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Assessing the natural and anthropogenic influences on basin-wide fish species richness

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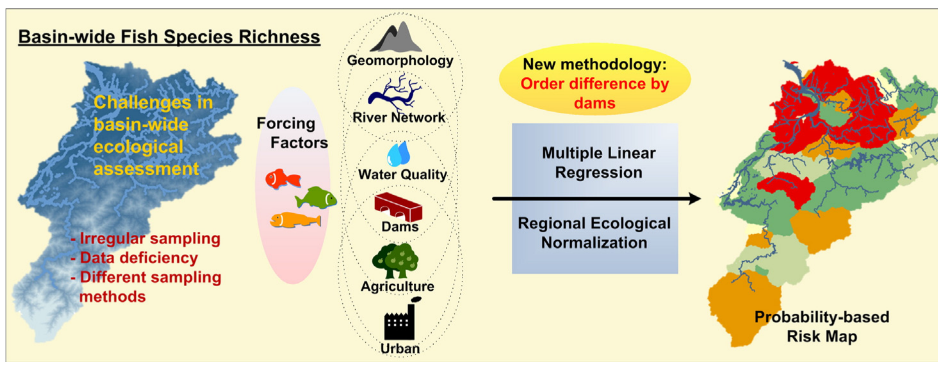
HIGHLIGHTS

- Integrate multi-metric measures to assess influences on fish species richness
- Apply regional ecological normalization to correct systematic data biases
- Use "order difference by dams" consistent with the structure of stream order
- Identify major forcing factors as stream order, dams, DO and TP
- Risk maps highlight areas needed for mitigation.

GRAPHICAL ABSTRACT



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ABSTRACT

Theory predicts that the number of fish species increases with river size in natural free-flowing rivers, but the relationship is lost under intensive exploitation of water resources associated with dams and/or landscape developments. In this paper, we aim to identify orthomorphic issues that disrupt theoretical species patterns based on a multi-year, basin-wide assessment in the Danshuei River Watershed of Taiwan. We hypothesize that multiple human-induced modifications fragment habitat areas leading to decreases of local fish species richness. We integrally relate natural and anthropogenic influences on fish species richness by a multiple linear regression model that is driven by a combination of factors including river network structure controls, water quality alterations of habitat, and disruption of channel connectivity with major discontinuities in habitat caused by dams. We found that stream order is a major forcing factor representing natural influence on fish species richness. In addition to stream order, we identified dams, dissolved oxygen deficiency (DO), and excessive total phosphorus (TP) as major anthropogenic influences on the richness of fish species. Our results showed that anthropogenic influences were operating at various spatial scales that inherently regulate the physical, chemical, and biological condition of fish habitats. Moreover, our probability-based risk assessment revealed causes of species richness reduction and opportunities for mitigation. Risks of species richness reduction caused by dams were determined by the position of dams and the contribution of tributaries in the drainage network. Risks associated with TP and DO were higher in human-activity-intensified downstream reaches. Our methodology provides a structural framework for assessing changes in basin-wide fish species richness under the mixed natural and human-modified river network and habitat conditions. Based on our analysis results, we recommend that a focus on landscape and riverine habitats and maintaining long-term monitoring programs are crucial for effective watershed management and river conservation plans.

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1. Introduction

Fish species community reflects the dynamic equilibrium of biological, ecological, and environmental interactions and the richness of fish species has been known to increase with stream size (usually modeled as distance (river mile) or drainage area; Zorn et al., 2002; Triantis et al., 2008). The increasing pattern of species richness with area is the species-area relationship based on island biogeography theory (MacArthur and Wilson, 1967). Besides distance or drainage area, studies have also found a positive relationship between fish species richness and stream order (Morgan and Cushman, 2005; Vieira and Tejerina-Garro, 2014). The stream order classifies streams as a hierarchical set of dynamic freshwater ecosystems from headwaters to the river mouth (Strahler, 1956). As a result, stream order has been used as a surrogate of stream size (Osborne and Wiley, 1992). In addition, the stream ordering system describes the geomorphic pattern of streams in river networks by simple mathematics (calculation detailed in Section 2.2), and has been used to assess the connection and complexity of tributaries in lotic systems (Osborne et al., 1992; Domisch et al., 2015). In fact, many studies have observed the concordance of species occurrence with different stream orders (D'Ambrosio et al., 2009; Neeson et al., 2012) and that stream order defines a hierarchy of habitat conditions that sustain diverse fish communities (Allan and Flecker, 1993; Poff et al., 1997).

Despite advancement in our understanding of stream size influences on fish species richness, human-induced habitat modifications have caused changes in fish species composition and distribution (Oberdorff et al., 1993; Wen et al., 2010). Many studies assessed changes in habitat conditions to relate anthropogenic influence on riverine fishes (Schlosser, 1985; Wang et al., 2011). Studies found that the fish species richness is associated with changes in flow regime (Katz and Freeman, 2015; McKenna et al., 2015), land-use (Jennings et al., 1999; Wen et al., 2010), dams (Chang et al., 1999; Kornis et al., 2015), and climate (Stevenson and Sabater, 2010; Leigh et al., 2015). Moreover, with increasing human activities in large urban rivers, a species-area relationship becomes less pronounced when compared with free-flowing rivers (Oberdorff et al., 2002).

Human-induced habitat modifications are serious stressors to fish communities (Cardinale et al., 2006; Elith and Leathwick, 2009). The most recognized anthropogenic stressor is the dam, which impounds water changing habitat from lotic to lentic and altering flow regime downstream. An extensive literature has been built largely around the river continuum, hydrological and ecological connectivity, and serial discontinuity concepts associated with dam effects on fish community composition (Pringle, 2001; Freeman et al., 2007; Griffiths, 2015). In addition to dams, the degradation of water quality has also been recognized as an abiotic steering factor to account for the changes of fish species richness (Lorenz et al., 1997). Most of these studies have taken place in the temperate zones, particularly North America or Europe (Baker et al., 2005; Tang et al., 2005; Neeson et al., 2012; Gonzalez Vilas et al., 2016), where long-term detailed hydrological, chemical, or biological data were more readily available. Unlike the temperate zones, complete long-term datasets are not frequently available in developing countries and in more tropical settings. Reduced environmental concern in areas undergoing economic development has placed environmental and ecological status in a lower priority; and the absence of sampling programs make basin-wide ecosystem assessment difficult.

Taiwan, historically named Formosa (i.e., beautiful island from Portuguese), has diverse flora and fauna with many endemic species (Chang et al., 2008). Unfortunately, some species are now extinct, and many have been designated as endangered (Day et al., 1993; Hung et al., 2005; Tzeng et al., 2006; Liu and Kuo, 2007). For example, in 1967 the very popular native sweetfish (Takada et al., 2010) was extirpated from the Danshuei River. The loss was attributed to the construction of the Feitsui Reservoir, which changed habitat and disrupted migration pathways. Along with poor water quality, particularly in the estuarine intertidal area (Cheng et al., 2012), a combination of upstream habitat disruption and downstream water pollution has combined to produce species loss in Taiwan. Unlike the temperate regions, there are few studies of basin-wide anthropogenic impacts on the richness of fish species in Taiwan where regional variance can be large in terms of physical, chemical, and physiographic habitat conditions. Fish faunas tend to have distinct patterns that reveal causes of ecological degradation and opportunities for mitigation. An improved understanding of regional variance of habitat and biological conditions requires data-intensive investigations to define and assess complex human-ecological-habitat problems. This is particularly important in developing countries, like Taiwan, where irregular sampling and limited correspondence between water quality and biological sampling sites challenge basin-wide analyses needed for watershed management.

In an effort to address this data deficiency, we developed a new methodology that related fragmentation effects from dams to fish species richness while accommodating deficiencies of site-specific hydrological and water quality data. In addition, we explored techniques for overcoming problems of different sampling methods that could confound a basin-wide analysis. In this study, we aim to identify orthomorphic issues that disrupt theoretical species composition patterns. We hypothesize, based on the island biogeography theory (MacArthur and Wilson, 1967), that multiple human-induced modifications fragment larger habitat areas into smaller island-like habitats so that local fish species richness decreases. To test this hypothesis, we assess the mixed natural and anthropogenic influences on fish species richness under Taiwan's unique disturbance dynamics by: (1) examining the species-area relationships; (2) identifying key forcing variables; (3) assessing quantitative stressor-response patterns; and (4) developing GIS-based risk maps. The objective is to assess natural and anthropogenic influences on fish species richness and to reveal opportunities for mitigation.

2. Methods

2.1. Study area and watershed data resources

The Danshuei River Watershed (淡水河, aka "Tamsui River" on Google) is located in northern Taiwan. The drainage basin is 2726 km^2 and the mainstem length is 158.7 km, with mountainous areas upstream, progressing to the mainstem of the Danshuei River at the southern border of the Taipei basin, and eventually draining into the Taiwan Strait. Three major tributaries, the Dahan (DH), Shindien (SD), and Keelung (KL) Rivers, merge to form the mainstem of the Danshuei River (DS) in the west of Taipei City. We examined fish distribution data from 45 fish sampling stations across the Danshuei River Watershed (Fig. 1). There were 552 samples collected by multiple groups that included Academia Sinica, Water Resources Agency of Ministry of Economic Affairs, and Environmental Protection Administration of Executive Yuan (Taiwan) during 2003 to 2013. Thirty-nine samples were available from earlier years (1981 to 1983, and 1996 to 1998). Sampling frequencies differed among sites and years due to funding and labor constraints. Sampling methods also differed to accommodate field requirements, project needs, and budget constraints. In smaller streams, fish were collected by electrofishing; in larger and deeper streams or near-shore areas, sampling employed barrage-type fish traps, a boat-mounted electrofishing device, and gillnets.

Water quality sampling produced measures of water temperature (°C), pH, conductivity (μS/cm), turbidity (NTU), dissolved oxygen (DO) saturation (%), and total phosphorus concentration (TP; mg/L). Water quality sampling was also conducted by various organizations including Academia Sinica, and the Environmental Protection Administration of Executive Yuan (Taiwan) and the Water Resources Agency of Ministry of Economic Affairs. Not all water-quality parameters were sampled at all sites and/or years or from the same location where fish were sampled.