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# A DYNAMIC CORRIDOR-SEARCHING ALGORITHM TO SEEK TIME-VARYING INSTREAM FLOW RELEASES FOR OPTIMAL WEIR OPERATION: COMPARING THREE INDICES OF OVERALL HYDROLOGIC ALTERATION

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## ABSTRACT

A full range of natural flow regime has been widely recognized as a primary driving force for sustaining the integrity of a riverine ecosystem. Existing instream flow methods strive to assure a constant minimum flow but not the natural flow variability. We present in this paper a dynamic corridor-searching algorithm to seek the optimal time-varying scheme for instream flow releases. A compromise programming (CP) is employed to search the optimal solution of an objective function aggregating the ecosystem and human needs objectives. The ecosystem need objective is represented by an overall index of hydrologic alteration, which integrates 32 indicators of hydrologic alteration (IHA) derived from the range of variability approach (RVA). The human need objectives are expressed by shortage ratios for the agricultural and municipal water supplies. The proposed method is applied to a weir operation in Taiwan. Three approaches to evaluating the overall degree of hydrologic alteration (i.e., the three-class, fuzzy-based, and overall-mean approaches) are compared here. The results show that the time-varying schemes improve the human need objective, but only slightly deteriorate the ecosystem need objective. Such advantages increase with the time-varying frequency. For the wet periods, smaller flow releases may be prescribed; for the dry periods, however, greater releases must be specified to secure a lower degree of overall hydrologic alteration. It is also revealed that use of the three-class approach to evaluate the overall hydrologic alteration facilitates to eliminate highly altered IHA and maintain those low-flow characteristics subtle to flow diversions. However, such outcomes are achieved at the cost of greater deficits for human water demands. 

KEY WORDS: instream flow; dynamic corridor-searching algorithm; indicators of hydrologic alteration (IHA); range of variability approach (RVA); compromise programming (CP)

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## INTRODUCTION

Increases in water demands due to rapid economic and population growths have led to installations of many water-resource facilities in Taiwan. Currently a total of 79 dams and diversion weirs are in service for the purposes of irrigation, power generation, industrial and domestic water supplies (Water Conservancy Agency, 2001). The impacts of these facilities on riverine ecosystems have recently received extensive attention (e.g., Wu, 2000; Wu and Wang, 2002; Wu and Chou, 2003, 2004). Establishment of the standards for instream flow releases is mandated by the governmental agencies as a requirement for licensing. Existing methods for evaluating the instream flow needs, such as $Q_{95}$ and $0.3\,m^3s^{-1}$ per $100\,km^2$ (Water Resources Bureau, 2001), seek to assure a minimum instream flow but not to maintain the variation patterns of natural flows. In fact, a full range of natural flow regime has been widely recognized as a primary driving force for sustaining the integrity of a riverine ecosystem (Karr, 1991; Poff *et al*., 1997; Rosenberg *et al*., 2000; Richter *et al*., 2003).

The natural hydrologic regime comprises five key components of variability, namely, magnitude, duration, timing, frequency, and rate of change (Richter *et al*., 1996; Poff *et al*., 1997). Based on this, Richter *et al*. (1997) proposed a range of variability approach (RVA) using 32 indicators of hydrologic alteration (IHA). The flow-based

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management targets for 32 IHA are established in a manner that minimizes anthropogenic influences, thereby minimizes the ecological impacts. Applications of the RVA in water resources management can be found in Maingi and Marsh (2002), Koel and Sparks (2002), Taylor *et al*. (2003), and Irwin and Freeman (2002), among many others. Shiau and Wu (2004a) used the RVA to assess the hydrologic alterations caused by the Chi-Chi diversion weir on Chou-Shui Creek (Taiwan) and evaluate the effect of a proposed water release scheme on restoring the natural flow regime. Shiau and Wu (2004b) also employed a three-class evaluation system to explore feasible combinations of flow diversion and water release for the proposed Taitung weir in Taiwan. Shiau and Wu (2006) further presented a three-class approach for combining individual degrees of hydrologic alteration and incorporated this integrated index in a compromise programming to seek the optimal scheme of constant release.

To date many efforts have been devoted to establishing the standards for a constant instream flow release. The major drawback of a constant release scheme stems from a lack of flexibility to adapt to the natural flow regime, which would significantly degrade the efficiency of water supplies. In this study we use a dynamic corridor-searching algorithm to seek the optimal time-varying schemes for instream flow release. The proposed method is applied to optimization of a weir operation. Three different approaches to evaluating the overall degree of hydrologic alteration are presented. The optimal time-varying schemes resulting from these approaches are compared.

## CASE STUDY—KAOPING DIVERSION WEIR

### *Overview*

The Kaoping Creek originates from the Jade Mountain, wanders southwestward, and discharges into the Taiwan Strait (Figure 1). The total length of the Kaopin Creek is 171 km, with the largest drainage area of 3,257 $km^2$ in Taiwan. The downstream alluvial Pingtung Plain, irrigated with the surface and subsurface water resources, has

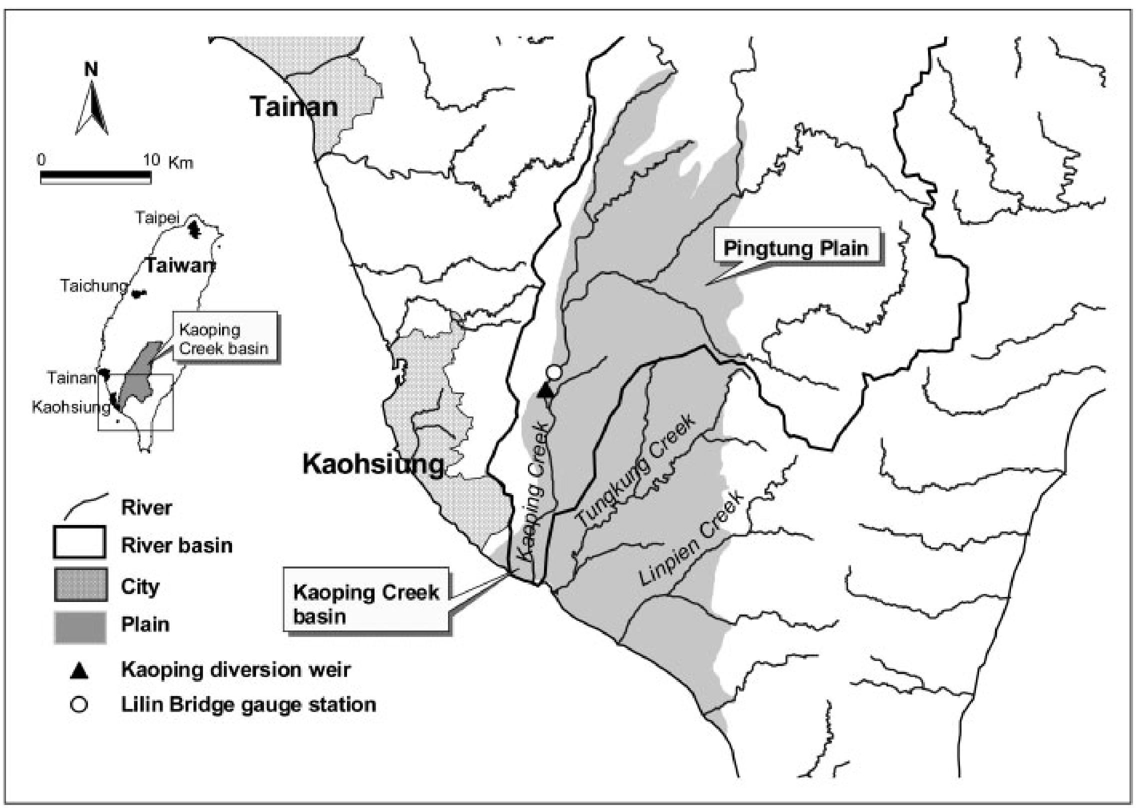


Figure 1. Location map of Kaoping Creek and Kaoping diversion weir



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Table I. Monthly flow characteristics at Lilin Bridge gauge station (1951–2001), registered agricultural water needs and projected municipal water demands at Kaoping diversion weir (units in $m^3s^{-1}$)

| | January | February | March | April | May | June | July | August | September | October | November | December |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Maximum flow | 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 flow | 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 flow | 2.7 | 1.2 | 2.3 | 8.2 | 13.8 | 25.1 | 25.1 | 31.0 | 87.7 | 23.5 | 18.6 | 17.5 |
| Registered agricultural water need | 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 municipal demand | 0 | 0 | 0 | 0 | 6.0 | 23.1 | 23.1 | 23.1 | 23.1 | 23.1 | 5.5 | 2.5 |

long been an important agricultural area. However, the overdraft of groundwater, mainly for domestic, agricultural, and aquacultural uses, had caused severe land subsidence and saltwater intrusion in the coastal region. Installation of the Kaoping diversion weir was proposed for replacing the groundwater use and meeting future municipal water demands (Water Conservancy Bureau, 1992).

The Kaoping diversion weir was completed in 1999, with a design capacity of 35 $m^3s^{-1}$ for supplying municipal water demands. The weir site is located at the midstream Kaoping Creek (Figure 1), with a mean annual runoff of 8,500 million $m^3$. Shown in Table I are the monthly flow characteristics at the Lilin Bridge gauge station located at immediately upstream of the Kaoping diversion weir. These data demonstrate a typical streamflow pattern in southern Taiwan, that is, an uneven and highly fluctuating distribution (Water Resources Bureau, 1999). Prior to installation of Kaoping diversion weir, there had been a long history of agricultural water withdrawals from the Kaoping Creek. The registered agricultural water rights sum up to 720.6 million $m^3$ per year (Table I). In addition to the existing agricultural water supply, the Kaoping diversion weir is also aimed to supply the projected municipal water demands, which remain zero in January to April because of insufficient water available in the dry season (Water Conservancy Agency, 2000).

It is generally believed that water withdrawals would affect the aquatic ecosystem downstream of the Kaoping diversion weir (Water Resources Bureau, 2001). Releases of a minimum instream flow are considered as a mitigation measure providing minimal protections. Currently a constant flow of 9.5 $m^3s^{-1}$ is released for the instream needs, which approximately equals to the 95th-percentile daily flow (Water Conservancy Agency, 2000). Such limited amount of water release is, however, unable to create sufficient variations for retaining the ecosystem integrity (Shiau and Wu, 2006). Recognizing the importance of natural flow variations, the optimal operation of the Kaoping diversion weir seeks to meet the agricultural water needs, projected municipal water demands, and targeted flow variability. Since the post-diversion flows vary as a function of the prescribed minimum instream flows, a weir operation model is used to simulate the post-diversion flows, as described below.

### *Weir operation model*

Operation of the Kaoping diversion weir is modeled with the flow system depicted in Figure 2, where three criteria are considered at time *t*, which include the agricultural water needs $Q_W^t$, municipal water demands $Q_D^t$, and minimum instream flows $Q_{\mathrm{IF}}^t$. The natural (or pre-diversion) flow is denoted by $Q_N^t$; the flow actually diverted for agricultural use is denoted by $Q_{\mathrm{WD}}^t$, the flow actually diverted for municipal use is denoted by $Q_{\mathrm{DD}}^t$, and the effluent (or post-diversion) flow is denoted by $Q_E^t$. The water demands $Q_W^t$ and $Q_D^t$ vary monthly, as shown in Table I; the minimum instream flow $Q_{\mathrm{IF}}^t$ is a decision variable to be prescribed. The operation rules are given by

$$\begin{cases} Q_E^t = Q_N^t,\ Q_{\mathrm{WD}}^t = 0,\ Q_{\mathrm{DD}}^t = 0 \text{ if } Q_N^t \le Q_{\mathrm{IF}}^t \\ Q_E^t = Q_{\mathrm{IF}}^t,\ Q_{\mathrm{WD}}^t = Q_N^t - Q_{\mathrm{IF}}^t,\ Q_{\mathrm{DD}}^t = 0 \text{ if } Q_{\mathrm{IF}}^t < Q_N^t \le Q_{\mathrm{IF}}^t + Q_W^t \\ Q_E^t = Q_{\mathrm{IF}}^t,\ Q_{\mathrm{WD}}^t = Q_W^t,\ Q_{\mathrm{DD}}^t = Q_N^t - Q_W^t - Q_{\mathrm{IF}}^t \quad \text{if} \quad Q_{\mathrm{IF}}^t + Q_W^t \le Q_N^t \le Q_{\mathrm{IF}}^t + Q_W^t + Q_D^t \\ Q_E^t = Q_N^t - Q_W^t - Q_D^t,\ Q_{\mathrm{WD}}^t = Q_W^t,\ Q_{\mathrm{DD}}^t = Q_D^t \quad \text{if} \quad Q_N^t > Q_{\mathrm{IF}}^t + Q_W^t + Q_D^t \end{cases} \tag{1}$$



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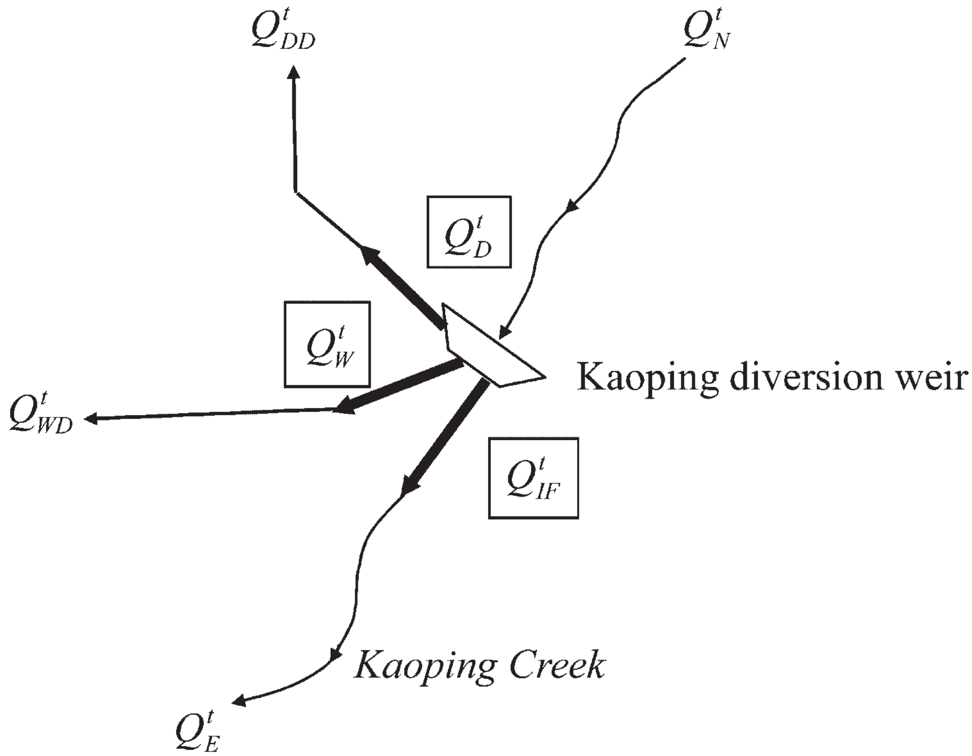


Figure 2. Flow system for Kaoping diversion weir operation. Flows in the boxes denote the registered agricultural water needs ($Q^t_W$), projected municipal demands ($Q^t_D$), and minimum instream flow releases ($Q^t_{IF}$); $Q^t_N$ and $Q^t_E$ denote the pre- and post-diversion flows, respectively; $Q^t_{WD}$ denotes the flows actually diverted for agricultural use; $Q^t_{DD}$ denotes the flows actually diverted for municipal use

The daily flow data at the Lilin Bridge gauge station are used as the pre-diversion flow series $Q^t_N$. The post-diversion flow series $Q^t_E$ determined from Equation (1) are then used to evaluate the hydrologic alteration.

*Water shortage index*

The shortage ratio, defined by Cancelliere *et al*. (1998) as the ratio of total deficit to total demand, is employed here to evaluate the water-supply performance. The shortage ratios for the agricultural and municipal water demands, respectively denoted as SRW and SRD, are evaluated by

$$\mathrm{SRW} = \frac{\sum_{t=1}^{N} \left|\min\{Q^t_{WD} - Q^t_W, 0\}\right|}{\sum_{t=1}^{N} Q^t_W} \times 100\% \tag{2a}$$

$$\mathrm{SRD} = \frac{\sum_{t=1}^{N} \left|\min\{Q^t_{DD} - Q^t_D, 0\}\right|}{\sum_{t=1}^{N} Q^t_D} \times 100\% \tag{2b}$$

where $N$, total number of days in the study period.



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## METHODS

### *Range of variability approach (RVA)*

The natural flow variability is an essential element for maintaining the integrity of a riverine ecosystem. The RVA (Richter *et al*., 1996, 1997, 1998) is employed in this study to evaluate the hydrologic alterations induced by flow diversions. A total of 32 IHA (Table II), grouped by five flow characteristics (i.e., magnitude, duration, timing, frequency, and rate of change), are used in this approach. Each IHA is ecologically relevant. For example, the extreme flows provide a general measure of the conditions that structure channel forms and physical habitats. The exchange of nutrient between the river channel and floodplains is intimately linked to the frequency and duration of high and low pulses. For more details, the readers are referred to the original work (Richter *et al*., 1997).

A targeted range of variation for each IHA is determined from the pre-impact flow data. Following Richter *et al*. (1998), in this study the target range is bracketed by the 25th- and 75th-percentile pre-impact values, implying that 50% of the pre-impact values would fall in this range. The operation goal is to allow the post-diversion flows attain the target ranges at the same frequency as for the pre-diversion flows.

The degree of alteration for the $i$-th IHA, denoted as $D_i$, is defined to quantify the deviation of the post-diversion flows from the pre-impact status:

$$D_i = \left| \frac{N_{o,i} - N_e}{N_e} \right| \times 100\% \tag{3}$$

where $N_{o,i}$, observed number of the post-impact years in which the $i$-th IHA falls in the target range; $N_e$, expected number of the post-impact years in which the IHA fall in the target ranges, $N_e = N_T \times r$, where $N_T$, total number of

Table II. Indicators of hydrologic alteration (IHA) used in range of variability approach (RVA)

| IHA group | Indicators |
|---|---|
| Group 1: magnitude of monthly flows | Mean flow of each calendar month |
| Group 2: magnitude and duration of annual extreme flows, 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 |
| | Annual 7-day minimum flow divided by annual mean flow (Base flow condition) |
| Group 3: timing of annual extreme flows | 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 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- and below the 25th-percentile pre-impact daily flows, respectively.



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the post-impact years, $r$, frequency of the pre-impact years in which the IHA fall in the RVA target ranges (=50% in this study). Richter *et al*. (1998) further suggested a simple three-class evaluation system for individual IHA, in which the values of $D_i$ ranging between 0% and 33% are classified as low alteration, 33%–67% as moderate alteration, and 67%–100% as high alteration.

*Overall degree of hydrologic alteration*

The value of $D_i$ offers a quantitative measure for assessing individual impacts of water diversion. A single integrated index rather than 32 individual values of $D_i$ is, however, needed for quantifying the overall extent of hydrologic alteration. Such an index can be further incorporated into the objective function of an optimization model. Here we propose three different methods, namely, three-class, fuzzy-based, and overall-mean approaches, for combining 32 values of $D_i$ as an overall degree of hydrologic alteration.

*Three-class approach.* Shiau and Wu (2004b) presented a discreet three-class system for evaluating overall hydrologic alteration based on the number of IHA classified in each alteration category. Shiau and Wu (2006) later proposed a modified approach to combining individual values of $D_i$ as a single index of overall hydrologic alteration. In the modified system, if all IHA are classified as lowly altered (i.e., $D_i < 33\%$), then the overall degree of hydrologic alteration, $D_T$, is given by

$$D_T = \frac{1}{32}\sum_{i=1}^{32} D_i \tag{4a}$$

The value of $D_T$ so obtained ranges between 0% and 33%, indicating an overall low alteration. If the most severely altered IHA is classified as moderate alteration (i.e., $33\% < D_i < 67\%$), then the overall degree of hydrologic alteration is given by

$$D_T = 33\% + \frac{1}{32}\sum_{i=1}^{N_m} (D_i - 33\%) \tag{4b}$$

where $N_m$, number of IHA classified as moderately altered. The value of $D_T$ so obtained ranges between 33% and 67%, indicating an overall degree of moderate alteration. If at least one IHA is classified as highly altered (i.e., $D_i > 67\%$), then the overall degree of hydrologic alteration is given by

$$D_T = 67\% + \frac{1}{32}\sum_{i=1}^{N_h} (D_i - 67\%) \tag{4c}$$

where $N_h$, number of IHA classified as highly altered. The value of $D_T$ so obtained ranges between 67% and 100%, thus indicating an overall degree of high alteration. This three-class approach places much weighting on the high alteration category, such that only one highly altered IHA would make the overall degree of hydrologic alteration $D_T$ classified as high.

*Fuzzy-based approach.* The fuzzy theory allows an object to belong partly to a category and partly to another (Zadeh, 1965). The degrees of belongingness to these categories are measured using the membership numbers ranging between 0 and 1 with a sum to unity. The proposed fuzzy-based system uses the trapezoidal membership functions to quantify the belongingness of $D_i$ to low, moderate, and high alteration categories (Figure 3), as given by

$$\mu_{L,i} = \begin{cases} 100\% & \text{if} D_i \le 20\% \\ \left(2 - \frac{D_i}{20\%}\right) \times 100\% & \text{if } 20\% < D_i \le 40\% \\ 0\% & \text{if } D_i > 40\% \end{cases} \tag{5a}$$



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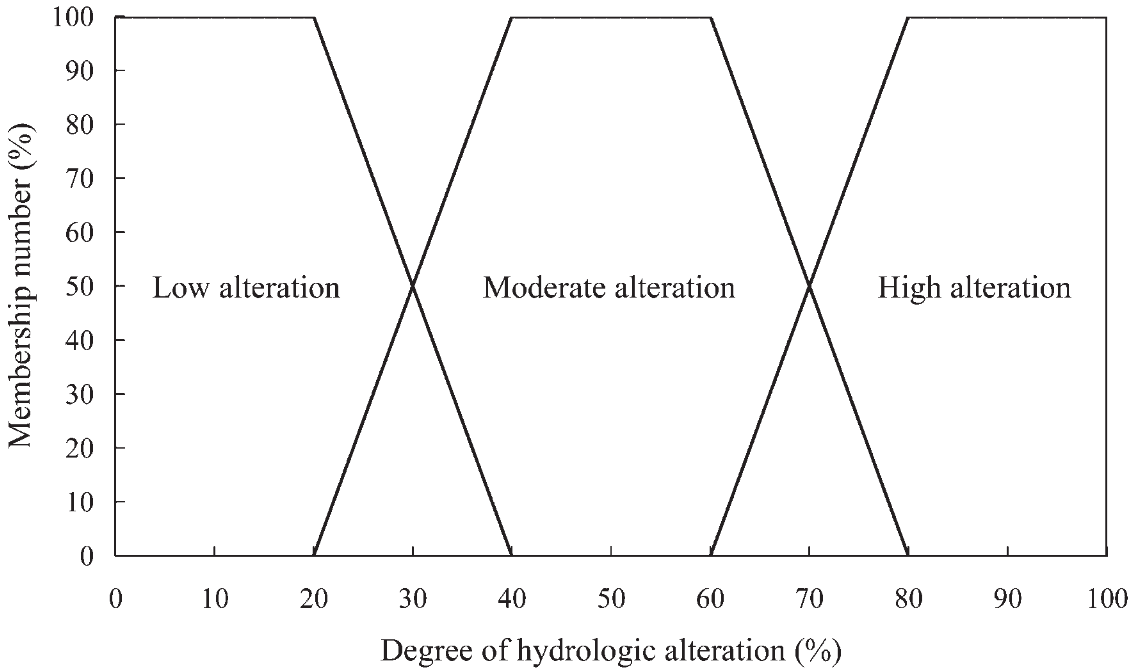


Figure 3. Fuzzy membership functions for low, moderate, and high alteration categories

$$\mu_{M,i} = \begin{cases} 0\% & \text{if } D_i \leq 20\% \\ \left(\frac{D_i}{20\%} - 1\right) \times 100\% & \text{if } 20\% < D_i \leq 40\% \\ 100\% & \text{if } 40\% < D_i \leq 60\% \\ \left(4 - \frac{D_i}{20\%}\right) \times 100\% & \text{if } 60\% < D_i \leq 80\% \\ 0\% & \text{if } D_i > 80\% \end{cases} \tag{5b}$$

$$\mu_{H,i} = \begin{cases} 0\% & \text{if } D_i \leq 60\% \\ \left(4 - \frac{D_i}{20\%}\right) \times 100\% & \text{if } 60\% < D_i \leq 80\% \\ 100\% & \text{if } D_i > 80\% \end{cases} \tag{5c}$$

where $\mu_{L,\ i}$, $\mu_{M,\ i}$, and $\mu_{H,\ i}$, membership numbers of $D_i$ in the low, moderate, and high alteration categories, respectively.

The belongingness of the overall hydrologic alteration to the low, moderate, and high categories are described by the average membership numbers $\sum_{i=1}^{32} \mu_{L,i}/32$, $\sum_{i=1}^{32} \mu_{M,i}/32$, and $\sum_{i=1}^{32} \mu_{H,i}/32$, respectively. In this study, minimizing the impacts of water diversion is equivalent to maximizing the average membership number of low alteration category. To be consistent, the fuzzy-based overall degree of hydrologic alteration to be minimized in the optimization model, is given by

$$D_F = 100\% - \frac{1}{32} \sum_{i=1}^{32} \mu_{L,i} \tag{6}$$

The fuzzy-based overall degree of hydrologic alteration so defined also ranges between 0% and 100%. Because the average membership number of low alteration category is used, the fuzzy-based $D_F$ would be unable to indicate explicitly the belongingness of the overall hydrologic alteration to the high or moderate category.



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*Overall-mean approach.* The overall-mean approach eliminates the classification of $D_i$. Instead, the mean value of all $D_i$ is used as the overall degree of hydrologic alteration, that is,

$$D_A = \frac{1}{32}\sum_{i=1}^{32} D_i \tag{7}$$

where $D_A$, overall-mean degree of hydrologic alteration. The value of $D_A$ so obtained also ranges between 0% and 100%. Although simple and straightforward, the overall-mean approach tends to even off the outliers from the mean value, thus reveals little information regarding the extreme effects of water diversion on the natural flow regime.

*Compromise programming (CP)*

Operation of the Kaoping diversion weir is aimed to meet the ecosystem and human needs criteria, that is, to maintain the natural flow regime and to supply the agricultural and municipal water demands, which formulate a typical multiobjective optimization problem. The objective function can be expressed by

$$\text{Min}\{D_O, \text{SRW}, \text{SRD}\} \tag{8}$$

where $D_O$, overall degree of hydrologic alteration; SRW and SRD, shortage ratios of the agricultural and municipal water demands, respectively.

Optimization problems involving multiple (and often conflicting) objectives introduce tradeoff solutions rather than a single optimal solution. Such problems were traditionally handled by aggregating multiple objectives into one weighted objective function or by optimizing one of the objectives and using others as constraints. Such approaches, although simple, offer little information about tradeoffs and may not fully evaluate the search space. More recently, multiobjective evolutionary algorithms (MOEAs) have emerged and are becoming increasingly popular. These MOEAs make use of population-based approaches to find the Pareto optimal solutions in a single simulation run (Deb, 2001). However, since the scope of this study is to demonstrate the merit of time-varying schemes and compare three indices of overall hydrologic alteration but not to investigate the tradeoffs between Pareto solutions, a traditional compromise programming (Zeleny, 1973) is employed herein for searching the optimal solution of an aggregated objective function. An extended study is currently carried out by the authors using the nondominated sorting genetic algorithm II (NSGA-II) (Deb *et al*., 2002) to find the Pareto sets of time-varying instream flow releases.

The compromise programming (CP) searches the optimal solution that has a smallest distance from the ideal point where multiple objectives simultaneously reach their minimal values. This ideal point is not practically achievable, but may be used as a base for finding the optimal solution. The aggregated objective function is given by

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

where $L$, distance from the ideal point ($D_O^b$, $\text{SRW}^b$, $\text{SRD}^b$), the superscripts $b$ and $w$ represent the best and worst (i.e., minimum and maximum), respectively; $w_1$, $w_2$, and $w_3$ are weighting factors, in this study $w_1 = w_2 = w_3 = 1/3$ and $p = 2$ are used, as suggested by Goicoechea *et al*. (1982).

Two steps are involved in the CP. The first step is to find the best and worst values of each objective, which is implemented discretely in the decision space ($Q_{\text{IF}}^t$). The second step is to search the solution of Equation (9). Shiau and Wu (2006) have used the CP to seek the optimal constant release scheme. However, applying the CP to search the optimal time-varying schemes would be extremely time-consuming since numerous combinations of flows must be tried in the first step. Here, we present a dynamic corridor-searching algorithm to overcome this problem.



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### *Dynamic corridor-searching algorithm*

The dynamic corridor-searching algorithm is incorporated into the CP for search of the optimal time-varying instream flows. To this end, an initial set of $Q^t_{\mathrm{IF}}$ is given, and a searching corridor is established by deviating one flow increments ($=\pm\Delta Q_{IF}$) from the initial values (Figure 4). A random combination of time-varying minimum instream flows is picked from the searching corridor; the objective value corresponding to this combination is calculated. Repeat this with different combinations of $Q^t_{\mathrm{IF}}$, an optimal solution can be found in the first corridor. A second corridor is then established by deviating one flow increments from the first set of optimal $Q^t_{\mathrm{IF}}$. This procedure is repeated until no significant improvement in the objective value $L$ can be made.

To accelerate convergences, the optimal solutions with lower time-varying frequencies can be used as the initial guess for search of the optimal solutions with higher frequencies. For example, the optimal constant scheme can be used as the initial guess for the optimal seasonally varying scheme; the optimal quarterly varying scheme can be used as the initial guess for the optimal monthly varying scheme.

## RESULTS AND DISCUSSION

### *Optimal constant scheme*

For the objective function given by Equation (9), the optimal constant scheme is searched by varying the value of $Q_{\mathrm{IF}}$ in the range between 0 and 100 $\mathrm{m^3s^{-1}}$ with an increment of 1 $\mathrm{m^3s^{-1}}$ (Figure 5). A value of $Q_{\mathrm{IF}} = 0\,\mathrm{m^3s^{-1}}$ would lead to the best (or minimum) values of shortage ratio ($\mathrm{SRW}^b = 7.5\%$, $\mathrm{SRD}^b = 3.5\%$) but worst (or maximum) values of $D_O$ ($D^w_T = 75.0\%$, $D^w_F = 52.1\%$, $D^w_A = 45.3\%$). A value of $Q_{\mathrm{IF}} = 100\,\mathrm{m^3s^{-1}}$ would, however, result in the worst (or maximum) shortage ratios ($\mathrm{SRW}^w = 59.9\%$, $\mathrm{SRD}^w = 33.5\%$) but best (or minimum) values of

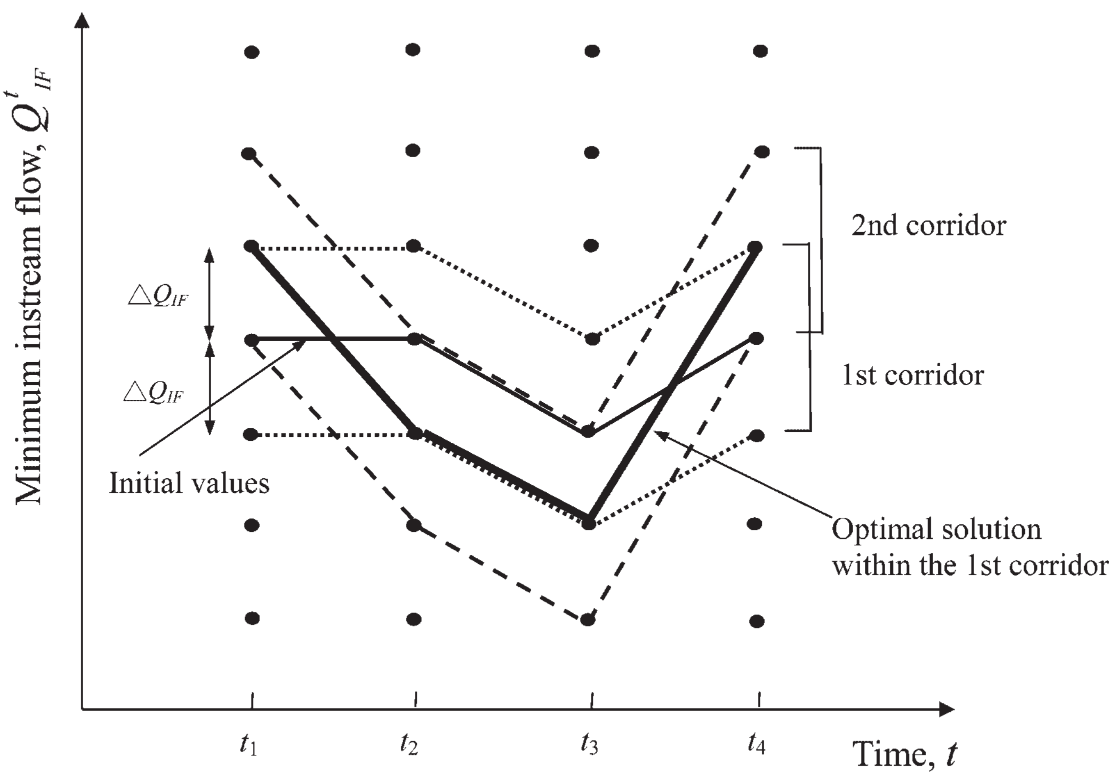


Figure 4. Schematic diagram of the dynamic corridor-searching algorithm



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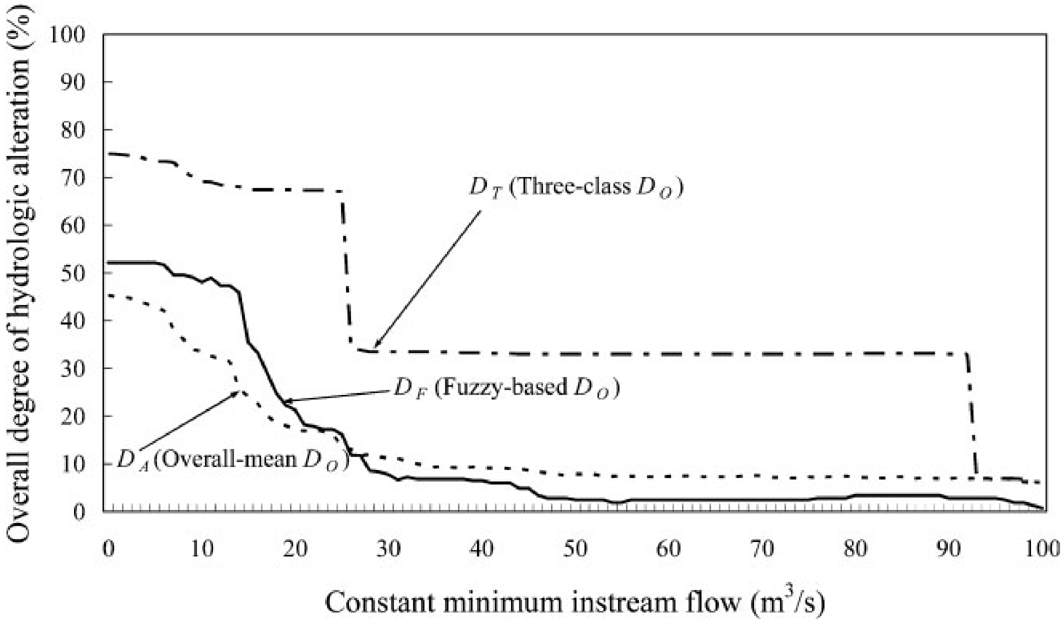


Figure 5. Variations of overall degree of hydrologic alteration as a function of minimum instream flow release

$D_O$ ($D_T^b = 6.1\%$, $D_F^b = 0.8\%$, $D_A^b = 6.1\%$). These extreme values are then used in Equation (9) to seek the minimal values of $L$ and the corresponding optimal values of $Q_{\mathrm{IF}}$.

The optimal values of $Q_{\mathrm{IF}}$ resulting from different definitions of $D_O$ are summarized in Tables III–V. The optimal $Q_{\mathrm{IF}}$ resulting from $D_T$ is 26 m$^3$s$^{-1}$, with SRW = 34.6%, SRD = 10.8%, and $D_T = 34.2\%$. The optimal values of $Q_{IF}$ resulting from $D_F$ and $D_A$ are 21 and 19 m$^3$s$^{-1}$, respectively, with SRW = 30.5% and SRD = 9.2% corresponding to $D_F = 18.2\%$, and SRW = 28.6% and SRD = 8.6% corresponding to $D_A = 18.6\%$. The values of $D_O$ generally

Table III. Optimal schemes of instream flow releases resulting from the three-class overall degree of hydrologic alteration

| | | Constant scheme | Semi-annually varying | Quarterly varying | Monthly varying |
|---|---|---|---|---|---|
| Minimum instream flow release (m$^3$s$^{-1}$) | January | 26 | 26 | 26 | 26 |
| | February | 26 | 26 | 15 | 15 |
| | March | 26 | 26 | 15 | 15 |
| | April | 26 | 26 | 15 | 12 |
| | May | 26 | 10 | 9 | 9 |
| | June | 26 | 10 | 9 | 8 |
| | July | 26 | 10 | 9 | 8 |
| | August | 26 | 10 | 0 | 0 |
| | September | 26 | 10 | 0 | 0 |
| | October | 26 | 10 | 0 | 1 |
| | November | 26 | 26 | 26 | 14 |
| | December | 26 | 26 | 26 | 26 |
| Shortage ratio SRW (%) | | 34.6 | 32.6 | 28.7 | 27.6 |
| Shortage ratio SRD (%) | | 10.8 | 7.5 | 7.0 | 6.4 |
| Three-class $D_T$ (%) | | 34.2 | 35.0 | 36.1 | 36.4 |
| Value of objective function $L_T$ | | 0.232 | 0.217 | 0.202 | 0.196 |
| Number of $D_i$ between 67% and 100% | | 0 | 0 | 0 | 0 |
| Number of $D_i$ between 33% and 67% | | 3 | 6 | 8 | 9 |
| Number of $D_i$ between 0% and 33% | | 29 | 26 | 24 | 23 |



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Table IV. Optimal schemes of instream flow releases resulting from the fuzzy-based overall degree of hydrologic alteration

| | | Constant scheme | Semi-annually varying | Quarterly varying | Monthly varying |
|---|---|---|---|---|---|
| Minimum instream flow release ($m^3/s$) | January | 21 | 21 | 10 | 19 |
| | February | 21 | 21 | 19 | 18 |
| | March | 21 | 21 | 19 | 19 |
| | April | 21 | 21 | 19 | 18 |
| | May | 21 | 17 | 12 | 9 |
| | June | 21 | 17 | 12 | 9 |
| | July | 21 | 17 | 12 | 8 |
| | August | 21 | 17 | 0 | 0 |
| | September | 21 | 17 | 0 | 0 |
| | October | 21 | 17 | 0 | 0 |
| | November | 21 | 21 | 10 | 4 |
| | December | 21 | 21 | 10 | 9 |
| Shortage ratio SRW (%) | | 30.5 | 30.0 | 23.4 | 24.6 |
| Shortage ratio SRD (%) | | 9.2 | 8.4 | 5.8 | 5.0 |
| Fuzzy-based $D_F$ (%) | | 18.2 | 19.4 | 21.0 | 19.6 |
| Value of objective function $L_F$ | | 0.196 | 0.195 | 0.168 | 0.165 |
| Number of $D_i$ between 67% and 100% | | 2 | 2 | 3 | 2 |
| Number of $D_i$ between 33% and 67% | | 2 | 2 | 3 | 3 |
| Number of $D_i$ between 0% and 33% | | 28 | 28 | 26 | 27 |

reduce with the increase of $Q_{IF}$ (Figure 5). However, due to the definition of $D_T$, just a single $D_i > 67\%$ would make $D_T$ jump to the high alteration class, which occurs when $Q_{IF} = 26\,m^3s^{-1}$. The other drop observed at $93\,m^3s^{-1}$ implies that the number of moderately altered IHA vanishes at this value of $Q_{IF}$. The sharp boundaries established by the three-class $D_T$ are diminished by the fuzzy-based $D_F$ and further eliminated by the overall-mean $D_A$, leading to a more continuous trend of variation.

Table V. Optimal schemes of instream flow releases resulting from the overall-mean degree of hydrologic alteration

| | | Constant scheme | Semi-annually varying | Quarterly varying | Monthly varying |
|---|---|---|---|---|---|
| Minimum instream flow release ($m^3/s$) | January | 19 | 19 | 19 | 19 |
| | February | 19 | 19 | 19 | 19 |
| | March | 19 | 19 | 19 | 19 |
| | April | 19 | 19 | 19 | 19 |
| | May | 19 | 19 | 19 | 19 |
| | June | 19 | 19 | 19 | 18 |
| | July | 19 | 19 | 19 | 16 |
| | August | 19 | 19 | 16 | 12 |
| | September | 19 | 19 | 16 | 12 |
| | October | 19 | 19 | 16 | 16 |
| | November | 19 | 19 | 19 | 18 |
| | December | 19 | 19 | 19 | 19 |
| Shortage ratio SRW (%) | | 28.6 | 28.6 | 28.6 | 28.5 |
| Shortage ratio SRD (%) | | 8.6 | 8.6 | 8.4 | 8.1 |
| Overall-mean $D_A$ (%) | | 18.6 | 18.6 | 18.5 | 18.4 |
| Value of objective function $L_A$ | | 0.180 | 0.180 | 0.179 | 0.177 |
| Number of $D_i$ between 67% and 100% | | 2 | 2 | 2 | 2 |
| Number of $D_i$ between 33% and 67% | | 4 | 4 | 4 | 4 |
| Number of $D_i$ between 0% and 33% | | 26 | 26 | 26 | 26 |



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It is shown in Table V that as the value of $Q_{\mathrm{IF}} = 19\,\mathrm{m^3s^{-1}}$, there are two IHA classified as highly altered ($D_i > 67\%$) and four classified as moderately altered ($33\% < D_i < 67\%$). As the value of $Q_{\mathrm{IF}}$ increases to $21\,\mathrm{m^3s^{-1}}$ (Table IV), the number of moderately altered IHA reduces to two; as the value of $Q_{\mathrm{IF}}$ increases to $26\,\mathrm{m^3s^{-1}}$ (Table III), the number of highly altered IHA vanishes. Table VI further demonstrates that two low-flow characteristics, that is, the mean flow of December and mean duration of low pulse, are consistently in the high alteration class, except for the optimal schemes resulting from the three-class $D_T$. Such outcomes with no highly altered IHA are, however, achieved at the cost of greatest deficits for water supplies, as shown in Tables III–V.

*Optimal time-varying schemes*

Three time-varying schemes are investigated here. The semi-annually varying scheme specifies two $Q^t_{\mathrm{IF}}$ for the wet and dry seasons (May to October and November to April). The quarterly varying scheme specifies four $Q^t_{\mathrm{IF}}$ for the periods of February to April, May to July, August to October, and November to January. The monthly varying scheme specifies 12 $Q^t_{\mathrm{IF}}$ for different months. Here, the time-varying schemes resulting from the three-class $D_T$ (Table III) are discussed. As compared to the constant scheme, the results of the seasonally varying scheme demonstrate substantial reductions in shortage ratios (6% in SRW and 31% in SRD) but a minor increase in the overall degree of hydrologic alteration (2% in $D_T$). The quarterly varying scheme improves the results to SRW = 28.7% and SRD = 7.0%, but slightly increases $D_T$ to 36.1%. The monthly varying scheme further improves the results to SRW = 27.6% and SRD = 6.4%, with a vanishingly small increase (0.8%) in $D_T$. The results imply that the time-varying schemes improve the human need objective, but only slightly deteriorate the ecosystem need objective. Such advantages increase with the time-varying frequency.

Table VI shows that the optimal schemes resulting from the three-class $D_T$ would have no highly altered IHA. The number of moderately altered IHA, however, increases from three to nine as the constant scheme is modified as a monthly varying scheme. Three low-flow characteristics, that is, the mean flows of October, November, and December, are consistently in the moderate class regardless of which scheme employed. Generally, these low-flow characteristics are easily affected by water diversion but difficult to restore. To demonstrate the minor improvement in the low-flow characteristics, we show in Figure 6 the pre- and post-diversion series of flows in October (1951–2001). It is revealed that the number of the post-diversion flows below the lower target is increased whereas the number of those flows above the upper target is reduced. Despite that different values of $Q^t_{\mathrm{IF}}$ are prescribed for these time-varying schemes, the post-diversion flows all appear to be similar.

The monthly mean shortage ratios associated with different schemes of flow releases are summarized in Table VII, where the values of SRW are reduced with the time-varying frequency, especially in the dry periods. The improvements in the wet periods are, however, less significant. In contrast, the improvements of SRD with the time-varying frequency mainly take place in the wet periods, implying that the overall SRW is more sensitive to the value of $Q^t_{\mathrm{IF}}$ specified for the dry periods whereas the overall SRD is more sensitive to those specified for the wet periods. Table III also reveals that the deviations of time-varying schemes from the constant scheme ($=26\,\mathrm{m^3s^{-1}}$) are greater in the wet periods. For those wet periods, lower values of $Q^t_{\mathrm{IF}}$ may be prescribed because of the excess water available for release and a lower degree of overall hydrologic alteration is assured. For those dry periods, however, higher values of $Q^t_{\mathrm{IF}}$ must be prescribed to secure a lower degree of overall hydrologic alteration because the available water is insufficient to meet all criteria.

*Comparing three indices of overall hydrologic alteration*

The optimal time-varying schemes resulting from the three-class $D_T$, fuzzy-based $D_F$, and overall-mean $D_A$ are summarized in Tables III–V, respectively. In general, the temporal patterns of $Q^t_{\mathrm{IF}}$ resulting from different definitions of $D_O$ appear to be similar but their values are different. To explore this, we demonstrate in Figure 7 the contour plots of SRW, SRD, $D_O$, and $L$ as a function of $Q^t_{\mathrm{IF}}$ in the wet and dry seasons. The values of SRW and SRD are independent of the definition of $D_O$ but increase with the value of $Q^t_{\mathrm{IF}}$. It is revealed that variation of SRW is more sensitive to the dry-season $Q^t_{\mathrm{IF}}$ (Figure 7a) while SRD varies more closely with the wet-season $Q^t_{\mathrm{IF}}$ (Figure 7b), consistent with our earlier findings. Possible explanations for these findings are: (1) the agricultural water needs are given a higher priority than the municipal water demands, (2) flows in the wet periods are sufficient



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Table VI. Highly and moderately altered IHA associated with different instream flow release schemes resulting from three indices of overall hydrological alteration

| Instream flow release scheme | Alteration class | IHA resulting from three indices of overall hydrological alteration | | |
|---|---|---|---|---|
| | | (1) Three-class $D_T$ | (2) Fuzzy-based $D_F$ | (3) Overall-mean $D_A$ |
| Constant scheme | High ($D_i > 67\%$) | None | Mean flow of December<br>Low-pulse duration | Mean flow of December<br>Low-pulse duration |
| | Moderate ($33\% < D_i < 67\%$) | Mean flow of October<br>Mean flow of November<br>Mean flow of December | Mean flow of October<br>Mean flow of November | Mean flow of October<br>Mean flow of November<br>Annual 30-day min.<br>Number of flow reversals |
| Semi-annually varying scheme | High ($D_i > 67\%$) | None | Mean flow of December<br>Low-pulse duration | Mean flow of December<br>Low-pulse duration |
| | Moderate ($33\% < D_i < 67\%$) | Mean flow of October<br>Mean flow of November<br>Mean flow of December<br>Annual 1-day min.<br>Date of 1-day min.<br>Low-pulse duration | Mean flow of October<br>Mean flow of November | Mean flow of October<br>Mean flow of November<br>Annual 30-day min.<br>Number of flow reversals |
| Quarterly varying scheme | High ($D_i > 67\%$) | None | Mean flow of Jan.<br>Mean flow of December<br>Low-pulse duration | Mean flow of December<br>Low-pulse duration |
| | Moderate ($33\% < D_i < 67\%$) | Mean flow of April<br>Mean flow of October<br>Mean flow of November<br>Mean flow of December<br>Annual 90-day min.<br>Date of 1-day min.<br>Low-pulse duration<br>Number of flow reversals | Mean flow of October<br>Mean flow of November<br>Date of 1-day min. | Mean flow of October<br>Mean flow of November<br>Annual 30-day min.<br>Number of flow reversals |
| Monthly varying scheme | High ($D_i > 67\%$) | None | Mean flow of December<br>Low-pulse duration | Mean flow of December<br>Low-pulse duration |
| | Moderate ($33\% < D_i < 67\%$) | Mean flow of April<br>Mean flow of October<br>Mean flow of November<br>Mean flow of December<br>Annual 90-day min.<br>Date of 1-day min.<br>Low-pulse duration<br>Number of low pulses<br>Number of flow reversals | Mean flow of October<br>Mean flow of November<br>Date of 1-day min. | Mean flow of October<br>Mean flow of November<br>Annual 30-day min.<br>Number of flow reversals |



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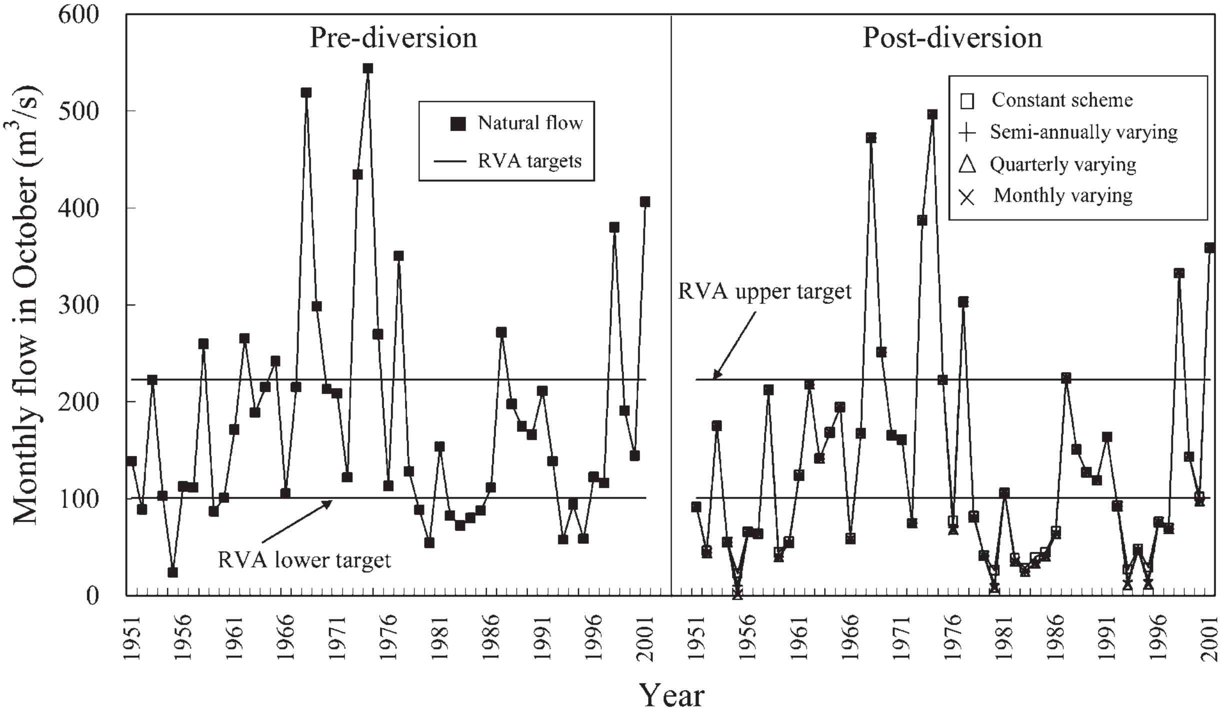


Figure 6. Pre- and post-diversion series of monthly flows in October associated with various schemes of instream flow releases resulting from the three-class overall degree of hydrologic alteration

to meet both instream flow and agricultural water needs, and (3) no diversions of water are projected for municipal use during January to April.

Figure 7c, e and g also shows that variations of $D_T$, $D_F$, and $D_A$ follow more closely the dry-season $Q^t_{\mathrm{IF}}$. The similar contour patterns shown in Figure 7d, f and h further demonstrates that the variation of objective value $L$ is dominated by the definition of $D_O$ rather than the value of SRW or SRD. The optimal results $L_T = 0.217$, $L_F = 0.195$,

Table VII. Monthly shortage ratios associated with different schemes of instream flow releases resulting from the three-class overall degree of hydrologic alteration (units in %)

| | Constant scheme | | Semi-annually varying | | Quarterly varying | | Monthly varying | |
|---|---|---|---|---|---|---|---|---|
| | SRW | SRD | SRW | SRD | SRW | SRD | SRW | SRD |
| January | 81.4 | 0.0 | 81.4 | 0.0 | 81.4 | 0.0 | 81.4 | 0.0 |
| February | 83.6 | 0.0 | 83.6 | 0.0 | 65.9 | 0.0 | 65.9 | 0.0 |
| March | 81.6 | 0.0 | 81.6 | 0.0 | 66.6 | 0.0 | 66.6 | 0.0 |
| April | 67.5 | 0.0 | 67.5 | 0.0 | 53.9 | 0.0 | 48.2 | 0.0 |
| May | 35.7 | 46.5 | 19.3 | 34.0 | 18.1 | 33.0 | 18.1 | 33.0 |
| June | 5.2 | 10.1 | 2.2 | 6.5 | 2.0 | 6.4 | 1.8 | 6.1 |
| July | 3.9 | 9.7 | 0.9 | 5.6 | 0.7 | 5.3 | 0.6 | 5.1 |
| August | 0.1 | 0.8 | 0.0 | 0.2 | 0.0 | 0.1 | 0.0 | 0.1 |
| September | 0.1 | 0.9 | 0.0 | 0.2 | 0.0 | 0.1 | 0.0 | 0.1 |
| October | 2.5 | 10.6 | 1.0 | 4.0 | 0.2 | 2.3 | 0.3 | 2.3 |
| November | 16.2 | 33.2 | 16.2 | 33.2 | 16.2 | 33.2 | 6.1 | 18.1 |
| December | 48.0 | 77.5 | 48.0 | 77.5 | 48.0 | 77.5 | 48.0 | 77.5 |



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and $L_A = 0.18$ occur as the combinations of the wet- and dry-season $Q^t_{\mathrm{IF}}$ are (10, 26), (17, 21), and (19, 19) $\mathrm{m^3 s^{-1}}$, respectively, confirming that the difference between the wet- and dry-season $Q^t_{\mathrm{IF}}$ established by the three-class $D_T$ is diminished by the fuzzy-based $D_F$, and further eliminated by the overall-mean $D_A$.

Table III shows that the numbers of highly altered IHA ($D_i$ between 67% and 100%) are consistently zero, which is attributable to the definition of $D_T$ in which much weighting is placed on the high alteration class such that the number of highly altered IHA tends to be minimized. In contrast, the numbers of lowly altered IHA ($D_i$ between 0% and 33%) resulting from the fuzzy-based $D_F$ (Table IV) are almost entirely greater than those resulting from the three-class $D_T$ and overall-mean $D_A$ (Tables III and V), which is due to the definition of $D_F$ that seeks to maximize

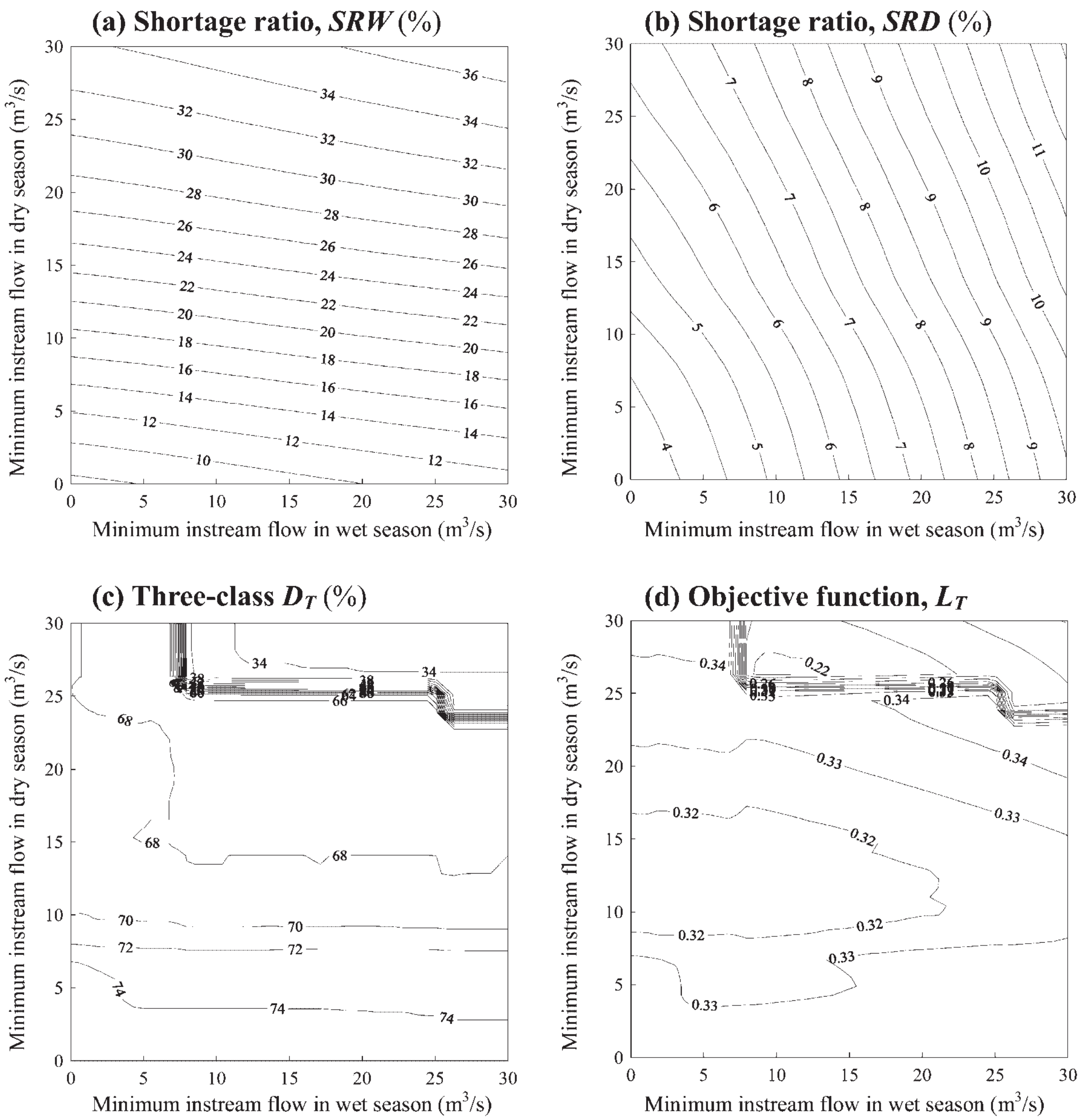


Figure 7. Contour plots of (a) shortage ratio of registered agricultural water needs, SRW, (b) shortage ratio of projected municipal water demands, SRD, (c) three-class overall degree of hydrologic alteration, $D_T$, and (d) value of objective function, $L_T$, for various combinations of wet- and dry-season (semi-annually varying) minimum instream flows. Contour plots of (e) fuzzy-based overall degree of hydrologic alteration, $D_F$, (f) value of objective function, $L_F$, (g) overall-mean degree of hydrologic alteration, $D_A$, and (h) value of objective function, $L_A$, for various combinations of wet- and dry-season (semi-annually varying) minimum instream flows



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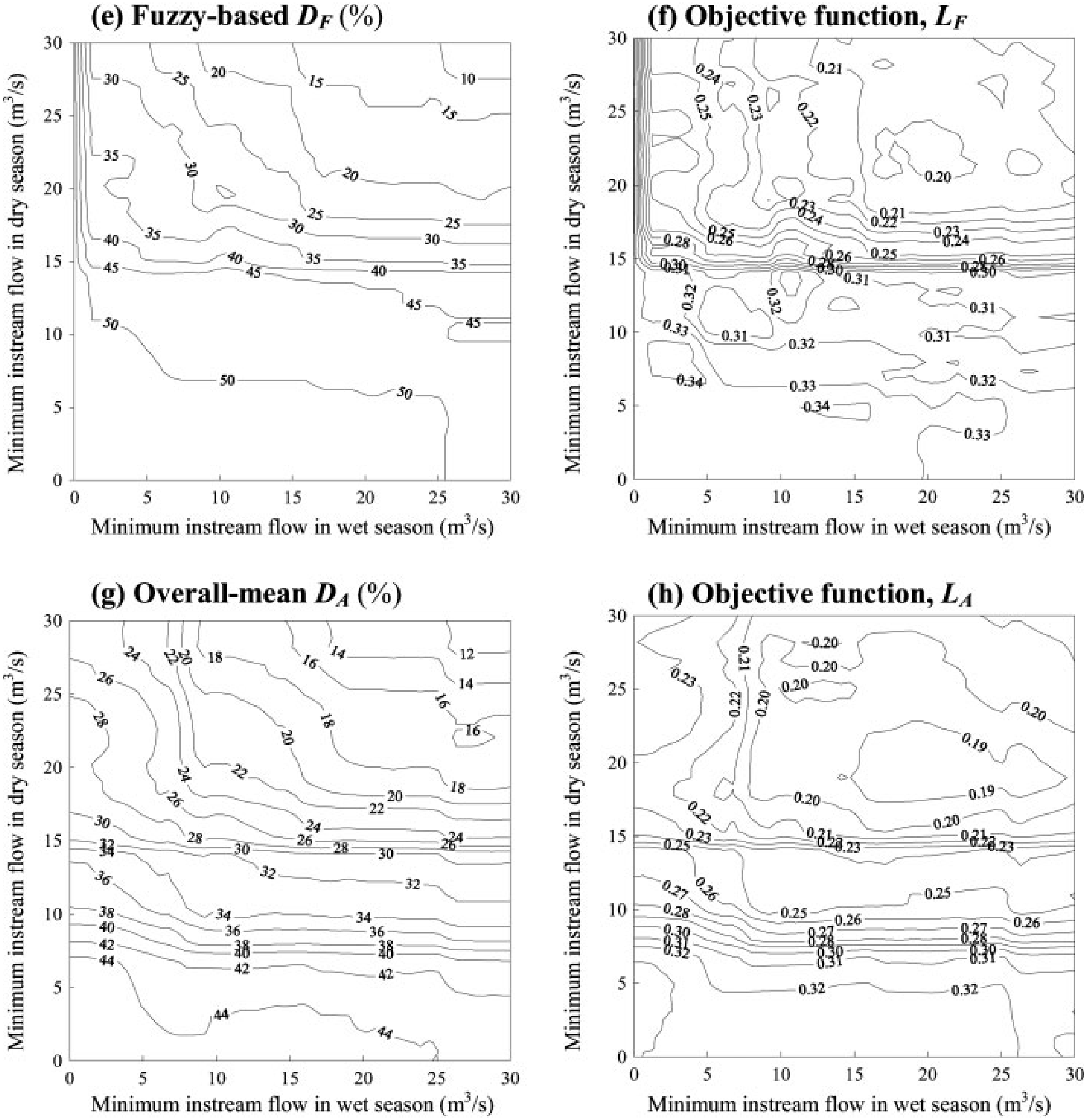


Figure 7. Continued

the average membership number of the low alteration category. The number of IHA in each alteration class resulting from $D_A$ remains unchanged regardless of the scheme employed (Table V), and the values of SRW, SRD, $D_A$, and $L_A$ associated with the time-varying schemes are nearly identical to those associated with the constant scheme. Table VI also shows that the highly and moderately altered IHA resulting from $D_A$ remain the same for all schemes. In summary, the three-class approach should be used where the purpose of instream flow releases is to minimize the number of highly altered IHA. The fuzzy-based approach is recommended if the purpose is to maximize the number of lowly altered IHA. By eliminating the classification of the alteration degree $D_i$, the overall-mean approach is unable to effectively detect the alteration of individual IHA and thus tends to undervalue the modification made by the time-varying schemes.

The greater values of $Q^t_{\mathrm{IF}}$ in the dry periods resulting from $D_T$ also provide a better protection of the low-flow characteristics. To demonstrate this, the pre- and post-diversion series of monthly flows in December and mean



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durations of low pulse associated with the monthly-varying schemes are shown in Figure 8. The post-diversion values resulting from the three-class $D_T$ fall in the target range more frequently than those resulting from the other two. The degree of alteration for the post-diversion flows in December resulting from the three-class $D_T$ is 59% (moderate class), while those resulting from the fuzzy-based $D_F$ and overall-mean $D_A$ are 82% and 78%,

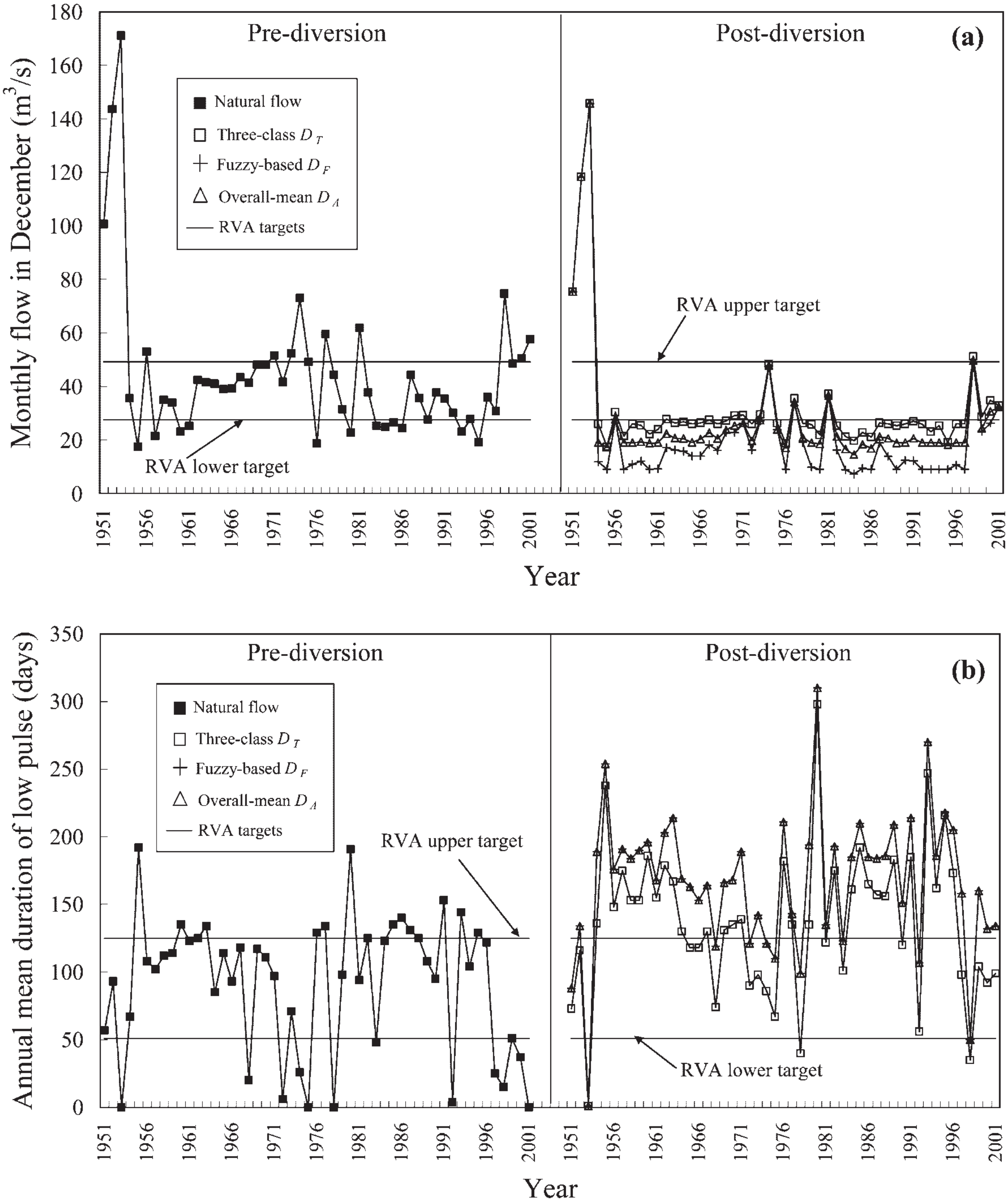


Figure 8. Pre- and post-diversion series of (a) monthly flows in December and (b) annual mean duration of low pulse associated with monthly-varying schemes resulting from different indices of overall hydrologic alteration



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respectively (both high class). Similarly, the degree of alteration for the post-diversion mean durations of low pulse resulting from $D_T$ is 37% (moderate class), while those resulting from the other two are both 70% (high class). The results indicate that use of the three-class $D_T$ as an index of overall hydrologic alteration is a more efficient way to eliminate highly altered IHA and retain the low-flow characteristics that are subtle to flow diversions. However, such results are achieved at the cost of greater deficits for human water demands.

## CONCLUSIONS

The natural flow regime has emerged as a paradigm for instream flow prescriptions. Existing methods strive to assure a constant minimum instream flow rather than the natural flow variations. In this paper we employ a dynamic corridor-searching algorithm to seek optimal time-varying schemes of instream flow release aiming to balance the ecosystem and human need objectives. As compared to the constant scheme, the time-varying schemes improve the human need objective, but only slightly deteriorate the ecosystem need objective. Such advantages increase with the time-varying frequency. The results reveal that the low-flow characteristics are easily affected by water diversions but difficult to restore. For the wet periods, smaller releases may be prescribed since the post-diversion flows still retain sufficient variations. For the dry periods, however, greater releases must be prescribed such that a lower degree of overall hydrologic alteration is secured.

The difference between the wet- and dry-season instream flow releases established by the three-class $D_T$ is diminished by the fuzzy-based $D_F$ and further eliminated by the overall-mean $D_A$. The number of highly altered IHA resulting from the use of $D_T$ is smallest because much weighting is placed on the high alteration class. The number of lowly altered IHA resulting from the use of $D_F$ is greater due to its definition seeking to maximize the membership of the low alteration class. By eliminating these classes, the overall-mean $D_A$ is unable to detect the alteration of individual IHA and thus undervalue the modification made by the time-varying schemes. Use of the three-class $D_T$ as an index of overall hydrologic alteration facilitates to eliminate highly altered IHA and retain the low-flow characteristics. However, such outcomes are achieved at the cost of greater deficits for human needs.

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