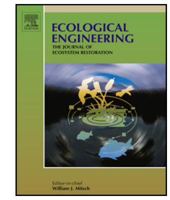
Ecological Engineering 97 (2016) 493–502

Contents lists available at ScienceDirect

Ecological Engineering

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



Relationships between stream ecosystem properties and landscape composition at multiple spatial scales along a heavily polluted stream in China: Implications for restoration

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ARTICLE INFO

Article history:
Received 10 April 2016
Received in revised form 27 July 2016
Accepted 5 October 2016

Keywords:
Heavily polluted stream
Landscape
Scale
Water quality
Macroinvertebrate

ABSTRACT

Restoration in seriously polluted streams has become an urgent issue in developing countries. In this study, we attempted to propose an effective restoration approach in a heavily polluted stream in China with the aid of relationships between ecosystem properties and landscape across multiple scales. Land cover and physical geometry at a fine gradient of spatial scales (doubling 60–960 m and whole catchment) were included as landscape predictive variables, while water quality and macroinvertebrate were involved as ecosystem response variables. The strong relationship between the stream properties and surrounding landscape indicated the stream still maintain its resilience, that is, the capacity to recover from disturbance without changing its fundamental functions and state, even undergoing severe pollution. Further, the primary predictors for water quality were agriculture and urban land, with most effective scale at local 60 m buffer, but independence tests pointed out most correlations between agriculture and water quality were attributed to urban land and spatial covariation. No direct association was detected between macroinvertebrate and surrounding land cover at all scales, but macroinvertebrate exhibited significant relationship with physical variables at in-stream habitat scale. Overall, it was quite possible for this heavily polluted stream to go back to its initial health state if appropriate restorations were taken. The extent and intensity of riparian urbanizations were high priority factors when performing water quality improvement, and increasing habitat complexity and heterogeneity at in-stream scale was crucial for increasing macroinvertebrates diversity.

1. Introduction

Streams and rivers are among the most damaged ecosystems by human activities (Naiman and Turner, 2000). In developing countries, dramatic expansions of industry, urbanization and population have posed much greater threats upon stream health. This undoubtedly leads to many heavily polluted streams with serious water pollution problems and the whole ecosystem deterioration (Sheng et al., 2013). Faced with such situations, restoration projects have been widely set up. Some of them have been proved to be able to recover the stream ecosystem and achieve its restoration goals, especially in those less polluted streams. In terms of heavily polluted stream, however, it seems that restoration projects are much more difficult, and reports of effective restoration outcome are very rare (Bernhardt and Palmer, 2011; Palmer et al., 2005).

Heavily polluted streams usually suffer degradations from major alterations to landscape, for example, substantial land use change (agriculture, urbanization and channelization) induced by human activities (Bernhardt and Palmer, 2011). As a result, their stream hydrology and geomorphology are greatly altered, which then impairs stream habitat integrity. Runoff from urbanized or agricultural area is discharged into streams with other contaminants which certainly cause serious water pollution and biodiversity declination (Paul and Meyer, 2001; Uriarte et al., 2011). In China, more than 31% streams have been categorized into heavily

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http://dx.doi.org/10.1016/j.ecoleng.2016.10.028
0925-8574/© 2016 Published by Elsevier B.V.

polluted levels whose water quality are characterized as Grade IV or worse in a five-level grading system and most of them locate along or near major cities which have induced rising threats to residential water security (Ministry of Water Resources of the People's Republic of China, 2013Fu et al., 2007). During recent years, many restoration projects have been established and billions of money was input to improve stream health, but minor effects were achieved. One major reason to explain the missing goals of these projects is the increasing serious human disturbance imposed on these streams has gradually eroded their resilience and made them more vulnerable to pressures which they could absorb previously (Folke et al., 2010). Resilience refers to the adaption capacity of stream ecosystem to disturbance from surrounding environment. If resilience is reduced, the response of stream to landscape changes would be greatly weakened (Cumming, 2011). With the decay of resilience, the relationships between stream and its landscape would be entirely diminished, and catastrophic regime shifts can occur in these highly polluted streams (Scheffer and Carpenter, 2003). In this case, stream ecosystem appears insensitive to restorations. Simply reductions of disturbance might be insufficient to draw the stream back to its initial health state, much more efforts are necessities to cross the threshold for reversing the state, and very long time periods are required for the stream to recover (Cumming, 2011; Scheffer and Carpenter, 2003).

The second main cause deteriorating the effectiveness of restorations in heavily polluted streams is poor understanding the response and related ecological processes of ecosystem to human disturbance. In China, many restoration projects are established by local governments or landowners and often occur arbitrary or opportunistically (Fu et al., 2007). Rarely are they planned and executed with deep consideration of ecosystem process and ecological theory (Xia et al., 2011; Wang and Huang, 2012). As we known, stream ecosystems are driven by ecological processes and mechanisms, which are characterized by a set of environmental predictors and ecological response variables operating and interacting at various spatial scales, ranging from local to whole catchment scale (Allan, 2004; Johnson et al., 2007; Lammert and Allan, 1999; Pratt and Chang, 2012; Strayer et al., 2003). Fully understanding the relations of predictors and response variables at multiple spatial scales could help to develop proper stream management and restoration (Johnson et al., 2007; Stephenson and Morin, 2009; Strayer et al., 2003). Besides, due to limited financial resources, many restoration projects merely perform one-offs and at small scales or some sections, which further reduce the likelihood of successful restoration (Wang and Huang, 2012). Admittedly, restoring all sites within a catchment requires enormous cost which is not feasible for local owners. The inherent links between streams and its surrounding landscape, however, could help people figure out the most effective predictors and their characteristic spatial scales for restoration (Lake et al., 2007; Uriarte et al., 2011). Then, some optimized scale and corresponding strategy can be chosen to minimize financial cost while maximizing environmental benefits (Mueller et al., 2014; Peacock and Hikuroa, 2012). For this reason, quantitatively investigating the relationships between streams and landscape is necessary for selecting prioritizing restoration sites and approaches. It is worth noting that spatial autocorrelation and landscape components collinearity sometimes will complicate the relationships.

In this study, we tried to plan an effective restoration in a heavily polluted stream (Jialu River Basin, China) receiving large amount of urban and agriculture wastewater, by investigating the relationships between stream response variables and predictive variables at a fine gradient of spatial scales (from the doubling 60–960 m buffer to the entire catchment). Water quality and macroinvertebrate indicators were selected as abiotic and biotic response variables, respectively, and land cover and physical geometry at various spatial scales were included as predictive variables. Our objectives were to answer the following questions: whether the heavily polluted stream has lost resilience and hence showed weak response to surrounding landscapes; if the resilience in this stream still exists, then what are the prime factors dominantly impacting the stream ecosystem properties (water quality and macroinvertebrate) and what are the characteristic scales at which different ecosystems properties respond to landscape factors most. After answering these questions, we hope to acknowledge the state of the heavily polluted stream and propose approaches towards effective management and restoration.

2. Methods

2.1. Study area description

Jialu River lies within the Huaihe River Catchment, listed among the seven largest rivers in China (Wang et al., 2003). Jialu River is one of the most seriously polluted branches of Huaihe River. It is 256 km long with basin area of 5896 km^2, and flowing through several major cities (Fig. 1). Due to excessive economic development and rapid urbanization and industrialization, the natural baseflow in Jialu River has been greatly diminished, but received massive discharge of urbanized and agricultural wastewater instead. From 1996 to 1999, the amount of treated and untreated sewage from the alongshore cities, towns and villages were estimated to be $25{,}124 \times 10^4$ t per year (Xiao et al., 1999). As a result, the water quality of Jialu River has been strongly degraded: the concentrations of NH_4-N in surface water of Zhengzhou section, varied from 25.8 to 87.8 mg L^{-1} with the average concentration of 63.9 mg L^{-1} in the year 2007, much worse than Grade V level of national standard surface water criteria (2.0 mg L^{-1}) (Tan and Liu 2011; Wang et al., 2012). Jialu River, however, still serves as an important drinking water reservoir for cities or villages it flows through. For example, Jiangang reservoir, located at the upstream of Jialu River, is the major drinking water source for nearly 8.0 million people. The biodiversity loss is another problem in Jialu River Basin. Varieties of aquatic plants species growing along the stream have been dramatically reduced, and replaced by a few high tolerance species such as *alligator alternenthera* and *phragmites*.

2.2. Sampling and field surveys

The sampling and field surveys were performed in August–September of 2009 and 2011, a period with moderate temperatures and base flow conditions. The 19 sampling sites originally based on a probabilistic sampling design are shown in Fig. 1. They were randomly selected but slightly adjusted depending on access along the Jialu River. At these sampling sites, measures of water quality, stream physical and hydrologic characteristics, in-stream habitat, and macroinvertebrate assemblage composition were conducted.

2.3. Water quality measurements

Triplicate water samples (left, middle, right) were collected in each sampling sections, and then filtered (0.45 μm pore Millipore nitrocellulose membrane) into 250 ml clean bottles respectively. All samples were stored in −4 °C no more than one week until being analyzed. Water quality values, including ammonium (NH_4-N), total phosphate (TP), total nitrogen (TN), nitrite (NO_3-N), soluble reactive phosphate (SRP), total organic carbon (TOC), and permanganate index (COD_{Mn}), were determined in the laboratory following the methods proposed by State Environmental Protection Administration of China (2002). Transparency was measured in field with a Secchi disk. Water temperature and pH were measured