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# Defining the ecological hydrology of Taiwan Rivers using multivariate statistical methods

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SUMMARY

The identification and verification of ecohydrologic flow indicators has found new support as the importance of ecological flow regimes is recognized in modern water resources management, particularly in river restoration and reservoir management. An ecohydrologic indicator system reflecting the unique characteristics of Taiwan's water resources and hydrology has been developed, the Taiwan ecohydrological indicator system (TEIS). A major challenge for the water resources community is using the TEIS to provide environmental flow rules that improve existing water resources management. This paper examines data from the extensive network of flow monitoring stations in Taiwan using TEIS statistics to define and refine environmental flow options in Taiwan. Multivariate statistical methods were used to examine TEIS statistics for 102 stations representing the geographic and land use diversity of Taiwan. The Pearson correlation coefficient showed high multicollinearity between the TEIS statistics. Watersheds were separated into upper and lower-watershed locations. An analysis of variance indicated significant differences between upstream, more natural, and downstream, more developed, locations in the same basin with hydrologic indicator redundancy in flow change and magnitude statistics. Issues of multicollinearity were examined using a Principal Component Analysis (PCA) with the first three components related to general flow and high/low flow statistics, frequency and time statistics, and quantity statistics. These principle components would explain about 85% of the total variation. A major conclusion is that managers must be aware of differences among basins, as well as differences within basins that will require careful selection of management procedures to achieve needed flow regimes.

## Introduction

Hydrology is recognized as a critical factor in the maintenance of the ecosystem integrity of streams and rivers (Karr, 1981). In a systems view of streams and rivers, hydrologic events are known to form and maintain channel planform and substrate while interactions among flow and channel structure create habitats for aquatic organisms. The understanding of the relationships between the flow regime characteristics of a river and its ecological functioning are crucial to the developing techniques to manage integrity and develop designs for restoring damaged streams (Hughes and Hannart, 2003; Sanborn and Bledsoe, 2006). This recognized connection between flow and ecosystems has resulted in the use of hydrologic statistics to characterize environmental flows and supports the development of ecohydrology as a focus for applications in hydrologic research.

Recently, there has been a call to develop comprehensive, river-specific methods to define and refine environmental flows (Arthington et al., 2006). The environmental flow standard approach advocated by Arthington et al. calls for the use of hydrological statistics to develop an appreciation of natural patterns of flow variability and connecting this definition of flow to biological data. They have proposed the development of hydrological classifications based on statistical analysis of hydrologic data combined with a connection to ecosystem characteristics for a range of natural and modified flow conditions. Although they provided an outline of analytical requirements, they did not provide an examination of data sets or a demonstration of environmental flow rules with a case study. This paper explores the approach advocated by Arthington et al. (2006) using the extensive hydrologic data collected in Taiwan as a case study.

The objective of this research is to use a knowledge of the ecological hydrology of natural flows from relatively undisturbed watersheds, mainly headwaters locations (Chang et al., 2008), with

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analysis of additional hydrologic data from watersheds with higher levels of human activity, mid to lower-watershed locations, to develop ecological hydrology characteristics for Taiwan. The connection between hydrology and ecology is achieved through the use of the Taiwan ecohydrological indicator system (TEIS) (Suen, 2005) and autecology information for Taiwan fish species (Suen and Eheart, 2006). The development of ecological hydrology characteristics is based on the connection among flow, habitat, and organisms. Channel planform and substrate conditions interact with flow to produce the habitats occupied by aquatic organisms. With flow variation, habitat conditions change. Aquatic organisms have evolved to accommodate natural changes in flow/habitat, but alteration of the magnitude, timing, or frequency of flow change may exceed the capacity of organisms to adjust to changing environments leading to aquatic community alteration or extirpation of species. In modern watershed management the emphasis on procedures that mimic natural flow regimes is intended to enhance native fauna using a regime approach. The regime of more natural flows then provides a reasonable target for flow management. There is a clear need for a management focus on natural flow regimes (Poff et al., 1997) suggested that natural flows provide habitat suited for indigenous fauna and maintenance of more natural fish communities. A number of hydrologic statistics have been proposed for use as hydrologic indicators for river restoration and water resources management (Hughes and James, 1989; Poff et al., 1996; Richter et al., 1996, 1997; Clausen and Biggs, 2000; Olden and Poff, 2003).

Taiwan presents an ideal opportunity to evaluate hydrological statistics for local and regional analysis of ecohydrologic indicators. Taiwan's land area is approximately 36,000 $km^2$ with mountains reaching 3952 m. In this relatively small area, hydrologic monitoring has been conducted for over 50 years, providing a rich resource of hydrologic data from a dense network of gauging stations. Physiographic conditions and climate, along with available data resources, make Taiwan an ideal location for the examination of natural flow issues in a sub-tropical climate. Taiwan annual mean rainfall is about 2.6 times the world annual mean rainfall, but nearly 78% of the rain occurs during the wet months of May to October. In addition, due to the presence of high mountains and limited land area the rivers are short and steep leading to rapid runoff of precipitation. Precipitation can occur in typhoon events where rainfalls in excess of 2000 mm per day have been recorded. The resulting natural flow regimes show marked seasonal periodicity punctuated by events that may produce massive flows. Flow data for Taiwan is abundant, existing for 102 stations located in watersheds with different physiography and land use. Discharge records of up to 50 years are available.

In addition to environmental conditions and flow data, previous research has provided tools to examine natural flow regime issues in Taiwan. The TEIS used hydrologic statistics identified by Olden and Poff (2003) and indicators of hydrologic alteration identified by Richter et al. (1996) with the ecological and environmental requirements of Taiwan freshwater fish species to develop an ecohydrologic indicator system that supports new water resources management approaches in Taiwan (Suen and Eheart, 2006). At issue is how hydrologic statistics used in the TEIS indicators can provide a useful addition to existing hydrologic analysis. In particular, a demonstration is needed that relates TEIS statistics to a better understanding of flow pattern, timing, frequency, and variability, which relates aquatic community habitat needs to well understood hydrologic conditions. Further, it is known that the actual values of hydrologic statistics can vary over a relatively small watershed areas, which effect discharge and flow concentration time. Taiwan provides the ideal location to address whether this variability influences the interpretation of regional or local ecohydrological conditions because of its dense network of flow monitoring stations and a reasonable flow history for that network. In addition, the calculation of hydrological statistics has brought the recognition that there is potential for redundancy in information provided to decision makers. It should be possible to reduce the number of measures and still provide an accurate characterization of flow regimes with a reduced set of hydrologic statistics that are more easily understood by watershed managers.

This paper examines data from an extensive network of flow monitoring stations in Taiwan and applies multivariate statistical methods to examine TEIS hydrological statistics for 102 stations representing the geographic and land use diversity of Taiwan. Analysis included use of a two-way analysis of variance (ANOVA) to determine if there were differences in TEIS statistics between upper and lower gage station locations in the same basin. Issues of multicollinearity were examined using Principal Component Analysis (PCA). The value of using an ecohydrologic approach was investigated to better connect aquatic organism requirements with a management alternatives.

## Methods

### *Two-way ANOVA*

The analysis of variance (ANOVA) is a widely used collection of statistical procedures, in which the observed variance is partitioned into components due to different explanatory variables (Lindman, 1974). The two-way analysis of variance is an extension to the one-way analysis of variance. There are two independent variables, called factors. Each factor will have two or more levels (means) within it. Three significance tests were used: a test of each of the two main effects and a test of the interaction of the variables.

The two-way ANOVA model used in this study is of the form:

$$E(Y_{ijk}) = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} \tag{1}$$

where $Y_{ijk}$ is the $k$th observation in the $ij$th group, $\alpha_i$, $i = 1,2$ represent factor A (upper and lower positions) main effects, $\beta_j$, $j = 1, 2, \ldots 9$ represent factor B (nine basins) main effects, and $\alpha\beta_{ij}$, is the AB interaction effects.

The total sum of squares SST is partitioned as:

$$\mathrm{SST} = \mathrm{SSA} + \mathrm{SSB} + \mathrm{SSAB} + \mathrm{SSE} \tag{2}$$

SSA & SSB are the sum of squares for factors A and B, respectively, SSAB the sum of squares for the interaction between factor A and factor B, and SSE is the error sum of squares.

### *Principal component analysis, PCA*

Principal component analysis (PCA) is a classical statistical method that could reduce the high dimensionality of the analyzed data while retaining most of the variation in the data set through orthogonal linear transformation of the correlated variables into a small number of uncorrelated variables called principal components. It reduces the dimension of a data set to reveal its essential characteristics and the principle components capture maximal variance. Principal component analysis is a popular data processing and has numerous applications in various science and engineering problems. The success of PCA depends on two important properties:

1. Principal components sequentially capture the maximum variability among data set, thus guaranteeing minimal information loss.
2. Principal components are uncorrelated, so one can deal with one component without referring to others.

A detail of the PCA method can be found in Jolliffe (2002).

## Case study

### Taiwan ecohydrology indicator system (TEIS)

The TEIS provides a means to integrate hydrologic, ecological, and human management influences using a new synthesis of hydrologic statistics and provides a useful tool for the ecosystem-based water resources management in Taiwan (Chang and Herricks, 2005; Chang et al., 2008). In the TEIS, the hydrologic statistics can be related to ecological conditions through consideration of general habitat conditions (Chang et al., 2008). For example, organism response and ecological conditions are related to trends in flow that provide an indication of how habitat needs for spawning, juvenile rearing, or adult maintenance are met. Rate of change statistics provide measures of habitat disruption or the duration stability of habitat needed to complete organism life history. Using the mean of all positive and negative differences between consecutive values provides a measure of the rate of change in habitat, supporting the analysis of the general the suitability of those conditions for the maintenance of a target aquatic community. What is important to recognize is that individual hydrologic statistics are a useful surrogate for ecological condition because these statistics relate to habitat conditions of a species or a guild. The implications for water resources management, when there is a focus on information redundancy, is that some statistics may provide redundant hydrologic information, but are still needed as part of a comprehensive ecohydrologic analysis (Chang et al., 2008). The TEIS hydrologic statistics for magnitude, frequency, duration, and rate of change were used in this analysis, Table 1.

### Description of data

For a small island, Taiwan has a relatively dense network of flow monitoring stations. The watershed characteristics of 430 stations were reviewed and only the stations with long data records (i.e. greater than 20 years) were chosen for use in this study. A final set of 102 stations from 23 river basins were identified, which distributes 52 stations in the upper reaches of watersheds and 50 stations in the lower reaches. The 66 hydrologic statistics of TEIS for these 102 stations were calculated using the daily average flow, which was obtained from "The Stream flow Database of Taiwan", maintained by Water Resources Agency, Taiwan.

### Selection of stations for two-way ANOVA

Two-way ANOVA was developed so that factor A addressed differences between upper and lower positions in the same basin, factor B the difference between basins and factor C the interaction between location and basin characteristics. The ANOVA thus simultaneously addressed three questions:

**Table 1**
The TEIS hydrologic statistics used in this analysis.

| TEIS statistics | Abbreviation |
|---|---|
| *Group 1 – differences between consecutive values ($m^3/s$)* | |
| 1. Mean of all positive differences between consecutive values in dry season | $F_{\mathrm{rate\_}d}$ |
| 2. Mean of all positive differences between consecutive values in wet season | $R_{\mathrm{rate\_}w}$ |
| 3. Mean of all negative differences between consecutive values in dry season | $R_{\mathrm{rate\_}d}$ |
| 4. Mean of all negative differences between consecutive values in wet season | $F_{\mathrm{rate\_}w}$ |
| *Group 2 – high/low flow event magnitudes ($m^3/s$)* | |
| 5. Dry season 1-day minimum | $Q_{\mathrm{1daymin\_}d}$ |
| 6. Dry season 10-day minimum | $Q_{\mathrm{10daymin\_}d}$ |
| 7. Dry season 30-day minimum | $Q_{\mathrm{30daymin\_}d}$ |
| 8. Dry season 90-day minimum | $Q_{\mathrm{90daymin\_}d}$ |
| 9. Dry season 1-day maximum | $Q_{\mathrm{1daymax\_}d}$ |
| 10. Dry season 10-day maximum | $Q_{\mathrm{10daymax\_}d}$ |
| 11. Dry season 30-day maximum | $Q_{\mathrm{30daymax\_}d}$ |
| 12. Wet season 1-day minimum | $Q_{\mathrm{1daymin\_}w}$ |
| 13. Wet season 10-day minimum | $Q_{\mathrm{10daymin\_}w}$ |
| 14. Wet season 30-day minimum | $Q_{\mathrm{30daymin\_}w}$ |
| 15. Wet season 1-day maximum | $Q_{\mathrm{1daymin\_}d}$ |
| 16. Wet season 3-day maximum | $Q_{\mathrm{3daymax\_}w}$ |
| 17. Wet season 10-day maximum | $Q_{\mathrm{10daymax\_}w}$ |
| 18. Wet season 30-day maximum | $Q_{\mathrm{30daymax\_}w}$ |
| *Group 3 – frequency of high/low flow events and reversals* | |
| 19. Number of low flow events with in each dry season (times) | $N_{\mathrm{low\_}d}$ |
| 20. Number of low flow events with in each wet season (times) | $N_{\mathrm{low\_}w}$ |
| 21. Number of high flow events with in each dry season (times) | $N_{\mathrm{high\_}w}$ |
| 22. Number of high flow events with in each wet season (times) | $N_{\mathrm{high\_}w}$ |
| 23. Number of low flow events with in consecutive three years (times/year) | $N_{\mathrm{low\_3year}}$ |
| 24. Number of high flow events with in consecutive three years (times/year) | $N_{\mathrm{high\_3year}}$ |
| 25. Number of hydrological reversals in dry season (times/year) | $RV_d$ |
| 26. Number of hydrological reversals in wet season (times/year) | $RV_w$ |
| *Group 4 – high/low flow event duration (day/time)* | |
| 27. Mean duration of low flow events in each dry season | $D_{\mathrm{low\_}d}$ |
| 28. Mean duration of low flow events in each wet season | $D_{\mathrm{low\_}w}$ |
| 29. Mean duration of high flow events in each dry season | $D_{\mathrm{high\_}d}$ |
| 30. Mean duration of high flow events in each wet season | $D_{\mathrm{high\_}w}$ |
| *Group 5 – mean 10-day flows ($m^3/s$)* | |
| 31.–66. The 36 mean 10-day flows | $Q_1, Q_2 \ldots Q_{36}$ |

Wet season: from May to October. Dry season: from November to next April. Low flow event: low than 25% of mean daily flow. High flow event: high than 200% of mean daily flow.

- Does station location (upper or lower position in the watershed) have a significant effect on TEIS values?
- Do different river basins have significantly different TEIS values?
- Is there a significant interaction between location and basin that reflects different flow patterns due mainly to rainfall patterns and watershed time of concentration?

In the two-way ANOVA, there are three F statistics that are calculated and then used in significance tests. Two of these statistics test for the main effects and one tests for interactions. From the flow records analyzed, nine river basins with a total of 63 gauge stations were selected. Each basin had at least five gauge stations. The selected basins and physiographic characteristics (watershed area and river length) and number of stations in upper and lower locations are shown in Table 2.

## Results and discussion

### *ANOVA of TEIS statistics from nine basins*

Table 3 shows the results of the two-way ANOVA. In the table the UL column presents the *F*-value for the difference in group means between upper and lower position in the watershed where the *F*-value determined for is the between-group variability/within-group variability, which is presented in bold when statistical significance, $p < 0.05$. The difference between basins is presented in the BASIN column, and UL*BASIN column provides the results for the interaction difference between UL and BASIN.

In the upper/lower (UL) watershed position assessment statistical significance is found for nearly 60% of the hydrologic statistics with the majority of rate statistics and flow magnitudes showing the expected differences between upper and lower locations. In the magnitude statistics indicators of short term change are not significant. Other significant differences for UL comparisons suggest the number of high flow events and flow reversals in the dry season, and the low flow duration differed. These results are expected because of known concentration time and watershed area influences on flow and confirm the importance of recognizing fundamental differences between upstream locations with smaller watershed areas and steeper terrain while downstream reaches are often affected by flow management structures.

The comparisons between basins (BASIN) indicate significant differences in event frequency and duration with only the mean duration of low flow events in each dry season significantly different between basins. These results suggest that the TEIS hydrologic statistics reflect different patterns in rainfall and the hydro-geology in different basins, including the incidence of typhoon-related flows based on the significance of positive differences in consecutive values. Flow volume and event magnitude statistics did not suggest significant differences among basins. Different basins do have different values for TEIS statistics that reflect flow station location and the characteristics of the hydro-geology in each basin. In this case, upper and lower location issues are subsumed in differences in the hydrology of each basin. These results will help focus management to the specific needs of each basin while alerting managers to the different needs between upper and lower locations in a watershed.

**Table 2**
The selected nine river basins and their gauge stations for two-way ANOVA.

| Basins | No. of stations | | Drainage (sq. km) | Length (km) |
|---|---|---|---|---|
| | Up | Down | | |
| Danshui River Basin | 9 | 6 | 2726 | 159 |
| Dajia River Basin | 5 | 2 | 1236 | 124 |
| Wu River Basin | 1 | 4 | 2026 | 119 |
| Jhuoshuei River Basin | 5 | 5 | 3157 | 187 |
| Beinan River Basin | 3 | 2 | 1603 | 84 |
| Siouguluan River Basin | 2 | 3 | 1790 | 81 |
| Hualien River Basin | 3 | 3 | 1507 | 57 |
| Lanyang River Basin | 2 | 3 | 978 | 73 |
| Da-an River Basin | 3 | 2 | 758 | 96 |

**Table 3**
Two-way ANOVA results of TEIS.

| TEIS characteristic | UL | | BASIN | | UL*BASIN | |
|---|---|---|---|---|---|---|
| | *F* value | *p* | *F* value | *p* | *F* value | *p* |
| *Group 1 – differences between consecutive values* | | | | | | |
| 1. $R_{\mathrm{rate\_}d}$ | **12.42** | 0.000 | 1.77 | 0.106 | 0.63 | 0.755 |
| 2. $R_{\mathrm{rate\_}w}$ | **5.27** | 0.026 | **2.61** | 0.019 | 0.39 | 0.918 |
| 3. $F_{\mathrm{rate\_}d}$ | **14.71** | 0.000 | 1.72 | 0.118 | 1.66 | 0.133 |
| 4. $F_{\mathrm{rate\_}w}$ | **5.75** | 0.020 | 1.00 | 0.445 | 0.45 | 0.880 |
| *Group 2 – high/low flow event magnitudes* | | | | | | |
| 5. $Q_{\mathrm{1daymin\_}d}$ | 2.23 | 0.141 | 0.69 | 0.695 | 1.32 | 0.257 |
| 6. $Q_{\mathrm{10daymin\_}d}$ | 3.44 | 0.070 | 0.64 | 0.743 | 1.40 | 0.222 |
| 7. $Q_{\mathrm{30daymin\_}d}$ | **4.74** | 0.034 | 0.60 | 0.776 | 1.35 | 0.242 |
| 8. $Q_{\mathrm{90daymin\_}d}$ | **6.41** | 0.015 | 0.67 | 0.711 | 1.24 | 0.295 |
| 9. $Q_{\mathrm{1daymax\_}d}$ | **8.85** | 0.004 | 0.75 | 0.646 | 0.46 | 0.880 |
| 10. $Q_{\mathrm{10daymax\_}d}$ | **12.01** | 0.001 | 0.29 | 0.967 | 0.68 | 0.704 |
| 11. $Q_{\mathrm{30daymax\_}d}$ | **12.62** | 0.000 | 0.24 | 0.980 | 0.82 | 0.592 |
| 12. $Q_{\mathrm{1daymin\_}w}$ | 3.76 | 0.058 | 1.05 | 0.413 | 1.80 | 0.101 |
| 13. $Q_{\mathrm{10daymin\_}w}$ | **6.39** | 0.014 | 1.52 | 0.176 | **2.32** | 0.034 |
| 14. $Q_{\mathrm{30daymin\_}w}$ | **7.50** | 0.008 | 1.34 | 0.247 | 1.70 | 0.124 |
| 15. $Q_{\mathrm{1daymin\_}d}$ | **4.43** | 0.040 | 1.21 | 0.312 | 0.40 | 0.913 |
| 16. $Q_{\mathrm{3daymax\_}w}$ | **5.18** | 0.027 | 1.37 | 0.236 | 0.44 | 0.893 |
| 17. $Q_{\mathrm{10daymax\_}w}$ | **6.45** | 0.014 | 1.25 | 0.293 | 0.52 | 0.833 |
| 18. $Q_{\mathrm{30daymax\_}w}$ | **5.52** | 0.023 | 1.04 | 0.419 | 0.75 | 0.645 |
| *Group 3 – frequency of high/low flow events and reversals* | | | | | | |
| 19. $N_{\mathrm{low\_}d}$ | 2.25 | 0.140 | **2.95** | 0.009 | 2.08 | 0.057 |
| 20. $N_{\mathrm{low\_}w}$ | 0.02 | 0.881 | **2.42** | 0.026 | 2.03 | 0.062 |
| 21. $N_{\mathrm{high\_}w}$ | 0.01 | 0.917 | **6.35** | 0.000 | 1.91 | 0.081 |
| 22. $N_{\mathrm{high\_}w}$ | **4.43** | 0.042 | **3.31** | 0.004 | 1.69 | 0.125 |
| 23. $N_{\mathrm{low\_3year}}$ | 0.44 | 0.509 | **2.87** | 0.011 | 1.80 | 0.100 |
| 24. $N_{\mathrm{high\_3year}}$ | 1.28 | 0.264 | **4.04** | 0.001 | 1.74 | 0.114 |
| 25. $RV_d$ | **5.31** | 0.025 | **10.32** | 0.000 | 3.93 | 0.001 |
| 26. $RV_w$ | 0.91 | 0.346 | **8.62** | 0.000 | 1.84 | 0.092 |
| *Group 4 – high/low flow event duration* | | | | | | |
| 27. $D_{\mathrm{low\_}d}$ | **4.82** | 0.033 | 1.68 | 0.128 | 2.33 | 0.034 |
| 28. $D_{\mathrm{low\_}w}$ | **15.11** | 0.000 | **4.89** | 0.000 | **4.05** | 0.000 |
| 29. $D_{\mathrm{high\_}d}$ | 0.00 | 0.977 | **2.82** | 0.012 | **4.57** | 0.000 |
| 30. $D_{\mathrm{high\_}w}$ | 1.67 | 0.203 | **3.66** | 0.002 | 1.27 | 0.283 |

* *F*-value presented in bold when statistical significance, $p < 0.05$.

Few significant differences were identified for UL*BASIN comparisons with only the 10 day minimum, duration of low flows in the wet season and duration of high flows in the dry season significant. This result suggests little consistent interaction among basin location and location within basins except for statistics that relate to low flow and event description (see Fig. 1).

The results of these analyses are specific for Taiwan, but are consistent with similar analyses on continental scales, so application to other water resources management programs is appropriate. These results indicate that flow regimes will differ between upper and lower locations in watersheds in ways that are consistent, and predictable. Rates of change and magnitude of flows will be sufficiently different so as to require specific management approaches to assure a comprehensive, watershed-scale regime-based management approach. This finding can be considered intuitive, but the demonstration of how consistently a range of hydrologic statistics, selected for ecological relationships, shows this difference is an important foundation for ecological flow regime development in Taiwan, and are expected to be applicable globally. These results also demonstrate that management schemes should also be basin specific because there are significant differences in frequency and duration among basins. The relationships summa-

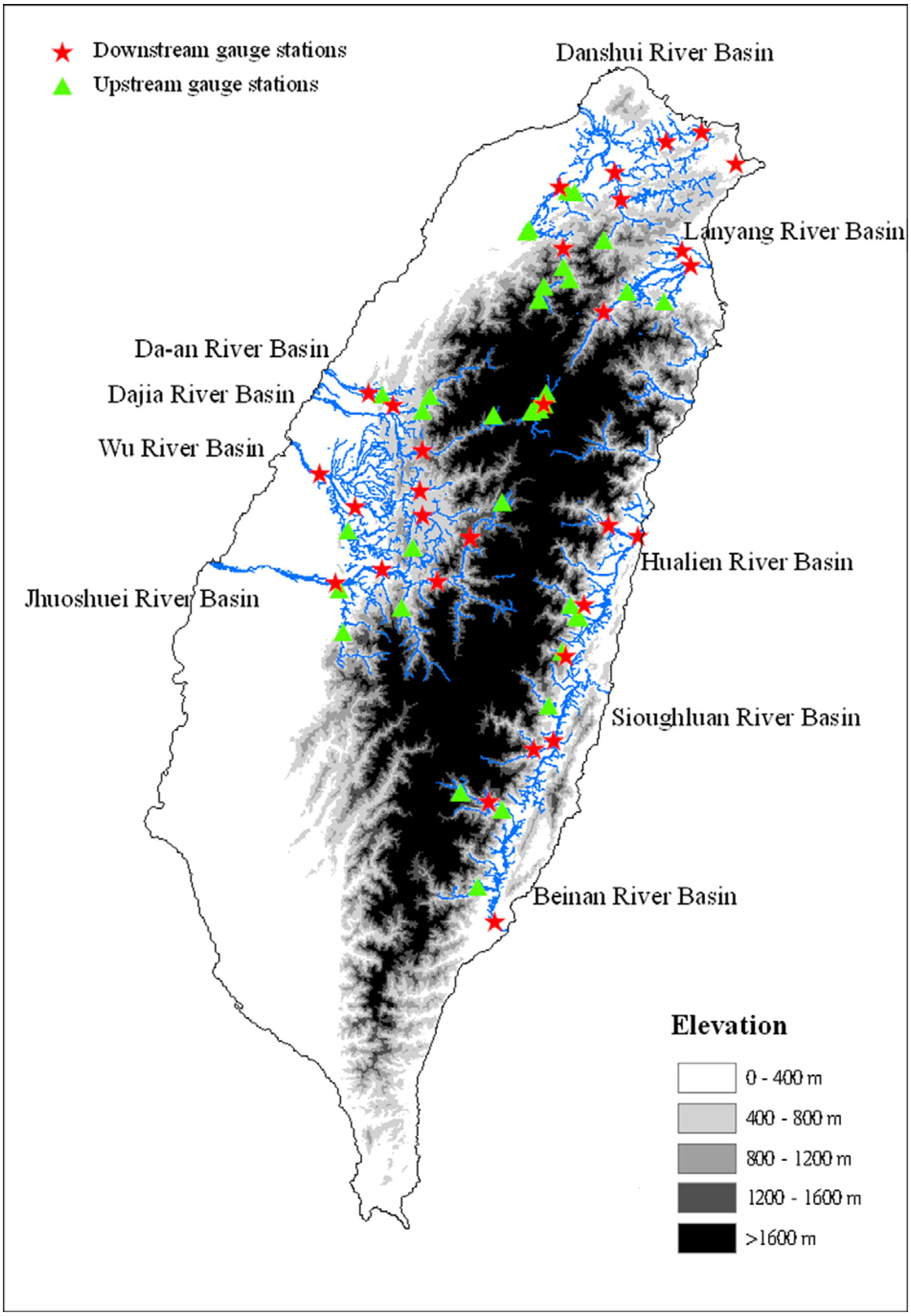

**Fig. 1.** Flow stations in the nine basins used for two-way ANOVA analysis.

rized in Fig. 2 provide a guide to the consideration of the types of hydrologic statistics useful in capturing regime characteristics for different project basins and locations.

*Redundancy of Taiwan ecohydrological indicators*

The correlation coefficient matrix of the 66 TEIS indicators was based on all 102 stations. The Pearson correlation coefficient, *r*, showed high multicollinearity between the TEIS statistics (Table 4). There are 36% of the *r*-values higher than 0.8, and about 65% of the *r*-values higher than 0.6. In the analysis negative correlations of 11% and 10% were determined for *r*-values 0 to −0.2 and −0.2, respectively. This result is also consistent with other studies (Olden and Poff, 2003; Monk et al., 2007). What is important is that there is a consistency in the pattern for a group of statistics selected for ecological significance. These results support the notion that when choosing hydrologic statistics for ecological flow regime analysis, it is possible to identify statistics that effectively characterize hydrologic variability and provide statistics important to regime selection and ecological importance. There is no need for choice between hydrologic and ecohydrologic indicators, rather there is a need to recognize which hydrologic indicators have ecological significance.

Principal component analysis (PCA) used results extracted from the 66-by-66 correlation matrix (i.e. 66 TEIS indexes) to identify subsets of statistics that describe the major sources of variation while minimizing redundancy (i.e. multicollinearity). In addition the PCA supports further assessment of the transferability of the statistics by identifying those statistics that consistently explain dominant patterns of variation related to station location

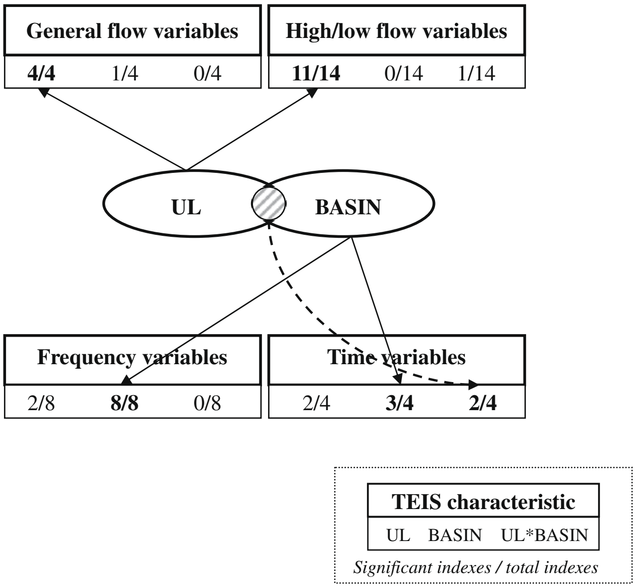

**Fig. 2.** The tendency of two-way ANOVA results, the linked arrow represent high correlation between the factor with the TEIS statistics.

(upstream or downstream). This analysis is intended to further illustrate issues of redundancy and improve our understanding of how to best select statistics that adequately describe the hydrology while providing sufficient information to ecological flow regime development. To investigate the applicability and consistency of principle component analysis, three different cases have been examined: (1) 102 gauge stations, (2) 52 gauge stations in upstream areas, and (3) 50 stations in downstream areas.

The results from the PCA show that the three cases have similar explained variability in first three principle components (PC1–PC3), shown in Table 5. The first principle component is related to general flow and high/low flow statistics, explaining approximately 66% of the variation observed. The second principle component is related to frequency and time statistics, explaining approximately 10% of the total variation. The third principle component is related to quantity statistics and explains about 7.5% of the variation. These first three principle component would explain about 85% of the total variation. In other words, if we use the first three principle components to replace 66 TEIS statistics, we would only lose 15% hydrologic information. The relationship between TEIS statistics and the principal components can be illustrated by the principal components loading. The loading is given between 1 and −1 where higher loading values are related to increased influence of a variable. Fig. 3 shows the loading of the principal components calculated using all 102 stations and the 66 TEIS statistics, including the loading for PC1, PC2, PC3, respectively. There are generally opposite results in the loading of PC1 and PC2 with the separation is due to indicators 19–26, which are frequency statistics. PC3 shows the higher loading for some frequency and time indicators and different loading for the 36 10-day flow average, which suggests potential seasonality.

These results suggest that is possible to replace 66 TEIS statistics with three principle components (PC1–PC3) and represent hydrologic variability. This simplification of the number of statistics that will describe hydrologic variability is often needed to make further modeling and optimization of water resources and flow possible. In Chang et al. (2008) a cautionary note was provided that there is a difference between adequately describing hydrologic variability, and the need for statistics that are related to flow conditions important to aquatic life in an ecological flow regime determination.

## Conclusions

The importance of an ecological flow regime approach is recognized in modern water resources management, particularly in river restoration and reservoir management. A major challenge for the water resources community is developing a reasonable set of hydrologic statistics that effectively use data from an extensive network of flow monitoring stations to generate ecohydrologic indicators that improve existing water resources management. The Taiwan Ecohydrological Indicator System (TEIS) includes hydrologic statistics that reflect unique characteristics of Taiwan's water resources and ecology. This paper examined data from an extensive network of flow monitoring stations in Taiwan to examine the hydrological statistics recommended in the TEIS. In this analysis multivariate statistical methods were used to examine the TEIS hydrological statistics from 102 stations representing the geographic and land use diversity of Taiwan. Analyses focused on the following questions:

1. How is the hydrologic regime of Taiwan captured in the TEIS hydrologic statistics?
2. Does station location (upper or lower position in the watershed) have an effect on TEIS values?
3. Do different river basins have different TEIS values?
4. Is there an interaction between location and basin?

The results of this research showed that TEIS hydrologic statistics provided a detailed characterization of hydrologic conditions, providing information on flow change, magnitude, frequency, and

**Table 4**
Correlation coefficients between 66 TEIS parameters.

| Range of correlation | >0.8 | 0.8 | 0.6 | 0.4 | 0.2 | 0 | <−0.2 | Sum |
|---|---|---|---|---|---|---|---|---|
| | | 0.6 | 0.4 | 0.2 | 0 | −0.2 | | |
| Number | 1582 | 1288 | 140 | 122 | 286 | 504 | 434 | 4356 |
| Ratio | 0.36 | 0.29 | 0.03 | 0.03 | 0.06 | 0.11 | 0.10 | 1.00 |

**Table 5**
Explain variances of principle component analysis of TEIS.

| | Principle component (%variance) | | | First three PCA variances |
|---|---|---|---|---|
| | I | II | III | |
| Upstream ($n = 52$) | 65.9 | 10.5 | 7.6 | 84.0 |
| Downstream ($n = 50$) | 65.9 | 10.6 | 7.1 | 83.6 |
| Total ($n = 102$) | 66.4 | 10.0 | 7.6 | 84.0 |

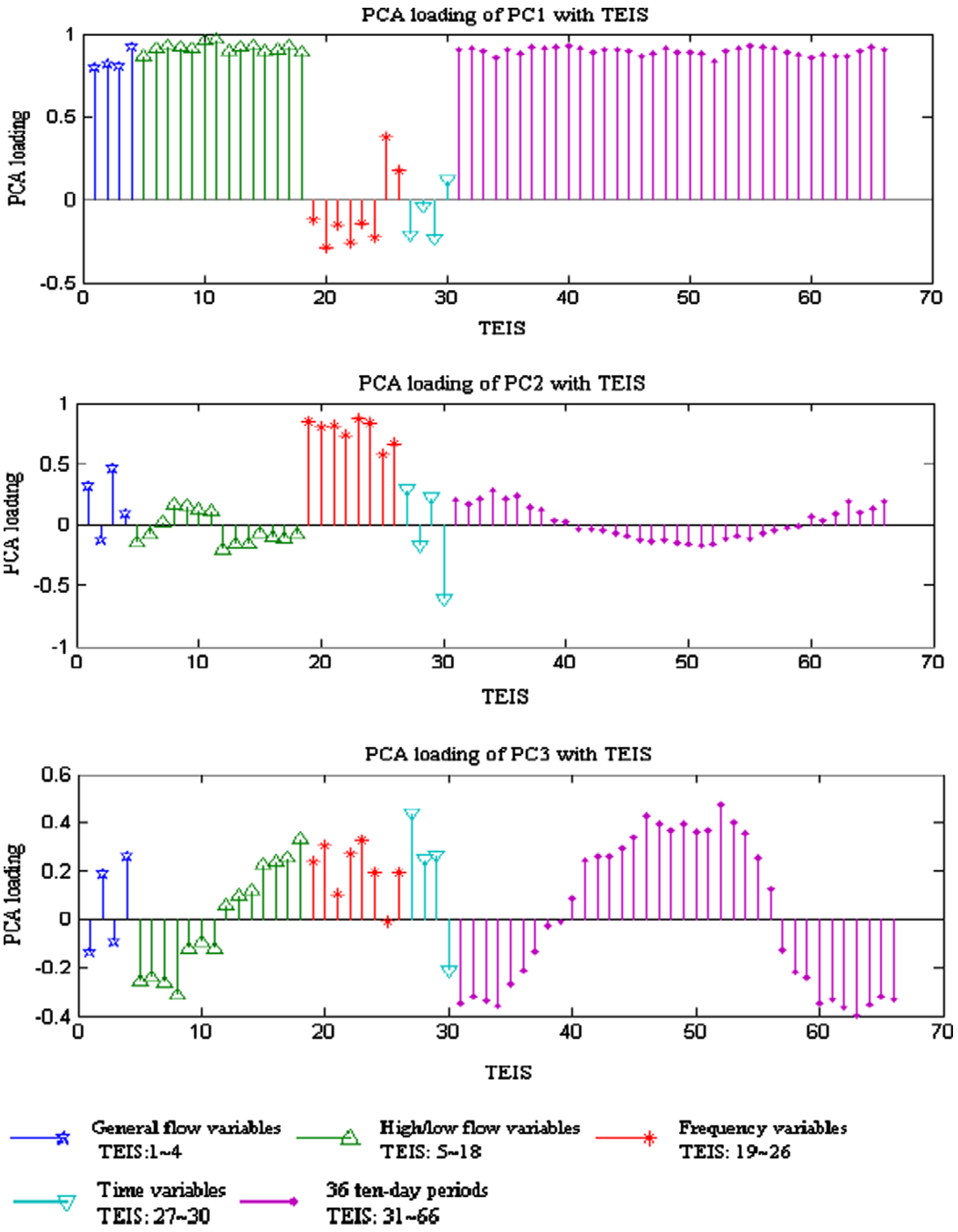

**Fig. 3.** PCA loading of principle component with TEIS.

duration. This summary of statistics in the TEIS is useful in providing a detailed characterization of hydrologic regime for basins throughout Taiwan. The detailed statistics of the TEIS were examined for redundancy. The results of PCA analysis suggested the 66 hydrologic statistics in the TEIS could be replaced by three components and represent hydrologic variability. What is lost in this replacement is the utility of hydrologic statistics that relate to ecological requirements of aquatic life. The TEIS provides a fuller characterization of flow regime elements that is essential in the development of management strategies intended to provide ecological flow regimes.

ANOVA results indicated differences between upstream, more natural, and downstream, more developed, locations in the same basin with a corresponding hydrologic indicator redundancy in flow change and magnitude statistics. Correlation of TEIS indicators with basin area, elevation, and slope indicated the importance of flow frequency-related indicators in ecohydrology. Watersheds were separated into headwaters and mid-watershed locations. An analysis of variance (ANOVA) indicated differences between upstream, more natural, and downstream, more developed, indicators in the same basin. Of importance in these results is that differences between upper and lower locations in watersheds in ways that are consistent, and predictable. The differences in rates of flow change and the magnitude of flows is sufficiently different between upper and lower locations that management approaches should be site specific to meet ecological needs. This argues for careful watershed management that considers local needs as a part of any basin management scheme.

ANOVA results also indicated that in the nine watersheds assessed, each basin has individual characteristics that make it difficult to generalize for all basins. Although the cause of differences between basins has not been identified, it is likely that differences in rainfall patterns and the unique hydro-geology of each basin contributes to the observed differences in hydrological statistics. The major conclusion is that managers must be aware of differences among basins, as well as differences within basins that will require careful selection of management procedures to achieve needed flow regimes.

A final conclusion that can be drawn from this analysis is that well designed ecological indicators provide a range of hydrologic statistics that adequately represent hydrologic conditions. *Although the TEIS was developed for Taiwan, its foundation included indicators proposed for North America, so with modification for timing related to life history of target species the conclusions about hydrologic statistics should be applicable outside of Taiwan.* Unfortunately, simply selecting non-redundant hydrologic statistics to represent flow, magnitude, frequency, or duration do not provide sufficient information to develop ecological flow regimes. The selection of hydrologic statistics for modern regime analysis must account for species needs as is accomplished in the TEIS. In this analysis, we have provided a comprehensive review of a case study and have addressed a number of the issues raised by Arthington et al., 2006.

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