Ecological Engineering 87 (2016) 9–19

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Exploring the ecological response of fish to flow regime by soft computing techniques

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ARTICLE INFO

Article history:
Received 12 March 2015
Received in revised form 14 October 2015
Accepted 10 November 2015

Keywords:
Flow regime
Taiwan Eco-hydrologic Indicator System (TEIS)
Fish diversity
Soft computing techniques
Self-organizing feature map (SOM)
Clustering analysis

ABSTRACT

Ecosystem integrity has become a focus of watershed management. Recently much attention has been paid to the analysis of eco-hydrological data for developing a better understanding of how flow regimes influence the structures and functions of riverine ecosystems. This study explores ecosystem integrity in Taiwan rivers through characterizing the relationship between flow regimes (long-term continuous hydrological observational datasets) and fish communities (non-continuous ecological monitoring datasets) using soft computing techniques (self-organizing feature map (SOM) and clustering methods). The analysis is driven by the Taiwan Eco-hydrologic Indicator System (TEIS) statistics and biodiversity measures, in which data sets consist of 74 long-term monitoring records of flow and fisheries at 38 locations in 12 rivers in Taiwan. Results indicate that: (1) flow regimes of the 12 rivers can be related to watershed locations, namely upstream, midstream and downstream regions; (2) fish diversity is significantly higher in midstream regions than in up- and downstream regions; and (3) a consistent relationship between flow regime and fish community can be obtained when using presence–abundance data. Flow regime characteristics are consistent with respect to the hydro-geographical and ecological characteristics of streams, especially for midstream reaches, which provides further evidence of the importance of natural flow regimes in sustaining ecological integrity. These analysis results offer valuable insights into management options that support decision-makers in evaluation and classification of ecological status and provide further analyzed evidence to address ecological flow regime issues in water resources management.

1. Introduction

The integrity of ecosystems in undisturbed watersheds is generally high because natural processes provide a full range of ecological requirements for indigenous species. As known, the characteristics of ecosystem functions in riverine are the lumped efforts of long-term bio-geo-hydrological processes and flow is a major determinant of physical habitats in streams as well as their biotic compositions. A crucial element in retaining ecological integrity is the natural flow regime, which is the key driver of river and floodplain wetland ecosystems (Bunn and Arthington, 2002; Yang and Yang, 2014). Natural flow regime also provides habitat diversity in response to the dynamic interactions of climate and channel morphology over time (Kiernan, 2012; Poff et al., 1997). Under equilibrium conditions habitats are not static but vary with the interactions between flow and channel structures (Poole, 2010; Chen et al., 2015), which produces varying habitat conditions meeting the life history requirements of aquatic organisms, and therefore produces diverse riverine flora and fauna. Many studies explored the relationships of flow with habitat conditions and proposed ecosystem sustainability guidelines based on flow management (Bunn and Arthington, 2002; Richter et al., 2003; Stanley et al., 2004; Arthington et al., 2006; Macklin and Rumsby, 2007; Poff et al., 2010; Kingsford et al., 2011; McClain et al., 2012; Warner et al., 2014; Li et al., 2015).

Flow regime is thus considered as a key element of ecosystem integrity, and the patterns of flow quantity, timing and variability determine habitats, which consequently influence ecosystem integrity. Understanding how altered flow regimes mediate the interactions among native and nonnative species is the key to conserve aquatic systems (Franssen et al., 2007). Human development in watersheds inevitably produces changes in flow regimes, however, such unmanaged changes in flow regime would produce a

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http://dx.doi.org/10.1016/j.ecoleng.2015.11.015
0925-8574/

cascade of effects on riverine ecosystems. For instance, watershed disturbance changes the variability of flow regimes by increasing peak flow and reducing base flow. Increased peak flow and reduced base flow may alter physical habitats and exacerbate water quality. Even though plenty of results in the last decades did indicate the importance of flow regime to ecological integrity (Sparks, 1995; Stanford et al., 1996; Richter et al., 1996, 1997; Jackson and Feder, 2006; Blettler et al., 2014), the influence of natural flow on the sustainability of healthy aquatic ecosystems is somewhat piecemeal (Bunn and Arthington, 2002) and the translation of research findings into management procedures is rare. Consequently, a pivotal issue for managing ecological integrity in watersheds is to develop a better understanding of the influence of flow regimes on the structures and functions of riverine ecosystems, where the analysis of eco-hydrological data is essential to provide a comprehensive approach to managing complex riverine systems. Investment in the flow-regime focused operation of dams, weirs and regulators can help increase both the health of regulated river ecosystems and the social values derived from them (Bryan et al., 2013).

The natural flow of a river varies on time scales of hours, days, seasons, years, or longer intervals. Long term observation at streamflow gauging locations is essential to describe the characteristic patterns of flow quantity, timing and variability. A natural flow regime consists of five main components: magnitude, frequency, duration, timing and rate of change (Olden and Poff, 2003; Suen and Herricks, 2009; Chang et al., 2011). The Taiwan Eco-hydrologic Indicator System (TEIS) was developed to relate hydrologic statistics to known organism habitat requirements. The TEIS provides an analytical foundation to assess how hydrologic alteration influences the communities of organisms and associated diversity indicators (Chang et al., 2008; Suen and Herricks, 2009). Long-term flow records provide an opportunity to compare a present flow regime with historical conditions and support modeling to adjust future flows, or plan management actions to address future hydrologic variability. Relating historical flow conditions to watershed and landscape features including changes in land use thus provides a basis for identifying the causes of flow alteration, a better definition of overall habitat variability (Poole, 2010), and options for watershed management.

Flow may constrain habitat, but any approach to sustainability must consider the aquatic community, which points out the importance of historical community characterization. Long-term ecological records typically established by regular sampling at fixed locations constitute the foundation for historical ecosystem analysis. Unfortunately, detailed ecological data, comparable to hydrologic data, seldom exist. When available, aquatic community data usually fall well short of the details or consistency found in typical hydrologic records. Ecological information is often limited to target groups such as fish or macro-invertebrates, and census information is site specific with sampling seldom capturing the full variability of aquatic community dynamics (Herricks and Suen, 2006). Long-term ecological data, when available, are typically confined to watershed locations where point or non-point discharges are expected to alter community structures or functions, which is the focus of assessments. The correlations between hydrologic records and ecosystem state and condition are thus subject to data availability, the aquatic communities sampled, and the overall objectives of the assessment (Bradley and Ormerod, 2002; Wagner and Schmidt, 2004; Wood and Armitage, 2004; Chang et al., 2013).

The relationships between variables in ecology are almost always very complicated and highly non-linear. Furthermore, the lack of corresponding data quality makes it difficult to relate flow regimes to riverine ecosystem state and condition, and it is equally difficult to develop insights into eco-hydrology. For that reason, the development of appropriate methodologies to identify and/or simulate eco-hydrological interactions in data-poor environments is a current necessity. However, traditional regression models are hardly suitable to address the non-linearity, contingency, and complexity of the cause-effect relationships among ecological variables (Marsili-Libelli, 2004). Artificial neural networks (ANNs) have shown great promise for tackling complex pattern recognition problems and modeling of multivariate non-linear relationships, such as the modeling of biological variables as a function of multiple descriptors of the environment (Gevrey et al., 2003; Vander Zanden et al., 2004). ANNs have become increasingly popular in the analysis of ecological phenomena (Olden et al., 2004; Jeong et al., 2008; Lek and Guégan, 2012; Gebler et al., 2014; Millie et al., 2014; Zhang et al., 2015). A critical element is the selection of metrics that contribute to the understanding of complex relationships between flow regimes and ecosystems. Freshwater fish communities are acknowledged as indicators that can be adopted to assess the ecological conditions of rivers (European Commission, 2000; Olaya-Marín et al., 2012).

This study aims to extract and establish the relationship between flow regimes (long-term continuous hydrological observed datasets) and fish communities (non-continuous ecological monitoring datasets) through data mining techniques. This study is metric focused with soft computing techniques and explores the ecosystem integrity in Taiwan rivers by analyzing the relationships between flow regime metrics and metrics used to describe fish community state and condition. Study results illustrate the influence of natural flow, related to watershed location, on the sustainability of healthy aquatic ecosystems and provide further analyzed evidence to address ecological flow regime issues in water resources management.

2. Study area and materials

Taiwan, with an area of 35,883 km^2, is an island located in the subtropical monsoon zone of the North Pacific Ocean. The terrain of Taiwan consists of five rugged mountain ranges with several peaks over 3500 m (the highest peak over 3950 m), and thus rivers in Taiwan have short lengths and steep gradients. Its abundant rainfall during typhoon events often causes extremely high flood peaks, and river flows vary greatly between wet and dry periods because of the non-uniform tempo-spatial distribution of rainfall. In major rainfall events related to typhoons the maximum flood volumes may exceed flood flows of major rivers, such as the Mississippi in the United States. The response time of torrential rain on river flow usually takes only few hours. Overall, flow in Taiwan is highly variable, posing challenges to the organisms in riverine ecosystems. Even though the environmental conditions are challenging, indigenous organisms have adapted to the natural variability in flow, and, in fact, may require certain levels of variability to meet all life-history requirements. To identify flow regimes suitable for retaining high quality fish communities dominated by indigenous species, data for use in this study comprise long-term flow records (more than 20 years) collected at 38 flow gauging stations and samples of fish communities available at sites located less than 10 km from their corresponding flow gauging stations (Fig. 1).

2.1. Flow data—Converted into statistics of Taiwan Eco-hydrologic Indicator System (TEIS)

Flow information was investigated based on the daily flow data of 38 gauging stations for the period of 1981 and 2008 retrieved from “The stream flow database of Taiwan” maintained by the Water Resources Agency in Taiwan. The ecological implications of flow data were identified through the TEIS. The TEIS was developed to identify species specific environmental requirements using hydrologic statistics with reported relationships between