duration, and rate of change (Table 1). To calculate the indicators in Table 1, the pre-impact and post-impact flow series for each time step should first be obtained. The historic daily flow records are used as the pre-impact flow records. The optimized e-flow releases of reservoir are used as the post-impact flow records. To sustain the health of downstream ecosystem, the reservoirs have to release considerable water every day. Even for multi-days' reservoir operation (e.g., 2-day), the reservoirs also have to release water every day, while the release might remain the same for the 2 days (like O_1, O_1, O_2, O_2, O_3, O_3, ..., $O_{365/2}$, $O_{365/2}$). The optimized outflow could be treated as rhythmic daily series data, which can be used to calculate the flow regime alteration. Meanwhile, some indicator might have several values based on the rhythmic daily outflow series, such as the 1-day maximum (or minimum). In this study, if one indicator has several same values, we will only take the first one as the value of this indicator as the IHA software did. To determine the influence of

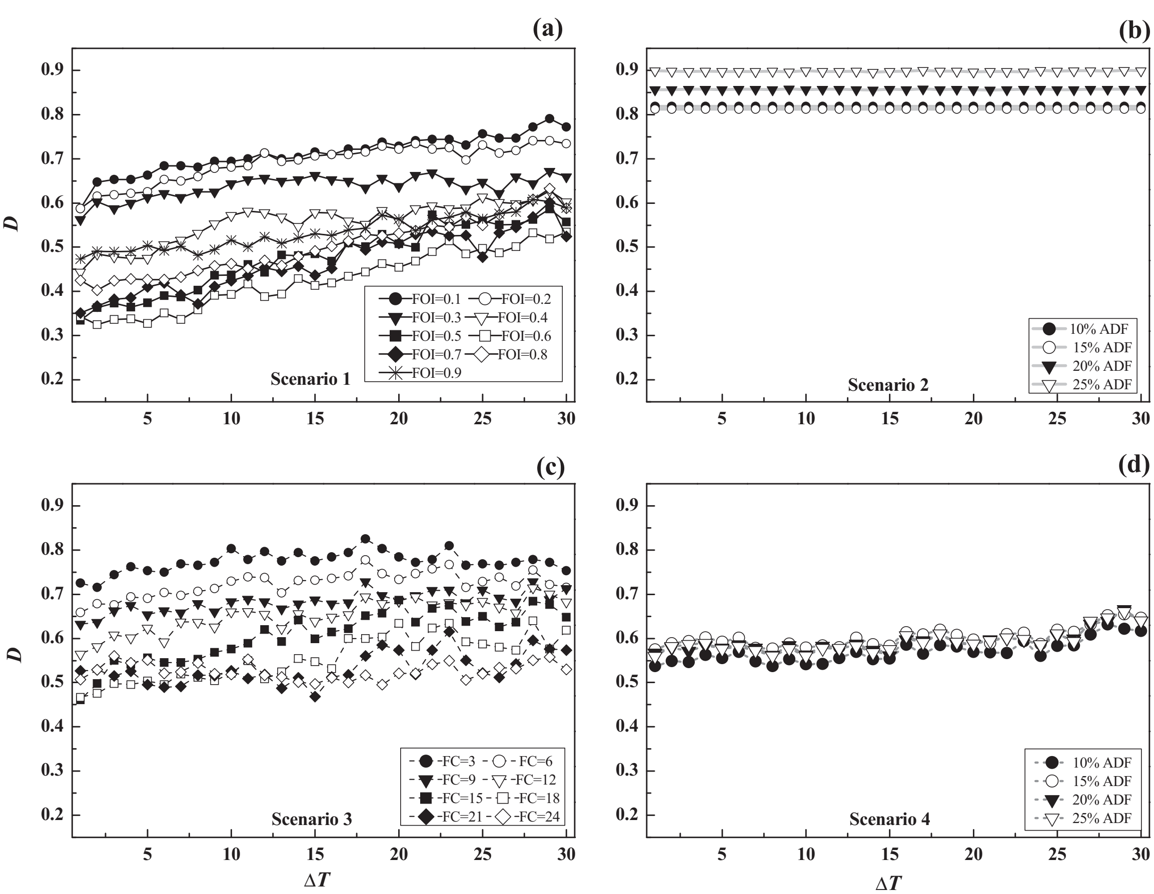

Fig. 4. The relationship between the time step (ΔT) and total flow regime alteration (D) for the four e-flow release scenarios. FOI, fraction of inflow; ADF, average daily flow; FC = flow components.

different time steps on the flow regime, we chose the degree of alteration of the hydrologic regime (D_m) to measure the deviation of the modified flow regime from the natural regime for mth hydrological indicator, which is defined as follows:

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

where $N_{o,m}$ is the observed number of post-impact years in which the value of the mth hydrological indicator falls within its RVA target range, and $N_{e,m}$ is the expected number of post-impact years in which the indicator value falls within the RVA target range. The average degree of alteration of these hydrological indicators was applied to quantify the overall impact on the river, which can be expressed as follows:

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

where D is the total (overall degree of) flow regime alteration, and H is the number of hydrological indicators.

Richter et al. (1996) further proposed that the degree of alteration of flow regimes could be grouped into three classes: low ($D \leqslant 33\%$), moderate ($33\% < D < 67\%$), and high ($D \geqslant 67\%$).

2.2. Reservoir optimization model

RORCs are the most commonly used tools for directing reservoir operation. The operating rules include three curves: one each for the upper limit, lower limit, and a critical limit (Chen et al., 2007; Taghian et al., 2013). The three curves divide a reservoir into four water level zones, and different values of water supply reliability are possible when water levels are in the different zones. Fig. 1 shows a typical RORC. There are also some other rules curves and the readers could choose certain one according to their own purpose (Lane et al., 2015). To maintain the reservoir's flood-control function, the upper limit curve, which is defined during the reservoir's design by means of simulations, is assumed to remain constant in this paper, but the lower and critical limit curves will be optimized as part of our analysis (Yin et al., 2012). Each of these curves can be described by six parameters: two 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 the other four describe the initial and ending times of the linear transitions 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).

Changes in these curves can influence both the water supply reliability and the provision of e-flows. The reservoir release policy is determined by the water level for a particular group of limit curves, and can be described as follows: When the reservoir water levels are in different zones, different water supply hedging rates are applied to provide a safety margin for reservoir operations; a low water level corresponds to a high hedging rate. The hedging rates α and β ($0\% < \alpha < \beta < 100\%$) are determined empirically by the reservoir managers:

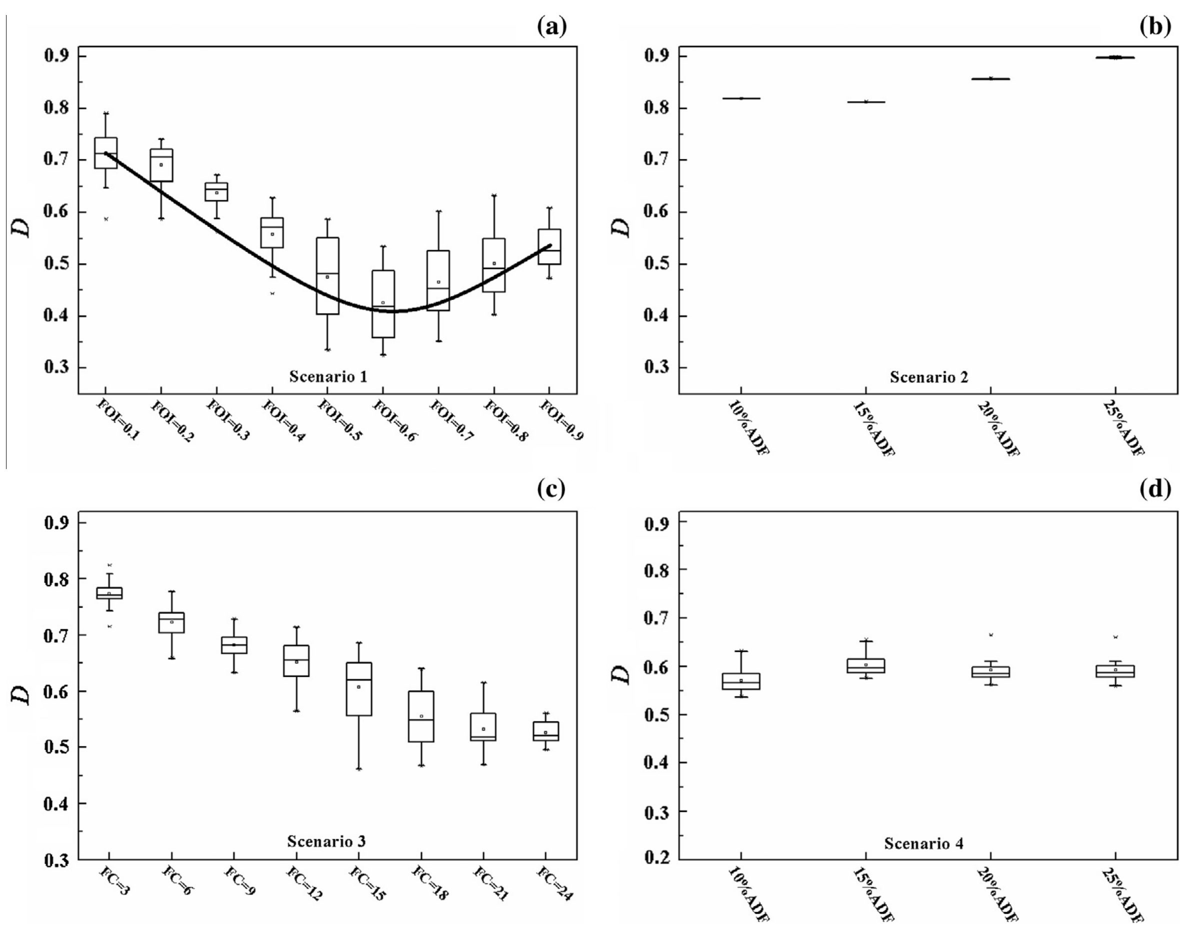

Fig. 5. The distribution of the total flow regime alteration (D) for the e-flows in Fig. 4, which result from various reservoir operating rules. FOI, fraction of inflow; ADF, average daily flow; FC = flow components. Values represent the minimum value, 25th percentile, 50th percentile, 75th percentile, and maximum value. The horizontal line represents the median.

1. If the water level is above the upper-limit curve, water releases should be increased to keep the water level below the upper limit.
2. If the water level is between the upper- and lower-limit curves, the releases, including human water supply and e-flow requirements for downstream parts of the river, are under normal operating conditions.
3. When the water level is between the lower and critical limits, e-flow releases can be supplied as usual, but water releases for human consumption must be cut back by α%.
4. When the water level is below critical limits, water releases for human consumption must be cut back by β%. To keep the water level above the dead storage level, some of the e-flow releases will not be satisfied.

To obtain the values of the *X* and *T* variables shown in Fig. 1 for RORCs with the e-flow allocation considered, the reservoir's operating objective and constraints are designed. First, the basic structure of the reservoir operations model is described by a simple mass-balance equation that equates the change in storage to the difference between inflows and outflows:

$$S_i - S_{i-\Delta T} = I_i - (W_i + M_i) \quad (3)$$

where S_i is the reservoir storage at end of period *i*; $S_{i-\Delta T}$ is the reservoir storage at end of the previous period; I_i is the inflow to the reservoir during period *i*; W_i is the water release from the reservoir during period *i*; and M_i is the mass of water diverted from the reservoir to water supply uses during period *i* (equal to the e-flow release; e-flow is defined as the streamflow release immediately downstream of the reservoir which may consist of either or both a required release intended for protection of the downstream flow regime as well as uncontrolled spills) (Cardwell et al., 1996). That is to say, there are 365 values for inflow, storage and release for 1-day time step. Then there are also 365 values for inflow for 2-day time step (inflows over the previous 2 days from initially available daily data is used to determine the storage and release in the following 2 days), and there are 365/2 values for storage and release. There are 365 values for inflow for 3-day time step, and 365/3 values for storage and release, and so on.

At each time step (ΔT from 1 to 30 days) in the reservoir optimization process, the operating objective is to maximize the water supply reliability, using the following objective function:

$$R_{\Delta T} = \max(SI_{\Delta T}) \quad (4)$$

where $R_{\Delta T}$ is the water supply reliability under ΔT time steps, and $SI_{\Delta T}$ = (the actual amount of water supply)/(the planned amount of water supply) under ΔT time steps. As shown in the equation (4), the water supply reliability is calculated based on the relationship between the actual amount of water supply and the planned amount of water supply (Homa et al., 2005). The water supply reliability calculated by this equation is fair for different time step because the final result is not influenced by the time scales. Meanwhile, the basic problem of the reservoir optimization models is to find the relationship between inflow, reservoir storage capacity, reservoir release, and reliability of reservoir operations (Simonovic, 1992). In this study, the initial input of reservoir optimization (inflow and reservoir storage capacity) remains the same for all time steps. While under certain e-flow allocation scenario,

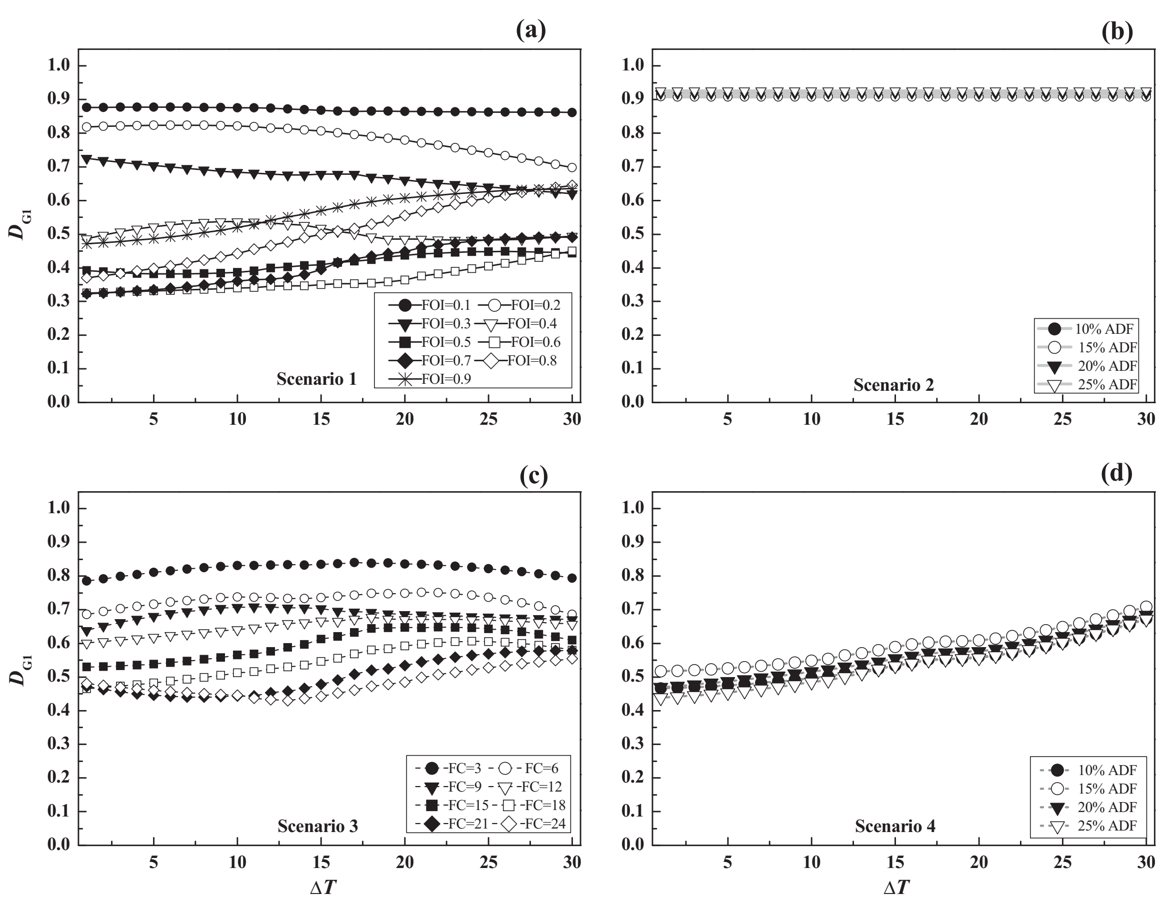

Fig. 6. The degree of alteration for the indicators of hydrological alterations (IHAs) in Group 1 (D_{G1}, based on monthly mean flow). FOI, fraction of inflow; ADF, average daily flow; FC = flow components.

the release of reservoir for e-flow is the same. Only the different operation time steps will lead to different reliability of reservoir. The water supply reliability of different time steps is comparable with each other.

Subject to the following constraints for X_i and T_j:

$$\text{MAXLEVEL} > X_1 > X_2 \quad (5)$$

$$\text{MAXLEVEL} > X_1 > X_3 \quad (6)$$

$$X_2 > X_4 > \text{MINLEVEL} \quad (7)$$

$$X_3 > X_4 > \text{MINLEVEL} \quad (8)$$

$$1 \leqslant T_1 < T_2 < T_3 < T_4 < 365/\Delta T \quad (9)$$

$$1 \leqslant T_5 < T_6 < T_7 < T_8 < 365/\Delta T \quad (10)$$

where MAXlevel is the maximum allowable storage level, and MINlevel is the minimum allowable storage level.

2.3. Optimization using Genetic algorithms

Genetic algorithms (GA) are search and optimization techniques based on the principles of natural selection and genetics (Wardlaw and Sharif, 1999). This approach represents an efficient and robust solution for nonlinear optimization problems, and has been successfully applied to reservoir optimization (Yun et al., 2010; Louati et al., 2011). We used the standard GA to carry out our optimization of reservoir operations in this study, and the version 7.1 of MATLAB (www.mathworks.com) to perform the reservoir optimization under the different time steps.

3. Study site for a case study

The Tanghe Reservoir is in the upper reaches of China's Tang River. Construction of the dam was completed in 1969. It is a multipurpose reservoir with daily regulation. The storage capacity and drainage area total 707×10^6 m^3 and 1228 km^2, respectively. The reservoir's valve release capacity is 282 m^3 s^{-1} and the spillway capacity is 2713 m^3 s^{-1}. We used daily inflow records at the Tang River gauging station from 1950 to 1969 (immediately downstream of the reservoir site) to describe the river's natural flow regime. This flow record was used because it is a relatively unregulated gage and includes very wet and very dry year record for this region. The dry season of Tang River is from November to April and the wet season is from May to October. We used these data because the river near the gauging station was relatively unregulated prior to the construction of the Tanghe reservoir (1969). The reservoir is used for flood control as well as for domestic and industrial water supply.

The four major water users are the Liaoning Chemical Industry Group (54.8×10^6 m^3/yr), Anshan Domestic Water Supply Company (73×10^6 m^3/yr), Liaoyang Domestic Water Supply Company (36.5×10^6 m^3/yr), and Gongchangling Mine Industry Company (18.3×10^6 m^3/yr). The Anshan Domestic Water Supply Company and Gongchangling Mine Industry Company withdraw their water directly from the reservoir, whereas the Liaoning Chemical Industry Group and Liaoyang Domestic Water Supply

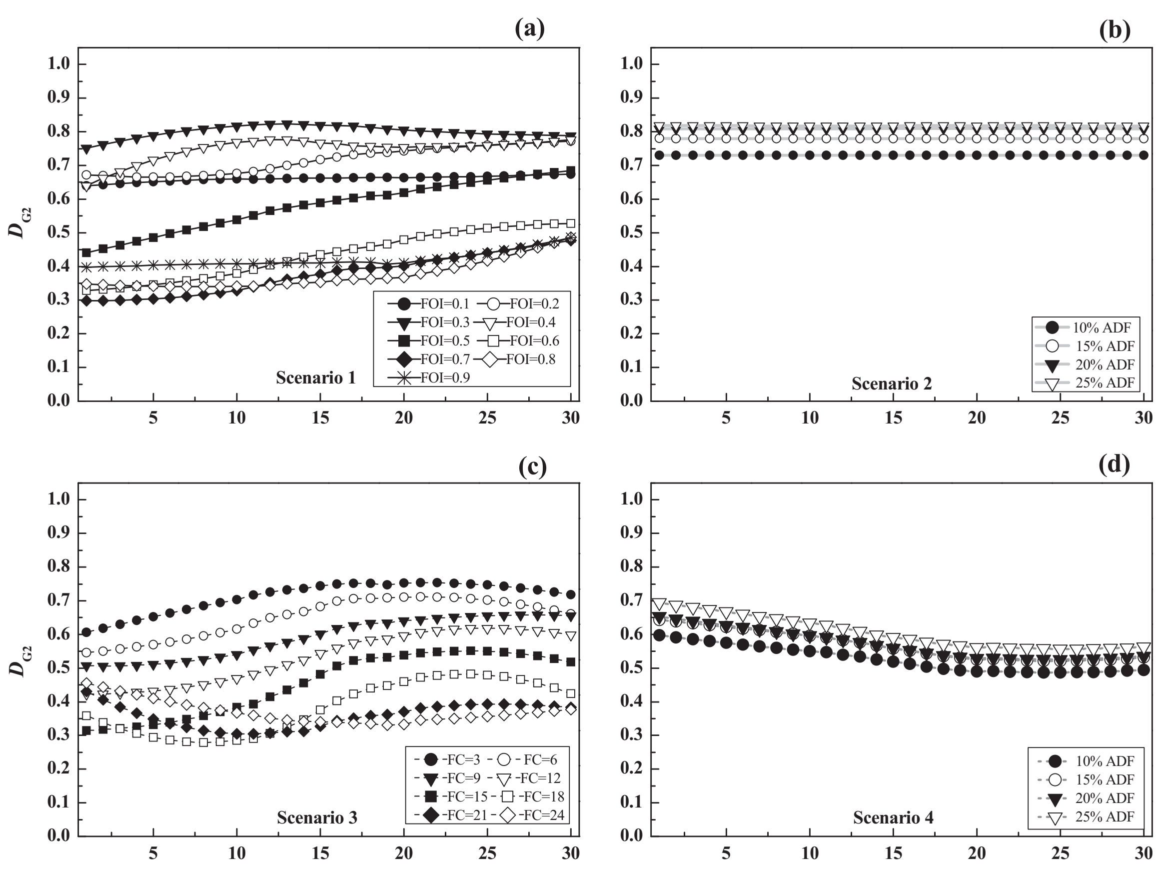

Fig. 7. The degree of alteration for the indicator of hydrological alterations (IHA) in Group 2 (D_{G2}, based on annual extreme flows). FOI, fraction of inflow; ADF, average daily flow; FC = flow components.

Company withdraw water from the Liaoyang water intake, which is located downstream of the reservoir. No tributary exists between the reservoir and the water intake.

4. Results and discussion

The ADF of the Tanghe reservoir was 6.9 $m^3\,s^{-1}$. According to the method in Section 2.2, the base flows for the dry season were 0.69 $m^3\,s^{-1}$ (10% of ADF), 1.04 $m^3\,s^{-1}$ (15% of ADF), 1.38 $m^3\,s^{-1}$ (20% of ADF), and 1.73 $m^3\,s^{-1}$ (25% of ADF), versus 2.06 $m^3\,s^{-1}$ (30% of ADF) for the wet season. The number of high-flow events in a dry year totaled 25, thus Scenario 3 had eight policies (from FC = 3 to FC = 24). The hedging rates α and β ($0\% < \alpha < \beta < 100\%$) are usually determined empirically by the reservoir managers. Herein, the parameters α and β were assumed to equal 20 and 30 according to existing literature (Chang et al., 2005; Yin et al., 2012). Based on 30 time steps and 25 e-flow release policies, we examined $30 \times 25 = 750$ sets of optimal RORCs. We have chosen one of the optimal RORCs, with a 99.8% water supply reliability and a low value of flow regime alteration (0.44, FOI = 0.4 in Scenario 1) as an example of the optimal reservoir operation RORCs (Fig. 2).

In the following sections, we discuss the optimal outcomes (i.e., operation time steps, water supply reliability and flow regime alteration) associated with different e-flow release scenarios.

4.1. Relationship between time step (ΔT) and water supply reliability (R)

Fig. 3 shows the maximum water supply reliability under the four different e-flow release scenarios (25 policies), for each of the 30 time steps. It is evident that R is influenced by ΔT in most policies and in all scenarios, except Scenario 2. Unexpectedly, the lowest R did not result from the maximum e-flow release (FOI = 0.9; Fig. 3a). The lowest R was obtained when FOI = 0.8. Since hedging of the water supply is controlled by the reservoir's water level (a low water level corresponds to a high hedging rate), policies that incorporate the high FOIs release for e-flows would lead to a low water level. However, when FOI is greater than 0.8, the water level is always below the critical limit curve. To maintain the water level above the reservoir's dead storage line, the e-flows are barely satisfied and R is increased when the FOI is bigger than 0.8.

Of particular interest is the shape of the curve for the policy with FOI = 0.8 in Scenario 1 (which is based on FOI) in Fig. 3a and for all policies in Scenario 3 (with FC = 9–24) in Fig. 3c. In these policies, R increases as ΔT increases. Such results highlight the influence of ΔT on the proposed e-flow release scenarios. Although e-flow allocation can decrease the water supply performance during reservoir operation, a longer ΔT will lead to higher R under the same conditions. How can reservoir R increase as ΔT increases while all other conditions remain the same? Apparently, the longer ΔT will lead to reducing the effects of the high inflow as a result of averaging with low inflows. That is, this ΔT increases the length of droughts to some degree. If longer droughts determine the e-flows, then the e-flow releases will decrease and R will accordingly increase. We conclude that longer ΔT values affect the operation of reservoir systems in the scenario with FOI and FC. From the perspective of actual reservoir operations, the e-flow scenarios based on FOI and FC combined with longer ΔT make it easier for reservoir managers to meet human demands.

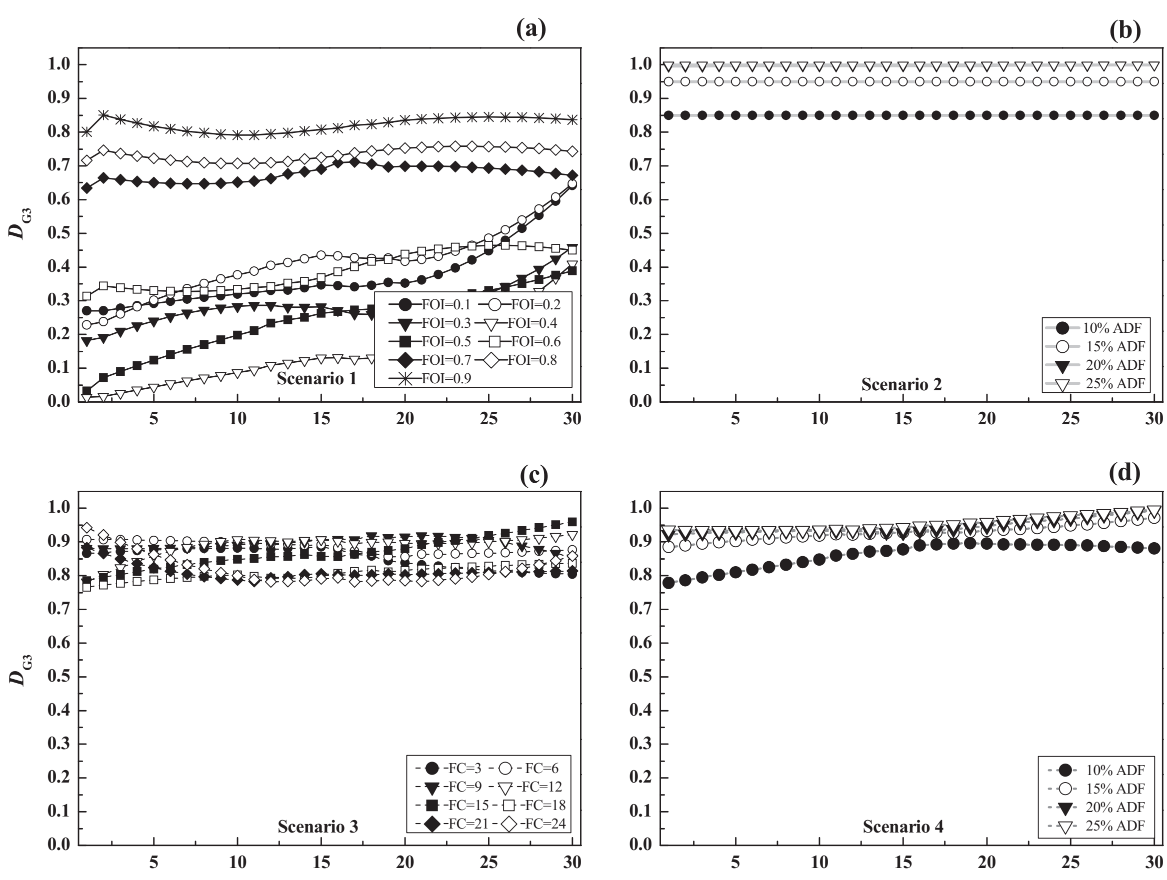

Fig. 8. The degree of alteration for the indicators of hydrological alterations (IHAs) in Group 3 (D_{G3}, based on the timing of annual extreme flows). FOI, fraction of inflow; ADF, average daily flow; FC = flow components.

4.2. Relationship between the time step (ΔT) and flow regime alteration (D)

Fig. 4 illustrates the flow regime alteration curves for the four e-flow release scenarios. As expected, the FMF release method (Scenario 2) produced the highest *D* values of the four scenarios. A comparison of the four scenarios in Fig. 4 indicates that previous assumptions of daily operation providing the greatest benefit for the downstream river are not correct in all e-flow release scenarios. In contrast with the FOI-based scenario (Scenario 1), which obtained the minimum value of *D* at the daily ΔT (Fig. 4a), the scenario with an FMF release (Scenario 2) showed no change in *D* as a function of ΔT, and the other scenarios showed similar *D* values for all ΔT values. It is worth noting that Scenario 3 is partly based on Scenario 2, but despite this, results in much lower *D* values than in Scenario 2. This suggests that the high-flow events will be an effective way to reduce the total *D* for the downstream river.

To examine the differences among the policies in each scenario in more detail, we created box plots for the range of total *D* for these policies (Fig. 5). A box plot is a convenient way to summarize the cumulative probability distribution of several sets of observations.

Fig. 5a indicates that as FOI increases, D initially decreases, and then increases. This result shows that the more water releases from reservoir are not always related to the lower the flow regime alteration. This is because of that increasing e-flow greater than natural low-flow conditions would deteriorate low-flow indicators. Instead, FOI must be adjusted based on a scientific analysis. The *D* values in Fig. 5b and d remain stable for all FMF values. The cumulative probability distributions for the 30 ΔT values in the four policies of Scenario 2 (FMF e-flows) are highly compressed, and the compression is higher than that in Scenario 4, which also accounts for FMF. This suggests that if reservoir managers want to create a lower but relatively stable degree of *D* across a range of ΔT, then Scenario 4 will accomplish this goal better than Scenario 2. Scenario 4 (Fig. 5d) represents a compromise among the four scenarios, and overall, it provides the lowest and most stable ranges of *D*. In contrast, total *D* decreases with increasing FC in Fig. 5c, as the number of released high flows increases. This suggests that more frequent high-flow events will lead to lower *D*.

Comparing the box plots for the total *D* resulting from the different FOI policies in Scenario 1, the lowest median *D* results from FOI = 0.6, but this also produces the largest range of *D* values. The variability in *D* also shows an initial decrease, followed by an increase, in Scenario 1. It can also be seen that the variability in flow regime alterations associated with these policies results are shown in the analogous shape of the letter "U" in Scenario 1. This is an interesting phenomenon. Before FOI = 0.6, the total *D* decreases with increasing FOI for e-flows, but the range of variation increases. At higher values of FOI, *D* increases again, but its variation decreases. The rules for the changes are similar to the results for *R* in Scenario 3 (Fig. 3c), but the inflection points are different (FOI = 0.8 for *R* and FOI = 0.6 for *D*). This demonstrates that *D* is more sensitive than *R* to the e-flow policies. From the perspective of protecting the river ecosystem, we therefore recommend an e-flow policy with FOI = 0.6, and a ΔT corresponding to higher *R* values could then be recommended as an alternative to daily allocation.

The total *D* represents a general description of changes in the flow regime of the downstream river. It can be more informative

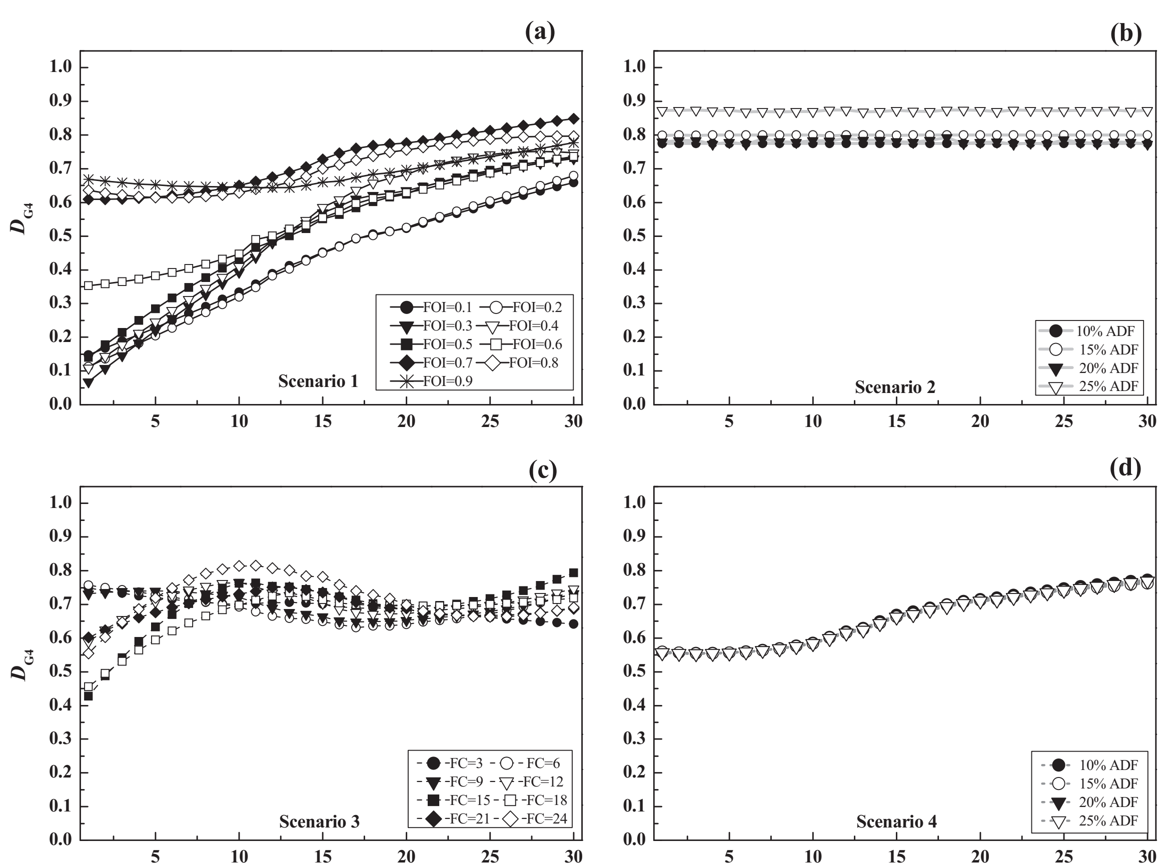

Fig. 9. The degree of alteration for the indicators of hydrological alteration (IHAs) in Group 4 (D_{G4}, based on the frequency and duration of high and low flow pulses). FOI, fraction of inflow; ADF, average daily flow; FC = flow components.

to examine the impacts of different ΔT on the IHAs. Understanding whether the alteration of each IHA also occurs at a 1-day ΔT will further enrich our results. In the rest of this discussion, we have explored the influence of the different ΔT values on the 32 IHAs in the four scenarios (Table 1). Because it seems redundant to reveal the alteration of all IHAs, we have integrated the alterations of IHAs into five groups based on the RVA (D_{Gi}, $i = 1, 2, 3, 4, 5$; Richter et al., 1996). Figs. 6–10 show the relationships between this index and ΔT.

(1) *Flow regime alteration for indicators in Group 1 (D_{G1}, based on monthly mean flow).* Fig. 6b clearly indicates that the alterations of monthly mean flow in Scenario 2 were little influenced by the different ΔT values, as was the case for the overall D in Fig. 4b. In contrast, D_{G1} in Scenario 4 increases as ΔT increases (Fig. 6d). The D_{G1} values in Scenarios 1 and 3 generally decrease as ΔT increases in the first few policies and then increase again (Fig. 6a and c). This suggests that optimization can lead to low alteration of IHAs in group 1 with a low FC and short ΔT.

(2) *Flow regime alteration for indicators in Group 2 (D_{G2}, based on annual extreme flows).* Fig. 7b shows that the alterations of IHAs based on annual extremes in Scenarios 2 were low and were influenced little by the different ΔT values. Fig. 7d shows that D_{G2} in Scenario 4 decreases as ΔT increases, whereas D_{G2} in Scenario 1 generally increases as ΔT increases (Fig. 7a). Fig. 7d shows that a low alteration of IHA can be obtained in Scenario 4 with a long ΔT. This indicates that annual extreme events could be could be adequately simulated with a long ΔT.

(3) *Flow regime alteration for indicators in Group 3 (D_{G3}, based on the timing of annual extreme flows).* Again, Scenario 2 was little influenced by ΔT (Fig. 8b). However, D_{G3} values in Scenarios 1 and 4 (Fig. 8a and d) generally increased as ΔT increased, with the exception of FOI $\geqslant$ 0.7 and FMF = 10% of ADF, whereas D_{G3} in Scenario 3 generally decreased as ΔT increased (Fig. 8c). In general, the IHAs in Scenarios 1 and 4 in Group 3 were strongly influenced by ΔT, and a short ΔT resulted in low alteration for IHAs in this group.

(4) *Flow regime alteration for indicators in Group 4 (D_{G4}, based on the frequency and duration of high and low flow pulses).* Again, Scenario 2 showed little or no change in D_{G4} as ΔT increased (Fig. 9b). D_{G4} in Scenarios 1 and 4 (Fig. 9a,d) increased as ΔT increased, whereas D_{G4} in Scenario 3 (Fig. 9c) generally increased to a maximum as ΔT increased, then decreased again.

(5) *Flow regime alteration for indicators in Group 5 (D_{G5}, based on the rate and frequency of flow changes).* Again, D_{G5} in Scenario 2 showed little change with increasing ΔT (Fig. 10b). D_{G5} in Scenario 1 increased as ΔT increased (Fig. 10a). It is interesting that D_{G5} in Scenarios 3 and 4 showed opposite patterns: concave down (Fig. 10c) and concave up (Fig. 10d), respectively.

Based on our analysis of the five groups in Figs. 6–10, we have compiled the ΔT values for each IHA that produced the minimum value of D_{Gi} (Table 2). Fig. 11 summarizes the frequency of occurrences of minimum D in the 32 IHAs for each ΔT. We found 145 instances when IHA showed the same D for all ΔT values. Of the remaining 655 instances, ΔT ranging from 1 to 7 days accounted

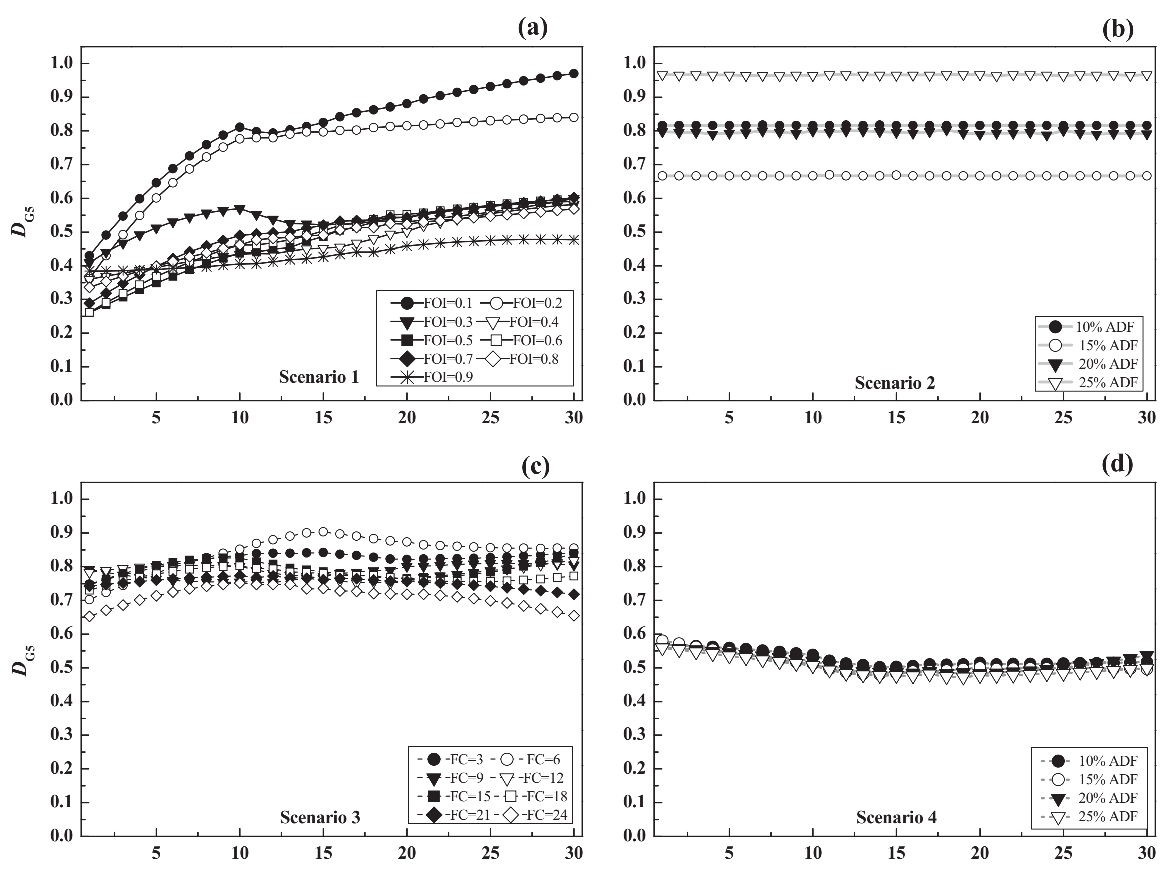

Fig. 10. The degree of alteration for the indicators of hydrological alterations (IHAs) in Group 5 (D_{G5}, based on the rate and frequency of flow changes). FOI, fraction of inflow; ADF, average daily flow; FC = flow components.

Table 2
Summary of the time steps (ΔT) that produced the lowest flow regime alteration (D) for each IHA. Values in square brackets represent the time steps for IHAs obtained the minimum alteration. Hydrological indicators represent the 32 IHAs described in Table 1.

Hydrological indicators	Scenario 1								Scenario 2					Scenario 3								Scenario 4			
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	10	15	20	25	3	6	9	12	15	18	21	24	10	15	20	25
1	–	29	27	[22,24]	23	17	8	[1,2]	1	–	–	–	–	–	–	[1,2]	1	1	[1,2]	9	26	[1,3]	4	25	28
2	–	–	–	–	[28,29]	30	[16,20]	[10,12]	14	–	–	–	–	21	29	[29,30]	29	30	2	9	28	1	18	3	2
3	–	–	[1,3]	[1,3]	5	7	12	12	1	–	–	–	–	3	12	[5,6]	6	[6,7]	7	[6,7]	5	[2,3]	[1,3]	8	4
4	[1,5]	[1,2]	[6,13]	1	1	15	[2,3]	2	4	–	–	–	–	[1,2]	[1,3]	[1,2]	4	10	14	15	16	14	8	2	1
5	–	[14,27]	[6,14]	[1,5]	[10,12]	1	2	[2,4]	[3,4]	–	–	–	–	1	4	9	17	5	9	5	5	1	16	2	1
6	–	[2,13]	28	14	11	17	30	18	30	–	–	–	–	30	25	28	22	28	27	6	16	7	7	7	8
7	–	24	[1,3]	[1,2]	1	1	1	[1,2]	[2,3]	–	[1,10]	–	13	1	[17,18]	24	[1,4]	1	[3,4]	1	1	[6,9]	[6,9]	[6,8]	[6,9]
8	[1,24]	[1,8]	[1,3]	[6,15]	[5,7]	4	[1,2]	[5,6]	11	14	11	[1,7]	–	4	4	2	[15,17]	2	[14,15]	[5,6]	10	[1,3]	[1,3]	[1,3]	[1,3]
9	21	29	[29,30]	[22,24]	26	21	16	[2,3]	[15,17]	–	–	–	13	28	27	27	24	13	3	[15,19]	19	19	21	19	19
10	30	28	[20,25]	[17,18]	[18,19]	21	[1,3]	7	27	–	–	–	–	[1,2]	[1,6]	[3,8]	[6,11]	12	12	12	1	1	1	1	1
11	–	[14,29]	[25,26]	30	25	[17,21]	18	6	1	–	–	–	11	9	27	[20,21]	21	[16,17]	15	15	10	26	26	26	1
12	–	[27,30]	26	20	[15,16]	7	8	6	[1,2]	–	–	24	6	22	15	27	24	24	18	14	19	[13,14]	[1,2]	2	1
13	–	–	15	29	19	12	4	[1,19]	[1,4]	–	–	–	–	27	27	27	27	–	6	–	–	3	–	–	–
14	[1,28]	[2,11]	1	1	2	[5,7]	3	6	1	14	11	–	13	[1,3]	1	1	2	[7,8]	2	2	2	17	17	17	17
15	–	–	15	29	21	29	4	[1,26]	13	–	–	12	14	27	27	27	27	–	26	11	14	19	10	1	–
16	–	[3,11]	[1,2]	1	[1,2]	[1,3]	[6,8]	[5,6]	1	14	11	–	13	[5,7]	1	2	2	1	2	[1,2]	[1,2]	[23,26]	[23,26]	[23,26]	[23,26]
17	–	–	15	30	27	29	4	[1,26]	6	–	–	–	–	–	[1,5]	[1,4]	1	1	12	17	24	[1,10]	10	[4,5]	[7,8]
18	[1,27]	[1,2]	[1,8]	2	[2,3]	[1,2]	[5,6]	4	[1,7]	14	11	–	[1,2]	[1,2]	[2,3]	[2,3]	3	3	5	2	[1,5]	[20,21]	[20,21]	[20,21]	[20,21]
19	–	–	–	[4,30]	30	29	[19,20]	16	6	–	–	[5,6]	2	–	[1,5]	[1,4]	3	1	9	25	24	[1,10]	21	17	23
20	–	[1,9]	[1,12]	[1,11]	12	10	[1,17]	[2,4]	25	14	11	–	13	29	3	7	[6,7]	[7,11]	[10,12]	[1,3]	[4,6]	30	30	28	28
21	–	–	–	[1,4]	[1,7]	[2,3]	1	2	1	–	–	–	8	15	3	6	6	6	6	6	14	[1,3]	1	3	1
22	[1,2]	[1,10]	15	[1,6]	[1,13]	[1,29]	21	3	16	–	[1,10]	–	3	–	10	15	2	7	10	7	14	22	18	24	18
23	[10,27]	[1,8]	27	[1,14]	[1,4]	12	4	[1,16]	[3,16]	–	–	2	17	24	12	12	[1,2]	13	17	23	7	[1,11]	[1,6]	16	–
24	4	4	4	4	3	7	25	[5,6]	8	–	–	–	–	[22,25]	22	13	24	1	29	15	11	[2,3]	7	3	14
25	[13,14]	5	3	[1,2]	[1,2]	[1,2]	[1,2]	[1,2]	[1,2]	–	11	–	13	11	10	14	18	[1,2]	[1,2]	2	2	[2,5]	[2,5]	[2,5]	[2,5]
26	[3,5]	[3,5]	[3,5]	[3,5]	2	2	25	–	–	–	–	6	[6,7]	–	1	[1,4]	3	1	4	21	[20,21]	–	–	–	–
27	[4,6]	[4,8]	[4,8]	5	5	5	7	11	16	–	–	–	13	22	20	20	1	1	1	1	1	8	8	8	6
28	1	1	1	1	1	2	25	–	–	–	–	27	8	–	1	24	22	1	4	17	22	–	–	–	–
29	2	2	[1,3]	[1,2]	1	1	3	1	3	–	–	–	13	[2,3]	[4,6]	[12,13]	17	17	19	21	1	1	1	1	1
30	1	[2,3]	27	[12,13]	5	3	7	11	10	–	–	27	8	11	1	2	4	1	6	13	28	11	8	8	8
31	1	2	22	5	8	3	2	2	22	–	–	–	13	[1,2]	[1,2]	[1,5]	6	[1,3]	1	1	1	26	28	28	26
32	1	1	1	1	1	1	1	1	1	[1,6]	[1,10]	5	2	–	–	–	–	–	–	–	–	1	1	1	1

Note: "-" indicates that the same flow regime alteration (D) occurred for all time steps.

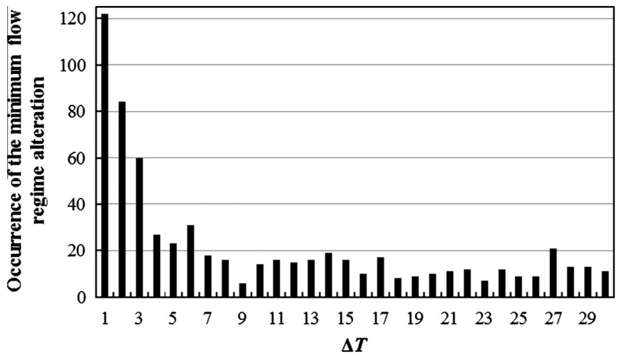

Fig. 11. Frequency of occurrence of the minimum flow regime alteration for each time step (ΔT).

for 55.7% of the total. We therefore conclude that the lowest alteration of the IHAs generally occurred for ΔT ranging from 1 to 7 days.

4.3. Finding efficient time steps (ΔT) to minimize the flow regime alteration (D) and maximize the water supply reliability (R)

This section is designed to identify optimal trade-offs between two contrasting objectives: the maximization of water supply reliability and the minimization of downstream flow regime alteration. To identify the efficient ΔT with low D and high R, we combined the results for each ΔT in Fig. 11 for nine time steps (the change of the figures are continuous, so we only choose nine typical figures). For the four scenarios, Fig. 12 compares the total D and R for ΔT values of 1, 2, 5, 7, 10, 15, 20, 25, and 30 days. The results show that R remains roughly constant but D changes as a function of ΔT. For Scenario 1, the data for all ΔT values form a concave-up curve with D values below those in the other scenarios, with a minimum D at or near a value of $R = 0.8$ for FOI = 0.6. Thus, to protect downstream ecosystems, reservoir operation could be based on an e-flow policy with FOI = 0.6 and a ΔT with higher R could be recommended as an alternative to daily allocation. Based on these results, we conclude that reservoir operation with a ΔT of 2, 3, 4, or 5 days for allocation of e-flows can simultaneously achieve low D and high R, and represent an eco-friendly alternative to daily allocation.

5. Conclusions

We believe that this paper represents one of the first studies to generalize the impact of the time step used in reservoir management on the water supply for humans and the environmental flow regime. Using a simple case study, we demonstrated that the choice of time step in optimization of reservoir management can have a strong impact on both the water supply reliability and the alteration of the flow regime. Different types of e-flow release policies may have different most suitable time steps. Overall, a longer

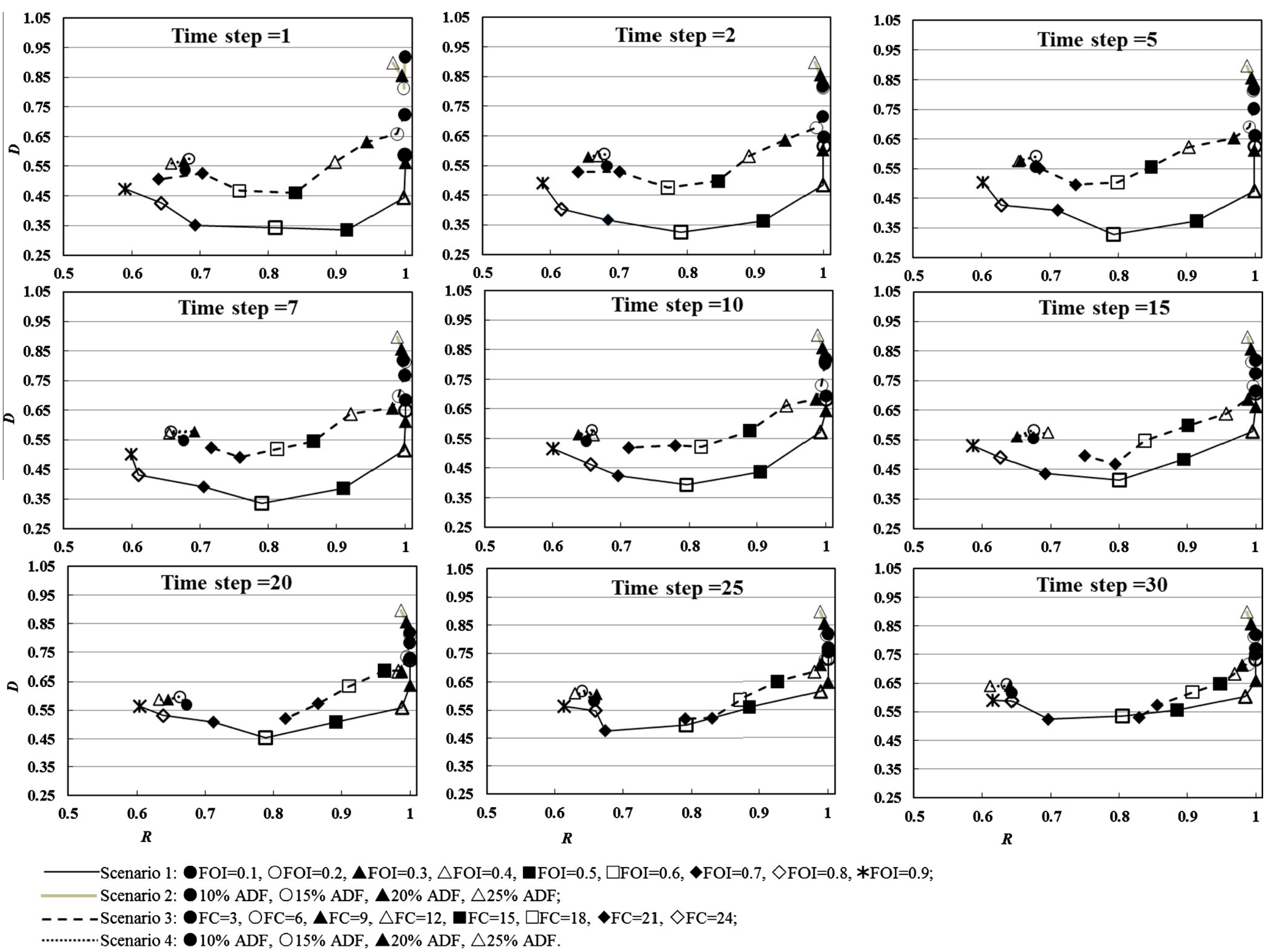

Fig. 12. Illustration of the tradeoff between the total flow regime alteration (D) and water supply reliability (R) for various time steps (ΔT, in days).

time step will lead to higher water supply reliability. Meanwhile, under these long time steps, adding high-flow events into e-flow scenarios can reduce the influence on flow regime to some extent. In general, our results based on the total flow regime alteration show that previous assumptions of daily operation providing the optimal benefit for the downstream river are not correct for all e-flow release scenarios. These results therefore provide a new perspective for reservoir management and operation. Meanwhile, using the results of this study to identify the most suitable time step should be aware of that the choice of time-step and e-flow allocation scenarios in this study have a major influence on the quantification of performance metrics. It may illuminate or obscure the true ecological performance of proposed reservoir operation policies.

There are several promising future extensions to this initial study. First, some methods are more sensitive than others to time step changes, and these methodological decisions should therefore be well supported and sensitivity analyses performed in future studies. Second, the objective for optimal reservoir management should simultaneously consider both water supply reliability and the flow regime alteration. If ecosystem health is a priority, flow regime alteration should be the primary objective. A useful and interesting extension of this study would be to optimize the eco-friendly reservoir operation using an optimization framework with the goal of exploring the Pareto frontier solutions between human and environmental flow requirement. The distinguishes between the results of this study and that of Pareto frontier could be that each point on a Pareto frontier would be the optimal one in the content of a particular objective combined the needs of various stakeholders involved. Third, in the present study, we limited the time steps for e-flow allocation to from daily to 30 days, which represents the most commonly used range of times. This does not account for the possibility that shorter time steps (subdaily) may have unexpected benefits under certain circumstances. The effects of subdaily time steps on other reservoir operating goals, such as peak-load hydropower generation and flood-control measures, should also be involved in the future development of this study. In addition, our study focused on a reservoir designed to support only two primary uses (human and ecosystem needs). Thus, performing an analysis with more time steps and more types of reservoir would provide a useful extension to the present analysis.

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