

**COMPROMISE PROGRAMMING METHODOLOGY FOR
DETERMINING INSTREAM FLOW UNDER MULTIOBJECTIVE
WATER ALLOCATION CRITERIA¹***Jenq-Tzong Shiao and Fu-Chun Wu²*

ABSTRACT: This paper presents a quantitative assessment framework for determining the instream flow under multiobjective water allocation criteria. The Range of Variability Approach (RVA) is employed to evaluate the hydrologic alterations caused by flow diversions, and the resulting degrees of alteration for the 32 Indicators of Hydrologic Alteration (IHAs) are integrated as an overall degree of hydrologic alteration. By including this index in the objective function, it is possible to optimize the water allocation scheme using compromise programming to minimize the hydrologic alteration and water supply shortages. The proposed methodology is applied to a case study of the Kaoping diversion weir in Taiwan. The results indicate that the current release of 9.5 m³/s as a minimum instream flow does not effectively mitigate the highly altered hydrologic regime. Increasing the instream flow would reduce the overall degree of hydrologic alteration; however, this is achieved at the cost of increasing the water supply shortages. The effects on the optimal instream flow of the weighting factors assigned to water supplies and natural flow variations are also investigated. With equal weighting assigned to the multiple objectives, the optimal instream flow of 26 m³/s leads to a less severely altered hydrologic regime, especially for those low-flow characteristics, thereby providing a better protection of the riverine environment.

(KEY TERMS: surface water; water supply; optimization; instream flow; Range of Variability Approach (RVA); Indicators of Hydrologic Alteration (IHA); multiobjective compromise programming.)

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INTRODUCTION

Depletion of available water resources through human consumption for domestic use, irrigation, navigation, industry, hydropower, and other uses has caused significant changes in natural flow regimes and negative impacts on aquatic biota (Jackson *et al.*, 2001). Increasing efforts have been devoted to mitigating the anthropogenic impacts on water environments (Benjamin and Van Kirk, 1999; Flug *et al.*, 2000; Smith *et al.*, 2000; Wu, 2000; Cowell and Stoudt, 2002; Wu and Wang, 2002; Wu and Chou, 2003, 2004; Shiao and Wu, 2004a,b). A number of methods also have been presented to provide a better protection of the aquatic ecosystem (Jowett, 1997; Richter *et al.*, 1997; King and Louw, 1998). However, most existing protection measures are limited to assuring the minimum instream flows (Poff *et al.*, 1997; Baron *et al.*, 2002). Lately a concept called "ecologically sustainable water management" has been proposed (Richter *et al.*, 2003). The philosophy behind this concept is that human water demands should be met in a manner that sustains the integrity of the aquatic ecosystem.

To date, not many quantitative studies have addressed the problem of compromises between human water demand and instream flow requirements. The major difficulty involved stems from the quantitative assessment of the impacts of water diversions on natural hydrologic regimes. The Range of Variability Approach (RVA), proposed by Richter *et al.* (1996), offers a useful approach to quantitatively evaluating the hydrologic impacts in terms of 32

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Indicators of Hydrologic Alteration (IHAs). Shiau and Wu (2004a) have used the RVA to assess the impacts of weir flow diversion and the effects of instream flow release. Shiau and Wu (2004b) further employed a three-class evaluation system to explore the feasible combinations of flow diversion and instream flow release for a projected diversion weir. However, such an evaluation system is not applicable to an optimization model for multiobjective weir operations, primarily due to the lack of a single index for the overall hydrologic alteration. In fact, a comprehensive evaluation of the hydrologic alterations constitutes one of the most difficult tasks of an environmental impact assessment.

In this work, a quantitative assessment framework is presented to incorporate the natural flow variations into an optimization model for the multiobjective weir operation. The RVA is used to evaluate the hydrologic alterations, and the resulting 32 IHAs are integrated into a single index such that optimization of the allocation scheme among multiple conflicting objectives is made possible. The proposed methodology is applied to a case study of the Kaoping diversion weir in Taiwan that is designed to simultaneously assure the water supply reliability and sustain the natural flow variability.

CASE STUDY: KAOPING DIVERSION WEIR

The Kaoping Creek in southwestern Taiwan (Figure 1) is 171 km long and has the largest drainage area ($3,257 \text{ km}^2$) on the island. The average annual runoff is 8.5 billion m^3 . Shown in Table 1 are the monthly flow characteristics at the Lilin Bridge gauge station immediately upstream of the Kaoping diversion weir. These data demonstrate a typical streamflow pattern in southern Taiwan (i.e., a highly uneven distribution in wet and dry seasons and significant flow fluctuations).

The demands of water for various purposes in southwestern Taiwan are largely supplied by the Kaoping Creek. The Kaoping diversion weir, completed in 1999, was built to supply increasing municipal water demands. The design diversion capacity for the municipal use is $35 \text{ m}^3/\text{s}$. However, prior to the weir construction, there was a long history of agricultural water withdrawals from downstream Kaoping Creek. The registered agricultural water withdrawals total 720.6 million m^3 annually. The monthly flow diversions for the registered agricultural and projected municipal uses are summarized in Table 2, where it is shown that no flow diversions for municipal use were implemented between January and April because of the insufficient water available in the dry season

(WCA, 2000). The total projected water diversion for municipal use in the remaining months is 343 million m^3 . Since no significant amount of water is diverted from upstream of the Lilin Bridge gauge station, the daily flow records available at this station (from 1951 to 2001) are used to characterize the prediversion flow regimes, establish the evaluation criteria, and assess the impacts caused by water diversions at the Kaoping weir.

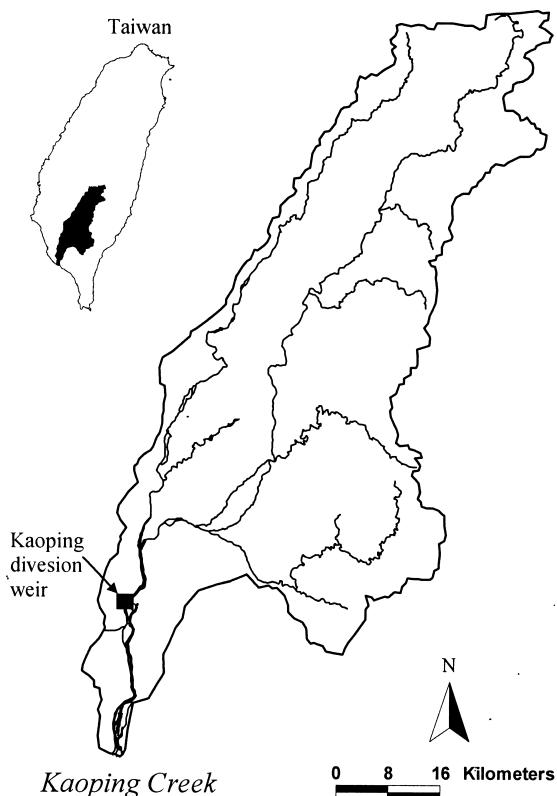


Figure 1. Location Map of Kaoping Creek Basin and Kaoping Diversion Weir.

The Kaoping Creek has been providing instream habitats for several endemic species (Fan *et al.*, 1996), such as *Sinogastromyzon puliensis* (Pulin river loach), *Cobitis taenia* (Siberian spiny loach), and *Anguilla marmorata* (Marbled eel). It is believed that the agricultural water withdrawals and municipal water diversions both considerably affect the aquatic biota downstream of the Kaoping diversion weir. The instream flow release is a measure for providing a minimum protection of the downstream riverine environments. Currently a minimum instream flow of $9.5 \text{ m}^3/\text{s}$ is released at the Kaoping diversion weir, which is the flow that is exceeded on about 95 percent of all daily flows (WCA, 2000). However, a limited amount of water release is unable to provide sufficient flow variation, given the fact that the natural

TABLE 1. Monthly Flow Characteristics of Kaoping Creek at Lilin Bridge Gauge Station (1951-2001).

| | Month | | | | | | | | | | | |
|---------|-------|-------|-------|-------|-------|--------|--------|--------|--------|-------|-------|-------|
| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| Maximum | 69.8 | 131.6 | 278.8 | 357.3 | 786.3 | 1812.8 | 1385.4 | 1958.0 | 1381.4 | 544.0 | 350.2 | 171.1 |
| Mean | 26.4 | 27.3 | 37.3 | 57.7 | 184.9 | 546.2 | 466.1 | 715.4 | 481.1 | 182.5 | 81.9 | 44.5 |
| Minimum | 2.7 | 1.2 | 2.3 | 8.2 | 13.8 | 25.1 | 25.1 | 31.0 | 87.7 | 23.5 | 18.6 | 17.5 |

Note: Unit = m³/s.

TABLE 2. Registered Agricultural Water Withdrawals and Projected Flow Diversions for Municipal Use at Kaoping Diversion Weir.

| | Month | | | | | | | | | | | |
|--|-------|------|------|------|------|------|------|------|------|------|------|------|
| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| Registered Agricultural Water Withdrawal | 22.6 | 22.5 | 22.1 | 22.1 | 22.1 | 22.2 | 22.3 | 24.4 | 23.9 | 24.3 | 22.9 | 22.8 |
| Projected Flow Diversion for Municipal Use | 0 | 0 | 0 | 0 | 6.0 | 23.1 | 23.1 | 23.1 | 23.1 | 23.1 | 5.5 | 2.5 |

Note: Unit = m³/s.

flow variability is recognized as a primary driving force for sustaining the integrity of the aquatic ecosystem (NRC, 1992; Poff *et al.*, 1997; Richter *et al.*, 2003). In this study, the hydrologic alterations caused by the current weir operation scheme are evaluated. The optimal operation schemes are then determined using the compromise programming among multiple conflicting objectives.

METHODOLOGY

Range of Variability Approach

Streamflow dominates important factors of physical habitat such as water depth and velocity. Natural flow variability facilitates the healthy riverine ecosystem, which includes a floodplain, river channel, and hyporheic zone (Poff *et al.*, 1997; Richter *et al.*, 1998). Thus, a full range of natural flow variability has been considered as a primary driving force for sustaining the integrity of a riverine ecosystem (Poff *et al.*, 1997; Richter *et al.*, 1998; Rosenberg *et al.*, 2000). The RVA is used to evaluate the hydrologic alterations caused by the flow diversions in this study. This approach is designed to manage river system operations in a manner that minimizes the impact on natural hydrologic variability, thereby minimizing the ecological impact (Richter *et al.*, 1996, 1997, 1998). The RVA assesses the anthropogenic influences on the hydrologic regimes in terms of 32 ecologically relevant IHAs

characterizing the flow magnitude, timing, frequency, duration, and rate of change. A list of the 32 IHAs is given in Table 3, where each group of IHAs has different impacts on the riverine ecosystem. For example, the first group (flow magnitude) provides a general measure of habitat availability. The life cycle of aquatic biota is intimately linked to the timing of annual extremes, which is described in the third group. A detailed description of the influences of each IHA on the riverine ecosystem can be found in Richter *et al.* (1996, 1998).

A range of variation for each IHA is determined from the predivision flows. In this study, the RVA target range for each IHA is bracketed by the 25th and 75th percentile predivision values, as suggested by Richter *et al.* (1998). Weir operations are aimed to make the post-diversion flow conditions reach the established RVA target ranges at the same frequency as that of the predivision flows. The dates of the one-day maximum and minimum flows included in Group 3 are counted from May 1 and November 1, respectively, since the wet season in Taiwan is between May and October.

Overall Degree of Hydrologic Alteration

The degree of hydrologic alteration, D , is used as a measure to quantify the deviation of the post-impact flow regime from the preimpact one (Richter *et al.*, 1998), which is defined by

TABLE 3. Indicators of Hydrologic Alteration (IHAs) Used in the Range of Variability Approach (RVA).

| IHA Group | Hydrologic Parameters |
|--|---|
| Group 1: Magnitude of Monthly Flow Conditions | Mean flow for each calendar month |
| Group 2: Magnitude and Duration of Annual Extreme Flow Conditions, and Base Flow Condition | Annual 1-day minimum flow Annual 1-day maximum flow Annual 3-day minimum flow Annual 3-day maximum flow Annual 7-day minimum flow Annual 7-day maximum flow Annual 30-day minimum flow Annual 30-day maximum flow Annual 90-day minimum flow Annual 90-day maximum flow 7-day minimum flow divided by mean flow in each year (Base flow condition) |
| Group 3: Timing of Annual Extreme Flow Conditions | Date of annual 1-day maximum flow Date of annual 1-day minimum flow |
| Group 4: Frequency and Duration of High and Low Pulses* | Number of high pulses in each year Number of low pulses in each year Mean duration of high pulse in each year Mean duration of low pulse in each year |
| Group 5: Rate and Frequency of Flow Condition Changes | Mean of all positive differences between consecutive daily flows (flow rise rate) Mean of all negative differences between consecutive daily flows (flow fall rate) Number of flow reversals |

*High and low pulses are those periods in which the daily flows are above the 75th percentile and below the 25th percentile preimpact daily flows, respectively.

$$D = \left| \frac{N_o - N_e}{N_e} \right| \times 100\% \quad (1)$$

where N_o is the observed number of post-impact years in which the hydrologic parameter in question falls within the RVA target range; and N_e is the expected number of post-impact years in which the parameter value falls within the RVA target range. N_e can be estimated using $r \times N_T$; here, r is the percentage of preimpact years in which the parameter value falls within the RVA target range; and N_T is the total number of post-impact years.

To evaluate whether a specific IHA is severely altered, the tolerance of a particular species to different degrees of hydrologic alteration should be known, but such data are very limited (Richter *et al.*, 1998). Thus, a simple three-class system is used to evaluate the severity of hydrologic alteration. Richter *et al.* (1998) suggest that the D values between 0 and 33 percent can be classified as low alteration, 33 to 67 percent as moderate alteration, and 67 to 100 percent as high alteration.

The D values of 32 IHAs offer a quantitative evaluation system for the effects of water diversions on natural flow regimes. However, a single integrated index is needed to represent the overall hydrologic alteration. Richter *et al.* (1998) used the average value of 32 degrees of alteration to provide an assessment of the overall impact. The shortcoming of this average value is that one or two high degrees of alteration could be offset by the remaining low degrees, resulting in an overall low degree of alteration, which may undermine the high impacts on some of the IHAs. Shiau and Wu (2004b) presented a three-class evaluation system that relies on the number of IHAs in each class to categorize the overall degree of alteration as low, moderate, or high without specifying a quantitative index. It is difficult to incorporate such an evaluation system into an optimization model in which the degree of hydrologic alteration is a component of the objective function. Here, a useful method is proposed to integrate 32 degrees of alteration into one single index representing the overall degree of hydrologic alteration. If all 32 IHAs belong to the low alteration category, the overall degree of hydrologic alteration D_o is calculated as

$$D_o = \frac{1}{32} \sum_{i=1}^{32} D_i \quad (2a)$$

where D_i is the D value of the i th IHA. The value of D_o so obtained lies between 0 and 33 percent, thus indicating an overall low alteration. If at least one of the 32 IHAs belongs to the moderate alteration category and none of the remaining belongs to the high alteration one, the overall degree of hydrologic alteration is calculated as

$$D_o = 33\% + \frac{1}{32} \sum_{i=1}^{N_m} (D_i - 33\%) \quad (2b)$$

where N_m is the number of IHAs belonging to the moderate alteration category; D_i is the D value of the i th moderately altered IHA. The value of D_o obtained from Equation (2b) lies between 33 and 67 percent, indicating an overall moderate alteration. If at least one IHA belongs to the high alteration category, the overall degree of hydrologic alteration is determined by

$$D_o = 67\% + \frac{1}{32} \sum_{i=1}^{N_h} (D_i - 67\%) \quad (2c)$$

where N_h is the number of IHAs belonging to the high alteration category; D_i is the D value of the i th highly altered IHA. The value of D_o obtained from Equation (2c) lies between 67 and 100 percent, indicating an overall high alteration.

As such, the overall degree of hydrologic alteration D_o is in the continuous interval of 0 to 100 percent and can be used as an index for defining the severity of the overall hydrologic alteration but is not a continuous function of its inputs. This method places much weight on the categories of high and moderate alteration, such that just one highly or moderately altered IHA would cause the overall degree of hydrologic alteration to be classified as high or moderate, respectively. Therefore, incorporating this integrated index into an optimization model that aims to minimize the overall degree of hydrologic alteration would lead to the least number of highly and moderately altered IHAs.

Weir Operation Model

The Kaoping diversion weir is built to supply the demands of water for multiple purposes. The existing registered agricultural water withdrawals should be reserved, and the projected flow diversion for

municipal uses is also a main purpose of the Kaoping diversion weir. In addition, the natural flow variations need to be sustained through the release of minimum instream flow. Therefore, the operation model of the Kaoping diversion weir includes three components – registered agricultural water withdrawals, projected flow diversion for municipal uses, and instream flow release.

The flow allocation system at the Kaoping diversion weir is illustrated in Figure 2, where Q_N^t denotes the natural (or prediversion) flow at time t , Q_D^t denotes the projected flow diversion for municipal uses at time t , Q_{DD}^t denotes the actual diversion for municipal uses at time t , Q_W^t denotes the registered agricultural water withdrawals at time t , Q_{WD}^t denotes the actual diversion for agricultural uses at time t , Q_{IF}^t denotes the instream flow release at time t , and Q_E^t denotes the post-diversion flow at time t . In this system, Q_{IF}^t is a decision variable to be specified. For simplicity, Q_{IF}^t is taken to be a constant (i.e., not varying with time t), denoted by Q_{IF} . The values of Q_D^t and Q_W^t vary monthly, as given in Table 2. In recognition of the increasing importance of environmental protection, the water allocation priorities are assumed so that the instream flow release is the highest priority for water allocation, the registered agricultural water withdrawals are the second priority, and the projected flow diversion for municipal uses is the third priority, although this assumption would not actually occur in many water rights systems. The relations among these flow variables for the assumed water allocation priorities are thus constrained by

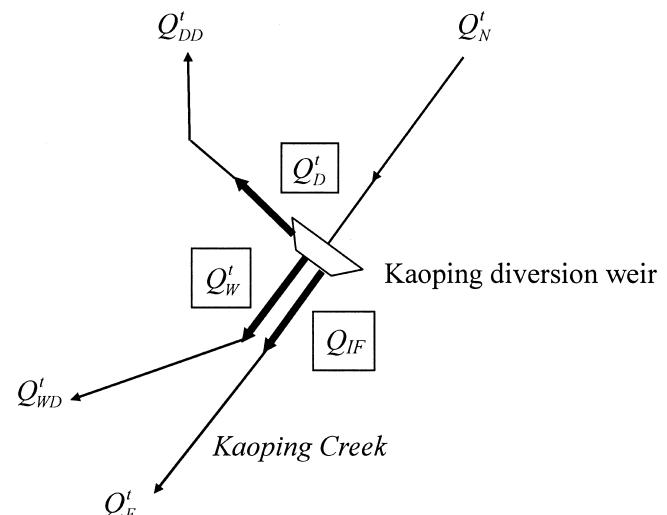


Figure 2. Definition Diagram of Flow System at Kaoping Diversion Weir. Flows in the boxes represent the registered agricultural water withdrawal (Q_W^t), projected flow diversion for municipal uses (Q_D^t), and specified value of instream flow release (Q_{IF}), respectively.

$$\left\{ \begin{array}{l} Q_E^t = Q_N^t, Q_{WD}^t = 0, Q_{DD}^t = 0 \text{ if } Q_N^t \leq Q_{IF} \\ Q_E^t = Q_{IF}, Q_{WD}^t = Q_N^t - Q_{IF}, Q_{DD}^t = 0 \text{ if } Q_{IF} < Q_N^t \leq Q_{IF} + Q_W^t \\ Q_E^t = Q_{IF}, Q_{WD}^t = Q_W^t, Q_{DD}^t = Q_N^t - Q_W^t - Q_{IF} \text{ if } Q_{IF} + Q_W^t < Q_N^t \leq Q_{IF} + Q_W^t + Q_D^t \\ Q_E^t = Q_N^t - Q_W^t - Q_D^t, Q_{WD}^t = Q_W^t, Q_{DD}^t = Q_D^t \text{ if } Q_N^t > Q_{IF} + Q_W^t + Q_D^t \end{array} \right\} \quad (3)$$

Given the values of Q_W^t , Q_D^t , and Q_{IF} , the post-diversion flow Q_E^t can be determined from Equation (3). The values of Q_E^t are then used to evaluate the degrees of hydrologic alteration on the basis of the RVA target ranges established with the prediversion flow records Q_N^t . The available daily flow records (from 1951 to 2001) at Lilin Bridge gauge station (upstream of Kaoping diversion weir) are used as the natural flows to establish the RVA targets and also as the input to the weir operation model.

Water Supply Shortages

Two goals to be achieved by the Kaoping diversion weir are to supply the registered agricultural and projected municipal water demands. In the optimization model, the water supply objective is to minimize the values of shortage ratio corresponding to these two goals. The shortage ratio is defined as the ratio of total deficit to total demand over a study period (Cancelliere *et al.*, 1998). The shortage ratio of the registered agricultural water withdrawals, SRW , is defined by

$$SRW = \frac{\sum_{t=1}^N S_W^t}{\sum_{t=1}^N Q_W^t} \quad (4)$$

where N is the total number of days in the study period; S_W^t is the shortage of the registered agricultural water withdrawals at time t , determined by

$$S_W^t = \left\{ \begin{array}{l} |Q_{WD}^t - Q_W^t|, \text{ if } Q_{WD}^t < Q_W^t \\ 0, \text{ if } Q_{WD}^t \geq Q_W^t \end{array} \right\} \quad (5)$$

The shortage ratio of the projected diversion for municipal uses, SRD , is defined by

$$SRD = \frac{\sum_{t=1}^N S_D^t}{\sum_{t=1}^N Q_D^t} \quad (6)$$

where S_D^t is the shortage of the projected diversion for municipal uses at time t , determined by

$$S_D^t = \left\{ \begin{array}{l} |Q_{DD}^t - Q_D^t|, \text{ if } Q_{DD}^t < Q_D^t \\ 0, \text{ if } Q_{DD}^t \geq Q_D^t \end{array} \right\} \quad (7)$$

Multiobjective Compromise Programming

In this work, the philosophy of river management seeks a measure that uses water resources but does not cause deterioration in the aquatic environment. In many arid regions throughout the world, water resources used by humans still take priority over maintenance of aquatic environments. Despite increased knowledge of the effects of hydrologic alteration on aquatic and riparian ecosystems, water use and management for human use continues to deteriorate aquatic and riparian environments around the world. There is now more recognition of the effects of human water use on aquatic environments, but management of water resources to benefit these environments usually only occurs after all human uses are met and only when such management does not limit water supplies. Minimizing both hydrologic impacts and water supply shortages is the operation goal for the Kaoping diversion weir, which formulates a multi-objective decision-making problem. The objective function of the weir operation can be expressed as

$$\text{Min } \{SRW, SRD, D_o\} \quad (8)$$

The values of SRW , SRD , and D_o all vary as a function of the decision variable Q_{IF} . Goicoechea *et al.* (1982) documented a number of optimization techniques for solving multicriteria problems, such as the utility function method, surrogate worth tradeoff method, weighted average method, elimination and choice translating algorithm (ELECTRE), and compromise programming. The compromise programming algorithm is adopted in this study because it is suitably accurate for the discrete problem and meanwhile sufficiently flexible for incorporating the decision makers' preferences concerning the relative importance of each operation goal (Simonovic and Burn, 1989).

Compromise programming was initially proposed by Zeleny (1973) and subsequently used by many researchers to determine the optimal reservoir operation policy (e.g., Duckstein and Opricovic, 1980; Simonovic and Burn, 1989; Simonovic *et al.*, 1992). Compromise programming identifies the optimal solution as the one that has the shortest distance to an ideal point where the multiple objectives simultaneously reach their minimal values. The ideal point is not practically achievable but may be used as a base point. Accordingly, the objective function can be rewritten as

$$\text{Min } L = \text{Min} \left[w_1^p \left(\frac{SRW^b - SRW}{SRW^b - SRW^w} \right)^p + w_2^p \left(\frac{SRD^b - SRD}{SRD^b - SRD^w} \right)^p + w_3^p \left(\frac{D_o^b - D_o}{D_o^b - D_o^w} \right)^p \right]^{1/p} \quad (9)$$

where L = distance between the ideal point (SRW^b , SRD^b , D_o^b) and (SRW , SRD , D_o). Here the superscripts b and w denote the best and worst (i.e., minimum and maximum) values, respectively. w_1 , w_2 , and w_3 are weighting factors and $w_1 + w_2 + w_3 = 1$. p is a parameter ≥ 1 ; for $p = 1$, all distances from the ideal point are equally weighted; for $p = 2$, each deviation is weighted in proportion to its magnitude; for $p = \infty$, Equation (9) becomes a min-max problem.

The objective function shown in Equation (9) can be used for the situation where different objectives are expressed in noncommensurable terms, although in this study the shortage ratio and overall degree of hydrologic alteration are both expressed in percentage. Two steps are involved in the compromise programming. The first step is to find the best and worst values of each objective within the computation domain, and the second step is to seek the optimal solution using Equation (9). The decision variable of Kaoping weir operation constitutes the computation domain, which is composed of a finite range of potential instream flow release with a constant increment. For such discrete values of instream flow release, compromise programming offers an efficient algorithm for seeking the optimal solution.

RESULTS AND DISCUSSION

In this section, the hydrologic alterations and water supply shortages associated with the current allocation scheme of the Kaoping diversion weir are evaluated. The effects of different instream flow releases and the role of weighting factors in decision making are also investigated. The optimal water allocation scheme is sought by minimizing the value of

the objective function, which is a compromised result among multiple conflicting objectives.

Hydrologic Alteration and Water Supply Shortage Under Present Operation Scheme

The current operation scheme of the Kaoping diversion weir includes the registered agricultural water withdrawals, the projected flow diversions for municipal uses, and a minimum instream flow release of 9.5 m³/s. The allocation of flow follows the operation rules given in Equation (3). The outcomes associated with the current operation scheme are summarized in Table 4. The numbers of individual IHAs classified as low, moderate, and high alteration are 18, 9, and 5, respectively. The overall degree of hydrologic alteration is 69.3 percent, classified as highly altered, which implies that the current release of 9.5 m³/s does not effectively serve to restore the natural flow variations. The value of SRW (= 17.9 percent) is greater than that of SRD (= 5.7 percent), although the registered agricultural water withdrawals are of higher allocation priorities, which is due to a much greater amount of water demanded for agricultural than municipal uses when insufficient water is available during the dry season.

As shown in Table 4, without releasing a minimum instream flow the value of D_o would be 75 percent. This reveals that the current release of 9.5 m³/s only provides a modest mitigation of hydrologic alterations and is insufficient to restore the natural flow variability. Figure 3 shows the time series of monthly flow for December and annual one-day minimum flow for the prediversion and post-diversion conditions. Without releasing a minimum instream flow, most of the monthly flows for December and annual one-day

TABLE 4. Summary of Overall Degrees of Hydrologic Alteration, Water Supply Shortage Ratios, and Values of Objective Function Corresponding to Different Instream Flow Releases.

| Instream Flow Release Q_{IF} (m ³ /s) | Overall Degree of Hydrologic Alteration D_o (percent) | Shortage Ratio of Projected Municipal Diversion SRD (percent) | Shortage Ratio of Registered Agricultural Withdrawal SRW (percent) | Values of Objective Function L | No. of IHAs | | |
|--|--|---|--|---|-------------------|------------------------|--------------------|
| | | | | | Low Alteration | Moderate Alteration | High Alteration |
| 0 | 75 | 3.5 | 7.5 | 0.333 | 16 | 4 | 12 |
| 9.5 ^a | 69.3 | 5.7 | 17.9 | 0.315 | 18 | 9 | 5 |
| 26 ^b | 34.2 | 10.8 | 34.6 | 0.232 | 29 | 3 | 0 |
| 93 ^c | 7.6 | 31.5 | 58.5 | 0.449 | 32 | 0 | 0 |

^aInstream flow release under current operation scheme.

^bOptimal instream flow release for $w_1 = w_2 = w_3 = 1/3$.

^cInstream flow release resulting in overall low degree of hydrologic alteration.

minimum flows are below the RVA lower targets, resulting in severely altered hydrologic regimes. Releasing a minimum instream flow of 9.5 m³/s makes most of the annual one-day minimum flows fall within the RVA targets, while most of the monthly flows for December are still smaller than the RVA lower target. In the next section, effects of releasing different instream flows on the hydrologic regimes and water supply shortages are further explored.

Effects of Different Instream Flow Releases

To evaluate the effects of different instream flow releases on the hydrologic alterations and water supply shortages, different values of Q_{IF} are taken in increments of 1 m³/s between 0 and 100 m³/s. The corresponding post-diversion flow series are obtained through the operation rules given in Equation (3). The resulting shortage ratios (SRW and SRD), overall degree of hydrologic alteration (D_o), and value of objective function (L) are shown in Figure 4 as a function of Q_{IF} , where different variation trends of D_o , SRW , SRD , and L are demonstrated. The value of SRW increases rapidly at smaller Q_{IF} but less rapidly at larger Q_{IF} , demonstrating an overall increase from 7.5 to 59.9 percent. The value of SRD , however, increases linearly from 3.5 to 33.5 percent. As expected, the value of D_o decreases with the increase of Q_{IF} , and two drops are observed at $Q_{IF} = 26$ and 93 m³/s. The first drop modifies the highly altered flow regime to a moderately altered one (the numbers of IHAs classified as low, moderate, and high alteration are 29, 3, and 0, respectively), while the second drop further modifies the flow regime to a low altered one (all the IHAs are classified as low alteration). The values

of D_o , SRD , and SRW corresponding to these two drops are also given in Table 4. For $Q_{IF} = 26$ m³/s, the value of $D_o = 34.2$ percent, classified as overall moderate alteration, is associated with $SRD = 10.8$ percent and $SRW = 34.6$ percent. For $Q_{IF} = 93$ m³/s, the value of D_o reduces to 7.6 percent, classified as overall low alteration, which is, however, achieved at the cost of increasing SRD to 31.5 percent and SRW to 58.5 percent.

For a given Q_{IF} , the values of D_o , SRD , and SRW are fixed (as shown in Figure 4). Thus, the value of objective function L is dependent upon the weighting factors w_1 , w_2 , w_3 and the parameter p . In Figure 4, four L curves resulting from different combinations of (w_1, w_2, w_3) , denoted by $L(w_1, w_2, w_3)$, are demonstrated. The value of p is taken to be 2, as suggested by Goicichea *et al.* (1982). Three extreme conditions ($w_1 = 1$, $w_2 = 1$, and $w_3 = 1$) and an equal weighting ($w_1 = w_2 = w_3 = 1/3$) are used to demonstrate the effect of weighting factors on the values of objective function. The L curves corresponding to the first two extreme conditions, $w_1 = 1$ and $w_2 = 1$, are the upper and lower bounds of the curve family for $w_1 + w_2 = 1$ (i.e., $w_3 = 0$), which are monotonically increasing with Q_{IF} , and the minimum value of $L (= 0)$ is associated with $Q_{IF} = 0$ m³/s. For the other extreme condition, $w_3 = 1$, the shape of the $L(0, 0, 1)$ curve is similar to that of the D_o curve (i.e., monotonically decreasing with Q_{IF} , two drops occur at $Q_{IF} = 26$ and 93 m³/s). The minimum value of $L (= 0)$ is associated with $Q_{IF} = 95$ m³/s. For the equal weighting condition, the shape of the L curve appears to be a combination of the D_o and shortage ratio curves, which demonstrates a general increasing trend with Q_{IF} ; however, two drops are also observed at $Q_{IF} = 26$ and 93 m³/s. The minimum value of the $L(1/3, 1/3, 1/3)$ curve is 0.232, which

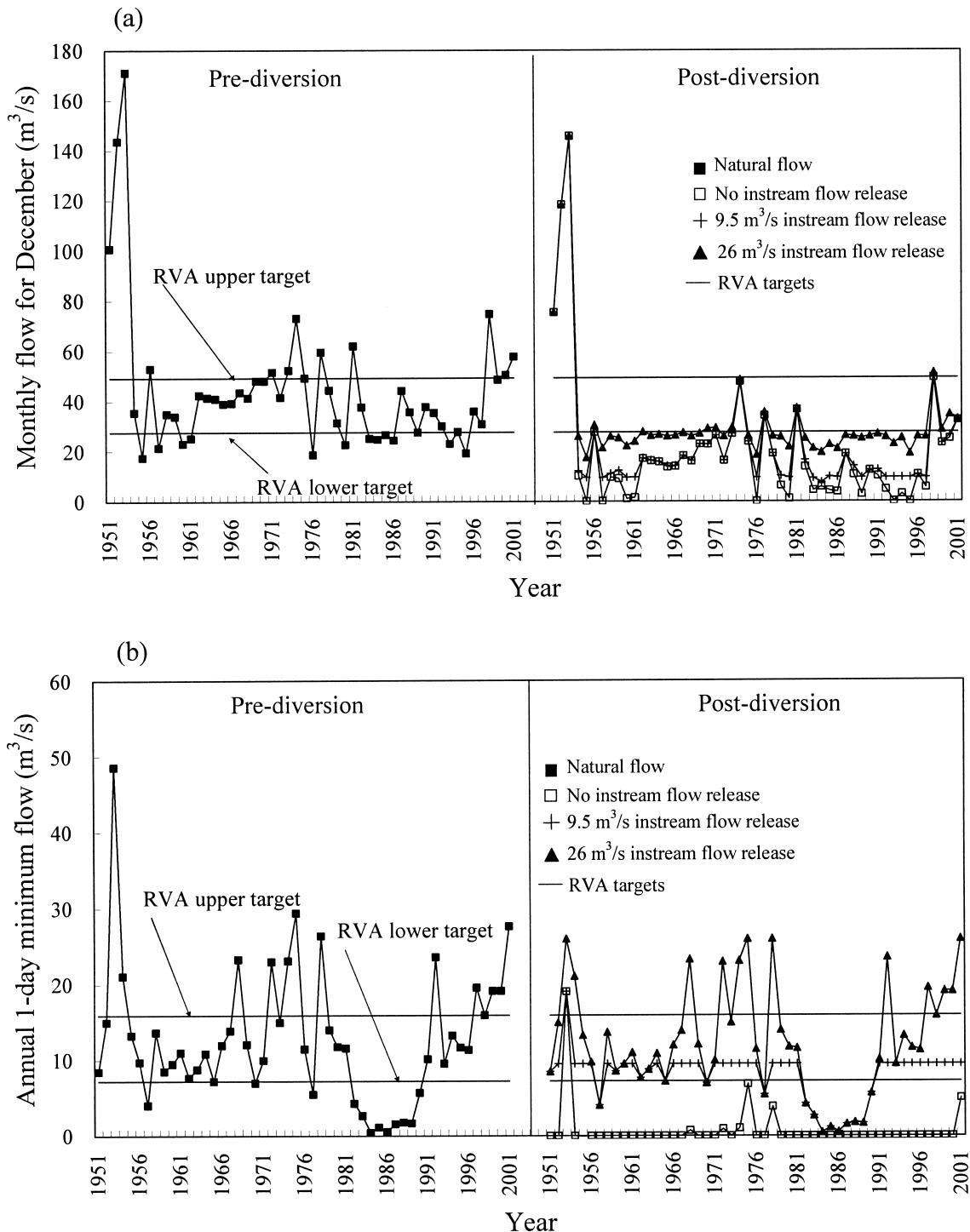


Figure 3. Time Series of (a) Monthly Flow for December and (b) Annual One-Day Minimum Flow for Predivision and Post-Division Conditions.

occurs at an optimal value of $Q_{IF} = 26 \text{ m}^3/\text{s}$. The post-diversion time series of monthly flow for December and annual one-day minimum flow under the release of this optimal Q_{IF} are also shown in Figure 3. The post-diversion annual one-day minimum flows are almost identical with the predivision values, while

the post-diversion monthly flows of December remain moderately altered despite the release of optimal Q_{IF} . Such results are consistent with the previous finding that monthly mean flows in the dry season are easily affected by the flow diversions but more difficult to restore (Shiau and Wu, 2004b).

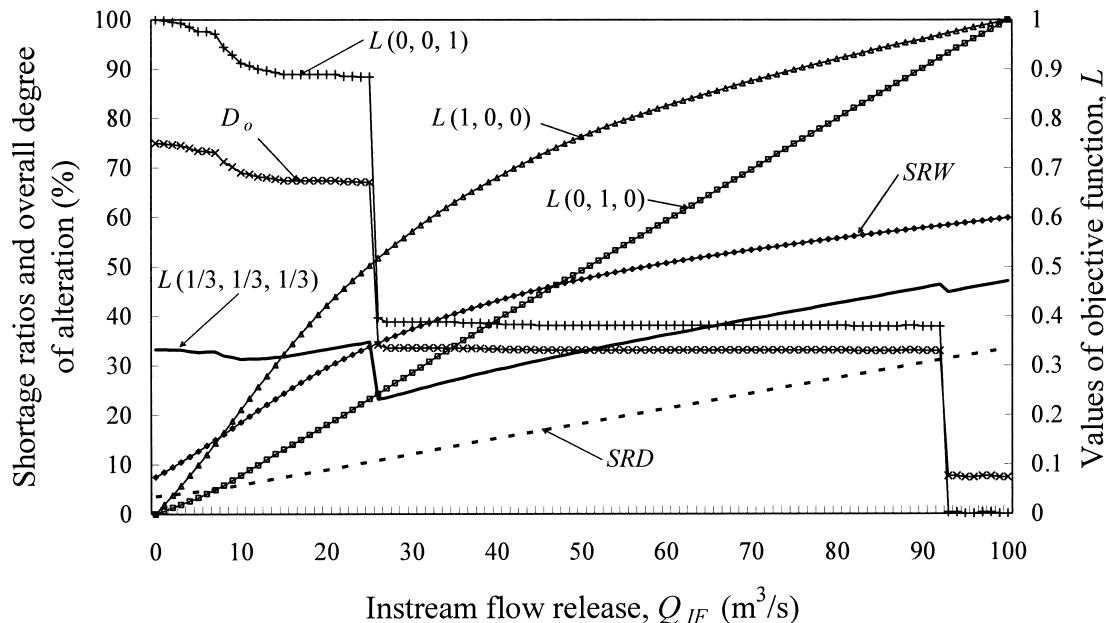


Figure 4. Shortage Ratio of Projected Flow Diversions for Municipal Use, SRD ; Shortage Ratio of Registered Agricultural Water Withdrawals, SRW ; Overall Degree of Hydrologic Alteration, D_o ; and Values of Objective Function, L ; All Varying as a Function of Instream Flow Release, Q_{IF} .

Effects of Weighting Factors on Optimal Q_{IF} and Minimum L

The effects of weighting factors on the optimal Q_{IF} and minimum L are further investigated. For each combination of (w_1, w_2, w_3) , a minimum value of L can be found by Equation (9), and the corresponding optimal Q_{IF} can be obtained. The contour plots of the optimal Q_{IF} and minimum L corresponding to various combinations of w_1 and w_2 are demonstrated in Figure 5, where the value of w_3 is not shown because it can be obtained by $1 - (w_1 + w_2)$. The contour plots of the resulting SRD , SRW , and D_o have variation patterns similar to that shown in Figure 5(a) (i.e., approximately symmetric about the 45 degrees diagonal and thus not shown here). It is revealed in Figure 5(a) that the optimal values of Q_{IF} are consistently zero for $w_1 + w_2 = 1$ (i.e., $w_3 = 0$), indicating that no water would be allocated to the instream flow release if a zero weighting is assigned to D_o . The values of SRD , SRW , and D_o associated with $Q_{IF} = 0 \text{ m}^3/\text{s}$ are 3.5 percent, 7.5 percent, and 75 percent, respectively. The optimal value of Q_{IF} increases as the values of w_1 and w_2 decrease (i.e., as the value of w_3 increases). For a full weighting of D_o (i.e., $w_3 = 1$), the optimal value of Q_{IF} would be $95 \text{ m}^3/\text{s}$, and the corresponding values of SRD , SRW , and D_o are 32 percent, 59 percent, and 7.4 percent, respectively. Three classes of D_o associated with the optimal Q_{IF} are also

demonstrated in Figure 5(a), where the region of high D_o corresponds to the values of Q_{IF} is less than $26 \text{ m}^3/\text{s}$, the region of low D_o corresponds to the values of Q_{IF} greater than $93 \text{ m}^3/\text{s}$, and the region of moderate D_o corresponds to the values of Q_{IF} between 26 and $93 \text{ m}^3/\text{s}$. Such results are consistent with the variations of D_o curve shown in Figure 4, given the fact that D_o is a function of Q_{IF} but not the weighting factors. However, for those combinations of greater w_1 and w_2 (smaller w_3) that result in the optimal Q_{IF} less than $26 \text{ m}^3/\text{s}$, to obtain the outcomes associated with moderate or low D_o would be impossible. Similarly, for those combinations of smaller w_1 and w_2 (greater w_3) that lead to the optimal Q_{IF} greater than $93 \text{ m}^3/\text{s}$, it would be unlikely to obtain the outcomes associated with moderate or high D_o . In this sense, the weighting factors indirectly affect the value of D_o through the selection of optimal Q_{IF} .

The contour plot of the value of objective function L associated with the optimal Q_{IF} is demonstrated in Figure 5(b), where it is found that the global minimum value of L ($= 0$) occurs for $w_1 + w_2 = 1$ (i.e., $w_3 = 0$) and $w_3 = 1$. These two extreme conditions correspond to a zero and a full weighting of D_o , respectively. For $w_3 = 0$ (i.e., $w_1 + w_2 = 1$), the optimal Q_{IF} would be $0 \text{ m}^3/\text{s}$, and the resulting SRD and SRW are both the minimum (the best) values, leading to a minimum value of L ($= 0$). For $w_3 = 1$ (i.e., $w_1 = w_2 = 0$), the optimal Q_{IF} equals $95 \text{ m}^3/\text{s}$ and the resulting D_o is the minimum value, which would also lead to a minimum

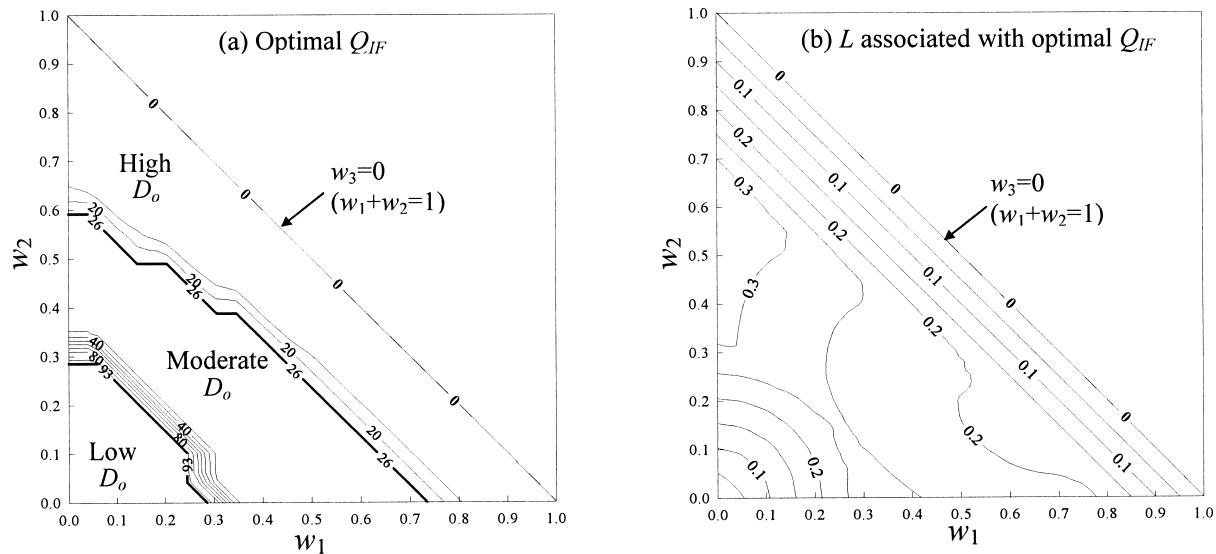


Figure 5. Contour Plots Showing (a) Optimal Q_{IF} (m^3/s), and (b) Values of Objective Function L Associated with Optimal Q_{IF} for Various Combinations of w_1 and w_2 .

value of L ($= 0$). These results indicate that the global minimum L can be achieved only if a zero or full weighting is assigned to D_o . The former represents an attitude in favor of water supplies only; the latter represents an attitude toward sustaining the fully natural flow variability. These extreme attitudes for decision making, however, violate the compromise among conflicting objectives. Nonzero weighting factors should be used if multiple conflicting criteria are to be met simultaneously, which is, however, achieved at the cost of degrading the value of objective function. For example, when $w_1 = w_2 = w_3 = 1/3$ are employed to equally weight SRW, SRD, and D_o , the optimal Q_{IF} would be $26 m^3/s$ and the corresponding value of L would increase to 0.232. By doing so, some disputable results can be avoided, although none of the resulting SRW, SRD, and D_o would be the best (or minimum) values. The values of weighting factors w_1 , w_2 , and w_3 can be specified according to the decision maker's preference.

Ecological Effects of Proposed Instream Flow Release

Currently the data available from the biological monitoring program of Kaoping Creek are limited. However, the impacts of hydrologic alterations on aquatic biota are well documented in the literature. For example, Ligon *et al.* (1995) indicate that declined salmon population was observed in the Mckenzie River (USA), caused by the reduced peak flows resulting from upstream flood-control dams. Koel and Sparks (2002) report that the hydrologic regime of the

Illinois River (USA) altered by the navigation had caused a dramatic decline in fisheries resources. Their results also reveal that the reversals in water surface elevation, maximum stage level, and length of spring flood were the most important factors influencing the abundance of age-zero fishes, such as small-mouth buffalo, black crappie, freshwater drum, and white bass. Extence *et al.* (1999) and Wright *et al.* (2004) have pointed out that the low flows during prolonged drought had significant impacts on the population size of the macroinvertebrates.

Although the species in the Kaoping Creek are different from those mentioned above, the impacts on aquatic biota of the hydrologic alterations should be similar. Without the instream flow releases, the low flow characteristics would significantly deteriorate from the reduction of flow magnitudes during the low flow season (demonstrated in Figure 3) and extension of the low flow durations. The proposed optimal instream flow release is not to fully restore the altered hydrologic regime to the prediversion condition. It is, however, to mitigate the negative impacts in a way that the number of highly and moderately altered IHAs can be minimized. As such, it provides a better protection of the riverine ecosystem than the current scheme.

CONCLUSIONS

In this work, an RVA-based assessment framework incorporating the natural flow variability into the

multiobjective weir operation is presented. The individual degrees of alteration associated with the 32 IHAs are integrated into an overall degree of hydrologic alteration. With this index included in the objective function, optimization of the weir operation scheme is made possible through compromise programming that involves the hydrologic alteration and water supply shortages. The proposed methodology is applied to a case study of the Kaoping diversion weir in Taiwan. The results indicate that the current release of 9.5 m³/s as a minimum instream flow does not effectively restore the natural flow variations. Increasing the amount of instream flow release would reduce the overall degree of hydrologic alteration; however, this is achieved at the cost of increasing the water supply shortage ratios. With equal weighting assigned to the natural flow variability and water supply reliability, the optimal instream flow release of 26 m³/s leads to a less severely altered hydrologic regime, especially for those low flow characteristics. It is believed that this optimal scheme provides a better protection of the riverine ecosystem than the current scheme.

The current RVA aims to minimize the degree of hydrologic alteration, which is considered equivalent to minimizing the ecologic impacts. The improvement on riverine environment made by the proposed instream flow release is achieved in terms of a smaller value of overall degree of hydrologic alteration and a smaller number of severely altered IHAs, but not in terms of the biological consequences. In the future a biological component should be incorporated into the RVA and the multiobjective optimization model.

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