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Potential impacts to freshwater ecosystems caused by flow regime alteration under changing climate conditions in Taiwan

J.-P. Suen

Dept. of Hydraulic and Ocean Engineering, National Cheng Kung University, Tainan, Taiwan

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Correspondence to: J.-P. Suen (jpsuen@mail.ncku.edu.tw)

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Abstract

Observed increases in the Earth's surface temperature bring with them associated changes in precipitation and atmospheric moisture that consequentially alter river flow regimes. This paper uses the Indicators of Hydrologic Alteration approach to examine climate-induced flow regime changes that can potentially affect freshwater ecosystems. Analyses of the annual extreme water conditions at 23 gauging stations throughout Taiwan reveal large alterations in recent years; extreme flood and drought events were more frequent in the period after 1991 than from 1961–1990, and the frequency and duration of the flood and drought events also show high fluctuation. Climate change forecasts suggest that such flow regime alterations are going to continue into the foreseeable future. Aquatic organisms not only feel the effects of anthropogenic damage to river systems, but they also face on-going threats of thermal and flow regime alterations associated with climate change. This paper calls attention to the issue, so that water resources managers can take precautionary measures that reduce the cumulative effects from anthropogenic influence and changing climate conditions.

1 Introduction

The water that flows through river systems maintains the fisheries and habitat of aquatic ecosystems. Both the temporal and spatial variability of the abundance of water therefore significantly affects the persistence of aquatic communities. Over its lifetime, a river system develops natural and seasonal patterns of rising and falling water levels that shape the instream and riparian habitat, provide cues for organism breeding and migration, and allow aquatic processes to function properly (Poff et al., 1997). Many aquatic organisms have adapted to the predictable flow variation associated with these natural fluctuations; deviation from such patterns may increase the threat to organism survival and persistence (Poff and Ward, 1989; Bunn and Arthington, 2002). Because alteration of the natural flow patterns may so strongly affect the aquatic organisms that

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depend on them, streamflow is considered a dominant variable that influences many fundamental ecological processes in aquatic ecosystems.

Over the last century, the Earth's surface temperature has increased approximately 0.56 to 0.92 degrees Celsius worldwide and 1.0 to 1.4 degrees in Taiwan specifically – and this increasing trend is expected to continue into the foreseeable future (Hsu and Chen, 2002; IPCC, 2007). In addition to the direct warming effect, increased air temperature may cause changes in global atmospheric circulation, inducing changes in precipitation and atmospheric moisture over space and time. Streamflow approximately reflects the changing precipitation patterns, and flow series reveal a certain level of climate change-induced hydrologic alteration. The alteration includes changes in the magnitude and timing of extreme flow events, shifts in the frequency and duration of high and low flow events, and changes to the magnitude of monthly or yearly flow (Richter et al., 1996).

While ecosystem responses to such recent warming trends have been widely observed and documented (Walter et al., 2002), changes to a river's natural flow regime threaten the river's native aquatic ecosystems. This makes climate change perhaps one of the greatest on-going threats to stream communities (Richter, 2007). Although aquatic organisms are commonly resilient to some anthropogenic disturbances, the rate of change caused by the current environmental global warming effects is probably too rapid for some organisms to adapt (Dudgeon et al., 2006; Angeler, 2007).

Most recent analyses of the impacts of climate change on water resources or streamflow management focus on the trend determination (Yu et al., 2002; Burns et al., 2007; Novotny and Stefan, 2007), paying special attention to extreme water conditions such as flood and drought (Milly et al., 2002; Lehner et al., 2006); very few consider the changes of the entire flow regime. While the trends of water quantity fluctuation are very important for water resources management purposes, the changes in characteristics of the entire regime are quite crucial, especially in aquatic ecosystems. In this paper, the Indicators of Hydrologic Alteration (IHA) developed by The Nature Conservancy (Richter et al., 1996) are used to assess the potential streamflow alterations caused by changing climate conditions in Taiwan. The aim is to examine these changes and determine their possible effects on aquatic organisms. Unlike other projections of future climate conditions based on global circulation models (GCMs) (e.g. Caballero et al., 2007), this paper uses observed daily streamflow data to examine the flow regime alterations of the past. By recognizing hydrologic alteration and its potential impacts to freshwater ecosystems, new management strategies could be developed to both mitigate negative impacts and enhance benefits to aquatic ecosystems.

2 Methods

2.1 Station selection and data

Taiwan is an island of 36 000 km^2 east of Mainland China and south of Japan in the Western Pacific. The island is long and narrow with the Central Mountain Range running north-south along its middle. The annual rainfall in Taiwan is approximately 2500 mm, which is 2.6 times the world average. Three-quarters of this rainfall is concentrated in the months from May through October, which is aptly considered the wet season. Because of the high-gradient topography, rivers in Taiwan are basically short but steep, with large runoff differences between the wet and dry seasons as discharges respond rapidly with rainfall intensity and flood flows. The subtropical climate and high elevation gradient change make Taiwan rich in aquatic ecosystems ranging from high mountain streams to low estuaries.

The amount of data is very crucial in climate change research, and therefore gauging stations throughout Taiwan are considered for this study based on the available length of daily streamflow data and the natural flow condition. Longer periods of data can reduce the effects caused by short-term natural fluctuations and show any trends that are triggered by climate change. Unfortunately, the streamflow datasets of most gauging stations in Taiwan are either relatively short or are affected by upstream hydraulic constructions such as dams. After careful review the list of "no upstream control gauging station" of the "Taiwan Streamflow Database" (http://water.hre.ntou.edu.tw/~river/), only

23 stations were considered suitable for this analysis based on data length and the extent of anthropogenic influence. Eleven rivers that collectively cover the expanse of the island are included in this analysis. The drainage areas in which these gauges are found range from 82 km^2 to 812 km^2. Elevations of the sample points range from 20 m to 1630 m above sea level. They are grouped according to geographic region in Fig. 1 and Table 1.

2.2 Streamflow alteration and ecological responses

In a natural stream, aquatic organisms evolve strategies for surviving in different kinds of environmental conditions that are particularly driven by the magnitude, frequency, duration and timing of flow (Poff et al., 1997). A large and rapidly growing body of literature has stressed the connection between hydrologic conditions and stream organisms (e.g. Poff et al., 1997; Petts et al., 2006). In one arena, engineers and system analysts use numerical models to simulate hydrologic variability and river hydrodynamics in relation to species populations or biological indexes (e.g. biodiversity index) (Yang et al., 2008). These models build mathematical relationships between the inputs, which are hydrologic variables, and the outputs, which are biological/ecological parameters. The relationships allow manipulation of hydrologic variables and prediction of biological/ecological responses. Meanwhile, ecologists and biologists continue to develop an understanding of organisms' interactions with these hydrologic variables, paying special attention to life history requirements, microhabitat conditions, and movement behaviours. Experimental designs and field work campaigns are conducted to provide a solid scientific basis at a holistic level that spans several temporal and spatial scales (Herbert and Gelwick, 2003; Jowett et al., 2005). Attempts from both engineers and ecologists reflect the importance of the connection between streamflow and aquatic organisms. However, due to the highly stochastic characteristics of hydrologic variables and extremely complicated responses of aquatic ecosystems, the connections between hydrology and ecology often still focus on target species, and studies are often site specific.

2.3 Indicators of hydrologic alteration

Hydrologic indicators have been widely applied in ecological water resources management (Koel and Sparks, 2002; Suen and Eheart 2006). Such indicators are recognized as being ecologically relevant, and they can be easily calculated from historical flow data (e.g. Richter et al., 1996; Poff et al., 1997; Sanz and del Jalon, 2005; Monk et al., 2007; Suen and Herricks, 2008[1]). The Indicators of Hydrologic Alteration (IHA) approach developed by The Nature Conservancy (Richter et al., 1996) is one of the most frequently used methods. This approach uses daily streamflow data to calculate thirty-one 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 (see Table 2). These parameters adequately represent the majority of the variation of the flow regime for hydroecological studies and can be easily calculated.

In this research, the observed daily streamflow data are transferred into the set of IHA indicators for examination. Since no studies can be found to show that one of these IHA groups is more important than or can replace any of the other groups, the complete IHA suite is considered with equal weight in the analysis. Altering any of the groups or indicators will affect the flow regimes in various ways.

2.4 The range of variability approach

The primary function of the IHA is to examine changes in flow regime caused by hydraulic constructions. Using the IHA to compare flow data before (pre-impact) and after (post-impact) hydrologic construction provides the percent change in each of the

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[1] Suen, J. P. and Herricks, E. E.: Developing fish community based ecohydrological indicators for water resources management, Hydrobiologia, submitted, 2008

ecologically-relevant IHA statistics (column 3 in Table 2). These changes indicate the degree of hydrologic alteration and can be applied to assess potential impacts to the aquatic ecosystem. An enhancement of this analysis, though, is the Range of Variability Approach (RVA), also proposed by Richter et al. (1997), which offers a more quantitative way to evaluate the degree of alteration by giving a target range for each hydrologic indicator. In this research, the target for alteration assessment is the percent change between the 25th- and 75th-percentile pre-impact baseline indicator values. If there is no obvious climate change, the post-impact values should occur with similar frequency as the natural or pre-impact baseline flow regimes. The equation used to measure such hydrologic alteration, A, expressed as a percentage, is:

$$A = \left| \frac{Y_o - Y_e}{Y_e} \right| \times 100\%. \tag{1}$$

where Y_o is the observed count of post-impact years for which the value of the hydrologic indicator falls within the RVA target range, and Y_e is the expected count of post-impact years for which the value of the hydrologic indicator falls within the RVA target range.

3 Results and discussions

3.1 Descriptive statistics comparison

The hydrologic indicators for 23 gauging stations were calculated using the daily streamflow data and IHA software. In order to determine flow regime alterations due to changing climate effects, historical daily streamflow data from November 1960 to October 1990 ("baseline", 1961–1990) are used as the baseline condition (IPCC-TGCIA, 1999), and streamflow data from November 1990 to October 2005 ("post-baseline", 1991–2005) are used to assess the potential impacts of recent climate change influences. For each of the thirty-one hydrologic parameters, the absolute percent change in both mean and coefficient of variation (CV) between "baseline" and "post-baseline" periods were calculated. Table 3 shows the mean absolute percent change of indicator values from the 23 Taiwanese gauging stations separated into four geographic sub-regions. All parameters are used in the comparison except those in IHA Group 3. These parameters, which refer to the Julian date of the annual 1-day minimum and maximum, are negligible in this analysis because they do not represent the magnitude of the flow parameters. Besides that, the annual 1-day minimum in Taiwan usually occurs in the dry season, which is from November to April; therefore the value of the Julian date of the annual 1-day minimum may have a large variation because it can occur anytime from November-December (large Julian date number) to January-April (small Julian date number).

In order to compare the degree of hydrologic alteration between the "baseline" (1961–1990) and "post-baseline" (1991–2005) periods, "baseline" data are divided into two subperiods for further analysis. Data from 1976–1990 are used as the "lower-baseline" condition to test the hydrologic alteration to the "upper-baseline" period (1961–1975). Table 4 shows the comparisons of the mean absolute percent change between the "baseline" and the "post-baseline" periods and between the two sub-periods within the "baseline" period. Table 4 also shows the probability of a first period (e.g. "post-baseline") value mean or CV being larger than its corresponding second period (e.g. "baseline") value. A probability value close to 100% indicates that the first period values of the hydrologic parameters are larger than the second period values in most of the observed gauging stations. In other words, the parameter's value has increased in recent times if the probability value in Table 4 is close to 100%. A probability value close to 50% indicates that the two periods are similar to each other.

Most mean absolute percent changes between the "baseline" and "post-baseline" periods (23 out of 31) are larger than those between the two sub-periods (see Table 4). This is especially true for Group 2, the Annual Extreme Water Conditions group, which shows consistently greater absolute changes. These results indicate that the extreme water conditions (1-, 3-, 7-, 30-, 90-day annual minima or maxima) have a higher degree of alteration during the later subperiod and, more importantly, in the period after 1991. Using the same probability evaluation (even though most probability values of "baseline"/"post-baseline" periods are less than 50%), both "baseline"/"post-baseline" and "upper-baseline/lower-baseline" periods do not show such obvious change. The results may suggest that the indicator values of the "post-baseline" period reveal a slightly decreased condition compared to the indicator values of the "baseline" period. Although the observed air temperature has shown an increasing trend – especially in recent years – the annual streamflow over the past 50 years does not show a significant increasing or decreasing trend. Precipitation in Taiwan also shows no significant trends (Tsuang et al., 1996; Hsu and Chen, 2002; Lu et al. 2007). Using this information along with the full range of flow regime assessment, attention can be paid to some special indicators and that connect to further analysis.

3.2 RVA comparison

Though the RVA method was originally developed to guide streamflow management strategies to sustain native aquatic ecosystem biodiversity and integrity after construction of a hydraulic control structure (Richter et al., 1997), in this research the RVA is adapted to measure the hydrologic alteration between two periods of streamflow data under changing climate conditions. The full range of pre-impact RVA data for each hydrologic indicator is divided into three categories, high, middle, and low, which are used to evaluate RVA post-impact data. The middle RVA category, for example, indicates that the value of each hydrologic indicator of the post-impact period lies between the 25th and 75th percentile of the pre-impact indicator value (this also happens to be the target). The high and low RVA categories indicate that the value of each post-impact hydrologic indicator lies above the 75th percentile or below the 25th percentile of the pre-impact values, respectively.

The hydrologic alteration at each gauging station, A, can be calculated using Eq. (1). Richter et al. (1998) suggest that A between 0% and 33.3% represents low alteration, 33.3%–66.7% represents moderate alteration, and 66.7%–100% represents high alteration. Tables 5 and 6 show the probability (as a percentage) that streamflow changes belong to the low, moderate, or high alteration level. These are shown for both the "baseline"/"post-baseline" comparison (Table 5) and the comparison of two sub-periods of the "baseline" period (Table 6), indicating the degree of alteration. For instance, if the probability of low alteration in the middle RVA category is low, it means fewer stations can reach the RVA target – the degree of hydrologic alteration is high.

The monthly mean flow values do not show obvious differences between the "baseline"/"post-baseline" and "upper-baseline/lower-baseline" periods. Group averages of the probability of low alteration in the middle RVA category are 73.3% and 73.0%, respectively. Group 2, the Annual Extreme Water Conditions group, shows lower probability values for low alteration in the middle RVA category in "baseline"/"post-baseline" comparison (52.9%) than in "upper-baseline/lower-baseline" comparison (72.4%). The extreme water conditions have been altered more during the post-baseline period than from 1961 to 1990. "Number of reversals" shows the lowest probability values for both low alterations in the middle RVA category (52.9%) and high RVA category (50.0%) in the "baseline"/"post-baseline" comparison, and these values are smaller than those in "upper-baseline/lower-baseline" comparison. Streamflow fluctuation is therefore higher during the post-baseline period than from 1961 to 1990.

Figure 2 shows the degree of hydrologic alteration, *A*, of each of the 23 gauging stations based on this RVA analysis. Comparison of the two plots in Fig. 2 indicates that hydrologic alteration during the "post-baseline" period is a function of observed counts that are lower than actual counts. The points in Fig. 2a, representing the "baseline"/"post-baseline" comparison, are less evenly distributed about the zero line than the points in Fig. 2b ("upper-" and "lower-baseline" comparison), where the observed and actual counts values are more equal to each other. The strong trend of points in Figure 2a to be located below the zero line indicates that the cause of the distribution is decreased observed parameter value counts.

3.3 Potential impacts to freshwater ecosystems

Various changes in flow regimes can translate into effects on aquatic communities. For instance, the results of the analysis on Group 2, the Annual Extreme Water Conditions group, indicate greater alteration in both magnitude and CV of each extreme hydrologic parameter during the "post-baseline" period (see Table 4). Most of these parameter values decrease with greater within-year flow fluctuation (which are times of low predictability), especially so for "post-baseline" than for "baseline". The increased frequency of flooding and drought events that are the physical translation of these results may threaten aquatic ecosystems. The resident invertebrate community could be impacted by increased drought frequency, subsequently being replaced by drought resistant fauna (Hogg and Williams, 1996). Increasingly frequent flood events can interrupt riparian plant succession and reduce the amount of available low-energy, backwater habitat for aquatic organisms (Poff, 2002). High magnitude, short duration events may create high velocity and turbulence that lead to injury or death of fish (Harvey, 1987); the accompanying extended duration of low flows are expected to reduce available channel habitat and increase the risk of organism loss due to changing water quality or increased predation risk (Magoulick and Kobza, 2003). All of these examples suggest ways in which basic changes to the annual extreme water conditions – changes to the original flood and drought patterns – affect their primary function for aquatic ecosystems.

Organisms will also experience greater hydrologic instability. The increased values of the mean and CV of hydrograph reversals for the period after 1991 (compared to the subperiod evaluation) in Table 4 suggest greater flow fluctuation in this period. Such increased flow variation may favor non-native species and affect the number of Age 0 fish in annual collections (Koel and Sparks, 2002). The rising rate of the hydrograph, which describes the rate at which the hydrograph increases, also shows high alteration (Table 4, Group 5). As a result of the increase, aquatic organisms will have less time to find refuge areas and avoid being flushed out by the approaching flood and high-flow conditions.

4 Conclusions

Temperature alteration is an important concern for aquatic ecosystems; this has been discussed both worldwide and in Taiwan specifically (Meyer et al., 1999; Han et al., 2007). This paper raises another related concern – flow regime alteration – which can also have strong potential effects on aquatic ecosystems. The complexity of determining responses of aquatic ecosystems to the effects of climate change exists due not only to the above concerns but also to the direct or indirect interactions of other forms of anthropogenic impacts (e.g. landuse change) (Meyer et al.,1999; Gibson et al., 2005). Unfortunately, it is almost impossible to precisely predict the impact of climate change to freshwater ecosystems, even in the near future (Malmqvist and Rundle, 2002). The human residents of Taiwan have suffered from intense competition for limited water resources between agricultural, municipal, and industrial water demands; hydrologic alteration caused by climate change will only make the situation more complicated. Proper actions should immediately be applied to reduce future harm to both nature and society. Management strategies with increased flexibility could effectively respond to both long-term and short-term flow regime change, yet these strategies need to be developed for water resources management that preserves the potential capacity in adapting streamflow change to maintain healthy aquatic ecosystems.

The length of historical data is always a limitation in climate change research. This is especially so for streamflow data. While this paper acknowledges such a drawback, the work adequately uses the limited data to describe the flow regime alteration resulting from changing climate conditions. Although the results only show slight changes in the analysis, the potential impact of climate change on freshwater ecosystems needs to be brought into the spotlight.

This study examines flow regime alteration in Taiwan and connects it to the potential impact to freshwater ecosystems since 1961. IHA analysis of currently available historical data suggests increased alterations of annual extreme water conditions, frequency and duration of flood and drought events, hydrograph rising rate and hydrograph reversal. Unlike the future climate scenario predictions generated by GCMs, the results of the IHA analysis show the kinds of hydrologic changes that are currently happening in a full range of flow regime characteristics. The potential threat caused by flow regime alteration can now be analyzed as precautionary information for water resources and aquatic ecosystem management.

Policy makers and water resources managers must recognize the potential impact to freshwater ecosystems caused by climate change and, in response, develop prompt strategies to maintain healthy aquatic ecosystems that can adapt to the changing climate. The collaboration of engineers and ecologists will better define the influence of hydrologic alteration on aquatic ecosystems. Any new polices and water resources management strategies should attempt to reduce anthropogenic influence and climate change effects in order to sustain healthy freshwater communities in river systems.

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Table 1. Listing of streamflow gauging stations used in this study.

Station number	Elevation (m)	Drainage area (km^2)
North region		
1140H002 (N1)	525	107.8
1140H010 (N2)	352	160.4
1140H041 (N3)	827	115.9
1140H043 (N4)	438	542.0
1140H048 (N5)	30	125.3
1140H049 (N6)	20	52.9
1300H013 (N7)	249	139.1
1300H014 (N8)	211	221.7
2510H001 (N9)	772	36.8
Central region		
1420H014 (C1)	1468	125.7
1420H015 (C2)	1446	257.9
1420H016 (C3)	1452	156.5
1420H034 (C4)	1630	110.7
1420H035 (C5)	1434	417.1
1510H024 (C6)	214	259.2
1510H049 (C7)	475	367.4
South region		
1580H001 (S1)	221	83.2
1730H031 (S2)	295	812.0
East region		
2170H001 (E1)	54	166.0
2200H007 (E2)	151	476.2
2370H011 (E3)	194	82.1
2370H016 (E4)	171	249.4
2460H005 (E5)	379	434.6

Table 2. The Index of Hydrologic Alteration developed by Richter et al. (1996).

IHA statistics	Regime characteristics	Hydrologic parameters
Group 1: Magnitude of monthly water conditions	Timing	Mean value for each calendar month
Group 2: Magnitude and duration of annual extreme water conditions	Magnitude, Duration	Annual minima 1-day means Annual maxima 1-day means Annual minima 3-day means Annual maxima 3-day means Annual maxima 7-day means Annual minima 7-day means Annual maxima 30-day means Annual maxima 30-day means Annual minima 90-day means Annual maxima 90-day means
Group 3: Timing of annual extreme water conditions	Timing	Julian date of each annual 1 day maximum Julian date of each annual 1-day minimum
Group 4: Frequency and duration of high and low pulses	Magnitude, Frequency, Duration	No. of high pulses each year No. of low pulses each year Mean duration of high pulses within each year Mean duration of low pulses within each year
Group 5: Rate and frequency of water consecutive daily means condition	Frequency, Rate of Change	Means of all positive (or negative) differences between change No. of rises No. of falls

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Table 3. The mean absolute percent change of hydrologic parameter values comparing the 1961–1990 period to the 1991–2005 period at each of the gauging stations, separated in four geographic sub-regions.

Hydrologic parameters	Taiwan Island		North Region		Central Region		South Region		East Region	
	Absolute change (%)									
	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
Parameter Group #1										
November mean flow	18.5	79.8	17.2	43.2	11.2	46.7	46.7	294.8	16.3	88.2
December mean flow	16.9	45.6	16.5	37.6	11.2	44.0	59.5	70.6	7.1	43.4
January mean flow	20.5	42.6	19.6	26.2	9.0	30.2	86.9	115.3	9.5	50.1
February mean flow	28.6	75.5	21.6	101.6	29.1	42.2	101.3	83.7	9.3	59.7
March mean flow	25.0	53.8	10.6	42.0	24.3	21.1	120.5	57.5	11.4	99.3
April mean flow	19.7	28.2	12.6	27.6	17.5	28.2	75.2	32.8	11.1	22.7
May mean flow	16.9	42.6	19.5	54.3	17.7	32.3	15.8	42.4	9.7	30.1
June mean flow	28.1	27.8	24.5	25.3	27.9	25.4	39.9	46.8	25.2	23.3
July mean flow	15.2	28.6	15.2	20.1	14.7	43.8	3.8	14.2	17.0	23.9
August mean flow	19.1	32.8	18.3	30.7	20.9	38.1	14.3	39.2	16.5	22.0
September mean flow	15.3	37.5	12.7	28.7	19.4	55.7	20.7	54.1	10.0	17.8
October mean flow	21.3	48.2	16.0	68.7	23.5	27.7	36.5	55.9	18.0	31.0
Group average	20.4	45.2	17.0	42.2	18.9	36.3	51.8	75.6	13.4	42.6
Parameter Group #2										
1-day minimum	23.1	81.2	32.3	45.3	8.3	106.8	28.1	86.5	21.1	89.7
3-day minimum	23.2	88.7	30.5	38.3	6.0	95.9	45.6	153.2	21.3	119.8
7-day minimum	21.0	78.4	25.9	40.3	5.6	84.8	45.8	146.6	19.9	92.3
30-day minimum	18.4	65.6	18.9	41.2	6.2	74.6	51.9	95.3	17.4	70.9
90-day minimum	17.5	56.2	13.5	33.0	14.8	52.2	57.0	63.9	10.7	83.8
1-day maximum	29.7	100.4	30.0	100.8	23.2	100.8	51.6	291.8	24.8	18.7
3-day maximum	25.3	87.9	21.9	84.2	22.8	105.4	48.2	227.3	21.5	11.7
7-day maximum	21.7	78.6	23.4	64.6	21.4	103.4	46.3	171.6	7.6	26.7
30-day maximum	18.1	62.0	14.6	73.6	17.1	52.4	33.4	76.5	16.2	40.6
90-day maximum	17.6	61.9	14.7	77.1	15.1	67.2	26.9	14.4	18.7	38.5
Group average	21.6	76.1	22.6	59.8	14.0	84.3	43.5	132.7	17.9	59.3

Table 3. Continued.

Hydrologic parameters	Taiwan Island		North Region		Central Region		South Region		East Region	
	Absolute change (%)									
	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
Parameter Group #3										
Date of minimum	19.5	25.6	25.2	27.0	11.5	27.0	11.5	0.0	19.7	26.2
Date of maximum	6.1	55.2	6.1	90.0	5.3	35.3	1.3	28.6	7.6	25.8
Group average										
Parameter Group #4										
Low pulse count	21.0	60.3	17.0	58.7	23.0	60.0	29.2	144.0	18.6	25.0
Low pulse duration	35.5	59.0	32.0	39.1	39.3	112.3	31.2	19.4	31.9	30.1
High pulse count	10.4	49.9	7.5	56.2	10.4	39.9	5.0	97.5	14.9	28.0
High pulse duration	22.2	40.7	12.2	33.5	35.3	28.8	21.7	100.1	18.5	38.5
Group average	22.3	52.5	17.2	46.9	27.0	60.3	21.7	90.3	21.0	30.4
Parameter Group #5										
Rise rate	32.5	52.4	20.7	33.6	39.6	76.5	48.2	43.8	31.5	46.4
Fall rate	19.2	39.5	12.8	40.0	27.0	44.4	21.4	44.9	15.9	24.6
Number of reversals	12.8	78.9	7.7	20.7	17.7	101.5	1.8	268.6	16.4	63.5
Group average	21.5	56.9	13.7	31.5	28.1	74.1	23.8	119.1	21.3	44.8

Table 4. Comparisons of hydrologic parameters between baseline and post-baseline periods and between the two sub-periods within the baseline period.

Hydrologic parameters	Baseline Post-Baseline		Upper-baseline Lower-baseline		Baseline Post-Baseline		Upper-baseline Upper-baseline	
	Absolute change (%)				Probability of increasing (%)			
	Mean	CV	Mean	CV	Mean	CV	Mean	CV
Parameter Group #1								
November mean flow	**18.5**	79.8	11.5	27.2	8.7	78.3	56.3	37.5
December mean flow	**16.9**	45.6	15.4	26.9	30.4	78.3	12.5	50.0
January mean flow	**20.5**	42.6	11.1	29.8	21.7	69.6	50.0	43.8
February mean flow	**28.6**	75.5	13.5	26.8	65.2	87.0	68.8	12.5
March mean flow	**25.0**	53.8	23.0	54.8	52.2	65.2	62.5	87.5
April mean flow	19.7	28.2	**51.5**	84.7	60.9	43.5	56.3	81.3
May mean flow	16.9	42.6	**38.0**	39.8	34.8	69.6	81.3	43.8
June mean flow	**28.1**	27.8	21.2	31.0	0.0	60.9	56.3	37.5
July mean flow	**15.2**	28.6	12.6	44.3	43.5	60.9	50.0	68.8
August mean flow	**19.1**	32.8	14.6	42.4	30.4	26.1	43.8	68.8
September mean flow	**15.3**	37.5	12.8	28.0	21.7	60.9	62.5	18.8
October mean flow	21.3	48.2	**29.5**	31.9	26.1	65.2	0.0	25.0
Group average	20.4	45.2	21.2	39.0	33.0	63.8	50.0	47.9
Parameter Group #2								
1-day minimum	**23.1**	81.2	9.9	33.9	43.5	78.3	31.3	81.3
3-day minimum	**23.2**	88.7	7.4	37.5	43.5	78.3	37.5	56.3
7-day minimum	**21.0**	78.4	8.1	27.7	39.1	82.6	37.5	56.3
30-day minimum	**18.4**	65.6	11.0	35.5	34.8	82.6	31.3	43.8
90-day minimum	**17.5**	56.2	12.5	19.3	39.1	69.6	37.5	37.5
1-day maximum	**29.7**	100.4	26.6	31.0	21.7	78.3	56.3	25.0
3-day maximum	**25.3**	87.9	24.0	23.6	26.1	78.3	68.8	18.8
7-day maximum	**21.7**	78.6	21.1	29.0	21.7	87.0	62.5	12.5
30-day maximum	**18.1**	62.0	13.9	31.7	13.0	82.6	31.3	43.8
90-day maximum	**17.6**	61.9	14.0	36.2	8.7	95.7	43.8	37.5
Group average	21.6	76.1	14.8	30.6	29.1	81.3	43.8	41.3

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Table 4. Continued.

Hydrologic parameters	Baseline Post-Baseline		Upper-baseline Lower-baseline		Baseline Post-Baseline		Upper-baseline Upper-baseline	
	Absolute change (%)				Probability of increasing (%)			
	Mean	CV	Mean	CV	Mean	CV	Mean	CV
Parameter Group #3								
Date of minimum	19.5	25.6	**19.6**	31.9	34.8	60.9	56.3	37.5
Date of maximum	6.1	55.2	**9.1**	36.7	39.1	82.6	18.8	37.5
Group average								
Parameter Group #4								
Low pulse count	21.0	60.3	**23.3**	43.4	39.1	69.6	37.5	25.0
Low pulse duration	**35.5**	59.0	28.4	30.2	52.2	52.2	62.5	50.0
High pulse count	10.4	49.9	**16.3**	51.0	30.4	73.9	56.3	43.8
High pulse duration	22.2	40.7	**37.9**	37.4	34.8	39.1	56.3	50.0
Group average	22.3	52.5	26.5	40.5	39.1	58.7	53.1	42.2
Parameter Group #5								
Rise rate	**32.5**	52.4	17.3	29.2	26.1	65.2	50.0	37.5
Fall rate	**19.2**	39.5	18.8	34.4	26.1	82.6	43.8	37.5
Number of reversals	**12.8**	78.9	6.6	56.5	69.6	56.5	50.0	62.5
Group average	21.5	56.9	14.2	40.0	40.6	68.1	47.9	45.8

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Table 5. Probability of the gauging stations belong to low, median, or high alteration level in each category in the baseline and post-baseline periods assessment.

Hydrologic parameters	Middle RVA Category Percent alteration			High RVA Category Percent alteration			Low RVA Category Percent alteration		
	Low	Moderate	High	Low	Moderate	High	Low	Moderate	High
Parameter Group #1									
November mean flow	50.0	37.5	12.5	91.7	4.2	4.2	54.2	45.8	0.0
December mean flow	75.0	25.0	0.0	87.5	12.5	0.0	70.8	29.2	0.0
January mean flow	75.0	20.8	4.2	87.5	12.5	0.0	75.0	25.0	0.0
February mean flow	70.8	20.8	8.3	70.8	29.2	0.0	87.5	12.5	0.0
March mean flow	66.7	29.2	4.2	87.5	12.5	0.0	66.7	33.3	0.0
April mean flow	79.2	16.7	4.2	95.8	4.2	0.0	79.2	20.8	0.0
May mean flow	62.5	33.3	4.2	91.7	8.3	0.0	62.5	37.5	0.0
June mean flow	79.2	16.7	4.2	87.5	12.5	0.0	58.3	41.7	0.0
July mean flow	83.3	16.7	0.0	87.5	12.5	0.0	91.7	8.3	0.0
August mean flow	87.5	8.3	4.2	91.7	8.3	0.0	83.3	16.7	0.0
September mean flow	79.2	16.7	4.2	100.0	0.0	0.0	62.5	33.3	4.2
October mean flow	70.8	16.7	12.5	87.5	12.5	0.0	58.3	41.7	0.0
Group average	73.3	21.5	5.2	88.9	10.8	0.3	70.8	28.8	0.3
Parameter Group #2									
1-day minimum	37.5	50.0	12.5	75.0	20.8	4.2	66.7	29.2	4.2
3-day minimum	54.2	37.5	8.3	79.2	16.7	4.2	58.3	37.5	4.2
7-day minimum	41.7	50.0	8.3	79.2	16.7	4.2	66.7	29.2	4.2
30-day minimum	54.2	41.7	4.2	83.3	16.7	0.0	62.5	33.3	4.2
90-day minimum	45.8	50.0	4.2	83.3	16.7	0.0	50.0	50.0	0.0
1-day maximum	54.2	41.7	4.2	91.7	8.3	0.0	54.2	45.8	0.0
3-day maximum	50.0	41.7	8.3	79.2	20.8	0.0	50.0	50.0	0.0
7-day maximum	62.5	33.3	4.2	91.7	8.3	0.0	41.7	58.3	0.0
30-day maximum	66.7	25.0	8.3	83.3	16.7	0.0	54.2	45.8	0.0
90-day maximum	62.5	29.2	8.3	83.3	16.7	0.0	25.0	70.8	4.2
Group average	52.9	40.0	7.1	82.9	15.8	1.3	52.9	45.0	2.1

Table 5. Continued.

Hydrologic parameters	Middle RVA Category Percent alteration Low	 Moderate	 High	High RVA Category Percent alteration Low	 Moderate	 High	Low RVA Category Percent alteration Low	 Moderate	 High
Parameter Group #3									
Date of minimum	75.0	25.0	0.0	70.8	29.2	0.0	66.7	33.3	0.0
Date of maximum	70.8	25.0	4.2	100.0	0.0	0.0	75.0	25.0	0.0
Group average	72.9	25.0	2.1	85.4	14.6	0.0	70.8	29.2	0.0
Parameter Group #4									
Low pulse count	54.2	37.5	8.3	70.8	20.8	8.3	66.7	29.2	4.2
Low pulse duration	58.3	37.5	4.2	83.3	16.7	0.0	83.3	16.7	0.0
High pulse count	70.8	29.2	0.0	70.8	29.2	0.0	58.3	41.7	0.0
High pulse duration	83.3	4.2	12.5	83.3	16.7	0.0	70.8	20.8	8.3
Group average	66.7	27.1	6.3	77.1	20.8	2.1	69.8	27.1	3.1
Parameter Group #5									
Rise rate	41.7	41.7	16.7	79.2	20.8	0.0	41.7	54.2	4.2
Fall rate	58.3	29.2	12.5	54.2	37.5	8.3	83.3	16.7	0.0
Number of reversals	33.3	37.5	29.2	50.0	37.5	12.5	87.5	12.5	0.0
Group average	44.4	36.1	19.4	61.1	31.9	6.9	70.8	27.8	1.4

Table 6. Probability of the gauging stations belong to low, median, or high alteration level in each category in between two sub-periods within the baseline period assessment.

Hydrologic parameters	Middle RVA Category Percent alteration			High RVA Category Percent alteration			Low RVA Category Percent alteration		
	Low	Moderate	High	Low	Moderate	High	Low	Moderate	High
Parameter Group #1									
November mean flow	88.2	11.8	0.0	94.1	5.9	0.0	94.1	5.9	0.0
December mean flow	88.2	11.8	0.0	82.4	17.6	0.0	58.8	41.2	0.0
January mean flow	70.6	29.4	0.0	82.4	17.6	0.0	70.6	29.4	0.0
February mean flow	100.0	0.0	0.0	100.0	0.0	0.0	94.1	5.9	0.0
March mean flow	70.6	29.4	0.0	76.5	23.5	0.0	100.0	0.0	0.0
April mean flow	76.5	17.6	5.9	47.1	47.1	5.9	88.2	11.8	0.0
May mean flow	52.9	35.3	11.8	47.1	29.4	23.5	52.9	47.1	0.0
June mean flow	64.7	35.3	0.0	82.4	17.6	0.0	94.1	5.9	0.0
July mean flow	70.6	29.4	0.0	88.2	11.8	0.0	82.4	17.6	0.0
August mean flow	70.6	29.4	0.0	94.1	5.9	0.0	88.2	11.8	0.0
September mean flow	82.4	17.6	0.0	82.4	17.6	0.0	88.2	11.8	0.0
October mean flow	41.2	58.8	0.0	47.1	52.9	0.0	58.8	41.2	0.0
Group average	73.0	25.5	1.5	77.0	20.6	2.5	80.9	19.1	0.0
Parameter Group #2									
1-day minimum	64.7	29.4	5.9	82.4	17.6	0.0	70.6	29.4	0.0
3-day minimum	52.9	41.2	5.9	76.5	23.5	0.0	64.7	35.3	0.0
7-day minimum	64.7	29.4	5.9	82.4	17.6	0.0	64.7	35.3	0.0
30-day minimum	82.4	17.6	0.0	94.1	5.9	0.0	76.5	23.5	0.0
90-day minimum	64.7	35.3	0.0	76.5	17.6	5.9	76.5	23.5	0.0
1-day maximum	76.5	23.5	0.0	82.4	17.6	0.0	88.2	11.8	0.0
3-day maximum	82.4	17.6	0.0	94.1	5.9	0.0	76.5	23.5	0.0
7-day maximum	88.2	5.9	5.9	88.2	11.8	0.0	64.7	29.4	5.9
30-day maximum	76.5	23.5	0.0	82.4	17.6	0.0	70.6	29.4	0.0
90-day maximum	70.6	23.5	5.9	70.6	29.4	0.0	64.7	35.3	0.0
Group average	72.4	24.7	2.9	82.9	16.5	0.6	71.8	27.6	0.6

Table 6. Continued.

Hydrologic parameters	Middle RVA Category Percent alteration			High RVA Category Percent alteration			Low RVA Category Percent alteration		
	Low	Moderate	High	Low	Moderate	High	Low	Moderate	High
Parameter Group #3									
Date of minimum	58.8	41.2	0.0	76.5	23.5	0.0	76.5	23.5	0.0
Date of maximum	76.5	23.5	0.0	88.2	11.8	0.0	64.7	35.3	0.0
Group average	67.6	32.4	0.0	82.4	17.6	0.0	70.6	29.4	0.0
Parameter Group #4									
Low pulse count	70.6	23.5	5.9	58.8	35.3	5.9	58.8	35.3	5.9
Low pulse duration	82.4	5.9	11.8	82.4	11.8	5.9	64.7	35.3	0.0
High pulse count	58.8	41.2	0.0	52.9	35.3	11.8	70.6	23.5	5.9
High pulse duration	76.5	23.5	0.0	70.6	23.5	5.9	58.8	41.2	0.0
Group average	72.1	23.5	4.4	66.2	26.5	7.4	63.2	33.8	2.9
Parameter Group #5									
Rise rate	47.1	41.2	11.8	41.2	52.9	5.9	70.6	29.4	0.0
Fall rate	58.8	35.3	5.9	82.4	17.6	0.0	41.2	52.9	5.9
Number of reversals	58.8	35.3	5.9	76.5	23.5	0.0	64.7	23.5	11.8
Group average	54.9	37.3	7.8	66.7	31.4	2.0	58.8	35.3	5.9

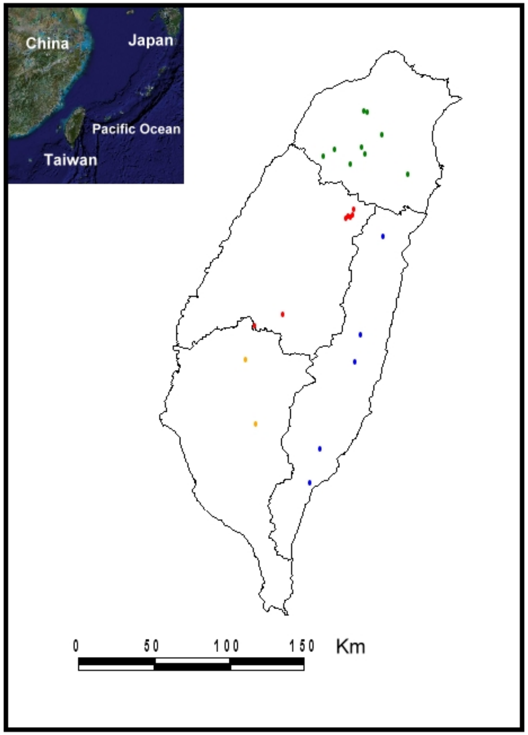
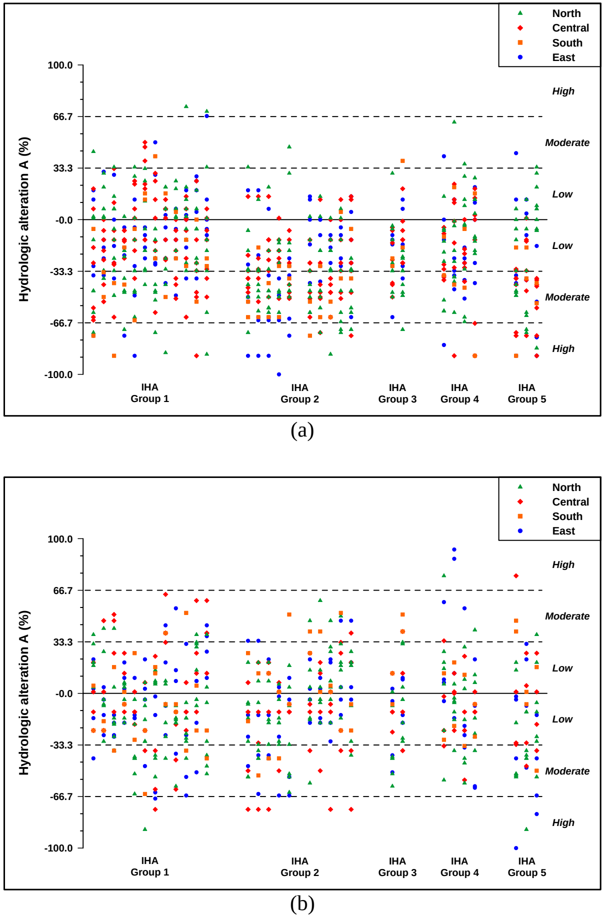


Fig. 1. Locations of streamflow gauging stations used in this study.



(a)

(b)

Fig. 2. The hydrologic alteration of each gauging station **(a)** in the baseline and post-baseline periods assessment; **(b)** in between two sub-periods within the baseline period assessment.