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Determining the Ecological Flow Regime for Existing Reservoir Operation

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Abstract Maintaining the natural variability of a river's flow regime is one of the most critical strategies sustaining the ecological integrity of aquatic ecosystems. This research seeks to determine the ecological flow regime for management of streamflow existing reservoirs. The ecological flow regime is a human-modified flow regime that captures the natural flow variability for maintaining the structure and the functional integrity of the aquatic ecosystems. The design procedure uses regionalization analysis, the ratio method, and linear regression analysis techniques with hydrologic indicators to simulate the altered flow variability caused by human-based annual streamflow reduction. Because it is difficult for reservoir operators to achieve the strict standard of natural flow regime, a discontinuity ratio method is used to express the reservoir's expected effect on the change in hydrologic indicator values. The final product of the ecological flow regime analysis produces a target reservoir operation and management that will provide a flow regime necessary to sustain the integrity of aquatic ecosystems.

Keywords Ecological flow regime · Reservoir operation · Discontinuity · Flow variability · Flow management

1 Introduction

Reservoir operation has significant impacts on river hydrology, primarily through changing the magnitude, frequency, duration, and timing of the flow regime. In order to maximize the multiple functional utilities of reservoirs (to provide water supply, power generation, recreation, navigation, and flood control), downstream flow release usually only considers the minimum flow approach for maintenance

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of aquatic ecosystems. The resulting low-flow release is approximately uniform, reducing the variability of the natural flow regime and contributing to the decline of ecological integrity. Reservoir construction alters the river systems in both biotic and abiotic ways (Ward and Stanford 1983). Downstream effects of reservoirs on aquatic ecosystems can be due to migration discontinuity, altered nutrient supply, and sediment transport, which have all been extensively documented (e.g., Ligon et al. 1995; Power et al. 1996; Thoms and Sheldon 2002; Ward 1976). Hydrology is the major driving force of the entire river system; altered flow regimes in the river system affect water quality, energy sources, physical habitat, and biotic interactions, resulting in damage to the ecological integrity of rivers. Restoring the natural flow regime is believed to benefit river ecosystems (Poff et al. 1997; Richter et al. 2003).

Streamflow variability came to the forefront of water resources management in the early twenty-first century (Poff 2009) and has since been occasionally incorporated into projects. This idea differs from the minimum instream flow method that is commonly used and can be determined through 'Instream Flow Incremental Methodology (IFIM)' (Bovee 1982) or other methods (e.g., Tennant Method (Tennant 1976)). Although the minimum instream flow approach has been applied worldwide, it is essentially an anthropocentric approach that concentrates on an approximately flat-line minimum flow that is usually based on a single dominant or target species. In contrast, the ecological flow regime approach focuses on reducing the ecological impacts of reservoirs by providing the necessary amount and variability of water for a river to support its downstream ecosystems (Jacobson and Galat 2008; Richter and Thomas 2007). The ecological flow regime approach is emerging as a new paradigm for multiobjective water resources planning and management because it provides decision makers with more information in finding a compromise strategy that satisfies the conflicting objectives of both environmental flow needs and human water needs (Marchetti and Moyle 2001; Shiau and Wu 2007; Suen and Eheart 2006; Tisdell 2010; Wang and Lu 2009; Xia et al. 2009).

The ecological flow regime is designed to preserve, protect, and restore the biological, geomorphological, physical, and chemical processes in a river that form and maintain aquatic ecosystems (Suen and Eheart 2006). Although the ecological flow regime is a human modified flow regime, it incorporates the essential features of the natural flow regime to maintain the structure and the functional integrity of the aquatic ecosystems. Some of the features of the natural flow regime (seasonal patterns of flow, different magnitudes of flood flow, annual and interannual flow patterns, duration of high or low flows) certainly play an important role in the aquatic ecosystem characteristics of rivers (Arthington 1994; Bernardo and Alves 1999; Bunn and Arthington 2002; Richter et al. 1997). To characterize the natural flow regime and ecological flow regime, hydrologic indicators are used for analysis (Richter et al. 1996; Suen and Eheart 2006).

In most countries' water resources development histories, reservoirs are usually built for economic development, and environmental concerns are usually seriously considered only years later when the economic growth of the area reaches a certain level. This raises several issues when discussing the environmental flow of existing reservoirs. First, there is usually no gauging station downstream of a reservoir, so it is difficult to find the ideal reference condition for environmental flow. Second, it can be argued that since the reservoir has been present for a period of time, the existing organisms should have already adjusted to the current flow regime, and the development of environmental flows should be based on those organisms. Those with the opposite view answer that the existing organism community is different from the original community inhabited the area before reservoir construction, and that restoring the natural flow for the original community is crucial to ecological restoration (Bunn and Arthington 2002; Hoagstrom et al. 2007; Propst and Gido 2004). Finally, although river channels downstream of the reservoir usually maintain adequate width for flood mitigation purposes, most of the time water is only found in the main channel area; the geomorphic habitat condition varies primarily in a smaller channel range balanced by the long-term reservoir releases. The development of an environmental flow should consider the original organism community, pre-dam natural flow conditions, and downstream geomorphic balance with flow variability.

Richter et al. (1997) proposed the Range of Variability Approach (RVA) to evaluate the hydrologic alteration caused by hydraulic control structures. The RVA approach provides a more quantitative way to evaluate the degree of alteration by giving a target range (e.g. the percent difference between the 25th- and 75th-percentile pre-impact indicator values) for each hydrologic indicator. Current RVA applications show high degrees of alteration at locations downstream of the hydraulic control structures, and changes are especially worse in water supply reservoirs (Shiau and Wu 2004; Yang et al. 2008a). The aim of this paper is to determine the ecological flow regime for the operation of existing reservoirs. Such a regime-based streamflow management approach has been implemented in only a few reservoirs (Jager and Smith 2008; Vogel et al. 2007). One of the most critical issues of this approach is determining the target flow regime for management purposes. The full range of natural flow variability developed by Richter et al. (1997) is a very strict standard for reservoir operation because a portion of the flow has been transferred to other places (e.g. downstream domestic water supply). An applicable flow regime target is needed for reservoir operation (Jacobson and Galat 2008). This research demonstrates a framework that incorporates regionalization analysis, the ratio method, linear regression analysis, and the discontinuity ratio concept in an ecological flow regime estimation model. The resulting model then provides an ecologically-based flow regime for the operation of existing reservoirs.

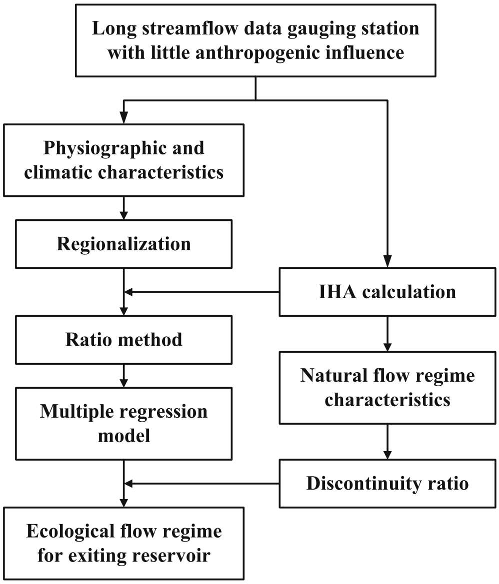
2 Methods

The research framework is shown in Fig. 1. Climatic and physiographic data from selected streamflow gauging stations are used for regionalization analysis. Streamflow data from the same region are analyzed by IHA method and then are analyzed by ratio method for regression model. Finally the selected discontinuity ratio is used determine the ecological flow regime for existing reservoirs.

2.1 Station Selection and Data Processing

In order to examine the hydrologic characteristics of natural flow regime in Taiwan, this research considers gauging stations with long periods (>20 years) of streamflow datasets and relatively little upstream anthropogenic influence. Unfortunately, the streamflow datasets of most gauging stations in Taiwan are either relatively short or are affected by upstream hydraulic structures such as dams or irrigation facilities.

Fig. 1 Framework of ecological flow regime regression model



Only 58 stations (from a total of 23 rivers) throughout the entire island were considered suitable for this analysis. Most of these stations are in midstream to upstream areas in the mountains, and few of them are in smaller coastal streams. Still, these gauging stations show a variety of physiographic and climatic characteristics. The twenty-three rivers that are included in this analysis collectively cover the expanse of the island. The controlled drainage areas of the gauges range from 11 to 812 km^2. Elevation of the gauging stations range from near sea level to 1,700 m. The average annual rainfall varies from 1,912 to 5,172 mm (Water Resources Agency 2009).

Hydrologic indicators have been widely applied in ecological water resources management (Richter et al. 2003; Richter and Thomas 2007; Suen and Eheart 2006; Suen 2010). Such hydrologic indicators are recognized as being ecologically relevant, and they can be easily calculated from historical flow data (e.g., Poff et al. 1997; Richter et al. 1996). The Indicators of Hydrologic Alteration (IHA) approach (Richter et al. 1996) developed by The Nature Conservancy, USA, is a novel and increasingly-used approach. It uses daily streamflow data to calculate 31 hydrologic parameters that are categorized into five groups: Group 1—Magnitude of Monthly Water Conditions; Group 2—Magnitude and Duration of Annual Extreme Water Conditions; Group 3—Timing of Annual Extreme Water Conditions; Group 4—Frequency and Duration of High and Low Pulses; and Group 5—Rate and Frequency of Water Consecutive Daily Means Condition. These parameters adequately represent the majority of the variation of the flow regime for hydroecological studies and are easily calculated using a Windows-based computer software (IHA V7.1) developed by The Nature Conservancy, USA (TNC 2005). More detailed information on the IHA development can be found in Richter et al. (1996). In this research, the 31 hydrologic indicators are used to characterize the essence of the natural flow regime and will be used to form the ecological flow regime for operating existing reservoirs.

2.2 Regionalization

In most cases, streamflow data for gauging stations downstream of reservoirs in Taiwan do not include both pre- and post-dam periods. There is therefore little data that can be used to determine the flow regime alteration caused by dam operation. Streamflow gauges downstream of reservoirs can be seen as redundant since the reservoir controls water release anyhow. Although some reservoirs may operate with the goal of restoring the natural variability of streamflow, it is difficult to retrieve the original flow regimes from times before reservoir construction. Consequently, the pre-dam natural flow regime downstream of the dam is essentially unknown. As an alternative, regionalization techniques can be employed to capture the hydrologic characteristics of streamflow data from similar climatic, physiographic and hydrologic gauging stations and used to estimate the natural pre-dam flow at downstream locations. Discussion of the regionalization procedure and spatial and temporal patterns can be found in Chiang et al. (2002a, b), Chang et al. (2008), Sanborn and Bledsoe (2006) and Thoms and Parsons (2003). In this research, the annual rainfall, drainage area, main channel river length, mean slope, mean elevation, longitude, and latitude of each gauging station are used for climatic and physiographic regionalization by cluster analysis. Chang et al. (2008) suggest three regions could adequately describe the ecological hydrology of natural flow conditions in Taiwan, so the number of the clusters in the regionalization process of this research is three. For determine the ecological flow regime, all locations downstream of a reservoir then could be classified into one of the regions by applying discrimination techniques to the locations' climatic and physiographic characteristics. The estimated flow regime can be generated using the hydrologic characteristics of the gauging stations from the same region.

2.3 Ratio Method

The "ratio to the mean" procedure groups multiple years of data and uses their average hydrologic characteristics to avoid bias that could be caused by extreme values observed in a single year (Gan et al. 1991; Pitlick 1994). Eliminating bias can allow for a higher correlation in regression analysis.

One of the major functions of reservoirs is storage of water for agricultural, industrial and public water supplies. The mean total annual streamflow of the post-dam period at a location downstream of a dam is usually smaller than that of the pre-dam period because of these human use demands. In Taiwan, the average annual precipitation is about 2,500 mm; however, under natural conditions, the total annual streamflow in an extremely wet year may be several times that of an extremely dry year (Shiau and Wu 2007). The annual total water volume from precipitation equals approximately 90 billion cubic meters and the average annual water supply is about 18 billion cubic meters. Approximately half of the water supply is provided from reservoirs. The total annual streamflow downstream of the reservoir may change after reservoir construction to only a fraction of the original, natural annual streamflow. Total post-dam streamflow amounts are likely more similar to the streamflow of a dry year in the pre-dam period. The total post-dam flow is therefore only a small portion of the total annual streamflow for a wet year in the pre-dam period.

In this research, the dry year case of the pre-dam natural streamflow condition is used as a surrogate to characterize the magnitude, frequency, duration, and rate of change of a post-dam total annual streamflow condition. A "ratio to the mean" method is used to estimate the change of hydrologic characteristics of the post-dam condition. The basic calculating procedure adheres to the following protocol:

1. For each gauging station, rank the total annual streamflow for all streamflow records. Divide the streamflow data into several groups according to rank order. Then calculate the mean of each group's total annual streamflow and the means of each group's 31 IHA indicators of that gauging station. Next, calculate the means of total annual streamflow and 31 IHA indicators of the same gauging station. Finally, calculate the ratio of each group's means of total annual streamflow and 31 IHA indicators to the gauging station's means of total annual streamflow and 31 IHA indicators. The first ratio is called the total annual streamflow ratio in the remainder of the article.
2. In order to understand how indicators change when total annual streamflow increases or decreases, use a linear regression model to find the relation between the total annual streamflow ratio and the 31 IHA indicators' ratios calculated in Procedure 1. It can be expressed as:

$$\text{IHA indicator ratio} = \text{a} \times \text{annual total streamflow ratio} + \text{b}$$

   Where a and b are constants. For each regression model, use ratio data from all gauging stations grouped into a single region according to the regionalization procedure. Gauging stations in the same region are assumed to have similar hydrologic characteristics and are therefore arguably comparable to each other.

2.4 Discontinuity Ratio

Compared to headwater and high-order reaches, the variation in streamflow is greater in the middle reaches of rivers (Sanford et al. 2007). The serial discontinuity concept proposes that reservoirs or dams within middle reaches may cause even greater changes to the streamflow variation (Ward and Stanford 1983). In this research, a discontinuity ratio (DR) is defined to express the expected change in ratio of hydrologic indicator values caused by dams based on the serial discontinuity concept. The DR is a suggested method that reservoir managers could use as a tool once the results from the ratio and linear regression methods are obtained. A DR value of 1.0 means the range of variability of the designed ecological flow regime is equal to the range of variability of the natural flow regime. A DR value of 0.0 means the range of variability of the designed ecological flow regime is equal to the range of variability of the proportional natural flow regime based on the serial discontinuity concept. Any DR value between 0.0 and 1.0 could be selected by reservoir managers and used as a target for regime-based ecological water resources management. Unlike the Range of Variability Approach, the use of the discontinuity ratio suggests that the hydrologic characteristics of the post-dam period are not necessarily the same as those required to match the pre-dam period's variation. A small reduction in streamflow is acceptable in dam operational management since the intercepted water, stored in the reservoir, is expected to be reserved for human use (Jacobs and Vogel 1998). However, the target ecological flow regime for streamflow management of existing reservoirs should be between the ideal natural flow regime and the current flow regime. The DR acknowledges that the current flow regime of an existing reservoir includes less variation but the pristine flow conditions of the ideal natural flow regime are usually an unreachable target.

3 Results

Climatic and physiographic data are initially used for regional cluster analysis, and 58 stations are classified into three regions based on their climatic and physiographic characteristics (Fig. 2 and Table 1). There are 14, 12, and 32 stations in Regions 1, 2, and 3, respectively. In order to test if the hydrologic characteristics of stations from the same region are similar, 31 IHA parameters calculated from the same 58 stations are also used for cluster analysis; three types of stations are identified by this clustering action. Comparison of the three types of natural flow regime characteristics and three climatic and physiographic regions shows that only 9 stations (15.5%) are not consistent in their grouping based on the two methods (Table 2). There are no discrepancies between the classifications of Region 1 and Region 2; the hydrologic characteristics are noticeably different between these two regions. Region 3 includes most stations, but it is not as easy to completely separate the Region 3 stations from those in Region 1 and Region 2. Although the three climatic and physiographic regions do not show a strong geographic relation, they indeed reveal different hydrologic characteristics. These three climatic and physiographic regions will be used for establishing three types of ecological flow regime estimation models.

Stations in Region 1 are generally in mid-order reaches with large drainage areas. Compared to streamflows in the other two regions, streamflows at these stations show the least number of high and low pulses and the longest periods of duration of both high and low pulses. Stations in Region 2 are generally located downstream of large rivers or small coastal streams in the western part of Taiwan. The drainage areas of these stations are much smaller, and the slopes are gentler. Streamflows in these stations have a higher number of high and low pulses, shorter periods of

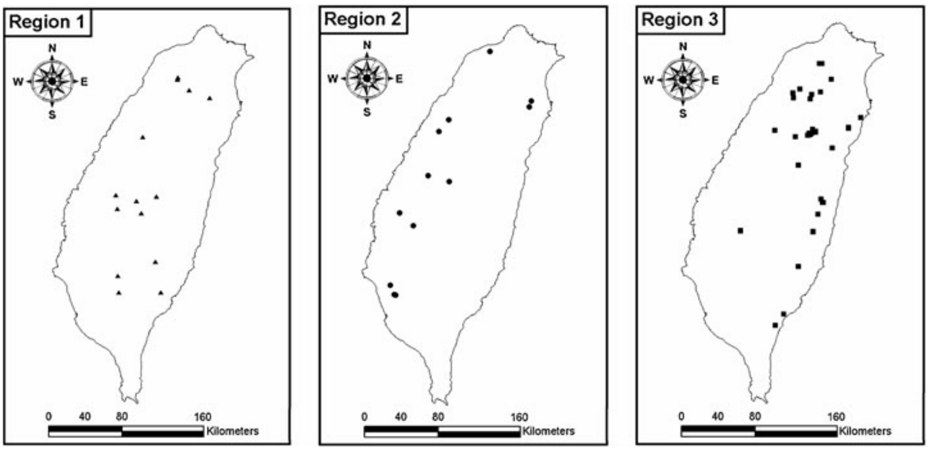


Fig. 2 Three climatic and physiographic regions

Table 1 The physiographic, climatic and hydrologic characteristics of three regions

	Region 1		Region 2		Region 3	
	Mean	CV*	Mean	CV*	Mean	CV*
Physiographic and climatic characteristics						
Drainage area (km^2)	470.4	0.416	92.5	0.754	183.8	0.693
Main channel length (km)	53.5	0.530	16.4	0.686	25.0	0.410
Mean elevation (m)	1543.3	0.238	390.0	0.946	1620.0	0.387
Mean slope	0.611	0.089	0.273	0.569	0.611	0.122
Annual rainfall (mm)	2610.6	0.093	2655.2	0.430	2650.5	0.177
Hydrologic characteristics						
January mean flow (m^3/s)	7.98	0.558	1.50	1.117	5.20	0.717
February mean flow (m^3/s)	9.97	0.657	2.23	1.174	7.18	0.691
March mean flow (m^3/s)	11.68	0.646	2.52	1.126	7.95	0.722
April mean flow (m^3/s)	14.62	0.586	3.24	1.027	8.02	0.744
May mean flow (m^3/s)	25.01	0.553	4.83	0.747	10.36	0.724
June mean flow (m^3/s)	60.69	0.644	10.46	0.609	18.79	0.750
July mean flow (m^3/s)	52.52	0.546	9.50	0.746	16.27	0.762
August mean flow (m^3/s)	70.11	0.506	12.74	0.696	22.40	0.677
September mean flow (m^3/s)	63.35	0.474	8.33	0.566	25.36	0.714
October mean flow (m^3/s)	33.98	0.577	3.75	0.922	18.53	0.787
November mean flow (m^3/s)	17.34	0.599	2.42	1.005	9.82	0.834
December mean flow (m^3/s)	10.08	0.506	1.69	0.995	6.24	0.810
1-day minimum (m^3/s)	4.19	0.617	0.44	1.348	2.46	0.872
3-day minimum (m^3/s)	4.33	0.632	0.47	1.359	2.51	0.862
7-day minimum (m^3/s)	4.45	0.642	0.53	1.385	2.61	0.854
30-day minimum (m^3/s)	5.09	0.650	0.72	1.328	3.00	0.819
90-day minimum (m^3/s)	6.14	0.691	1.05	1.231	3.78	0.760
1-day maximum (m^3/s)	862.29	0.501	175.75	0.656	288.18	0.712
3-day maximum (m^3/s)	526.86	0.479	99.25	0.622	179.98	0.735
7-day maximum (m^3/s)	320.47	0.466	56.07	0.602	111.21	0.730
30-day maximum (m^3/s)	136.02	0.451	23.00	0.566	49.92	0.686
90-day maximum (m^3/s)	79.10	0.474	13.49	0.571	28.76	0.672
Date of 1-day minimum	78.05	0.154	88.84	0.340	74.78	0.147
Date of 1-day maximum	222.44	0.076	216.55	0.114	230.11	0.075
Low pulse count	5.83	0.358	8.75	0.454	6.20	0.367
Low pulse duration (days)	18.44	0.319	12.78	0.324	18.24	0.312
High pulse count	3.82	0.120	7.04	0.393	4.33	0.351
High pulse duration (days)	4.46	0.364	2.31	0.252	4.36	0.280
Rise rate ($m^3/s/day$)	28.98	0.600	5.96	0.559	10.38	0.802
Fall rate ($m^3/s/day$)	−9.51	−0.480	−3.37	−0.592	−3.40	−0.637
Number of reversals	85.71	0.268	101.70	0.211	78.36	0.170

**CV:* Coefficient of variation

Table 2 Comparison of three hydrologic types and three climatic and physiographic regions

		Climatic and physiographic data		
		Region 1	Region 2	Region 3
Hydrologic data	Type 1	11	0	2
	Type 2	0	11	3
	Type 3	3	1	27

duration of both high and low pulses, and higher frequency of hydrograph reversals than streamflows in the other two regions. The average Julian date of the 1-day maximum flow in these stations is earlier and the average Julian date of the 1-day minimum flow is later than they are in the other two regions. Stations in Region 3 are generally located in mountain areas of northern Taiwan or costal mountain areas at eastern Taiwan. Because northeasterly monsoons bring intense precipitation in fall and early winter, the highest monthly mean streamflow in this region is September; the percentage of the streamflow occurring from September to December in this

Table 3 The parameters and r^2 of regression models ((IHA indicator ratio = a × annual total streamflow ratio + b)

Hydrologic parameters	Region 1			Region 2			Region 3		
	a	b	r^2	a	b	r^2	a	b	r^2
Statistic group #1									
January mean flow	0.392	0.604	0.194	0.625	0.371	0.413	0.177	0.822	0.067
February mean flow	0.568	0.429	0.277	0.919	0.079	0.458	0.881	0.117	0.373
March mean flow	0.696	0.314	0.347	0.696	0.298	0.249	0.744	0.254	0.405
April mean flow	0.988	0.010	0.593	0.910	0.092	0.529	0.822	0.181	0.611
May mean flow	0.859	0.142	0.609	0.685	0.311	0.556	0.702	0.298	0.546
June mean flow	0.980	0.017	0.667	0.764	0.234	0.640	0.917	0.084	0.588
July mean flow	0.895	0.105	0.816	0.878	0.125	0.641	0.635	0.366	0.356
August mean flow	1.189	0.183	0.737	1.150	0.149	0.793	1.208	0.207	0.694
September mean flow	0.993	0.006	0.587	1.209	0.206	0.637	1.250	0.248	0.746
October mean flow	0.858	0.141	0.667	1.141	0.143	0.785	1.286	0.289	0.719
November mean flow	0.526	0.472	0.307	0.816	0.183	0.609	0.591	0.408	0.406
December mean flow	0.453	0.545	0.346	0.735	0.265	0.598	0.441	0.561	0.307
Statistic group #2									
1-day minimum	0.480	0.512	0.315	0.631	0.364	0.253	0.209	0.790	0.108
3-day minimum	0.442	0.552	0.286	0.463	0.532	0.245	0.206	0.793	0.099
7-day minimum	0.412	0.585	0.318	0.369	0.626	0.192	0.223	0.775	0.123
30-day minimum	0.307	0.691	0.402	0.637	0.360	0.387	0.338	0.661	0.265
90-day minimum	0.227	0.770	0.259	0.611	0.389	0.401	0.391	0.610	0.382
1-day maximum	1.181	0.183	0.772	1.145	0.143	0.662	1.377	0.377	0.802
3-day maximum	1.204	0.208	0.808	1.149	0.148	0.745	1.374	0.372	0.833
7-day maximum	1.194	0.199	0.860	1.075	0.074	0.774	1.321	0.318	0.858
30-day maximum	1.167	0.169	0.917	1.123	0.123	0.854	1.319	0.319	0.924
90-day maximum	1.106	0.106	0.977	1.095	0.095	0.938	1.169	0.170	0.953
Statistic group #3									
Date of 1-day minimum	−0.319	1.315	0.159	−0.424	1.429	0.226	−0.240	1.256	0.034
Date of 1-day maximum	0.066	0.934	0.104	0.096	0.904	0.173	0.120	0.880	0.211
Statistic group #4									
Low pulse count	−0.617	1.617	0.465	−0.352	1.353	0.208	−0.578	1.576	0.487
Low pulse duration	−0.240	1.242	0.107	−0.275	1.273	0.139	−0.301	1.301	0.095
High pulse count	0.984	0.022	0.755	1.004	0.002	0.814	1.188	0.185	0.850
High pulse duration	0.798	0.193	0.768	0.416	0.579	0.512	0.965	0.022	0.701
Statistic group #5									
Rise rate	1.215	0.215	0.864	1.151	0.146	0.774	1.368	0.367	0.883
Fall rate	1.131	0.129	0.881	1.167	0.165	0.847	1.352	0.352	0.897
Number of reversals	−0.081	1.082	0.107	0.113	0.887	0.175	0.039	0.961	0.033

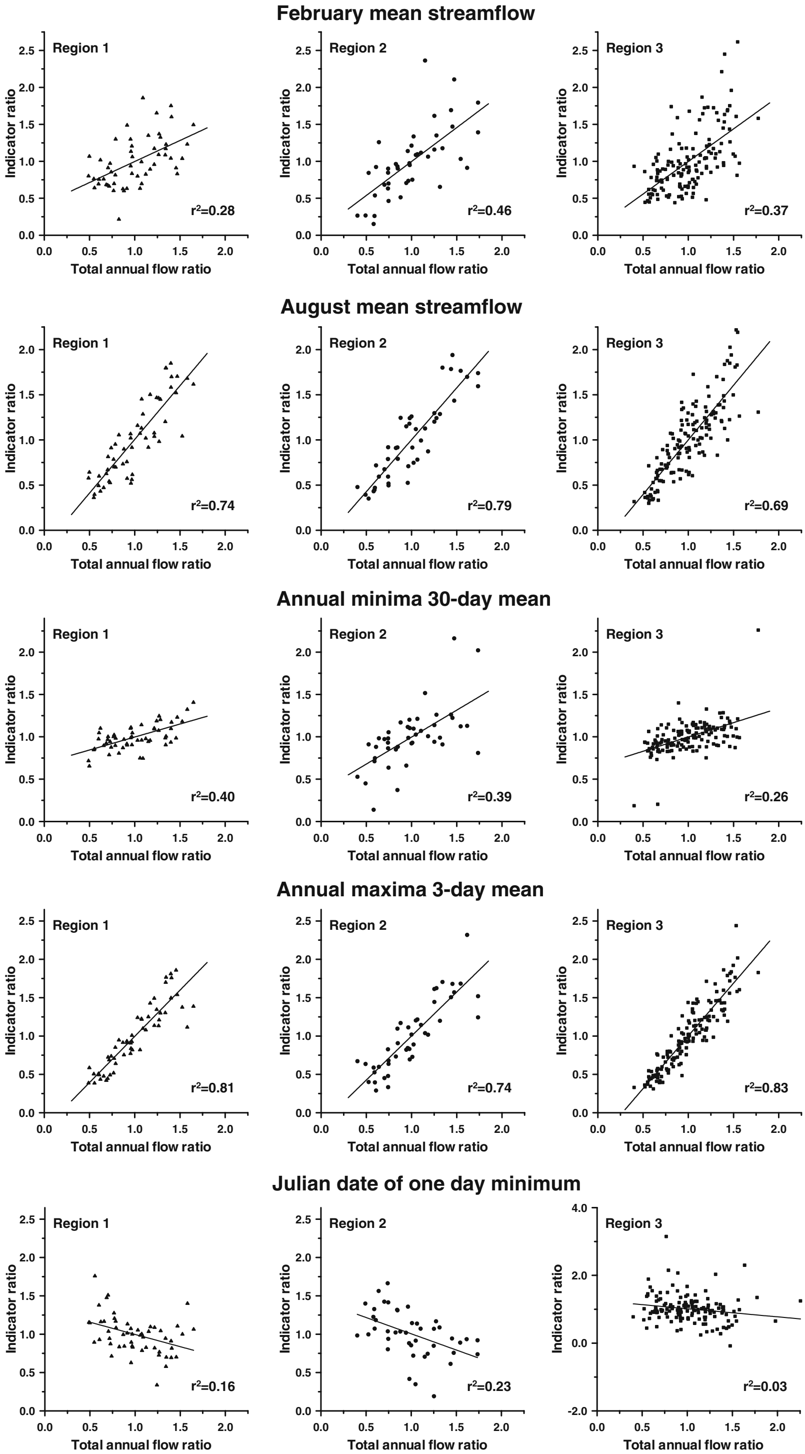


Fig. 3 Regression results of some of the hydrologic indicator ratios to annual total streamflow ratios

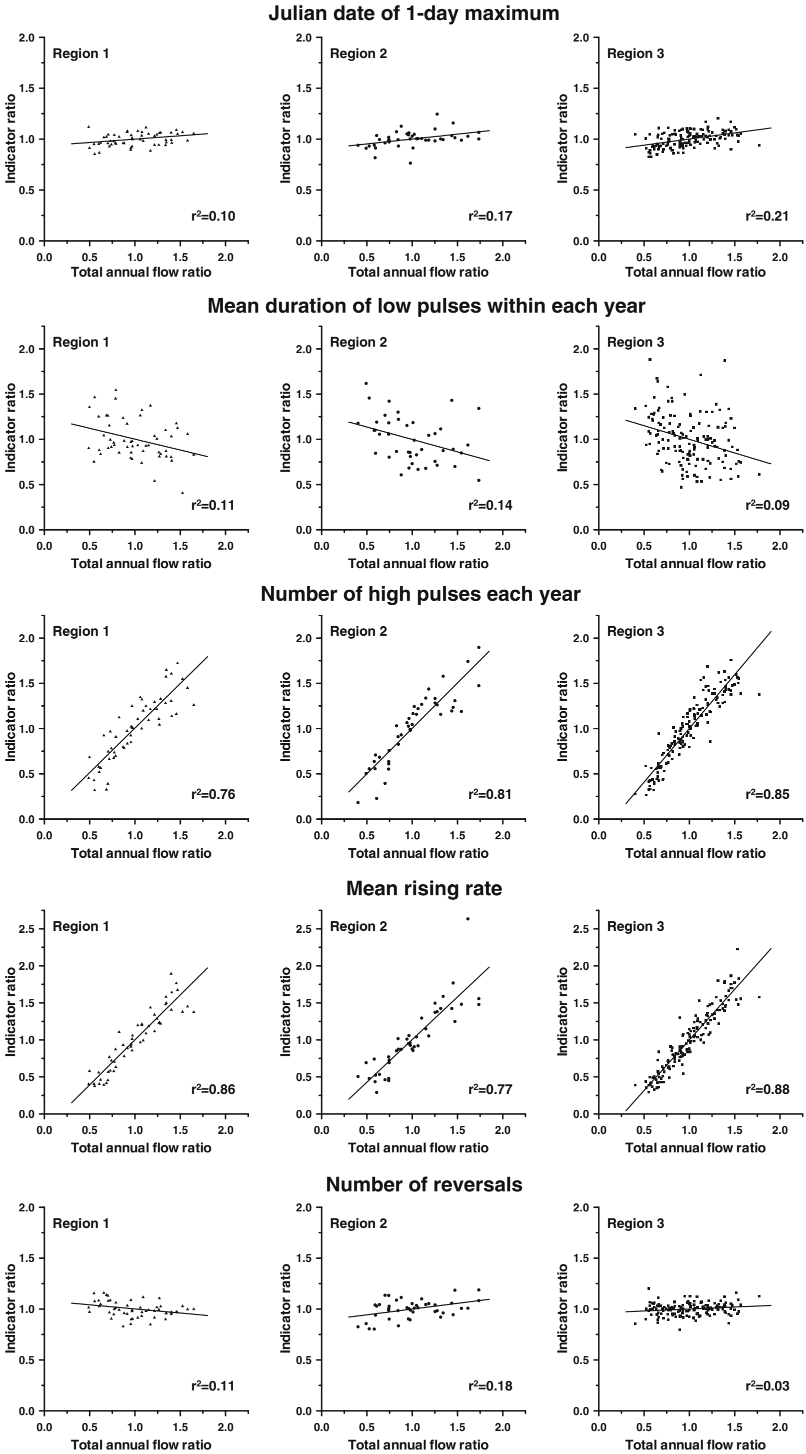


Fig. 3 (continued)

region is much higher than it is in the other two regions. The average Julian date of the 1-day maximum flow in this region is later and the average Julian date of the 1-day minimum flow is earlier than they are in the other two regions, and the streamflow record shows lower frequency of hydrograph reversals than in the other two regions.

For each gauging station, the 31 IHA indicators and means of ranked groups are calculated. The linear regression model is applied for determining the relations between the total annual streamflow ratio and the 31 IHA indicator ratios in each region. Table 3 shows the regression parameters and r^2 of each regression result. Approximately one third of the resulting r^2 values are larger than 0.700, indicating a high correlation between some of the indicators. In contrast, nearly half of the r^2 values are less than 0.500. These regressions primarily include low-flow variables. Fig. 3 shows the results of regression for the total annual streamflow ratio and the hydrologic indicator ratio; this is not used in any further analyses. For each region, ten indicators are selected to show the relations between the hydrologic characteristics and total annual streamflow ratio. These 31 hydrologic indicators for each region are used to form the ecological flow regime for operating the existing reservoirs.

4 Discussion

4.1 Correlations to High and Low Flow Indicators

Regression results show that some of the hydrologic indicators represent highly correlated relations between the total annual streamflow ratio and the hydrologic indicator ratio, especially for high-flow indicators. In hydrologic Statistic Group #1 (Table 3), monthly mean flow has a stronger relationship with total annual streamflow in the wet season (May to October) than it does in the dry season. In hydrologic Statistic Group #2, maximum-flow indicators reveal much higher r^2 values than do minimum-flow indicators. The r^2 of the 90-day maximum indicate ranges from 0.938 to 0.977. In hydrologic Statistic Group #4, the indicators for the number and duration of high pulses have a higher r^2 value than the indicators for the number and duration of low pulses. These highly correlated relations of high-flow indicators could be ascribed to typhoons and big storms that are typical of the wet season in Taiwan. Such events can bring more than 20% of the average annual precipitation over only a few days, usually filling the reservoir and requiring the release of large amounts of water. These conditions usually cause the high-flow indicators to be proportional to the total annual flow reduction. While the major purpose of this work is to estimate the ecological flow regime for operation of existing reservoirs, the strong relationships between total annual streamflow and high-flow indicators suggest that the ideal flow target of high-flow indicators could be proportionally reduced according to the total annual flow reduction.

On the other hand, regression results of low-flow indicators show poor correlation with total annual streamflow. The largest r^2 value for all minimum-flow indicators in hydrologic Statistic Group #2 is 0.402, and others are relatively smaller. The low pulse duration indicator also shows a very weak correlation with total annual streamflow. This shows the limitations of this approach due to the use of total annual means as the normalization factor. The characteristics of natural drought conditions may not be similar to those of downstream low-flow conditions (Nalbantis and Tsakiris 2010; Vangelis et al. 2010). Reservoir managers can manipulate streamflow fluctuation to avoid severe drought conditions by releasing small amounts of water to increase the low-flow indicator values. Previous research actually shows that reservoir operation may increase the magnitude of low-flow indicator values (Magilligan and Nislow 2005).

Although the dates of 1-day maximum and 1-day minimum flow show almost no relationship to total annual streamflow, the date of 1-day maximum flow indicates short range variation and the date of 1-day minimum flow shows long range variation (see Table 1 and Fig. 3). The number of reversals shows results similar to those of the date of 1-day maximum flow. Regardless of whether the total annual streamflow is double the mean or half the mean, there is little variation in the values of these two parameters. These flow events are important hydrologic characteristics that are frequently used by aquatic organisms as cues for spawning or migration. This presents some conflicts with reservoir operation—a major objective of flood control reservoirs is to both reduce and delay the peak flow, thereby altering the date of 1-day maximum, and many reservoirs (especially those powering hydropower dams) impose even greater fluctuation in streamflow, thereby altering the number of reversals. The ecological flow regime can be used to guide the streamflow management of existing reservoirs in order to reduce such conflicts.

In multipurpose reservoir operations, conflict management strategies can drastically alter natural flow variability. While managers try to store as much water as possible for use in the dry season, during an extremely large typhoon or storm event, flood control may require the release of large amounts of water in an attempt to both reduce and delay the original peak discharge, mitigate downstream flood pressure and prevent possible overflow that could damage the dam structure. It is possible for reservoir operations to produce the proportional maximum flow values and match the maximum date required to meet the ecological flow regime management targets while also focusing on flood control operation. On the other hand, during a long period of drought conditions, reservoir managers could release a large portion of the designed daily ecological base flow while collecting the remaining ecological base flow over a period of a few days to produce a relatively larger flow.

4.2 Example of the Ecological Flow Regime Determination

Ecological flow regimes will not always target the pre-dam condition. One gauging station used as an example in this study, Yu-Ten, located in the Ho-Ku Stream of southwest Taiwan, was selected to examine the flow regime alteration caused by the Nan-Hua Reservoir operation and to estimate the ecological flow regime for future management. The daily streamflow data used for this analysis includes 30 years of records (1959–1988) before the reservoir was built and 13 years of records (1994–2006) after reservoir construction. Table 4 shows the hydrologic alteration after reservoir construction by comparing the 31 IHA indicators for these two periods. Using climatic and physiographic data for discriminate analysis, Yu-Ten Station is assigned to Region 2 of the previous classification. The pre-dam 30-year average total annual streamflow is around 3,743 m^3/s, and the post-dam 13-year average total annual streamflow is 2,440 m^3/s, only 65.2% of the pre-dam average value. The

Table 4 The pre-dam and post-dam hydrologic alteration and estimated values for the post-dam condition from regression models of Yu-Ten gauging station

Hydrologic parameters	Pre-dam		Post-dam		Regression
	Means	CV	Means	CV	models
Annual total streamflow (m^3/s)	3,743	0.381	2,440	0.826	
Statistic group #1					
January mean flow (m^3/s)	0.257	1.672	0.204	0.619	0.200
February mean flow (m^3/s)	0.285	2.143	0.238	0.784	0.193
March mean flow (m^3/s)	0.302	2.327	0.325	1.350	0.227
April mean flow (m^3/s)	0.531	2.067	0.543	1.757	0.363
May mean flow (m^3/s)	6.980	1.290	1.947	1.140	5.286
June mean flow (m^3/s)	26.458	0.830	14.052	1.923	19.384
July mean flow (m^3/s)	22.394	0.775	20.188	1.413	15.615
August mean flow (m^3/s)	41.109	0.589	27.522	1.198	24.718
September mean flow (m^3/s)	19.229	0.710	11.561	1.335	11.199
October mean flow (m^3/s)	3.731	0.866	1.858	0.814	2.242
November mean flow (m^3/s)	0.733	0.594	0.642	0.994	0.525
December mean flow (m^3/s)	0.258	0.522	0.518	1.581	0.192
Statistic group #2					
1-day minimum (m^3/s)	0.008	1.156	0.024	1.656	0.006
3-day minimum (m^3/s)	0.009	1.163	0.037	1.549	0.007
7-day minimum (m^3/s)	0.011	1.178	0.044	1.483	0.010
30-day minimum (m^3/s)	0.028	1.075	0.092	1.083	0.022
90-day minimum (m^3/s)	0.072	0.772	0.143	0.877	0.056
1-day maximum (m^3/s)	375.9	0.477	577.7	1.136	226.8
3-day maximum (m^3/s)	247.5	0.473	296.4	1.064	148.6
7-day maximum (m^3/s)	139.9	0.423	151.2	0.988	87.6
30-day maximum (m^3/s)	59.0	0.413	47.3	0.830	35.9
90-day maximum (m^3/s)	34.0	0.433	23.6	0.905	21.0
Statistic group #3					
Date of 1-day minimum	66.83	0.507	92.38	0.807	85.89
Date of 1-day maximum	215.53	0.155	206.77	0.172	208.45
Statistic group #4					
Low pulse count	4.300	0.419	8.923	0.623	4.834
Low pulse duration (days)	21.092	0.667	8.434	0.595	23.077
High pulse count	6.167	0.390	2.692	0.733	4.025
High pulse duration (days)	2.607	0.344	2.327	0.566	2.216
Statistic group #5					
Rise rate (m^3/s /day)	16.503	0.439	9.412	0.885	9.969
Fall rate (m^3/s /day)	−7.552	−0.432	−6.147	−0.960	−4.505
Number of reversals	81.567	0.243	117.769	0.173	78.332

annual total streamflow ratio (65.2%) is used in the regression model (see Table 3) and the estimated 31 IHA indicator values are calculated in the column of Table 4. Ideally the ecological flow regime of this reservoir is assumed to result from the regression models based on the assumption that the post-dam flow regime is similar to the dry year flow regime. The pre-dam 30-year streamflow data is assumed to be the natural flow regime condition. The ecological flow regime condition is assumed to be between these two conditions, because it recognizes the inability to return to the natural flow regime yet still bases the results on and captures the natural variability of the system.

Approximately 35% of the water in the Nan-Hua Reservoir is assumed to be extracted for human use. Therefore, it is simply not reasonable to expect the post-dam reduced streamflow to have the same level of flow or variation as the natural flow regime condition. Based on the post-dam 13-year streamflow data, most indicator values are not between the natural flow regime condition and regression model results. Some high-flow indicator values are between these two conditions because of flood control operation of the reservoir. Almost none of the low-flow indicators are between these two conditions. This may be due to the weakly-correlated relationship shown in the regression models, but another potential cause is that reservoir operation eliminates the low-flow characteristics that are characterized in drought years. Reservoir operation usually has a stronger effect on low-flow conditions because the change is more easily detected (i.e., a small increase in absolute flow rate may correspond to a large percentage increase in flow rate).

In this case, reservoir operation strongly affects the downstream flow regime. The "number of reversals" is the most noticeable indicator of change. The number of reversals in the post-dam period (117.8) is approximately 1.44 times that of the pre-dam period (81.6) and more than 1.5 times that of the regression model condition (78.3). In the natural flow condition, the number of reversals is almost independent of the total streamflow variation (the slope ranges from $0.039 \sim -0.081$ in Table 3), but after reservoir construction, the number of reversals increases significantly.

Reservoir operation generally will eliminate smaller flood events at the downstream location, but will still produce large flood events due to the flood control operation. The result is a smaller value for the high pulse count indicator during the post-dam period when compared to the pre-dam and regression model values. The short duration (1-, 3-, and 7-day) maximum indicator values from the post-dam period are larger than pre-dam and regression model maximum values because there are extreme high flow events in three of the 13 post-dam years (1997, 2000, and 2005). Flood control operation releases approximately the same amount of flow as the reservoir inflow and these flow releases are reflected in the short duration (1-, 3-, and 7-day) maximum indicator values. The long duration (30- and 90-day) maximum indicator values of the post-dam data are smaller than those for the pre-dam data and between the pre-dam and regression model values. The function of storing water in the reservoirs causes these long duration (30- and 90-day) maximum indicator values to decrease.

Although there is no regulation for environmental flow release in the Taiwan Water Law, Nan-Hua Reservoir provides a constant minimum release as a so-called ecological base flow. Under this flow, all of the minimum indicator values (1-, 3-, 7-, 30-, and 90-day) of the post-dam period are larger than pre-dam and regression model maximum indicator values. The low pulse duration indicator during the post-dam period is also smaller than that for the pre-dam and regression model values.

4.3 Discontinuity Ratio Use

The discontinuity ratio (DR) can be selected by reservoir managers. A designed water reduction could be used to calculate the proportional flow regime and a DR could be used to determine the ecological flow regime for reservoir operation. Figure 4 shows examples of using different DR values for determining the 90-day maximum indicator of the ecological flow regime. The Range of Variability Approach (RVA)

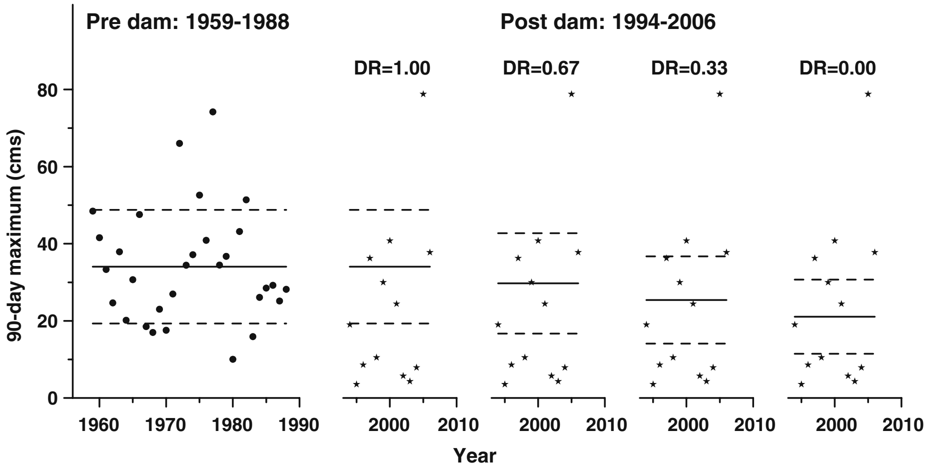
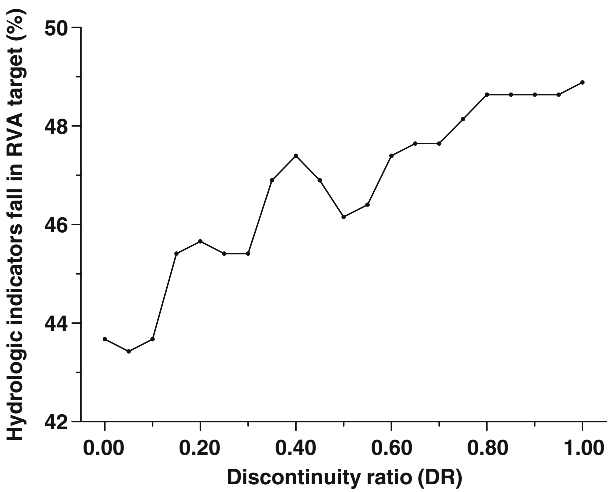


Fig. 4 Examples of different DR values for determining the 90-day maximum indicator of the ecological flow regime. The *dotted lines* are the 25th and 75th percentile of the RVA targets

is used here to illustrate how the RVA target range varies according to different DR values. The RVA target range for each IHA indicator is bracketed by the 25th and 75th percentile (dotted lines in the Fig. 4) of the natural flow condition. Figure 5 shows the percentage of the 90-day maximum indicator values that fall within the RVA target. In this case, the DR value of 1.0 achieves the highest percentage. The reservoir managers can select the DR ratios of all the IHA indicators for their operation purposes.

The current framework for determining ecological flow regimes for existing reservoirs is based on the hydrodynamic and physiographic points of view. Connecting hydrological characteristics with organism habitat properties and selecting important ecohydrological indicators for water resources management has been discussed

Fig. 5 Percentage of 90-day maximum indicators that fall within RVA target



(Souchon et al. 2008; Suen and Herricks 2009; Suen et al. 2009; Yang et al. 2008b). The discussions have included the use of artificial floods to provide spawning cues for organisms, allowing them to satisfy their life history requirements (Molles et al. 1995; Rubin et al. 1998). The approach presented in this work can incorporate the above research into future reservoir operation and ecological water resources management.

5 Conclusions

This paper presents a framework for determining the ecological flow regime for locations downstream of existing reservoirs. The framework is designed to allow reservoir managers to incorporate a regime-based approach for both reservoir operation and benefits to downstream aquatic ecosystems. The natural variability of the pre-dam flow regime is critical for aquatic ecosystems, but it is necessary to also acknowledge that a portion of the streamflow will be diverted to downstream users after the dam is built. In this framework, the regionalization procedure groups gauging stations with similar physiographic, climatic, and hydrologic characteristics. The ratio to the mean procedure and regression model provide the expected flow regime as a proportion of the natural flow regime. The discontinuity ratio gives the opportunity to find a compromise situation between the different priorities expressed by both managers and stakeholders. This framework is not limited by scale or region, but would require modification to be specific to a different area or extent.

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