

A dual active-restrictive approach to incorporating environmental flow targets into existing reservoir operation rules

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[1] Environmental flow schemes may be implemented through active or restrictive strategies. The former may be applied via reservoir releases, and the latter can be executed by reducing water demands. We present a dual active-restrictive approach to devising the optimal reservoir operation rules that aim to secure off-stream water supplies while maximizing environmental benefits. For the active part, a multicomponent environmental flow target (including the minimum and monthly flows) is incorporated in the operation rules. For the restrictive counterpart, we use a novel demands partitioning and prioritizing (DPP) approach to reallocating the demands of various sectors. The DPP approach partitions the existing off-stream demand and newly incorporated environmental demand and reassembles the two as the first- and second-priority demands. Water is reallocated to each demand according to the ratios derived from the prioritized demands. The proposed approach is coupled with a multicriteria optimization framework to seek the optimal operation rules for the existing Feitsui Reservoir system (Taiwan) under various scenarios. The best overall performance is achieved by an optimal dual strategy whose operational parameters are all determined by optimization. The optimal environmental flow target may well be a top-priority constant base flow rather than the variable quantities. The active strategy would outperform the restrictive one. For the former, a top-priority base flow target is essential; for the latter, the off-stream demand can become vanishingly small in compensation for the eliminated base flow target, thus promoting the monthly flow target as nearly the top-priority demand. For either the active or restrictive strategy, a prioritized environmental flow demand would provide a path toward the optimal overall performance. A significantly improved overall performance over the existing operation rules is unlikely if the active and restrictive parameters are both favorable to the off-stream demand.

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1. Introduction

[2] The effects of the reservoir operation on the downstream status of ecology, hydrology, and geomorphology are well known [e.g., Ligon *et al.*, 1995; Van Steeter and Pitlick, 1998; Magilligan and Nislow, 2005]. With increasing concern about the impacts of dams and flow regulation on river biota, contemporary scientists have come to recognize that the structure and function of a riverine ecosystem and adaptations of its biota are governed by the flow regime, i.e., the variation patterns of river flows [Poff *et al.*, 1997]. There is now a consensus among scientists and river managers that to protect freshwater biodiversity and maintain the ecological services that rivers can provide, managed releases of water from reservoirs, termed *environmental*

flows, are needed to mimic the components of natural flow variability, which include the magnitude, frequency, timing, duration, rate of change, and predictability of extreme events such as floods and droughts [Arthington *et al.*, 2006]. This may explain why, over the past three decades, the scientific field of environmental flows prospered to generate >200 methods for specifying the minimum instream flows or quantifying flow regimes required to sustain the riverine ecosystems and their valued features [Tharme, 2003; Shiau and Wu, 2004a, 2004b, 2006, 2007a, 2007b, 2008, 2009]. It has also become increasingly clear that failure to meet the environmental flow requirements would lead to adverse consequences for the river users, including the downstream ecosystems and the communities that rely upon them [Arthington and Pusey, 2003].

[3] Environmental flow strategies may be implemented through active and/or restrictive flow management [Dyson *et al.*, 2003]. When an active strategy is applied via dam releases, an entire flow regime, including the low flows and floods, may be generated by establishing the base flow and pulse targets [Harman and Stewardson, 2005]. As a restrictive strategy is executed by reducing water abstractions and diversions, it is aimed to secure the instream flow

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Figure 1. Location map of Feitsui Reservoir system and Hsintien Creek basin. The joint flow from the Peishih and Nanshih Creeks is diverted at the Chingtan Weir to supply the domestic demand of the Taipei metropolitan area.

requirements, particularly during the dry periods. In a multisector water-sharing system, the restrictive flow strategy often implies reallocation of water resources to the existing users, which constitutes a task that should be implemented in an equitable manner to ensure more effective sharing of water between the society and ecosystems [Wallace *et al.*, 2003].

[4] Although generally justified, equity is, however, a social psychological term whose definition is unsuitable for the mathematical programming of water allocation [Wang *et al.*, 2007]. It has also been pointed out that the public could make relatively complex judgments on the fairness in water allocation, using dimensions beyond the traditional scope of equity [Syme *et al.*, 1999]. As an alternative, the demand management perspective was proposed to promote a more equitable reallocation framework based on the performance objectives [Lankford, 2003]. Specifically, reducing water demands should be shared among sectors to secure significant marginal benefits or the optimal overall performance. The key challenge in developing such a framework is to incorporate environmental flow targets in the existing reservoir operation rules while seeking the balance between the demands of various sectors. Reservoir operation rules that take into consideration the environmental flow require-

ments or ecosystem needs have been proposed previously [e.g., Hughes *et al.*, 1997; Hughes and Ziervogel, 1998; Harman and Stewardson, 2005; Suen and Eheart, 2006; Hughes and Mallory, 2008]. These works mainly focused on the active strategy of aiming to establish dam release schemes that would maintain the targeted flow regime. None of these previous works, however, presented a restrictive strategy addressing the issue of demand management.

[5] In this paper we present a new, dual active-restrictive approach to devising the optimal reservoir operation rules that seek to secure off-stream water demands while maximizing environmental benefits. For the active part, a multicomponent environmental flow target (including the minimum and monthly flow components) is incorporated into the reservoir operation rules. For the restrictive counterpart, we present a novel demands partitioning and prioritizing (DPP) approach to reallocating the demands of the off-stream water user and environmental sector. The proposed dual approach is coupled with a multicriteria optimization framework to establish the optimal operational parameters for the existing Feitsui Reservoir system (Taiwan) under various operation scenarios. The outcomes associated with different operation strategies are compared, and their implications for more balanced management of water resources are further discussed.

2. Feitsui Reservoir System

[6] The Feitsui Reservoir is located at the Peishih Creek (north fork of the upper Hsintien Creek) in northern Taiwan (Figure 1). This multipurpose reservoir has been in operation since 1987. The capacity of the Feitsui Reservoir is 385 million m^3 , with its main purpose being to provide stable water supplies for the Taipei metropolitan area. The attenuation of flood peaks also serves to mitigate flooding, although it is not a primary function of the Feitsui Reservoir. In addition, the hydropower plant associated with the reservoir facilitates the generation of auxiliary electricity for the Taiwan Power Company.

[7] The domestic demand of the Taipei metropolitan area is jointly supplied by the water releases from the Feitsui Reservoir and unregulated flow from the Nanshih Creek (south fork of the upper Hsintien Creek). The Nanshih Creek joins the Peishih Creek at ~ 1 km downstream of the Feitsui Reservoir. Below the confluence is the Hsintien Creek, a major tributary of the Tanshui River. The annual inflow of the Feitsui Reservoir is ~ 10 billion m^3 (mean daily inflow = $31.6 m^3/s$), and the annual runoff of the Nanshih Creek is ~ 12 billion m^3 . The mean monthly inflows of the Feitsui Reservoir and monthly flows from the Nanshih Creek are summarized in Table 1, which also shows the projected domestic demands, which sum to a total of ~ 11.3 billion m^3 per year.

[8] The joint flow of the Peishih and Nanshih Creeks is diverted from the Chingtan Weir (Figure 1) to the water treatment plant and then distributed by the Taipei Water Company. Operation of the Feitsui Reservoir follows the predetermined rule curves shown in Figure 2, where the reservoir water level is divided into five distinct zones by four rule curves (i.e., the upper, middle, lower, and critical rule curves). The amount of water released for the domestic supply depends on to which rule-curve (RC) zone the reservoir storage level belongs and whether the flow from the

Table 1. Monthly Inflow of Feitsui Reservoir, Flow of Nanshih Creek, Projected Domestic Demand, Evaporation Rate, and Ratio of Monthly Flow Target

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Inflow of Feitsui Reservoir (m ³ /s)	22.6	26.0	19.5	18.8	23.7	31.2	22.5	36.4	66.1	51.8	36.2	25.2
Flow from Nanshih Creek (m ³ /s)	21.2	24.6	20.5	19.6	23.1	33.3	33.4	60.3	84.8	65.4	40.9	28.4
Projected domestic demand (10 ⁶ m ³)	93.4	84.5	94.0	91.6	94.7	96.9	99.8	99.3	95.8	93.7	90.9	94.2
Evaporation rate (mm/d)	1.05	1.30	1.85	2.72	3.03	3.21	4.67	4.62	3.46	2.16	1.33	1.04
T_S^t ratio	1.0	1.2	0.9	0.8	1.1	1.6	1.4	2.6	4.2	3.2	2.0	1.3

Nanshih Creek is sufficient to supply the projected domestic demand [Taipei Feitsui Reservoir Administration (TFRA), 2004]. The Feitsui Reservoir system has served as a stable source of water supply for the Taipei metropolitan area. Water rationing measures were rarely implemented over the past two decades.

[9] Currently, environmental flow releases are not included in the operation rules of the Feitsui Reservoir [TFRA, 2004]. The impacts of flow regulation (by dam) and diversion (by weir) and how much water should remain in the downstream reach of the Chingtan Weir need to be evaluated. The legislation process is currently underway, which requests the environmental flow demands to be included in the environmental impact assessment and the flow release plans to be prepared by the reservoir management agencies [Environmental Protection Administration, 2008]. If such a bill passes and becomes effective in the near future, it would mandate incorporation of the environmental flow targets into the existing operation rules. A simulation model is developed here for the Feitsui Reservoir system to assess the hydrologic alteration and reservoir performance associated with different operation schemes, which is described in the following section.

3. Methods

3.1. Simulation Model for Feitsui Reservoir System

[10] Simulations of the flows in the Feitsui Reservoir system (Figure 3), including the flow release from the reservoir, unregulated flow from the Nanshih Creek, and flow

diversion at the Chingtan Weir, are based on the continuity equation of water flow

$$Q_T^t = Q_N^t + (R_{EF}^t + R_D^t + SP^t) - Q_{AD}^t, \quad (1)$$

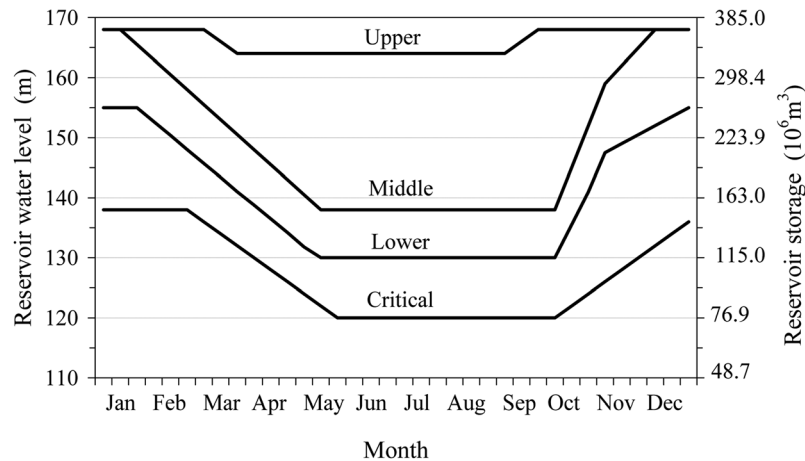
in which the superscript t denotes time, Q_T^t = postimpact flow below the Chingtan Weir, Q_N^t = flow from the Nanshih Creek, R_{EF}^t = environmental flow release, R_D^t = flow release for the domestic demand, SP^t = reservoir spill, and Q_{AD}^t = flow diversion for the domestic use. In Figure 3, the two flows in the boxes, denoted as D^t and T_{EF}^t , are projected domestic demand and environmental flow target, respectively; Q_I^t is reservoir inflow; and S^t is reservoir storage. Reservoir routing is based on the following equation of water balance:

$$S^{t+1} = S^t + Q_I^t - (R_{EF}^t + R_D^t + SP^t) - E^t, \quad (2)$$

where the reservoir storage S^t is constrained by $S_D \leq S^t \leq C$, with S_D and C being the dead storage and reservoir capacity, respectively; E^t is evaporation loss, estimated by

$$E^t = e^t(A^t + A^{t+1})/2, \quad (3)$$

where A^t and A^{t+1} = reservoir surface areas at time t and $t + 1$, e^t = evaporation rate, and the monthly mean evaporation rates of the Feitsui Reservoir [Water Conservancy Department, 1999] are summarized in Table 1. Equation (2) is an implicit scheme as A^{t+1} is unknown at time t . Iterations of

**Figure 2.** Rule curves for Feitsui Reservoir operation. Reservoir water level is divided into five distinct zones by four rule curves.

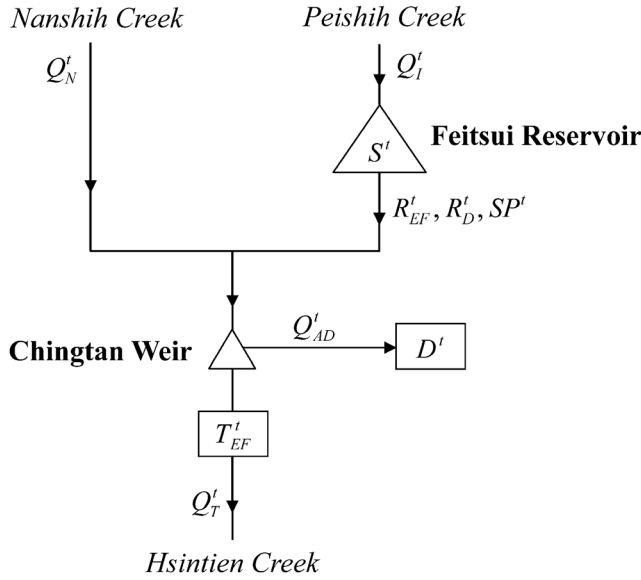


Figure 3. Flows of the Feitsui Reservoir system. Flows in the two boxes are projected domestic demand D^t and environmental flow target T_{EF}^t ; Q_I^t and S^t denote reservoir inflow and storage at time t ; R_{EF}^t and R_D^t denote reservoir releases for the environmental flow and domestic demands; SP^t denotes reservoir spill; Q_N^t denotes the flow from the Nanshih Creek; Q_{AD}^t denotes the flow diverted for domestic supply; Q_T^t denotes the postimpact flow below the Chingtan Weir.

equations (2) and (3) are carried out until E^t meets a specified criterion of convergence.

[11] The reservoir releases, R_{EF}^t , R_D^t , and SP^t , are determined from a set of decision and state variables, namely, the environmental flow target T_{EF}^t , projected domestic demand D^t , reservoir inflow Q_I^t , flow from the Nanshih Creek Q_N^t , and reservoir water level EL^t . The amount of flow actually diverted for domestic use, Q_{AD}^t , is dependent upon the values of Q_N^t , T_{EF}^t , D^t , and R_D^t . These are further explained in the subsequent sections.

3.2. Components of Environmental Flow Target

[12] The concept of environmental flow components (EFCs) was originally developed for assessment of hydrologic alterations [e.g., *Richter et al.*, 2003; *Postel and Richter*, 2003]. The five EFCs adopted in the Indicators of Hydrologic Alteration (IHA) software include (1) extreme low flows, (2) low flows, (3) high-flow pulses, (4) small floods, and (5) large floods [*The Nature Conservancy*, 2005]. Each EFC is ecologically relevant and exhibits direct and indirect links with a variety of biota. The concept of EFCs has been practically applied in a number of environmental flow designs. For example, the base flow and pulse components were incorporated in the environmental flow targets for optimizing the releases from the Thomson Dam in the Thomson River, Australia [*Harman and Stewardson*, 2005]. The flood and high-flow pulse components were adopted to develop the environmental flow recommendations that aim to restore the high flows of the Savannah River below the Thurmond Dam, USA [*Richter et al.*, 2006].

[13] Here we adopted a three-component environmental flow target, which consists of the minimum flow, monthly flow, and flood components (Figure 4). The minimum flow target is a base flow level to be met throughout the year, and is assumed to be a top priority over the off-stream demands. The monthly flow target is a time-varying component added to the minimum flow. The flood target is aimed to retain the extreme flow characteristic of the natural flow regime. The flood component is released by the reservoir spill rule (see section 3.4 for details); thus in this study it can be excluded from the environmental flow target. As such, the environmental flow target T_{EF}^t is simplified as follows:

$$T_{EF}^t = T_{\min} + T_S^t, \quad (4)$$

where $T_{\min}$ = minimum flow target and T_S^t = monthly flow target. The value of $T_{\min}$ is not to be set too high, or this top-priority target would result in severe shortages of water for the off-stream users. Herein, Q_{95} of the daily flows ($= 10.4 \text{ m}^3/\text{s}$) is taken to be the upper limit of $T_{\min}$. The temporal distribution of T_S^t is based on the natural pattern of monthly flows

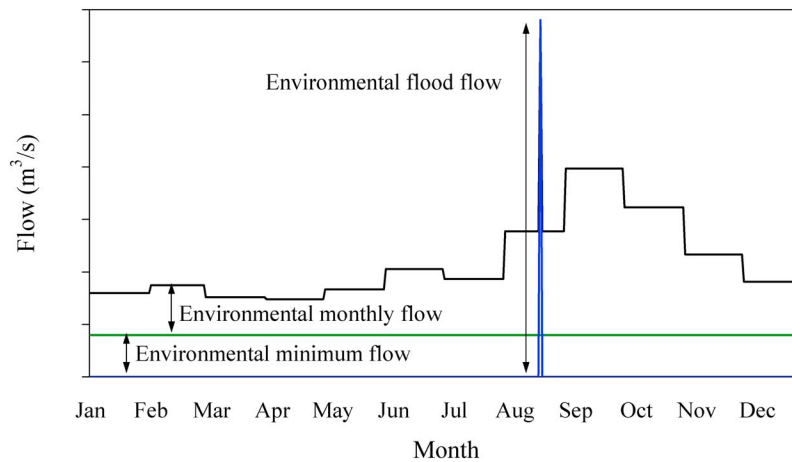


Figure 4. Three-component environmental flow target. The minimum flow target is a base flow level to be met throughout the year and assumed a top priority over the domestic demand. The monthly flow target is a time-varying component added to the minimum flow target. The flood target is aimed to retain the extreme flow characteristic of the natural flow regime, released via the reservoir spill rule.

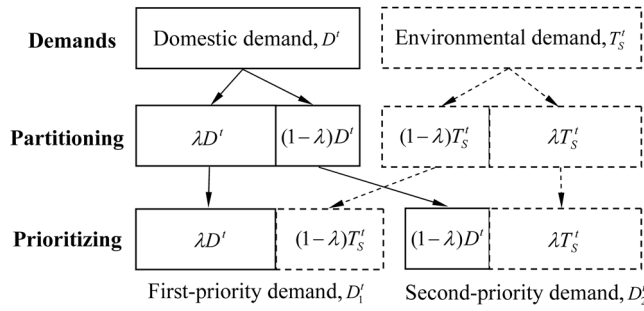


Figure 5. Demands partitioning and prioritizing (DPP) approach. Demands partitioning is applied at the first stage, followed by the second stage where the partitioned demands are reassembled as the prioritized demands. Reservoir releases are implemented with the allocation ratios derived from the prioritized demands. See section 3.3 of text for details.

from the Nanshih and Peishih creeks, as demonstrated in Table 1, where all the T'_S ratios are relative to the value of T'_S for January. Before the values of T'_S can be determined, the existing domestic demand and newly included environmental demand are reallocated using a DPP approach, which is described in the next section.

3.3. Demands Partitioning and Prioritizing Approach

[14] To incorporate environmental flows into the existing reservoir operation rules without deteriorating too seriously the off-stream water supplies is the main problem to be tackled here, bearing in mind that sharing of water between the off-stream user and environmental sector needs to be implemented in a more balanced manner. To this end, we present a novel reallocation strategy termed the demands partitioning and prioritizing approach. To our best knowledge, such an approach has never been published in a peer-reviewed journal. The idea of demands partitioning is applied at the first stage of the DPP approach, which is followed by the second stage, wherein the partitioned demands are reassembled as the prioritized demands (Figure 5). The reservoir releases are implemented with the allocation ratios derived from the prioritized demands. The details of the DPP approach are described in the following paragraphs.

[15] The dilemma of water allocation problems is to assign the priority rank to each of the demands. Here, instead of simply assigning the first or second priority to any demand, a reassembled demand that consists of partial off-stream and environmental demands is given the first priority, whereas the remaining are reassembled as the second-priority demand

(see Figure 5). The philosophy behind this approach is to avoid null supplies to any demands during the dry periods. The reassembled first- and second-priority demands are defined as follows:

$$D'_1 = \lambda D' + (1 - \lambda) T'_S \quad (5a)$$

$$D'_2 = (1 - \lambda) D' + \lambda T'_S, \quad (5b)$$

where D'_1 and D'_2 are the first- and second-priority demands, respectively; λ = demand partitioning factor, with $0 \leq \lambda \leq 1$; D' = projected off-stream demand (see Table 1); and T'_S = monthly flow target. For $\lambda = 1$, the off-stream demand is the first priority, while for $\lambda = 0$, the monthly flow target is the first priority. The first-priority demand is to be met first, and then the second-priority one. If the flow is insufficient for the full amount of D'_1 , water is distributed to the first-priority off-stream and environmental demands according to the following allocation ratios:

$$\lambda_D^1 = \frac{\lambda D'}{D'_1}, \quad \lambda_{EF}^1 = \frac{(1 - \lambda) T'_S}{D'_1}, \quad (6a)$$

where λ_D^1 and λ_{EF}^1 = first-priority allocation ratios for the off-stream and environmental demands, respectively. If, however, the flow is sufficient to meet the demand D'_1 but insufficient for D'_2 , distribution of the remaining water to the second-priority off-stream and environmental demands is based on the following allocation ratios:

$$\lambda_D^2 = \frac{(1 - \lambda) D'}{D'_2}, \quad \lambda_{EF}^2 = \frac{\lambda T'_S}{D'_2}, \quad (6b)$$

in which λ_D^2 and λ_{EF}^2 are the second-priority allocation ratios for the off-stream and environmental demands, respectively. It is noted that the demand partitioning factor λ is a decision variable to be determined by optimization on the basis of the objective functions that aim to optimize the environmental flow and reservoir performances; both correspond to the reservoir release schemes that are controlled by the rules described below.

3.4. Reservoir Release Rules

[16] Water releases from the Feitsui Reservoir include those for the domestic supplies and the environmental flows, and the reservoir spills. The rules for releasing these types of flow are described in the subsequent sections.

3.4.1. Release Rule for Domestic Supplies

[17] The reservoir releases for the domestic supplies, R'_D , are guided by the existing rule curves (Figure 2) and the prioritized allocation ratios, as expressed by the following equation:

$$R'_D = \begin{cases} \min\{C_{RC}[D' - \lambda_D^1(\max\{Q'_N - T_{\min}, 0\})], S' + Q'_I - R'_{EF} - S_D\}, & \text{if } \max\{Q'_N - T_{\min}, 0\} < D'_1 \\ \min\{C_{RC}[D' - \lambda_D^1 D'_1 - \lambda_D^2(\max\{Q'_N - T_{\min}, 0\} - D'_1)], S' + Q'_I - R'_{EF} - S_D\}, & \text{if } D'_1 \leq \max\{Q'_N - T_{\min}, 0\} < D'_1 + D'_2 \\ 0, & \text{if } \max\{Q'_N - T_{\min}, 0\} \geq D'_1 + D'_2 \end{cases} \quad (7)$$

where C_{RC} = coefficient of domestic release, whose value varies with the RC zone where the reservoir storage level belongs, i.e.,

$$C_{RC} = \begin{cases} C_{RC}^1, & S^t \geq RC_1^t \\ C_{RC}^2, & RC_2^t \leq S^t < RC_1^t \\ C_{RC}^3, & RC_3^t \leq S^t < RC_2^t, \\ C_{RC}^4, & RC_4^t \leq S^t < RC_3^t \\ C_{RC}^5, & S^t < RC_4^t \end{cases} \quad (8)$$

where RC_1^t , RC_2^t , RC_3^t , and RC_4^t represent the upper, middle, lower, and critical RCs. The values of C_{RC} , ranging between 0 and 1, are designed for the hedging measures during the dry periods. The existing values currently used for the operation of Feitsui Reservoir are $C_{RC}^1 = C_{RC}^2 = C_{RC}^3 = 1$, $C_{RC}^4 = 0.9$, and $C_{RC}^5 = 0.7$ [TFRA, 2004].

3.4.2. Release Rule for Environmental Flows

[18] Because the minimum flow target $T_{\min}$ is assumed a top priority over other demands, the release for $T_{\min}$ would occur only if the flow from the Nanshih Creek is insufficient for $T_{\min}$; therefore,

$$R_{\min}^t = \begin{cases} Q_N^t, & \text{if } Q_N^t + Q_I^t < T_{\min} \\ T_{\min} - Q_N^t, & \text{if } Q_N^t < T_{\min} \text{ and } Q_N^t + Q_I^t \geq T_{\min}, \\ 0, & \text{if } Q_N^t \geq T_{\min} \end{cases} \quad (9)$$

in which $R_{\min}^t$ = reservoir release for $T_{\min}$. The release rule for the monthly flow target T_S^t is more complex because T_S^t has to seek balances with the domestic demand; meanwhile, T_S^t is a decision variable whose value would depend on the flow from the Nanshih Creek, reservoir inflow, and prioritized allocation ratios, as expressed by the following equation:

in which R_S^t = reservoir release for T_S^t . The total release for the environmental flow target may thus be expressed as follows:

$$R_{EF}^t = R_{\min}^t + R_S^t. \quad (11)$$

[19] The release rule for the flood flow target is different from those for the minimum and monthly flow targets, because floods are released via the spill passage. The release of floods is triggered by the reservoir inflow and storage level that exceed the specified thresholds. For simplicity, herein these thresholds are taken to be the same values as those used for the compelling flood release as explained in the following section.

3.4.3. Release Rule for Reservoir Spill

[20] The reservoir spill comprises three parts. The first is the release for the flood target, R_F^t ; the second is the compelling release during the impending typhoons, Q_{FL}^t ; and the third is the release of excess flood for maintaining the reservoir storage to be below the maximum allowable level. Thus, the reservoir spill SP^t can be expressed as follows:

$$SP^t = \max\{R_F^t, Q_{FL}^t\} + \max\{0, S^t + Q_I^t - R_{EF}^t - R_D^t - \max\{R_F^t, Q_{FL}^t\} - C\}. \quad (12)$$

A simplified criterion for the compelling release Q_{FL}^t is used, which neglects the effect of rainfall and only takes into consideration the reservoir inflow and storage level, i.e.,

$$Q_{FL}^t = \begin{cases} FL, & \text{if } Q_I^t \geq T_I \text{ and } EL^t \geq T_{EL} \\ 0, & \text{otherwise} \end{cases}, \quad (13)$$

where EL^t = reservoir water level and T_I and T_{EL} = thresholds for reservoir inflow and storage level, respectively. The existing values currently used for the operation of Feitsui Reservoir are $FL = 500 \text{ m}^3/\text{s}$, $T_I = 1,000 \text{ m}^3/\text{s}$, and $T_{EL} = 165 \text{ m}$ [TFRA, 2004]. The criterion for R_F^t is such that when the reservoir inflow and storage and the flow from the Nanshih Creek are all exceeding the specified thresholds, the reser-

$$R_S^t = \begin{cases} \lambda_{EF}^1(Q_I^t - R_{\min}^t), & \text{if } \max\{Q_N^t - T_{\min}, 0\} < D_1^t \text{ and } Q_N^t + Q_I^t - T_{\min} < D_1^t \\ \lambda_{EF}^1(D_1^t - \max\{Q_N^t - T_{\min}, 0\}) + \lambda_{EF}^2(Q_N^t + Q_I^t - T_{\min} - D_1^t), & \\ & \text{if } \max\{Q_N^t - T_{\min}, 0\} < D_1^t \text{ and } D_1^t \leq Q_N^t + Q_I^t - T_{\min} < D_1^t + D_2^t \\ T_S^t - \lambda_{EF}^1(\max\{Q_N^t - T_{\min}, 0\}), & \\ & \text{if } \max\{Q_N^t - T_{\min}, 0\} < D_1^t \text{ and } Q_N^t + Q_I^t - T_{\min} \geq D_1^t + D_2^t \\ \lambda_{EF}^2 Q_I^t, & \\ & \text{if } D_1^t \leq \max\{Q_N^t - T_{\min}, 0\} < D_1^t + D_2^t \text{ and } Q_N^t + Q_I^t - T_{\min} < D_1^t + D_2^t \\ T_S^t - \lambda_{EF}^1 D_1^t - \lambda_{EF}^2(\max\{Q_N^t - T_{\min}, 0\} - D_1^t), & \\ & \text{if } D_1^t \leq \max\{Q_N^t - T_{\min}, 0\} < D_1^t + D_2^t \text{ and } Q_N^t + Q_I^t - T_{\min} \geq D_1^t + D_2^t \\ 0, & \text{if } \max\{Q_N^t - T_{\min}, 0\} \geq D_1^t + D_2^t \end{cases}, \quad (10)$$

voir inflow is released to the downstream for maintaining the flood-pulse component, as expressed by

$$R_F^t = \begin{cases} Q_I^t, & \text{if } Q_I^t \geq T_I, EL^t \geq T_{EL}, \text{ and } Q_N^t \geq T_N \\ 0, & \text{otherwise} \end{cases}, \quad (14)$$

where T_N = threshold of flow from the Nanshih Creek. The value of T_N is not specified in the existing operation rule and thus is to be determined by the multicriteria optimization on the basis of the eight evaluation indices described in the following section.

3.5. Evaluation Indices of Reservoir Operation

[21] The performance of reservoir operation is evaluated in three categories, namely, the domestic supply, flood mitigation, and environmental flows. Four reservoir indices are used for the first two categories, and four environmental flow indices are used for the third.

3.5.1. Domestic Supply Indices

[22] The flow actually diverted for the domestic water supply, Q_{AD}^t , is used to evaluate the performance of domestic supply, where Q_{AD}^t is determined by

$$Q_{AD}^t = \begin{cases} \lambda_D^1 (\max\{Q_N^t - T_{\min}, 0\}) + R_D^t, & \text{if } \max\{Q_N^t - T_{\min}, 0\} < D_1^t \\ \lambda_D^1 D_1^t + \lambda_D^2 (\max\{Q_N^t - T_{\min}, 0\} - D_1^t) + R_D^t, & \text{if } D_1^t \leq \max\{Q_N^t - T_{\min}, 0\} < D_1^t + D_2^t \\ D^t, & \text{if } \max\{Q_N^t - T_{\min}, 0\} \geq D_1^t + D_2^t \end{cases} \quad (15)$$

Three evaluation indices based on Q_{AD}^t , namely, the long-term shortage ratio, mean annual deficit duration, and maximum 1-day shortage ratio are used in this study. The long-term total shortage ratio (TSR), is defined as the ratio of total deficit to total demand over the entire study period [Shiau and Lee, 2005], i.e.,

$$TSR = \frac{\sum_{t=1}^N |\min\{Q_{AD}^t - D^t, 0\}|}{\sum_{t=1}^N D^t} \times 100\%, \quad (16)$$

where N = total number of days over the study period. The mean annual deficit duration (ADD) is defined as follows:

$$ADD = \frac{1}{N_Y} \sum_{i=1}^N \begin{cases} 1, & \text{if } Q_{AD}^t < D^t \\ 0, & \text{if } Q_{AD}^t \geq D^t \end{cases}, \quad (17)$$

where N_Y = number of years over the study period. The maximum 1-day shortage ratio (MSR) is a measure of extreme deficit [Shiau and Lee, 2005], as defined by

$$MSR = \max_i \left\{ \frac{|\min\{0, Q_{AD}^t - D^t\}|}{D^t} \right\} \times 100\% \quad (18)$$

3.5.2. Flood Mitigation Index

[23] The maximum flood attenuation (MFA), defined as the maximum difference between the reservoir inflow and

spill within the study period, is used to assess the effectiveness of flood mitigation, as expressed by the following equation:

$$MFA = \max_t \{Q_I^t - SP^t\} \quad (19)$$

3.5.3. Environmental Flow Indices

[24] The effectiveness of environmental flow releases on restoration of natural flow regime is evaluated on the basis of the comparison of the natural (preimpact) flows $Q_I^t + Q_N^t$ with the altered (postimpact) flows Q_T^t below the Chingtan Weir. Four hydrologic parameters, i.e., the large floods, low flows, annual flow regime, and flow variability, are used here for such evaluations [Jowett and Biggs, 2006], which are described in the following numbered paragraphs.

[25] (1) *Large floods*. The first evaluation index is to measure the alteration of the large-flood characteristic. The importance of large floods on maintaining the alluvial channel forms has been widely recognized (see a review by Whiting [2002]). It was also reported that restoring the predam 5-year flood would provide sufficient flows for preventing disconnection of riparian zones [Magilligan *et al.*,

2003]. The flood with 5-year recurrence interval was thus used here to represent the large floods, which was obtained by a frequency analysis of the annual 1-day maximum flows. The difference between the pre- and postimpact 5-year floods, denoted as ΔFLD , would quantify the alteration of the large-flood characteristic, expressed as follows:

$$\Delta FLD = |FLD_{5,N} - FLD_{5,A}|, \quad (20)$$

where $FLD_{5,N}$ and $FLD_{5,A}$ = pre- and postimpact 5-year floods, respectively.

[26] (2) *Low flows*. Low flows are ecologically important because they offer periods of high productivity. The annual 7-day minimum flows were taken here to be representative of the low flows [Richter *et al.*, 1996]. The mean difference between the pre- and postimpact annual 7-day minimum flows, denoted as ΔLF , defines the alteration of the low-flow characteristic, i.e.,

$$\Delta LF = \frac{1}{N_Y} \sum_{i=1}^{N_Y} |LF_{N,i} - LF_{A,i}|, \quad (21)$$

where $LF_{N,i}$ and $LF_{A,i}$ are, respectively, the pre- and post-impact annual 7-day minimum flows of the i th year.

[27] (3) *Annual flow regime*. The intra-annual flow variations are vital for preserving the ecological health of a river [Richter *et al.*, 1996]. The monthly flow hydrograph was used to characterize the annual flow regime. The mean deviation of the postimpact monthly flows from the pre-

Table 2. Maximum and Minimum Values of the Eight Evaluation Indices^a

Index	TSR (%)	ADD (d/yr)	MSR (%)	MFA (m ³ /s)	ΔFLD (m ³ /s)	ΔLF (m ³ /s)	ΔHYG (m ³ /s)	ΔCV
Maximum	100	365.25	100	1631.1	1309.4	13.9	433.6	4.27
Minimum	0.04	0.25	0.86	0	0	0	0	0

^aThese values were searched with a single-objective genetic algorithm.

impact monthly flows, denoted as ΔHYG , defines the alteration of the annual flow regime, i.e.,

$$\Delta HYG = \frac{1}{N_Y} \sum_{i=1}^{N_Y} \sum_{j=1}^{12} |Q_{N,i}^j - Q_{A,i}^j|, \quad (22)$$

where $Q_{N,i}^j$ and $Q_{A,i}^j$ are pre- and postimpact mean flows of the j th month in the i th year.

[28] (4) *Flow variability*. The natural flow variability is an important and necessary element for sustaining the integrity of a riverine ecosystem [Richter et al., 1996]. The coefficient of variation (CV) of the daily flows was used to quantify the flow variability [Clausen and Biggs, 1997, 2000]. The mean difference between the pre- and post-impact CVs of the daily flows, denoted as ΔCV , defines the overall alteration of the flow variability, as expressed by the following equation:

$$\Delta CV = \frac{1}{N_Y} \sum_{i=1}^{N_Y} |CV_{N,i} - CV_{A,i}|, \quad (23)$$

where $CV_{N,i}$ and $CV_{A,i}$ are pre- and postimpact CVs of the daily flows in the i th year.

3.6. Multicriteria Optimization Framework

[29] To optimize the above-mentioned eight evaluation indices constitute a multiple criteria decision-making (MCDM) problem. The objective functions may be written as follows:

$$\begin{aligned} &\text{Minimize}\{TSR, ADD, MSR, \Delta FLD, \Delta LF, \Delta HYG, \Delta CV\} \\ &\text{and Maximize}\{MFA\} \end{aligned} \quad (24)$$

The eight evaluation indices would cover different ranges of values; thus the following relations were used to normalize their values:

$$OBJ_i' = \frac{OBJ_i - \min(OBJ_i)}{\max(OBJ_i) - \min(OBJ_i)} \quad (25a)$$

$$OBJ_i' = \frac{\max(OBJ_i) - OBJ_i}{\max(OBJ_i) - \min(OBJ_i)}, \quad (25b)$$

where OBJ_i and OBJ_i' are original and normalized values of the i th index; $\max(OBJ_i)$ and $\min(OBJ_i)$ = maximum and minimum values of the i th index (see Table 2 for details). Note that equations (25a) and (25b) were used for the indices to be minimized and maximized, respectively. Equations (25a) and (25b) ensure that the normalized indices are bounded by [0, 1], with their most and least favorable values being 0 and 1, respectively. As a result, equation (24)

can be rewritten as the minimization of all the normalized indices, expressed by the following:

$$\text{Minimize}\{TSR', ADD', MSR', MFA', \Delta FLD', \Delta LF', \Delta HYG', \Delta CV'\} \quad (26)$$

[30] The multicriteria optimization problem posed by equation (26) was solved using the technique for order preference by similarity to ideal solution (TOPSIS) [Hwang and Yoon, 1981]. The TOPSIS is a popular and widely used approach to solving the MCDM problem [see e.g., Abo-Sinna and Amer, 2005; Cheng et al., 2006; Fu, 2008]. The basic idea behind this approach is that the best option is the least distant one from the positive ideal solution (PIS) and the most distant one from the negative ideal solution (NIS). The weighted total distances to the PIS and NIS, denoted as D^+ and D^- , were calculated by

$$D^+ = \sum_{i=1}^8 w_i (OBJ_i' - OBJ^+)^2 \quad (27a)$$

$$D^- = \sum_{i=1}^8 w_i (OBJ_i' - OBJ^-)^2, \quad (27b)$$

where w_i = weighting factor for the i th index, and $\sum_{i=1}^8 w_i = 1$; herein equal weighting was given to each index (i.e., $w_i = 0.125$), $OBJ^+ = 0$ (= PIS), and $OBJ^- = 1$ (= NIS). The optimal solution was obtained by maximizing the relative distance to the NIS, as expressed by the following:

$$\text{Maximize}\{D^*\} = \text{Maximize}\left\{\frac{D^-}{D^+ + D^-}\right\}, \quad (28)$$

where D^* = relative distance to D^- . In this study, the optimal solutions were searched with a genetic algorithm (GA) [Deb, 2001], which started with a random parent population of all decision variables. The objective functions corresponding to each member of the population were calculated. The TOPSIS was then used to evaluate D^* . With the selection, crossover, and mutation operators, an offspring population was generated. A population size of 1000 was adopted herein, and typical values of 0.8 and 0.05 were used for the crossover and mutation rates. The GA procedure was repeated until a stable solution was obtained.

[31] The proposed optimization framework was coupled with the simulation model of the Feitsui Reservoir system and applied to search of the optimal operation rules under various scenarios (for details, see section 4). A total of 12 decision variables were involved in the optimization, which included the environmental flow targets $T_{\min}$ and T_S^t ; thresholds for flood release T_L , T_N , and T_{EL} ; compelling release FL ; demand partitioning factor λ ; and the coeffi-

Table 3. The Outcome Associated with the Current Operation Rules of the Feitsui Reservoir System and the Optimal Outcomes Under Various Operation Scenarios

Scenario		Current Rules	Scenario 1 (Optimal Strategy)	Scenario 2 (Active Strategy)	Scenario 3 (Restrictive Strategy)	Scenario 4 (Partially Active Strategy)
Overall performance index, D^*		0.560	0.644	0.641	0.624	0.576
Reservoir indices	TSR'	0.00	0.08	0.08	0.10	0.02
	ADD'	0.03	0.23	0.22	0.25	0.09
	MSR'	0.23	0.47	0.47	0.53	0.25
	MFA'	0.46	0.35	0.35	0.35	0.35
Environmental flow indices	$\Delta FLD'$	0.03	0.03	0.03	0.03	0.03
	$\Delta LF'$	1.00	0.24	0.27	0.39	1.00
	$\Delta HYG'$	1.00	0.92	0.92	0.90	0.98
	$\Delta CV'$	0.48	0.19	0.18	0.16	0.32
Decision variables	$T_{\min}$ (m ³ /s)	0 ^a	10.4	10.3	0 ^a	0 ^a
	T_S^t (m ³ /s)	0 ^a	0.8	7.7	9.7	32.2
	T_I (m ³ /s)	1000 ^a	1140	1140	1070	1370
	T_N (m ³ /s)	-	1380	1370	1360	1250
	T_{EL} (m)	165 ^a	166.4	166.6	168.5	168.5
	FL (m ³ /s)	500 ^a	420	400	380	290
	λ	1.0 ^a	0.14	1.0 ^a	0.02	1.0 ^a
	C_{RC}^1	1.0 ^a	1.0	1.0	1.0	1.0
	C_{RC}^2	1.0 ^a	1.0	1.0	1.0	1.0
	C_{RC}^3	1.0 ^a	0.60	0.60	0.60	1.0
	C_{RC}^4	0.9 ^a	0.53	0.53	0.47	0.69
	C_{RC}^5	0.7 ^a	0.53	0.53	0.46	0.69

^aSpecified values not determined by optimization.

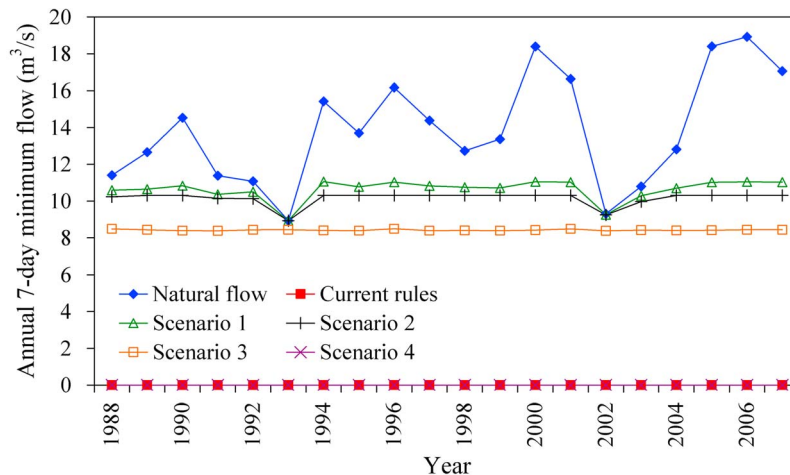
cients of domestic release $C_{RC}^1 \sim C_{RC}^5$. These decision variables are the operational parameters of those reservoir operation rules defined by equations (1) to (15).

4. Results and Discussion

[32] The outcomes associated with the five different operation scenarios are presented here, including (1) the current operation rules, with all the operational parameters being specified (see Table 3); (2) optimal operation rules (scenario 1), with all the operational parameters being determined by optimization; (3) active strategy (scenario 2), with the environmental flow targets $T_{\min}$ and T_S^t being determined by optimization under the specified value of $\lambda = 1$; (4) restrictive strategy (scenario 3), with the demand parti-

tioning factor λ being determined by optimization under the specified value of $T_{\min} = 0$; and (5) partially active strategy (scenario 4), with the second-priority monthly flow target T_S^t being determined by optimization under the specified values of $\lambda = 1$ and $T_{\min} = 0$.

[33] In these scenario simulations, the daily inflows of the Feitsui Reservoir Q_I^t and flow data from the Nanshih Creek Q_N^t (1988–2007) were used as the input natural (preimpact) flow series. The preimpact hydrologic characteristics at the Chingtan Weir site were mean daily flow = 69.7 m³/s, 5-year flood $FLD_{5,N} = 2562.9$ m³/s, mean annual 7-day minimum flow $LF_N = 13.9$ m³/s, and mean CV of the daily flows $CV_N = 1.83$. Flows diverted to the domestic supply Q_{AD}^t , reservoir spills SP^t , and the postimpact flows Q_T^t below the Chingtan

**Figure 6.** Annual 7-day minimum flow series for the natural (preimpact) flow and the postimpact flows below the Chingtan Weir under various operation scenarios.

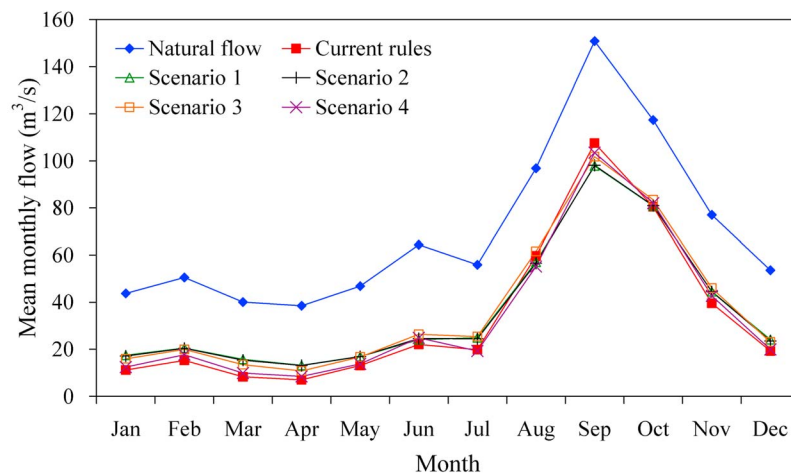


Figure 7. Mean monthly flow hydrographs for the natural (preimpact) flow and the postimpact flows below the Chingtan Weir under various operation scenarios.

Weir were then computed with the simulation model, where the decision variables were either specified or determined by optimization, depending on the scenario adopted.

4.1. Current Operation Rules

[34] The effectiveness of the currently used operation rules of the Feitsui Reservoir system on the domestic supply and flood mitigation and the impacts of flow regulation on the flow regime below the Chingtan Weir were evaluated. The outcomes associated with the current operation rules are summarized in Table 3, where it is clear that all the domestic supply indices are relatively low ($TSR' = 0$, $ADD' = 0.03$, $MSR' = 0.23$), whereas three of the environmental flow indices are relatively high ($\Delta LF' = 1$, $\Delta HYG' = 1$, $\Delta CV' = 0.48$), which reveals that the environmental flow objectives are not well handled by the current operation rules owing to a lack of the environmental flow target (i.e., $T_{\min}^t = T_S^t = 0$). However, the maximum shortage ratio $MSR' = 0.23$, corresponding to $MSR = 23.8\%$, implies that the current maximum deficit is well controlled, given that $C_{RC}^5 = 0.7$ allows for a maximum level of $MSR = 30\%$.

[35] The values of $\Delta LF' = 1$ and $\Delta HYG' = 1$ indicate that the low-flow characteristic and annual flow regime deviate significantly from the natural status as demonstrated in Figures 6 and 7. The persistent null values of the annual 7-day minimum flow (Figure 6) indicate that without preserving an environmental minimum flow for the downstream reach during the dry periods, the available water would be entirely diverted to the domestic user. The postimpact monthly flow hydrograph (Figure 7) reveals a nearly constant deviation from the natural status, which is attributed to the nearly constant daily diversions for the domestic supply ($\sim 35.8 \text{ m}^3/\text{s}$, from the data in Table 1). The pre- and postimpact CVs of the daily flows are shown in Figure 8, where the outcome associated with the current rules exhibits consistently the largest deviations from the preimpact values, resulting in a relatively large value of $\Delta CV' (= 0.48)$. The elevated CV of the daily flows arises from the many null postimpact flows (Figure 11) due to a lack of the minimum flow release.

[36] In contrast to the relatively low values of the domestic supply indices, the flood mitigation index $MFA' (= 0.46)$ is, however, not as favorable as its counterpart reservoir indices.

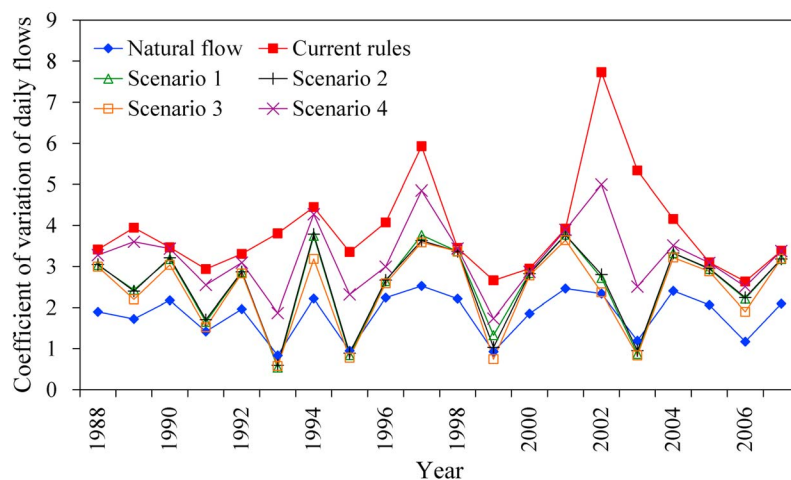


Figure 8. Annual coefficients of variation of daily flows for the natural (preimpact) flow and the postimpact flows below the Chingtan Weir under various operation scenarios.

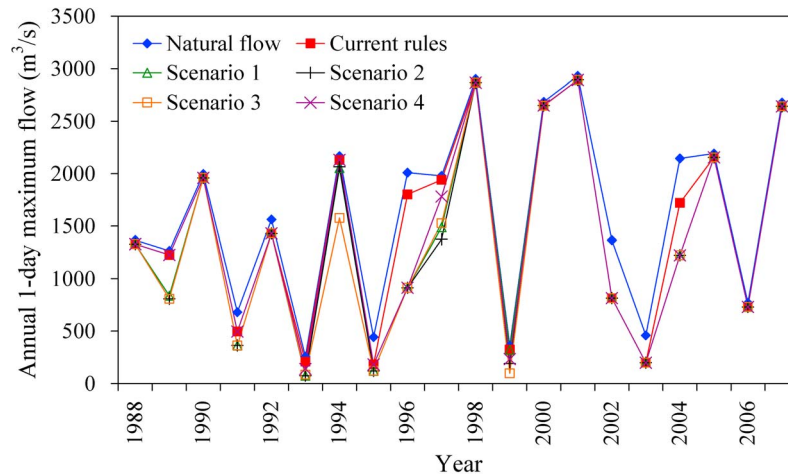


Figure 9. Annual 1-day maximum flow series for the natural (preimpact) flow and the postimpact flows below the Chingtan Weir under various operation scenarios.

This, again, is attributed to a lack of the environmental flow release, because such release would facilitate the spare capacity for flood attenuation. Without environmental flow releases, the reservoir level would remain higher and thus the greater spill, resulting in the less favorable values of MFA' . On the other hand, the pre- and postimpact annual maximum flows appear to be identical as demonstrated in Figure 9, resulting in a very low value of $\Delta FLD'$ ($= 0.03$). The nearly unaltered annual maximum flow below the Chingtan Weir is a combined result of the unregulated flow from the Nanshih Creek and the reservoir spill from the Peishih Creek.

4.2. Scenario 1: Optimal Operation Rules

[37] The optimal operation rules were obtained with all of the decision variables being determined by the optimization. The operational parameters so obtained, along with the corresponding optimal outcomes, are summarized in Table 3 under the title of Scenario 1. Compared to the value of $D^* = 0.560$ associated with the current rules, the optimal value of

$D^* = 0.644$ corresponding to scenario 1 exhibits a significant improvement. In contrast to the currently used value of $\lambda = 1$, the optimal value of λ for scenario 1 is considerably reduced to a value of 0.14, leading to the improved environmental flow indices but deteriorated domestic supply indices. For example, the value of $\Delta LF'$ reduces to 0.24 from the current value of 1, as revealed by Figure 6, where the annual 7-day minimum flows corresponding to scenario 1 resemble closely the preimpact values, indicating that the low-flow characteristic is well preserved. The value of $\Delta CV'$ reduces to 0.19 from the current value of 0.48 (see Figure 8), and the value of $\Delta HYG'$ slightly reduces to 0.92 from the current value of 1 (see Figure 7). The value of $\Delta FLD' = 0.03$ corresponding to scenario 1, however, remains identical to the current value (see Figure 9), as noted earlier, which is attributed to the extreme flows from the Nanshih and Peishih creeks such that no further improvement in the large-flood characteristic could be achieved. On the other hand, the value of TSR' slightly increases to 0.08 from the

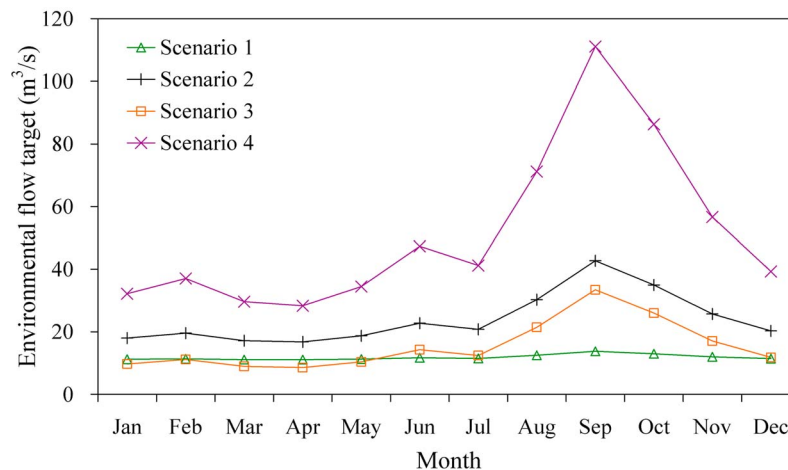


Figure 10. Optimal environmental flow targets under various operation scenarios.

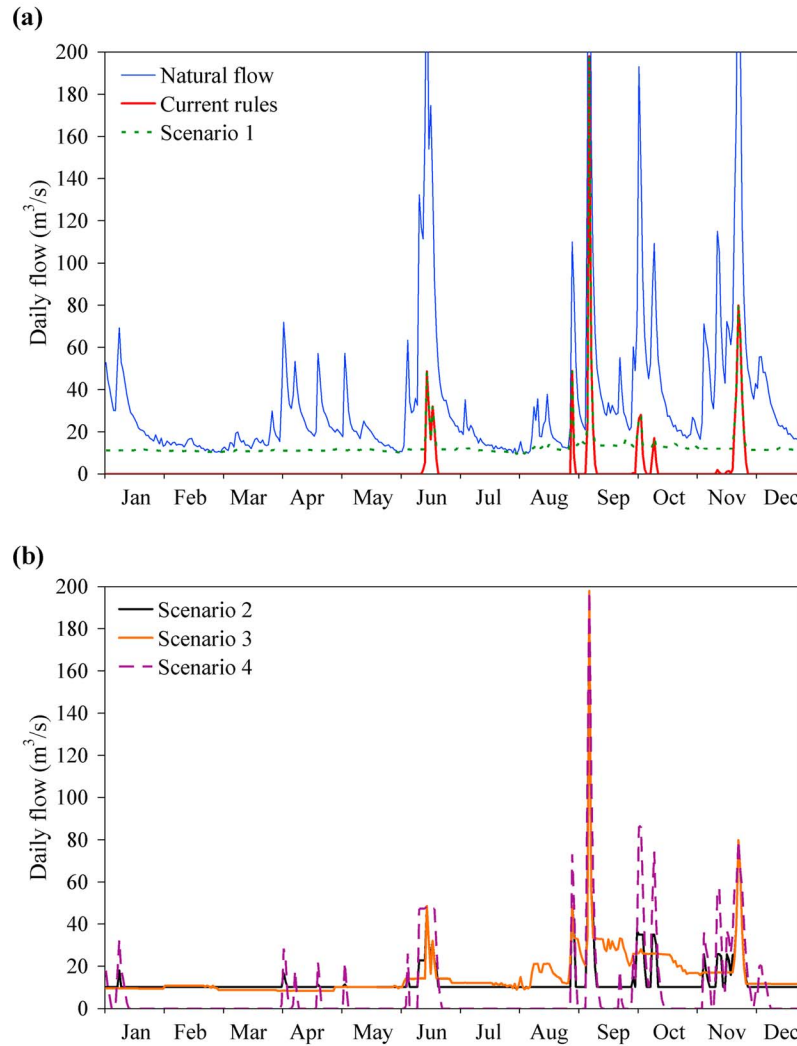


Figure 11. Natural (preimpact) daily flows and the postimpact daily flows below the Chingtan Weir under various operation scenarios (for 2003). Both the natural and postimpact maximum flows occurred on September 11, when the natural flood $460 \text{ m}^3/\text{s}$ was attenuated to the postimpact value of $198 \text{ m}^3/\text{s}$.

current null value, ADD' increases to 0.23 from the current value of 0.03, and MSR' increases to 0.47 from the current 0.23. The flood attenuation index MFA' , however, reduces to 0.35 from the current value of 0.46. This improvement is achieved thanks to the spare capacity that becomes available when the environmental flow release is implemented.

[38] The environmental flow targets associated with scenario 1 are $T_{\min} = 10.4 \text{ m}^3/\text{s}$ (upper limit) and $T_S^t = 0.8 \text{ m}^3/\text{s}$ (see Table 3). The monthly values of T_{EF}^t , derived from the ratios of T_S^t listed in Table 1, are demonstrated in Figure 10, where T_{EF}^t vary within a limited range between 11.0 and $13.8 \text{ m}^3/\text{s}$ due to the time-varying component T_S^t being much less than the constant component $T_{\min}$. As a result, the postimpact flows exhibit a relatively flat pattern in contrast to the preimpact flows, as shown in Figure 11a, where the daily flows below the Chingtan Weir are demonstrated for 2003, the driest year during the study period. Because of the top priority given to the minimum flow target $T_{\min}$, the postimpact flows corresponding to scenario 1 exhibit an improvement over the current postimpact flows in such a way that the base flow is well secured. Despite that the

postimpact hydrograph exhibits considerable deviations from the preimpact one, the pre- and postimpact annual 1-day maximum flows consistently take place on September 11, with the natural flood ($460 \text{ m}^3/\text{s}$) being attenuated to the postimpact value of $198 \text{ m}^3/\text{s}$. The daily flow deficits for the domestic supply (Figure 12), however, reveal that the water shortages associated with scenario 1 are almost entirely greater than the corresponding values associated with the current rules, with only rare exceptions found in the large floods. The coefficients of domestic release, C_{RC}^3 , C_{RC}^4 , and C_{RC}^5 , reduce to 0.6, 0.53, and 0.53, indicating that the currently used values (1, 0.9, and 0.7) become suboptimal when the environmental flows are taken into account. The maximum shortage ratio $MSR' = 0.47$, as noted earlier, corresponds to $C_{RC}^5 = 0.53$ that allows for a maximum of 47% shortage.

4.3. Scenario 2: Fully Active Strategy

[39] A fully active strategy was implemented by holding constant the value of $\lambda = 1$ in the optimization framework, such that no restrictions were imposed on the domestic

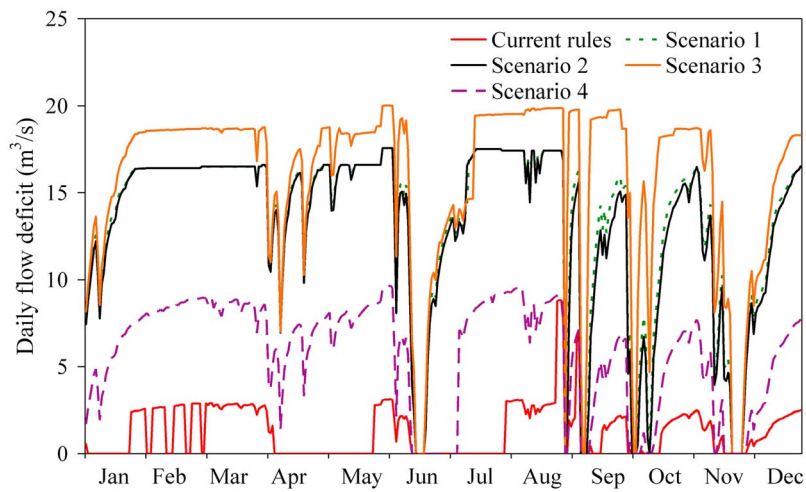


Figure 12. Daily flow deficits for domestic supply under various operation scenarios (for 2003).

demand. The top-priority minimum flow target $T_{\min}$, the second-priority monthly flow target T_S^t , and the remaining nine operational parameters were all determined by optimization. The optimal outcomes so obtained are summarized in Table 3 under the title of Scenario 2. With the specified value of $\lambda = 1$, scenario 2 exhibits a major difference from scenario 1 in the monthly flow target T_S^t , whereas the other results remain almost unaltered. For example, the value of $D^* = 0.641$ exhibits a negligible deterioration from the optimal value (0.644) obtained by scenario 1. The reservoir and environmental flow indices, minimum flow target $T_{\min}$, thresholds for flood release T_f , T_N , T_{EL} , compelling release FL , and the coefficients of domestic release all resemble the results of scenario 1. Such resemblances are also observed in Figures 6–9, where the postimpact annual 7-day minimum flows, CVs of the daily flows, 1-day maximum flows, and the monthly flow hydrographs resulting from both scenarios are similar.

[40] In response to the fact that T_S^t is treated as the second-priority demand in scenario 2, the monthly flow target T_S^t increases considerably to $7.7 \text{ m}^3/\text{s}$ from the value associated with scenario 1 ($= 0.8 \text{ m}^3/\text{s}$). The resulting monthly values of T_{EF}^t are shown in Figure 10, where scenario 2 exhibits a more fluctuating pattern than scenario 1. The elevated values of T_{EF}^t and the prioritized domestic demand jointly work to secure in scenario 2 the favorable values of reservoir and environmental flow indices and thus the overall performance index D^* . The evaluation indices are all comparable to the results of scenario 1 as evidenced by their similar patterns of postimpact daily flows and flow deficits shown in Figures 11 and 12, respectively.

[41] The similar results from scenarios 1 and 2 are also attributable to the similar values of $T_{\min}$, which is assumed a top priority and to be released unconditionally. The release of such base flow would prevent the downstream flow regime from being severely altered despite the prioritized domestic demand. An important implication revealed by Figure 10 is that the optimal environmental flow target may well be a top-priority constant base flow (scenario 1) rather than variable quantities (scenario 2) if the restrictive parameter λ is involved as a decision variable to be determined by the multicriteria optimization (scenario 1).

4.4. Scenario 3: Restrictive Strategy

[42] A restrictive strategy was implemented by assigning a null value to the minimum flow target $T_{\min}$, and the remaining eleven operational parameters were determined by the optimization. The corresponding outcome is shown in Table 3 under the title of Scenario 3, where it is revealed that the restrictive strategy would restrict the domestic demand by a vanishingly small value of $\lambda = 0.02$. The monthly flow target T_S^t is, however, further elevated to $9.7 \text{ m}^3/\text{s}$, with the overall performance index D^* being modestly deteriorated to 0.624. The negligible value of λ degrades consistently the domestic supply indices. Among the environmental flow indices, only the low-flow index $\Delta LF'$ deviates further from the natural status, as shown in Figure 6. The annual flow regime and flow variability indices $\Delta HYG'$ and $\Delta CV'$ are slightly improved, as shown in Figures 7, 8, and 11b.

[43] The monthly variation of T_{EF}^t exhibits a pattern similar to that obtained by scenario 2 (Figure 10), except that an offset is introduced by the specified null value of $T_{\min}$. The significant reduction in λ and the decreased values of C_{RC}^4 and C_{RC}^5 result in the most severe shortage of water for the domestic supply among all the scenarios tested (Figure 12). In summary, for the restrictive strategy, the negligible value of λ and the further elevated value of T_S^t jointly act to secure a modestly deteriorated overall performance, which is achieved, however, at the cost of the most severely degraded water supply performance.

4.5. Scenario 4: Partially Active Strategy

[44] A partially active strategy was implemented by holding constant the values of $\lambda = 1$ and $T_{\min} = 0$ in the optimization framework, aiming to explore how the remaining operational parameters, particularly the monthly flow target T_S^t , would react to secure the best operation performance. This scenario represents a partially active strategy because $T_{\min} = 0$ was specified, whereas T_S^t was determined by optimization. The optimal outcome associated with scenario 4 is summarized in Table 3, where T_S^t is further elevated to a high value $32.2 \text{ m}^3/\text{s}$ in response to the eliminated top-priority minimum flow target ($T_{\min} = 0$) and specified first-priority domestic demand ($\lambda = 1$). The

overall performance of scenario 4 is similar to that associated with the existing operation rules, with the value of $D^* = 0.576$ being slightly improved over the current value (0.56) thanks to the greatly elevated values of T_{EF}^t , or T_S^t (see Figure 10), leading to a moderate improvement in $\Delta CV'$ (from 0.48 to 0.32) and a slight improvement in $\Delta HYG'$ (from 1 to 0.98) as demonstrated in Figures 7, 8, and 11b.

[45] In contrast, the domestic supply indices are all slightly deteriorated from the current values, as shown in Figure 12, which is also attributable to the greatly elevated value of T_S^t . With the specifications of $\lambda = 1$ and $T_{\min} = 0$, the annual low-flow characteristic is simply a replicate of the current status (Figure 6), both with the unfavorable value of $\Delta LF' = 1$. The coefficients of domestic release are, however, similar to the values currently used, except that a smaller value of $C_{RC}^4 = 0.69$ is associated with scenario 4, implying that the current value of C_{RC}^4 (0.9) is suboptimal even for a scenario whose outcome exhibits a close resemblance to the current status.

4.6. Overall Comparison

[46] The five operational scenarios investigated herein represent typically different strategies that may be classified into two groups. The first group comprises the current operation rules and scenario 4; the second group includes scenarios 1–3. For the scenarios in the first group, the values of $\lambda = 1$ and $T_{\min} = 0$ were specified, implying that these are the domestic demand-dominated scenarios. The key difference between the two scenarios in the first group lies in a degree of freedom for T_S^t that is given to scenario 4, which would compensate for the eliminated $T_{\min}$. However, with $\lambda = 1$, the greatly elevated value of T_S^t is merely a second-priority demand in contrast to the first-priority domestic demand. As a result, the improvement achieved by scenario 4 over the existing operation rules is rather limited, implying that a significant improvement in the overall performance would be difficult when the active and restrictive parameters, $T_{\min}$ and λ , are both fully favorable to the domestic demand.

[47] For the scenarios in the second group, a degree of freedom is preserved for either the active parameter $T_{\min}$ or the restrictive parameter λ , or both. Compared to the outcomes of the first group, the environmental flow indices of the second group are considerably improved at the cost of the degraded domestic supply indices. Among all the scenarios tested, the best overall performance is associated with the optimal dual strategy (scenario 1), for which the active and restrictive parameters are both determined by optimization. The optimal environmental flow target may well be a top-priority constant base flow rather than the variable quantities if the restrictive parameter λ is involved as a decision variable in the multicriteria optimization. The fully active strategy (scenario 2) would outperform the restrictive strategy (scenario 3). The outcome of the fully active strategy exhibits a close resemblance to that of the optimal dual strategy. For the fully active strategy to be optimal, a top-priority base flow target $T_{\min}$ is essential. For the restrictive strategy, the optimal value of λ can be vanishingly small in compensation for the eliminated $T_{\min}$, thus promoting the monthly flow target T_S^t as nearly the top-priority demand. In summary, for either the active or restrictive strategy, a prioritized environmental flow demand, though inevitably deteriorating the water supply performance, would provide a

path toward the optimal overall performance of the reservoir operation.

[48] It should be noted that the large-flood index $\Delta FLD'$ remains identically as 0.03 for the five scenarios performed. Because $\Delta FLD'$ is evaluated from the pre- and postimpact 5-year floods and such floods are determined from the annual 1-day maximum flow series, the identical values of $\Delta FLD'$ appear to indicate that the large-flood characteristic is not affected much by the operation rules adopted. As noted earlier, such results stem from the fact that the post-impact flows below the Chingtan Weir are a combined result of the flows from the Nanshih and Peishih creeks. For the single annual extreme event, the postimpact flows associated with various scenarios would literally exhibit no difference because of the extreme flow from the Nanshih Creek and the large spill from the reservoir (Figure 11). Similarly, the values of MFA' remain identically as 0.35 for scenarios 1–4 because the maximum flood attenuation during the study period takes place consistently on August 24, 1996, regardless of the scenario adopted. With the reservoir inflow as high as 1060 m³/s, the minimum and monthly flow targets can be fully attained. As a consequence, the release of environmental flows would facilitate the spare capacity for a complete attenuation of the reservoir inflow (i.e., spill = 0), leading to the reduction of MFA' to 0.35 from the current value of 0.46. Moreover, the results also reveal that the thresholds for flood release, T_f and T_{EL} , in scenarios 1–4 are consistently greater than the currently used values (Table 3), whereas the compelling releases FL in these four scenarios are consistently smaller than the currently used value, which can be also taken as the benefits of releasing the environmental flows. On the basis of the flood-related evaluation indices, it can be inferred that the flood-related objectives are unlikely improved further with the modifications of the active and restrictive strategies, thus play only minor roles in the proposed multicriteria optimization.

5. Conclusions

[49] Reallocation of water resources to the existing off-stream user and newly incorporated environmental sector constitutes a difficult task that should be implemented in a balanced manner to ensure effective sharing of water. The demand management has been proposed as an alternative to promote a more balanced reallocation framework, where the reducing water demands should be shared among sectors to secure the optimal overall performance. In this paper we present a dual active-restrictive approach to devising the optimal reservoir operation rules aiming to secure off-stream water supplies while maximizing environmental benefits. For the active part, a multicomponent environmental flow target (including the base flow and monthly flow components) is incorporated into the reservoir operation rules. For the restrictive counterpart, we use a novel DPP approach to reallocating the demands of various sectors. The proposed approach is integrated with a multicriteria optimization framework to seek the optimal operation rules for the Feitsui Reservoir system under various operation scenarios.

[50] The results reveal that the best overall performance is associated with an optimal dual strategy (scenario 1) whose operational parameters are all determined by optimization. The corresponding optimal environmental flow target may well be a top-priority constant base flow rather than the

variable quantities. The results further show that the active strategy (scenario 2) would outperform the restrictive one (scenario 3). The outcomes of the active strategy resemble closely those of the optimal dual strategy. For the active strategy, a top-priority base flow target is essential, whereas for the restrictive one, the off-stream demand can become extremely small in compensation for the eliminated base flow target, promoting the monthly flow target as nearly the top-priority demand. For either the active or restrictive strategy, a prioritized environmental flow demand would provide a path toward the optimal overall performance. A significant improvement in the overall performance over the current operation rules is unlikely if the active and restrictive parameters are both favorable to the off-stream demand (scenario 4).

[51] The release of environmental flows would facilitate the spare reservoir capacity for flood attenuation. Moreover, the thresholds for flood release would become consistently greater with the inclusion of the environmental flow target, whereas the compelling releases would become consistently smaller with the modification of the operation rules, both of which can be taken as the benefits associated with the environmental flow release. However, the flood-related objectives are unlikely to be further improved with the modification of the operational rules and thus play only minor roles in the proposed optimization framework.

Notations and Abbreviations

A^t	Reservoir surface area at time t [km ²]	OBJ_i, OBJ'_i	Original and normalized values of the i th objective [original units], [–]
ADD	Mean annual deficit duration [d/yr]	OBJ^+, OBJ^-	PIS (0) and NIS (1) [–]
C	Reservoir capacity [million m ³]	$Q_{A,i}^j$	Postimpact mean flow of the j th month and i th year [m ³ /s]
$C_{RC}^1 \sim C_{RC}^5$	Coefficients of domestic release at RC zones 1 ~ 5 [–]	Q_{AD}^t	Flow diversion for domestic supply [m ³ /s]
CV	Coefficient of variation	Q_{FL}^t	Compelling release at time t [m ³ /s]
$CV_{N,i}, CV_{A,i}$	Pre- and postimpact CVs of daily flows for the i -th year [–]	Q_I^t	Reservoir inflow [m ³ /s]
D^t	Projected domestic demand [million m ³]	Q_N^t	Flow from Nanshih Creek [m ³ /s]
D_1^t, D_2^t	First- and second-priority demands [million m ³]	$Q_{N,i}^j$	Preimpact mean flow of the j th month and i th year [m ³ /s]
D^+, D^-	Weighted total distances to PIS and NIS [–]	Q_T^t	Postimpact flow below Chingtan Weir [m ³ /s]
D^*	Relative distance to D^- [–]	RC	Rule curve
DPP	Demands partitioning and prioritizing	R_D^t	Flow release for domestic demand [m ³ /s]
EFC	Environmental flow component	R_{EF}^t	Environmental flow release [m ³ /s]
E^t	Evaporation loss [million m ³]	R_F^t	Reservoir release for flood target [m ³ /s]
EL^t	Reservoir water level [m]	R_{min}^t	Reservoir release for minimum flow target [m ³ /s]
e^t	Evaporation rate [mm/d]	R_S^t	Reservoir release for monthly flow target [m ³ /s]
FL	Compelling release [m ³ /s]	RC_1^t	Upper rule curve [m]
$FLD_{5,A}$	Postimpact 5-year flood [m ³ /s]	RC_2^t	Middle rule curve [m]
$FLD_{5,N}$	Preimpact 5-year flood [m ³ /s]	RC_3^t	Lower rule curve [m]
GA	Genetic algorithm	RC_4^t	Critical rule curve [m]
IHA	Indicators of hydrologic alteration	S_D	Dead storage [million m ³]
$LF_{N,i}, LF_{A,i}$	Pre- and postimpact annual 7-day minimum flows of the i th year [m ³ /s]	S^t	Reservoir storage at time t [million m ³]
$MCDM$	Multiple criteria decision making	SP^t	Reservoir spill [m ³ /s]
MFA	Maximum flood attenuation [m ³ /s]	T_{EL}	Threshold for reservoir water level [m]
MSR	Maximum 1-day shortage ratio [%]	T_I	Threshold for reservoir inflow [m ³ /s]
N	Total number of days within study period [d]	T_{min}	Minimum flow target [m ³ /s]
NIS, PIS	Negative and positive ideal solutions	T_N	Threshold of flow from Nanshih Creek [m ³ /s]
N_Y	Number of years within study period [yr]	T_{EF}^t	Environmental flow target [m ³ /s]
		$TFRA$	Taipei Feitsui Reservoir Administration
		$TOPSIS$	Technique for Order Preference by Similarity to Ideal Solution
		T_S^t	Monthly flow target [m ³ /s]
		TSR	Long-term total shortage ratio [%]
		w_i	Weighting factor of the i th evaluation index [–]
		ΔCV	Mean difference between pre- and postimpact CVs of daily flows [–]
		$\Delta CV'$	Normalized value of ΔCV [–]
		ΔFLD	Difference between pre- and postimpact 5-year floods [m ³ /s]
		$\Delta FLD'$	Normalized value of ΔFLD [–]
		ΔHYG	Mean deviation of postimpact monthly flows from preimpact values [m ³ /s]
		$\Delta HYG'$	Normalized value of ΔHYG [–]
		ΔLF	Mean difference between pre- and postimpact annual 7-d min flows [m ³ /s]
		$\Delta LF'$	Normalized value of ΔLF [–]
		λ	Demand partitioning factor [–]
		λ_D^1, λ_D^2	First- and second-priority allocation ratios for off-stream demand [–]
		$\lambda_{EF}^1, \lambda_{EF}^2$	First- and second-priority allocation ratios for environmental demand [–]

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