Feasible Diversion and Instream Flow Release Using Range of Variability Approach

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Abstract: A methodology based on the range of variability approach (RVA) is presented for determining the feasible combinations of flow diversion and instream flow release for a projected diversion weir. The RVA is designed to support efforts to manage water system operations in a manner that minimizes impacts on natural hydrologic variability, and thereby minimizes ecological impacts. This approach is used to evaluate the prediversion flows and establish the riverine management targets in terms of 32 hydrologic parameters called indicators of hydrologic alteration (IHAs). The goal is to make the postdiversion flows attain the target ranges at the same frequency as that which occurred in the prediversion flow regime. A weir-operation simulation approach is employed to compute the postdiversion flows. Based on the simulation results, the degree of hydrologic alteration under various combinations of flow diversion and release is evaluated and plotted as a contour diagram for each IHA. Overlapping the contour diagrams of the 32 IHAs, three overall hydrologic-alteration regions are constructed. The feasible region, i.e., the overall low-alteration region, is defined by the combinations of flow diversion and instream flow release for which none of the 32 IHAs is significantly altered. The feasible combinations of flow diversion and release are further evaluated with their corresponding water-supply shortage indices. The proposed methodology allows for the incorporation of both water-supply and environmental protection concerns in water resources planning and management. The merits of this methodology are demonstrated with an application to the proposed Taitung diversion weir in Taiwan.

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Introduction

Mitigating the environmental impacts caused by hydraulic structures and facilities has become an essential component in water resources planning and management (Cardwell et al. 1996; Benjamin and Van Kirk 1999; Flug et al. 2000; Smith et al. 2000; Cowell and Stoudt 2002). Recently, this has also received extensive attention in Taiwan and many studies have been conducted to address this issue (Wu et al. 1998; Wu 2000; Chen et al. 2001; Hu and Yeh 2002; Wu and Wang 2002; Wu and Chou 2003, 2004; Shiau and Wu 2004). Protecting the riverine environment and sustaining biodiversity has been promoted as a goal of the ''New Centenary Water Resources Policy'' in Taiwan (Water 2002). However, due to population growth and economic development, the increasing water demands and the consequent flow diversion from rivers may have caused negative impacts on aquatic biota. Trade-offs between conflicting flow diversions and instream flow releases should be comprehensively explored for human and environmental benefits.

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A number of methods for the evaluation of the instream flow requirement, such as the historical flow, hydraulic, and habitat methods, were reviewed by Jowett (1997). These methods either contain no biological component or consider merely one or a few target species, and thus are not considered comprehensive approaches (Reiser et al. 1989). Moreover, in ignoring the natural flow variability, most protection measures have been limited to protecting the minimum flow (Poff et al. 1997). A full range of natural hydrologic regimes has been considered as a primary driving force for aquatic ecosystem integrity and as an essential element for sustaining the riverine environment (National 1992; Poff et al. 1997). Sale et al. (1982) and Cardwell et al. (1996) have used optimization models to search for optimal alternatives that maximize the aquatic habitat properties and minimize the water-supply shortfalls. However, natural flow variability was not addressed in their models. Richter et al. (1996, 1997, 1998) developed and demonstrated the range of variability approach (RVA) for establishing flow-based river management targets by incorporating the concept of natural hydrologic variability. This approach is designed to support efforts to manage water system operations in a manner that minimizes impacts on natural hydrologic variability, and thereby minimizes ecological impacts. Thirty-two hydrologic parameters called indicators of hydrologic alteration (IHAs) are employed to assess anthropogenic flow alterations in terms of magnitude, timing, frequency, duration, and rate of change (Richter et al. 1996). A brief description of the IHAs is given later and they are summarized in Table 1. More details can be found elsewhere (Richter et al. 1996, 1997, 1998). A range of variation for each IHA determined from the preimpact flows is set as the flow management target. The operation of hydraulic facilities aims to allow postimpact flow conditions to attain the established

Table 1. Indicators of Hydrologic Alteration (IHA)

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[a]	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

[a]High or low pulses are those periods in which the daily flows are above the 75th or below the 25th percentile preimpact daily flow.

RVA target ranges at the same frequency as for the preimpact flows.

In this study, the RVA target range for each parameter is bracketed by the 25th- and 75th-percentile values of the preimpact daily flow, as suggested by Richter et al. (1998). The management goal is to make the postimpact flow regime attain the target ranges at the same frequency as that which occurred in the natural or preimpact flow regime. Richter et al. (1998) used the degree of hydrologic alteration as a measure to quantify the deviation of the postimpact flow regime from the preimpact one. The degree of hydrologic alteration, D, is defined as

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

where N_o=observed number of postimpact years for which the value of the hydrologic parameter falls within the RVA target range; and N_e=expected number of postimpact years for which the parameter value falls within the RVA target range. N_e can be estimated by $p\times N_T$, where p=percentage of preimpact years for which the parameter value falls within the RVA target range, and N_T=total number of postimpact years. Richter et al. (1998) further suggested that the value of D ranging between 0 and 33% represents little or no alteration (i.e., low alteration), 33–67% represents moderate alteration, and 67–100% represents high alteration.

Presented herein is an RVA-based methodology to determine the feasible combinations of flow diversion and instream flow release for a proposed diversion weir. A feasible combination of flow diversion and instream flow release is defined as one that does not cause severe hydrologic alterations and thus is considered not to seriously disturb the riverine environment. The RVA is employed first to evaluate prediversion flow conditions and establish target ranges for the 32 IHAs. The degree of hydrologic alteration caused by various combinations of flow diversion and instream flow release is then evaluated and plotted as a contour diagram for each indicator. The feasible combinations of flow diversion and instream flow release are defined by a region in which the 32 IHAs are not significantly altered, and are evaluated with their corresponding water-supply shortage characteristics. The proposed methodology provides a useful approach to water resources planning and management, incorporating both concerns for water supply reliability and environmental protection.

Study Area—Peinan Creek Basin

Peinan Creek is located in eastern Taiwan (Fig. 1). It is 84 km in length and has a drainage area of 1,603 km^2. Average annual runoff is around 3,000 million m^3. Daily flow records for three existing streamflow gauge stations, Yenping (2200H007), Taitung Bridge (2200H011), and Hsinwulu (2200H020), are available, respectively, from July 1955, August 1941, and June 1978 to December 2001. The average daily flows for these gauge stations are shown in Fig. 2, where apparent seasonal variations are evident. The maximum, average, and minimum daily flows for the Yenping, Taitung Bridge, and Hsinwulu gauge stations are listed in Table 2. The considerable differences among the data listed in Table 2 reveal that highly fluctuated flows existed between wet and dry seasons for these three gauge stations.

The Peinan diversion weir, completed in 1982 and located at the midstream of Luyeh Creek (a tributary of Peinan Creek), is the only existing hydraulic structure in this basin (Water 2001). The primary function of the Peinan diversion weir is to supply agricultural water demands. Due to increasing municipal demand in the neighboring region, it has been proposed to build a Taitung diversion weir at Peinan Creek downstream to facilitate the water supply system. The design diversion capacity of the proposed Taitung weir is 3.6 m^3/s and further assessment of the instream flow requirement is undertaken currently. This design diversion capacity can increase the agricultural supply by 173

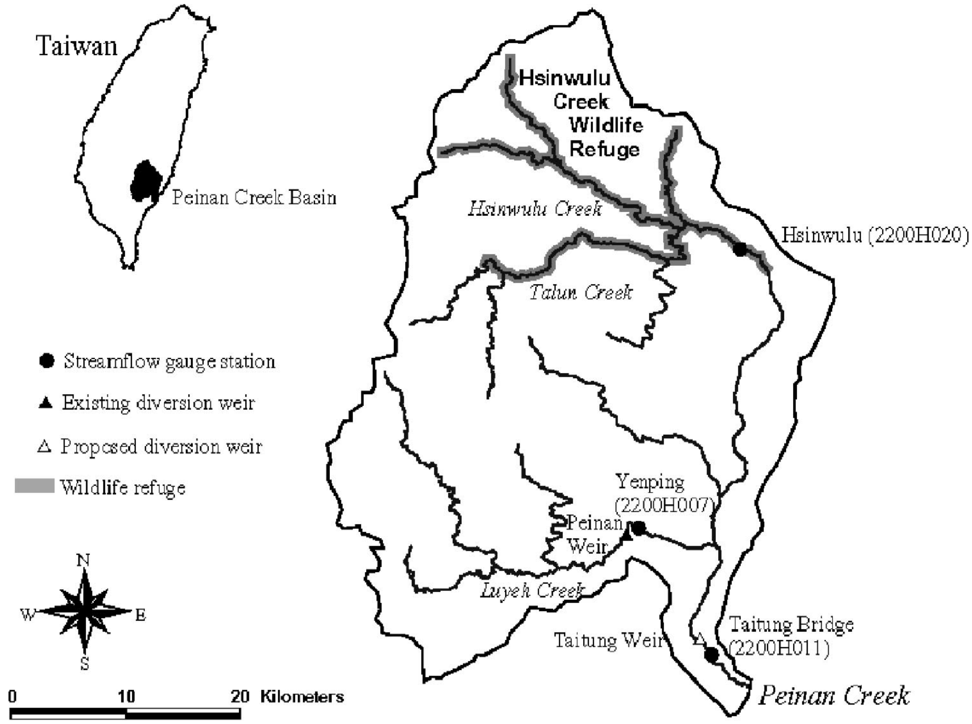

Fig. 1. Map of Peinan Creek basin

$\times 10^3\ m^3/day$ and the municipal supply by $138\times 10^3\ m^3/day$, which is expected to fulfill the municipal demand through 2020 (Water 1999).

Peinan Creek has been providing the instream habitats for several endemic species, such as *Anguilla marmorata* (marbled eel), *Hemimyzon taitungensis, Spinibarbus hollandi, Varicorhinus alticorpus* (sharp-jaw barbel), *Varicorhinus barbatulus* (Taiwan shovel-jaw carp), and *Zacco pachycephalus* (Taiwan 1998). The Hsinwulu Creek wildlife refuge on the upstream Peinan Creek was established in 1998 for restoring the endangered Taiwanese aquatic species, *Anguilla marmorata*, *Hemimyzon taitungensis*, and *Varicorhinus alticorpus*. Protecting the riverine environment and sustaining biodiversity in the Peinan Creek Basin is thus highly emphasized in the planning phase of the proposed Taitung diversion weir.

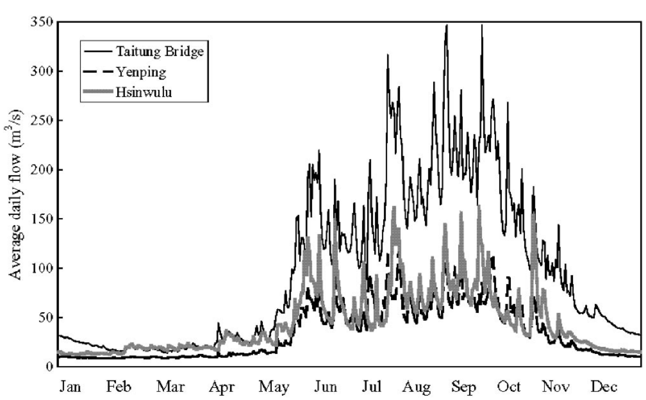

Fig. 2. Average daily flows at Yenping (1957–2001), Taitung Bridge (1949–2001), and Hsinwulu (1979–2001) gauge stations

Methodology

The aim of this study is to determine feasible combinations of flow diversion and instream flow release for the proposed Taitung diversion weir. Conflicting flow diversions and instream flow releases must be compromised to meet the environmental and water-supply constraints. A simulation approach using a simplified decision model of weir operation under various combinations of flow diversion and instream flow release is established to calculate the postdiversion flows. The hydrologic alterations of the postdiversion flows are evaluated by the RVA method and plotted as a contour diagram. The feasible region is then defined by the combinations of flow diversion and release that do not cause severe hydrologic alterations. The weir operation schemes are also evaluated with the corresponding shortage indices to address the reliability of the water supply.

Weir Operation Model

The flow system at the proposed Taitung diversion weir is illustrated in Fig. 3, where Q_N^t is the natural (or prediversion) flow at time t, Q_D is the projected flow diversion, Q_{DF}^t is the diverted flow at time t, Q_E^t is the postdiversion flow at time t, and Q_{IF} is the instream flow release. In this system, Q_D and Q_{IF} are two

Table 2. Maximum, Average, and Minimum Daily Flows at Yenping, Taitung Bridge, and Hsinwulu Gauge Stations

Station	Maximum (m^3/s)	Average (m^3/s)	Minimum (m^3/s)
Yenping	129.8	34.5	8.8
Taitung Bridge	347.0	97.0	14.2
Hsinwulu	162.7	44.6	12.8

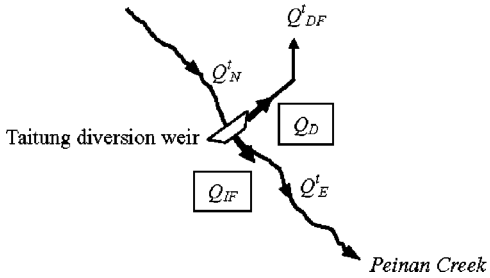

Fig. 3. Definition sketch of flow system at proposed Taitung diversion weir

decision variables to be specified. For simplicity, it is assumed that both Q_D and Q_{IF} are constant (i.e., not varying with time t). The instream flow release Q_{IF} has a higher priority than flow diversion Q_D. The relationships among these variables are constrained by

$$\begin{array}{ll} Q_E^t=Q_N^t, Q_{\mathrm{DF}}^t=0 & \text{if } Q_N^t<Q_{\mathrm{IF}} \\ Q_E^t=Q_{\mathrm{IF}}, Q_{\mathrm{DF}}^t=Q_N^t-Q_{\mathrm{IF}} & \text{if } Q_{\mathrm{IF}}\leqslant Q_N^t<Q_D+Q_{\mathrm{IF}} \\ Q_E^t=Q_N^t-Q_D, Q_{\mathrm{DF}}^t=Q_D & \text{if } Q_N^t\geqslant Q_D+Q_{\mathrm{IF}} \end{array} \quad (2)$$

Simultaneous determination of the flow diversion Q_D and instream flow release Q_{IF} is based on the philosophy that the alteration of Q_E^t between the pre and postdiversion regions should be made as small as possible. A numerical model is used to simulate the operation of the Taitung diversion weir under various combinations of Q_D and Q_{IF}. For any combination of Q_D and Q_{IF}, Q_E^t is determined with the established regulation rule given by Eq. (2). Since Q_E^t represents the postdiversion flow regime and is used to calculate the degree of hydrologic alteration, the value of D for each IHA is a nonlinear function of Q_D and Q_{IF}. Various IHAs may have different values of D. Thus, the D values of all of the 32 IHAs are used to define the degree of overall alteration, as described next.

1. Overall low alteration. The degree of hydrologic alteration of each IHA belongs to the low-alteration category; i.e., the D values of all IHAs are less than 33%.
2. Overall medium alteration. At least one of the 32 IHAs belongs to the moderate degree of hydrologic alteration category but none belongs to the high-alteration category.
3. Overall high alteration. At least one IHA belongs to the high degree of hydrologic alteration category.

Water Shortage Indices

When the diverted flow Q_{DF}^t is less than the projected flow diversion Q_D, the water shortage occurs. The water shortage Q_S^t is defined as

$$Q_S^t=\begin{cases} |Q_{\mathrm{DF}}^t-Q_D| & \text{if } Q_{\mathrm{DF}}^t<Q_D \\ 0 & \text{if } Q_{\mathrm{DF}}^t\geqslant Q_D \end{cases} \quad (3)$$

Two shortage indices that encompass the characteristics of shortage duration and magnitude are used to assess the performance of the water supply. The first index, shortage risk, is defined as the probability that the diverted flow is insufficient to meet the established requirement (Hashimoto et al. 1982). Specifically, the shortage risk can be evaluated by the ratio of the number of shortage periods to the total number of study periods; i.e.,

$$\text{Shortage risk}=\frac{\Sigma_{t=1}^N Z_t}{N} \quad (4)$$

where $Z_t=1$ if $Q_{\mathrm{DF}}^t<Q_D$, and $Z_t=0$ otherwise; and N=total number of study periods. The second index, shortage ratio, is defined as the ratio of total water shortage to the total projected flow diversion over the study periods (Cancelliere et al. 1998); i.e.,

$$\text{Shortage ratio}=\frac{\Sigma_{t=1}^N Q_S^t}{NQ_D} \quad (5)$$

Results and Discussion

The effects of the Peinan diversion weir on the downstream flow regimes of Luyeh Creek (tributary) and Peinan Creek (mainstream) are first evaluated, followed by a simulation approach to calculate the postdiversion flows at the proposed Taitung weir. Various combinations of flow diversion and instream flow release are assessed with their corresponding overall degree of hydrologic alteration. The performance of the water supply is further evaluated by exploring the shortage indices.

Hydrologic Alterations Caused by Peinan Diversion Weir

As shown in Fig. 1, the Yenping and Taitung Bridge gauge stations are both located downstream of the Peinan diversion weir—one immediately downstream of the Peinan weir and the other downstream of Peinan Creek below the proposed Taitung weir site. Construction of the Peinan diversion weir was started in 1979 and completed in 1982. Thus, daily flow data prior to 1979 and after 1982 are considered as the pre and postconstruction flow regimes, respectively. The RVA targets of the 32 IHAs derived from the preconstruction daily flow data (1957–1978 for Yenping and 1949–1978 for Taitung Bridge gauge stations, respectively) are taken to be the weir-operation goals. The RVA targets, pre and postimpact mean values of 32 IHAs, observed and expected number of postimpact years falling within the RVA targets, degree of hydrologic alteration, and alteration class for both stations are listed in Tables 3 and 4.

The data in Tables 3 and 4 reveal that the impact of the Peinan weir on the downstream flows at the Yenping station is more substantial than that at the Taitung Bridge station, although both belong to the low-alteration class (the average degrees of hydrologic alteration for the two stations are 30 and 21%, respectively). The numbers of individual IHAs classified as low, moderate, and high degrees of alteration are 22, 5, and 5 for the Yenping station, and 25, 6, and 1 for the Taitung Bridge station. Most of the moderately or highly altered parameters are those categorized as low-flow characteristics, such as the annual multiday minimum flows, and monthly mean flows in February and November. Such an outcome essentially indicates that the low-flow regime is easily altered by the flow diversion, which is consistent with the results of a previous study (Shiau and Wu 2004). As an example, the time series of annual 90-day minimum flows at the Yenping and Taitung Bridge stations are shown in Figs. 4 and 5, respectively. At the Yenping station, the RVA upper and lower targets of the annual 90-day minimum flow are 9.3 and 6.9 m^3/s, respectively, and 12 out of the 22 preimpact years fell within this range. For the 19 postimpact years, it is shown that only 1 year (i.e., 1985) was within the RVA target range, which results in a D value of 90%. At the Taitung Bridge station, expected and observed num-

Table 3. Hydrologic Alterations at Yenping Gauge Station Caused by Peinan Diversion Weir

Indicators of hydrologic alterations	Range of variability approach (RVA) targets[a] Lower	Upper	Mean Preconstruction	Postconstruction	N_o	N_e	D (%)	Class[b]
Group 1—January	7.90	11.70	10.60	8.40	8	10	23	L
February	7.20	11.00	9.70	9.60	4	10	61	M
March	6.70	9.80	9.80	10.40	7	10	33	L
April	6.80	13.00	11.70	12.50	6	10	42	M
May	9.00	32.80	21.10	24.30	9	10	13	L
June	21.10	88.90	61.70	56.60	11	10	6	L
July	20.90	107.00	74.10	47.30	10	10	4	L
August	44.10	92.50	66.40	55.50	4	10	61	M
September	37.70	143.20	93.90	58.50	11	10	6	L
October	22.90	93.10	65.30	44.80	11	10	6	L
November	13.70	28.20	23.60	25.20	2	10	81	H
December	9.50	16.20	13.60	10.90	8	10	23	L
Group 2—1-day minimum	5.00	6.20	5.90	3.20	2	10	81	H
3-day minimum	5.30	6.40	6.00	3.30	3	10	71	H
7-day minimum	5.50	7.00	6.30	3.60	3	10	71	H
30-day minimum	6.10	8.30	7.20	4.90	6	10	42	M
90-day minimum	6.90	9.30	8.30	7.40	1	10	90	H
1-day maximum	605.30	1,267.50	988.20	701.20	9	10	13	L
3-day maximum	427.60	878.40	662.80	475.00	9	10	13	L
7-day maximum	258.30	508.90	390.00	288.40	10	10	4	L
30-day maximum	102.40	213.50	165.10	120.00	10	10	4	L
90-day maximum	73.30	121.20	102.40	72.20	9	10	13	L
Base flow condition	0.13	0.25	0.18	0.13	8	10	23	L
Group 3[c]—Date of annual minimum	109.50	194.80	150.50	149.70	9	10	13	L
Date of annual maximum	75.80	147.80	109.50	113.00	9	10	13	L
Group 4—Low-pulse count	2.00	6.00	4.60	6.50	8	10	23	L
High-pulse count	4.00	7.00	5.60	7.20	7	10	33	L
Low-pulse duration	48.00	138.00	91.40	118.70	11	10	6	L
High-pulse duration	72.50	107.00	91.40	80.10	5	10	52	M
Group 5—Fall rate	−16.40	−7.80	−12.80	−9.10	9	10	13	L
Rise rate	25.50	58.40	40.70	30.20	9	10	13	L
Flow reversals	91.00	110.00	101.30	103.20	9	10	13	L
Average	—	—	—	—	—	—	30	L

[a]RVA lower and upper targets are the 25th- and 75th-percentile values of the preimpact hydrologic parameters.

[b]L, M, and H represent low, moderate, and high alterations, respectively.

[c]Dates of the annual minimum and maximum count from November 1 and May 1, respectively.

bers of postimpact years falling within the RVA target range are 10.1 and 10 years, respectively, leading to a D value of 1%. The less altered flow regime at the Taitung Bridge station is attributable to the nonaffected flow from the upstream Hsinwulu Creek and its more distant location from the Peinan diversion weir. From the data shown in Tables 3 and 4, it is clear that the D values of the low-flow IHAs are substantially greater than those of the high-flow IHAs. Severe alterations of the low-flow characteristics can be mitigated through the release of instream flow, which is investigated subsequently.

Flow Diversion and Instream Flow Release for Proposed Taitung Diversion Weir

As mentioned earlier, the postdiversion flow, Q_E^t, and thus the degree of hydrologic alteration, D, both vary with the specified flow diversion Q_D and instream flow release Q_{IF}. Hydrologic alterations associated with various combinations of Q_D and Q_{IF} are investigated, and feasible combinations are sought that do not cause severe alterations to the downstream flow regime. First, the flow records from 1983 to 2001 at the Taitung Bridge gauge station representing prediversion flow conditions are used to establish the RVA targets. The same flow sequence is then employed as the input (i.e., Q_N^t) to the simulation model. Based on Eq. (2), weir operations under various combinations of Q_D and Q_{IF} are simulated to obtain the postdiversion flow sequence Q_E^t. The prediversion flow includes the hydrologic impacts induced by the existing Peinan diversion weir; the impacts caused by the proposed Taitung diversion weir will be additive to the existing one. In the simulations, the values of Q_D and Q_{IF} both range from 0 to 20 m^3/s with an increment of 1 m^3/s. The output results of Q_E^t are used to calculate the degree of hydrologic alteration D for each IHA under various combinations of Q_D and Q_{IF}. Finally, the hydrologic alterations are plotted as contour diagrams corresponding to the simulated ranges of Q_D and Q_{IF}. The results of individual and overall alterations are reported next.

Within the simulation ranges of Q_D and Q_{IF}, the D values of the monthly mean flows for August, September, and October; the annual 1-, 3-, 7-, 30-, and 90-day maximum flows; the date of the

Table 4. Hydrologic Alterations at Taitung Bridge Gauge Station Caused by Peinan Diversion Weir

Indications of hydrologic alterations	Range of variability approach (RVA) targets[a] Lower	Upper	Mean Preconstruction	Postconstruction	N_o	N_e	D (%)	Class[b]
Group 1—January	17.70	37.50	30.40	18.50	7	10	31	L
February	7.30	22.90	17.30	21.30	10	10	1	L
March	6.90	17.30	13.80	26.50	7	10	31	L
April	9.50	41.40	27.00	32.30	12	10	18	L
May	12.80	86.30	55.10	65.60	11	10	9	L
June	33.80	180.90	143.60	154.10	10	10	1	L
July	46.60	291.20	181.70	133.90	10	10	1	L
August	111.30	290.40	206.20	174.20	7	10	31	L
September	107.20	369.50	255.40	198.00	12	10	18	L
October	65.10	228.70	181.20	135.80	8	10	21	L
November	43.60	81.00	91.00	75.40	3	10	70	H
December	25.90	58.60	51.90	32.90	11	10	9	L
Group 2—1-day minimum	2.60	11.30	7.50	4.70	14	10	38	M
3-day minimum	2.70	11.40	7.70	4.80	14	10	38	M
7-day minimum	2.90	11.50	8.00	5.30	12	10	18	L
30-day minimum	3.80	13.70	10.10	7.80	13	10	28	L
90-day minimum	6.80	21.00	14.60	15.40	10	10	1	L
1-day maximum	1,085.00	3,535.00	2,889.30	1,990.60	11	10	9	L
3-day maximum	1,184.30	2,468.40	1,850.70	1,355.10	10	10	1	L
7-day maximum	691.40	1,508.50	1,130.60	862.50	12	10	18	L
30-day maximum	307.10	589.30	490.40	369.10	14	10	38	M
90-day maximum	186.50	367.60	287.00	220.50	14	10	38	M
Base flow condition	0.03	0.10	0.08	0.06	12	10	18	L
Group 3[c]—Date of annual minimum	137.80	193.30	164.20	168.10	5	10	51	M
Date of annual maximum	84.50	157.00	119.50	121.00	9	10	11	L
Group 4—Low-pulse count	2.00	6.00	3.90	5.40	13	10	1	L
High-pulse count	4.80	7.00	6.00	6.50	10	10	1	L
Low-pulse duration	43.80	126.50	91.40	102.60	12	10	18	L
High-pulse duration	65.50	109.00	91.40	83.80	11	10	9	L
Group 5—Fall rate	−40.70	−20.90	−30.50	−24.50	13	10	28	L
Rise rate	72.20	183.00	123.00	104.50	12	10	18	L
Flow reversals	90.00	112.30	101.40	83.50	5	10	51	M
Average	—	—	—	—	—	—	21	L

[a]RVA lower and upper targets are the 25th- and 75th-percentile values of the preimpact hydrologic parameters.
[b]L, M, and H represent low, moderate, and high alterations, respectively.
[c]Dates of the annual minimum and maximum count from November 1 and May 1, respectively.

annual 1-day maximum flow; and the number of high pulses are all classified as low alteration. These IHAs represent the high-flow characteristics. In contrast, the low-flow hydrologic parameters are easily influenced by the flow diversion. To demonstrate this, the contours of the D values for the monthly mean flow in January, annual 1 day minimum flow, base flow condition, and annual fall rate are shown in Figs. 6–9, respectively. Others are not shown here because their variation patterns are similar to those in Figs. 6 and 7, only with larger regions of low alteration. Generally speaking, the D value increases with the increase in Q_D, but decreases with the increase in Q_{IF}. Figs. 6 and 7 demonstrate typical contours of the D values for the low-flow IHAs. Fig. 8 shows a somewhat different pattern of D values for the base flow condition. Since the base flow condition is defined as the ratio of the annual seven-day minimum flow to the annual mean daily flow, the D values of the base flow condition are controlled by these two parameters. The annual 7-day minimum flow increases with an increasing Q_{IF}, but the annual mean daily flow decreases with an increasing Q_D. Larger values of Q_{IF} and Q_D on the upper right corner of the contour diagram tend to jointly make this ratio (i.e., base flow condition) exceed the upper RVA target. The contours of the D values for the annual fall rate, as shown in Fig. 9, demonstrate another variation pattern. The flow diversion tends to eliminate the natural flow fluctuations; hence, increasing Q_D will increase the D values of the annual fall rate.

By overlapping the contour diagrams of the 32 IHAs, three overall alteration regions are developed, as shown in Figs. 10 and 11. The overall low-, medium-, and high-alteration regions are determined by the definitions provided previously. The overall low-alteration region, obtained by the intersection of the 32 low-alteration regions, is considered herein as the region corresponding to the feasible combinations of Q_D and Q_{IF}. It is found that the IHAs dominating the feasible combinations of Q_D and Q_{IF} are the monthly mean flow in January, annual 1-day minimum flow, base flow condition, and annual fall rate. The feasible region for the proposed Taitung diversion weir is bounded by the projected flow diversions of 1, 2, 3, 4, and 5 m^3/s associated with the minimum Q_{IF} of 3, 6, 8, 9, and 15 m^3/s, respectively, as shown in Figs. 10 and 11 with a white pattern. The overall medium- and

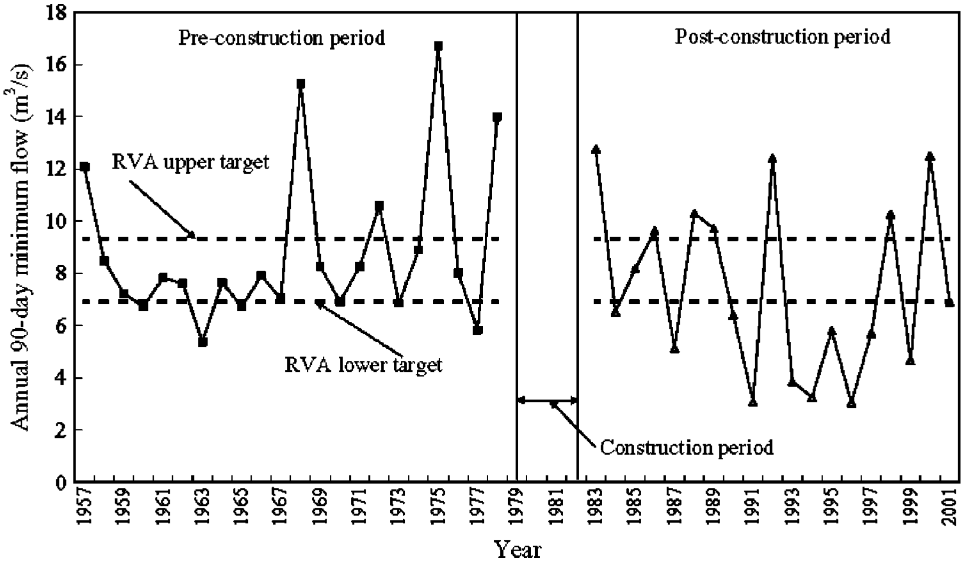

Fig. 4. Time series of annual 90-day minimum flow at Yenping gauge station before and after construction of Peinan diversion weir

high-alteration regions are also demonstrated in these figures with light and dark gray patterns, respectively. It is shown that the overall low-, medium-, and high-alteration regions are respectively located in the lower right, northeast-southwest diagonal, and upper left regions of the simulation domain. This indicates that, in general, a greater instream flow release and smaller flow diversion can reduce the hydrologic alteration, while larger flow diversions associated with smaller instream flow releases can cause severe hydrologic alterations.

The shortage risk and shortage ratio corresponding to various combinations of Q_D and Q_{IF} are also demonstrated in Figs. 10 and 11, respectively. For a constant Q_{IF}, the shortage risk and shortage ratio increase linearly with the projected flow diversion Q_D because of the higher water demand. Similarly, for a constant Q_D, the shortage risk and shortage ratio increase with the instream flow release Q_{IF} because of the reduced water supply. Since the instream flow release Q_{IF} has a higher priority than the flow diversion Q_D, a larger Q_{IF} would result in less diverted flow Q^t_{DF} and would thus produce a greater shortage risk and shortage ratio. However, this trend is not valid for the lower right region of Figs. 10 and 11; there, the shortage risk and shortage ratio remain nearly constant with an increasing Q_{IF}. This appears to indicate that the shortage risk and shortage ratio are independent of the instream flow release in cases where the water demand is low. The results imply that the increased Q_D needs the larger Q_{IF} to sustain the natural flow variations, but at the same time leads to the less stable water supply. For example, combinations of $Q_D = 2\ m^3/s$, $Q_{IF} = 6\ m^3/s$; and $Q_D = 5\ m^3/s$, $Q_{IF} = 18\ m^3/s$ are both classified as overall low alteration, as shown in Figs. 10 and 11. However, their corresponding shortage risks are 0.13 and 0.36, and their shortage ratios are 0.12 and 0.33, respectively. As shown in Figs. 10 and 11, the contours of the shortage risk and shortage ratio run in the southwest-northeast direction with increasing magnitude, which is opposite to the variation trend of the overall hydrologic alteration. The conflicting goals of ensuring water-

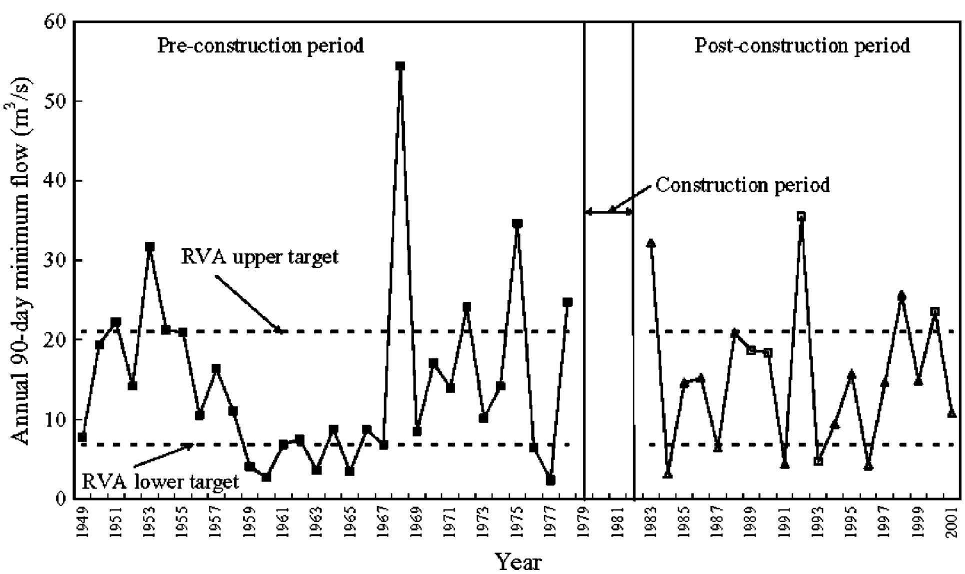

Fig. 5. Time series of annual 90-day minimum flow at Taitung Bridge gauge station before and after construction of Peinan diversion weir

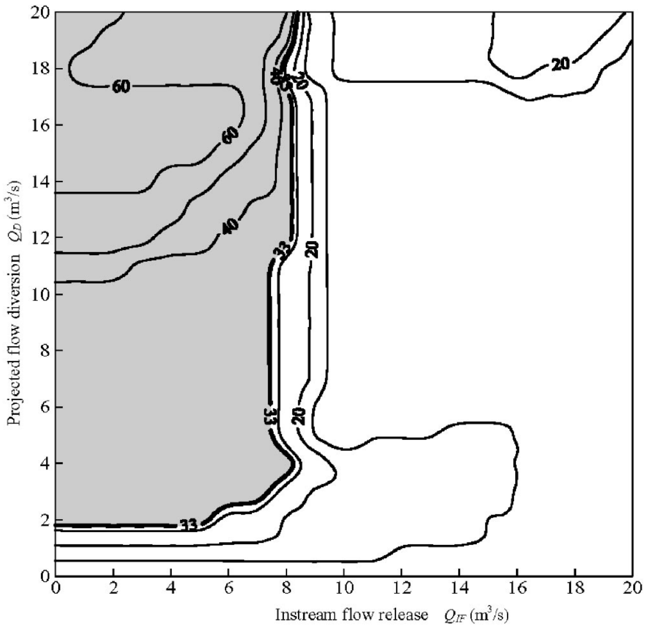

Fig. 6. Contours of degree of hydrologic alteration for monthly flow in January under various combinations of flow diversion and instream flow release (white area=low alteration; light area=moderate alteration; dark area=high alteration)

supply reliability and sustaining natural-flow variations are quantitatively demonstrated in Figs. 10 and 11. Nevertheless, decisions can be made within the feasible region of Q_D and Q_{IF}, considering both water-demand and supply-reliability constraints. Note in Figs. 10 and 11 the similar contour patterns but steeper slope of the shortage-risk plane than that of the shortage-ratio plane, indicating that the shortage risk (or shortage duration) is a more sensitive parameter than the shortage ratio (or shortage magnitude).

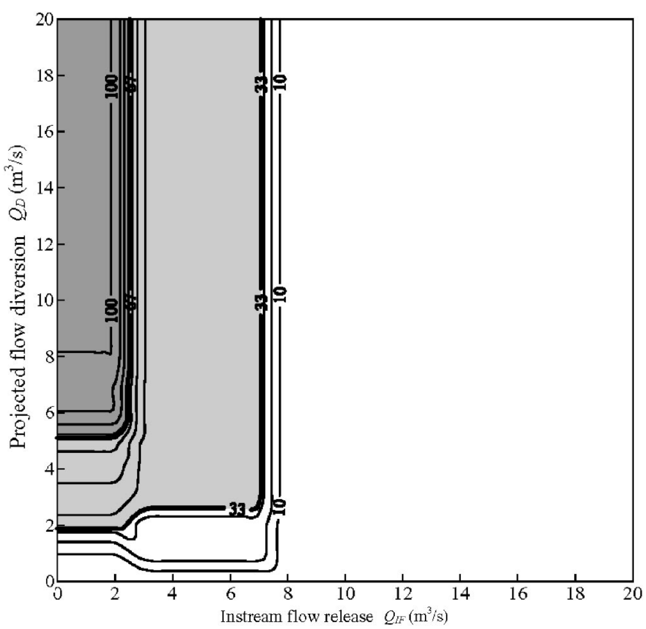

Fig. 7. Contours of degree of hydrologic alteration for annual 1-day minimum flow under various combinations of flow diversion and instream flow release (white area=low alteration; light area =moderate alteration; dark area=high alteration)

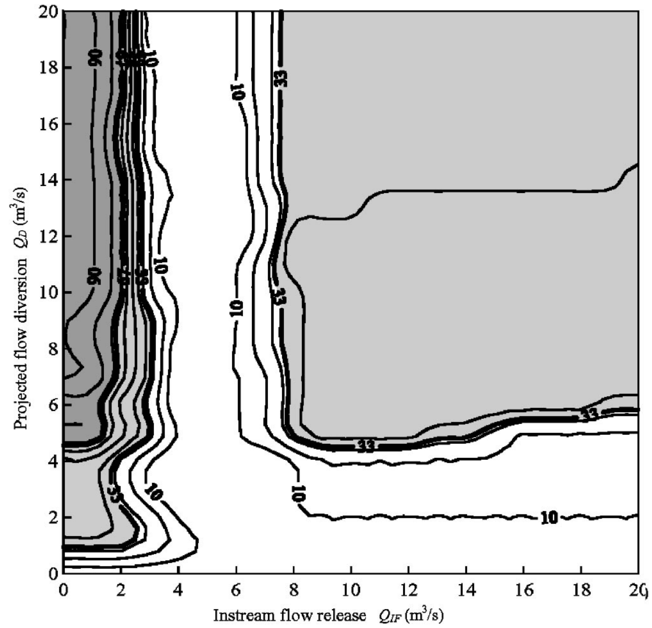

Fig. 8. Contours of degree of hydrologic alteration for base flow condition under various combinations of flow diversion and instream flow release (white area=low alteration; light area=moderate alteration; dark area=high alteration)

The information shown in Figs. 10 and 11 is useful in determining feasible combinations of Q_D and Q_{IF} that not only sustain the desirable flow variability, but also ensure the reasonable water-supply reliability. For instance, if an overall low alteration of the flow regime is desirable, the specified flow diversion of 2 m^3/s must be accompanied by a minimum instream flow release of 6 m^3/s to sustain the desired flow variations. If the shortage risk

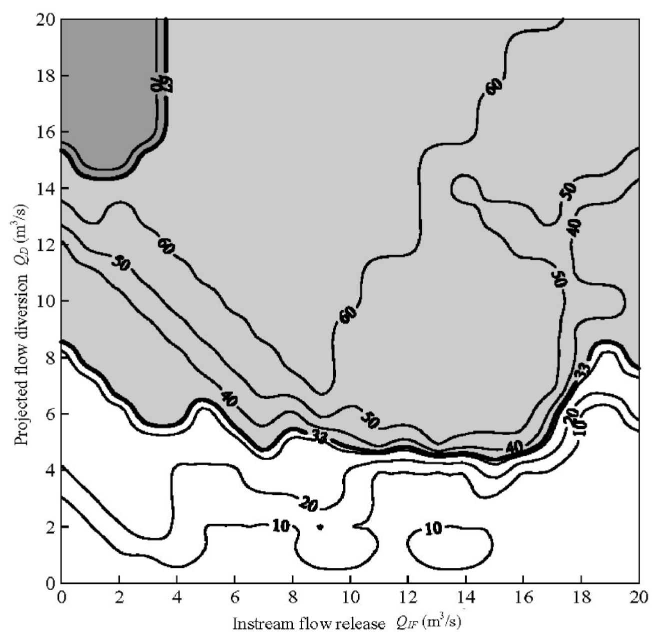

Fig. 9. Contours of degree of hydrologic alteration for annual fall rate under various combinations of flow diversion and instream flow release (white area=low alteration; light area=moderate alteration; dark area=high alteration)

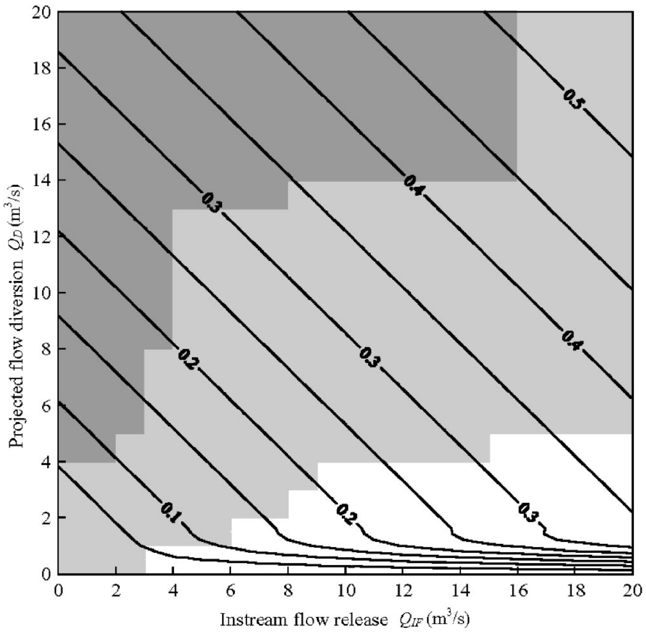

Fig. 10. Contours of shortage risk and three overall alteration regions corresponding to various combinations of flow diversion and instream flow release (white area=overall low alteration region; light area=overall medium alteration region; dark area=overall high alteration region)

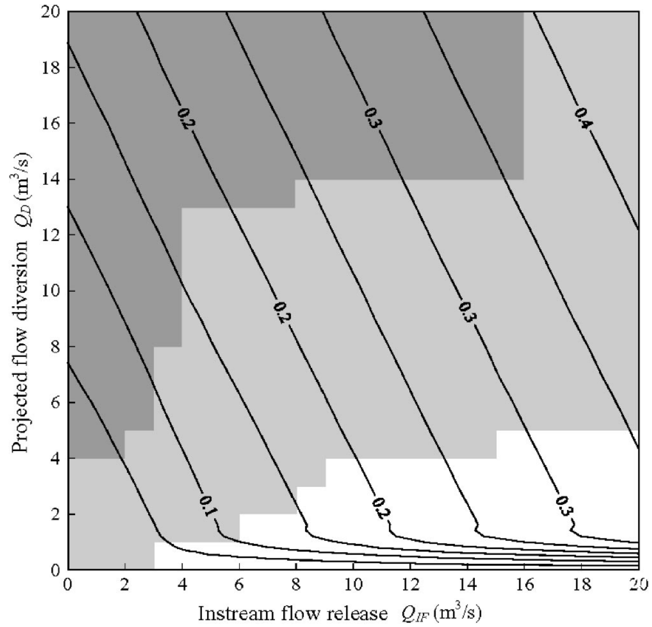

Fig. 11. Contours of shortage ratio and three overall alteration regions corresponding to various combinations of flow diversion and instream flow release (white area=overall low alteration region; light area=overall medium alteration region; dark area=overall high alteration region)

and shortage ratio are further taken into consideration, the instream flow release of 6 m^3/s would be an optimal choice. On the other hand, if the shortage risk of 0.1 is taken to be the design criterion for the water-supply reliability, the maximum Q_D would be 1 m^3/s and it must be accompanied by a minimum Q_{IF} of 3 m^3/s to sustain the desired flow variations. However, if an overall medium alteration of the flow regime is acceptable, the maximum Q_D would become 4 m^3/s and no instream flow release would be necessary to meet the water-supply and flow-variation constraints. The design diversion capacity of the proposed Taitung weir (i.e., 3.6 m^3/s) must be accompanied by a minimum instream flow release of 9 m^3/s to make the overall hydrologic regime lowly altered, with the corresponding shortage risk slightly higher than 0.2 and the shortage ratio slightly lower than 0.2.

Summary and Conclusions

An RVA-based methodology for determining the feasible combinations of flow diversion and instream flow release is presented. The proposed methodology allows simultaneous considerations of protecting the riverine environment and ensuring the water-supply reliability. The merits of the proposed methodology are demonstrated with its application to the projected Taitung diversion weir in Taiwan. Some general conclusions can be drawn from this study.

1. The impact of the tributary flow diversion (Peinan weir) on the downstream tributary flows (at the Yenping station immediately downstream of the Peinan weir, Luyeh Creek) is more substantial than that on the mainstream flows (at the Taitung Bridge station downstream of Peinan Creek). Among the 32 IHAs, most of the moderately or highly altered parameters are those that belong to low-flow characteristics, such as the annual multiday minimum flows and monthly mean flows in the dry season, indicating that the low-flow regime is easily influenced by the flow diversion.
2. The degree of hydrologic alteration generally increases with the increases of flow diversion, but decreases with the increase of the instream flow release. The overall low-alteration region, defined by the intersection of the 32 low-alteration regions, is dominated by the low-flow characteristics, such as the monthly mean flow in January, annual 1-day minimum flow, base flow condition, and annual fall rate. Generally, increasing the instream flow release and decreasing the flow diversion can reduce the overall hydrologic alteration, while a large flow diversion accompanied with a small instream flow release could cause severe hydrologic alterations.
3. Weir operation under various combinations of flow diversion and instream flow release is assessed by two shortage indices to reveal its corresponding water-supply reliability. For a constant instream flow release, the shortage risk and shortage ratio increase linearly with the projected flow diversion. Similarly, for a constant flow diversion, the shortage risk and shortage ratio increase with the instream flow release except for the very low water demands, for which the shortage risk and shortage ratio remain nearly constant with the instream flow release, indicating that the shortage indices are independent of the instream flow release when the water demands are very low. The results imply that, generally, the greater projected flow diversions require larger instream flows to sustain the natural flow variations, but, in the meantime, they lead to less stable water supplies. The conflicting nature of water-supply reliability and natural-flow variability has been quantitatively demonstrated. The steeper slope of the shortage risk than that of the shortage ratio indicates that the shortage risk is a more sensitive index.

The methodology presented here employs a simplified three-class scheme suggested by Richter et al. (1998) to classify the degree of hydrologic alteration. A more comprehensive scheme for demonstrating the continuous variation of overall hydrologic alterations, rather than the three discrete alteration classes, should be developed in future studies to offer a detailed trade-off analysis between the conflicting objectives and establish the noninferior options.

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