

A method for estimating watershed restoration feasibility under different treatment levels

Jian Zhang, Yi-Cheng Fu, Wan-Li Shi and Wen-Xian Guo

ABSTRACT

The restoration of watershed health can be influenced by ecological, technical and socio-economic factors. The paper presents a conceptual framework and typology to assess watershed ecological restoration based on the properties and processes of sustainable watershed development. According to multiple life stages, habitat properties and existing legal frameworks and applicable valuation approaches, the bio-indicator that integrates natural, political and socio-economic dimensions is proposed. With existing assessment results and official web-pages as references, evaluation systems concerning human impacts on aquatic systems are set forth. Suitable aquatic bio-indicators can standardize the monitoring methodology with respect to water quality, organic pollutants and pesticides, generation time, migration ability, saprobic status, taxonomic composition and diversity. A large number of fish-based indexes have been developed to monitor and manage river ecosystems. Biophysical and statistical models are being used to identify influential stream variables that correlate with macroinvertebrate indices. A probabilistic fuzzy hybrid model to assess river water quality is proposed. The method and process of ecological risk assessment are provided based on adaptive management principles. The environmental sustainability index (ESI) is used to estimate the degree of environmental restoration sustainability with the emergy triangle as a reference.

Key words | bio-indicators, ecological restoration, ecological risk assessment, ESI

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INTRODUCTION

Numerous rivers cease flow and dry up in the world with an increase of flow intermittency due to climate change and human activities. It is difficult to monitor and assess the ecological integrity of watersheds because we cannot determine the extent to which anthropogenic activities have changed the conventional indicators. Therefore, it is of significance to understand the ecological consequences of the flow intermittency of river systems (Datry *et al.* 2011). For temporary rivers, the content of environmental monitoring includes

surface waters, dry riverbeds, and hyporheic zones (Steward *et al.* 2011). The hyporheic zones of watersheds nourish substantial invertebrates beneath the dry and wet channels. Hyporheic invertebrates have long been indicators for estimating the health of temporary rivers, which is identical to the macroinvertebrate richness as indicators for overall river health. However, due to a lack of appreciation of the ecological interactions between surface and hyporheic ecosystems in most rivers, only a few cases have been made to include hyporheic invertebrates in river health assessments (Moldovan *et al.* 2013).

To assess the potential of hyporheic invertebrates in temporary rivers as ecological indicators for river health,

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Leigh *et al.* (2013) analyzed the factors influenced by geographical location, climate zone, sampling techniques and hydrological conditions, geographical region, and conditions of surface water and surface flow. Based on relevant research results, the lowest levels of within-group taxonomic resolution are used to standardize the invertebrate records. Patterns of variation in assemblage composition among the cases, as indicated by the ANOSIM analyses, were visualized using non-metric multi-dimensional scaling ordination.

Biotic integrity may be the best tool to assess the ecological health of hyporheic rivers. Fish communities were first applied to assess biological conditions in aquatic systems. In the IBI, metrics are scored in six qualitative classes from an absence of fish to excellent conditions (Karr 1981). In many parts of the world, biological condition has largely been used in conservation studies. Therefore, assessments at the ecosystem scale include several levels of biological organization. The restoration of freshwater habitats is essential to maintain ecosystem services, especially food and drinking water supply (Millennium Ecosystem Assessment 2005). The integration of standardized eco-indicators is useful in converting from current single species-based to holistic community-based restoration assessments. There are naturally complex interactions among ecological, technical and socio-economic factors. The change of impact factor depends on the complexity of biological organization

during restoration (Figure 1). Because of the high complexity of the goals and measures during river restoration, it is difficult to focus on a single universal factor to get successful restoration. Ecological restoration in terms of river value or improved services protection is not necessarily correlated with the improvement of river ecological function for aquatic species (Jähnig *et al.* 2011).

A feasibility study for the restoration of watershed ecosystems took a broad view. Potential solutions for watershed ecosystem health were conceptually designed, then tested for their performance using numerical simulation and analytical methods. To meet the restoration objectives in a cost-effective manner, we supplied relationships between ecological restoration and bio-indicators; identified potential restoration possibility by using ecological quality assessment and ecological risk assessment (ERA) and assessed eco-sustainable development using an environmental sustainability index (ESI) system that focuses on restoration feasibility and the potential to improve water quality, and wildlife habitat.

THE LEADING ROLE OF BIO-INDICATORS

Bio-indication and suitable indicators are feasible to detect the predominant factors driving successful restoration. To restore the ecological function of rivers, it is crucial to

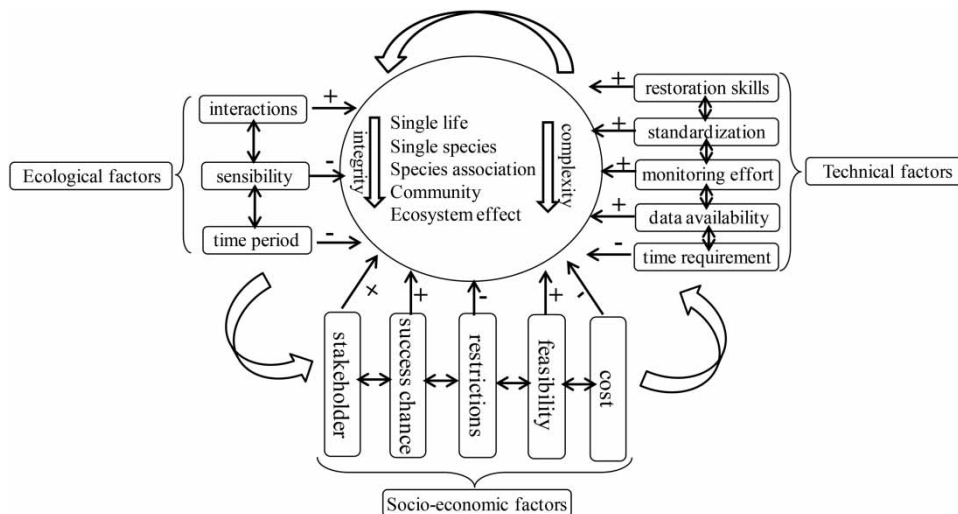


Figure 1 | Interactions among ecological, technical and socio-economic factors. The symbols '+' and '-' respectively indicate the increased and decreased impact on ecological health restoration.

detect the predominant factors driving successful restoration. Bio-indicators are useful for monitoring the effect of changing environmental conditions on surface water (Bellinger & Sigeo 2010). By analyzing the response of bio-indicators, the influence of potential stressors on ecological integrity can be deduced. Bio-indicators are easy and cost-effective tools for monitoring changes of environment and ecosystem integrity. At present, fish, invertebrates, macrophytes, and algae are commonly used to monitor changes in freshwater ecosystems (Friberg et al. 2011). The evaluation systems of human impacts on aquatic systems are listed in Table 1. These evaluation systems can be constructed by exposing target species to ambient conditions (Schubert 1991). In this context, the paper aims to analyze some of the theoretical aspects of bio-indicators and to provide a review on the use of aquatic indicators. This part evaluates the methodological applications and their advantages/disadvantages with respect to traditional surveying methods.

Aquatic indicator

Suitable aquatic bio-indicators can standardize the monitoring methodology in terms of water quality, organic

pollutants and pesticides, taxonomic composition and diversity. The aquatic indicator ranges from changes in physiology, behavior and morphology to survival and mortality. Therefore, factors for determining the status of river ecology should include composition, richness, tolerance, trophic measures, health condition, age structure, growth and recruitment of aquatic species. To assess the natural probability of an aquatic organism occurring in different river regions, the indicators are restricted by their applicability for eco-toxicological tests. Algae and macroinvertebrates are frequently used for such purpose. These organisms are useful in detecting the lethal effects of environmental pollutants or water quality (Connon et al. 2012). Number of species/individuals and distribution of individuals are important factors to demonstrate diversity. Therefore, all life stages (eggs, juveniles and adults) should be recorded to make high numbers and standardized quality available. The early life stages of salmonid fishes are sensitive to changes in water and substratum quality (Sternecker & Geist 2010). The incubation systems are adapted to bio-indication requirements, but the production of other potential bio-indicators is still a challenge.

As bio-indicators, the organisms should meet some basic criteria, i.e. relevance, reliability, viability, response and

Table 1 | The bio-indication assessment tools and indicators in water ecology of different water types

Indicator	Assessment tool	Topic	Literature
Freshwater fish	Index of Biological Integrity	Classification of river ecological status	Karr (1981)
	Fish-based evaluation system for running waters	Classification of river ecological status	Dußling et al. (2004)
	European Fish Index	Classification of river ecological status	FAME Consortium (2004)
	Fish Regions Index	Classification of river ecological status	Dußling et al. (2005)
Macro-invertebrates	Biological Monitoring Working Party	Organic pollution	Armitage et al. (1983)
	Ephemeroptera, Plecoptera, Trichoptera	Water quality	Lenat (1988)
	Species at Risk	Toxic pollution	Liess & Von Der Ohe (2005)
	Saprobic Index	Saprobic status of rivers	Meier et al. (2006)
	Macroinvertebrate-based evaluation system for running waters	Classification of river ecological status	Meier et al. (2006)
	Macroinvertebrate-based nutrient biotic index	Measure of nutrient enrichment	Smith et al. (2007)
Phytobenthos	Acidification Index Periphyton	River acidification	Schneider & Lindstrøm (2009)
	Periphyton Index of Trophic Status	Trophic status	Schneider & Lindstrøm (2011)
Macrophytes	Trophic Index of Macrophytes	Water quality, trophic status	Schneider & Melzer (2003)
Comprehensive indicators	Macrophyte and Phytobenthos	Classification of river ecological status	Schaumburg et al. (2006)
	Rapid Bioassessment Protocols	Classification of river ecological status	Barbour et al. (1999)

reproduction. The breeding of laboratory organisms and bioassays are more available and can be widely applied in industry. The products of detergent decomposition often contribute to a eutrophication of surface waters, and these changes on the phenotypic expression in developing organisms are observed. To predict the long-term ecological effects of toxic chemicals, the development of experimental embryology and its use in environmental bio-technology are both performed. There are many bio-tests available on the market. They are designed to assess the toxicity of water, wastewater and other chemical substances (Mazur *et al.* 2013). The aquatic plant communities were suggested as bio-indicators of nutrient availability in the surrounding water. Transplant experiments demonstrated that the growth and survival of *Potamogeton coloratus* Hornem were not significantly impaired by ammonium (NH₄) toxicity. High nitrate concentrations were shown to have a detrimental effect on *Littorella uniflora* (L.) Asch. (Robe & Griffiths 1994). The wide distribution of freshwater organisms means dispersal and lessened competition in aquatic habitats. Meiofauna is an important component of benthic communities in freshwater and has been increasingly explored during the last two decades. Meiofauna biodiversity in the stream consists of 58–82% of present species richness and contributes up to 44% of the annual mean biomass of invertebrates.

Ecological restoration

By exposing the indicator organisms to corresponding measurement units, the factors contributing to the status or performance of exposed organisms can be measured. Aquatic bio-indication is a system for assessing substratum quality and physicochemical variables in the interstitial zone of rivers. For example, the SEFLOB was more sensitive than chemical measurements in detecting water quality (Pander & Geist 2010). Therefore, the indicator system is an easy and cost-effective tool to evaluate the ecological function of watersheds. Fish species or macroinvertebrates are important indicator organisms in various biogeographic or ecological regions. In the context of reflecting the cryptic nature of hyporheic fauna, the potential for hyporheic invertebrates to act as indicators of health has been recognized. Biota are a potential eco-indicator of river health, and the choice of indicator(s) plays a major role in

monitoring or detecting changes in river health. The technical capacity and funding level of any assessment program will dictate the sampling methods, sampling efforts, taxonomic resolution and other identification protocols implemented (Lindenmayer *et al.* 2012).

Many fish-based indexes have been developed in the past decades to monitor and manage river ecosystems. Fish have been particularly identified as one of the best bio-indicators for evaluating aquatic health, because many fish have the features of wide distribution, intermediate life span, high fecundity, and early maturation as well as benthic habit. In most cases, river restoration does not follow a target-oriented procedure but is rather based on trial and error. The ecological restoration process is related not only with uncertainty or variability to random phenomena, but also with subjective uncertainty to conservationists, linguistics, and subjectivity. Therefore, the proceeding chain of restoration is a step-by-step complex procedure, which is the game among project managers, restoration experts and scientists (Figure 2).

ECOLOGICAL QUALITY ASSESSMENT

In rivers with poor species composition and richness, a genetic algorithm is proposed for evaluating ecological status and quality; biophysical and statistical models are also used to identify the variables that correlate with macroinvertebrate indices. The Soil and Water Assessment Tool (SWAT) model can be used to predict and assess the potential effects of different best management practices (BMPs) on watersheds. The reference condition for river ecosystem restoration activities can be predicted by species distribution models (SDMs). The natural fish assemblages and condition of the test river are then assessed as the ratio of observed to expected species (O/E) as was developed by the SDMs (Growth *et al.* 2013). Environmental variables may affect the distribution and ecological quality of the study objects. For example, environmental disturbance factors (dams and weirs) may have a substantial effect on fish communities through modified flow regimes, and cold-water pollution.

The integration of water quality monitoring variables is essential in the ecological quality assessment of watersheds. Parameter uncertainty is a major aspect of the model-based

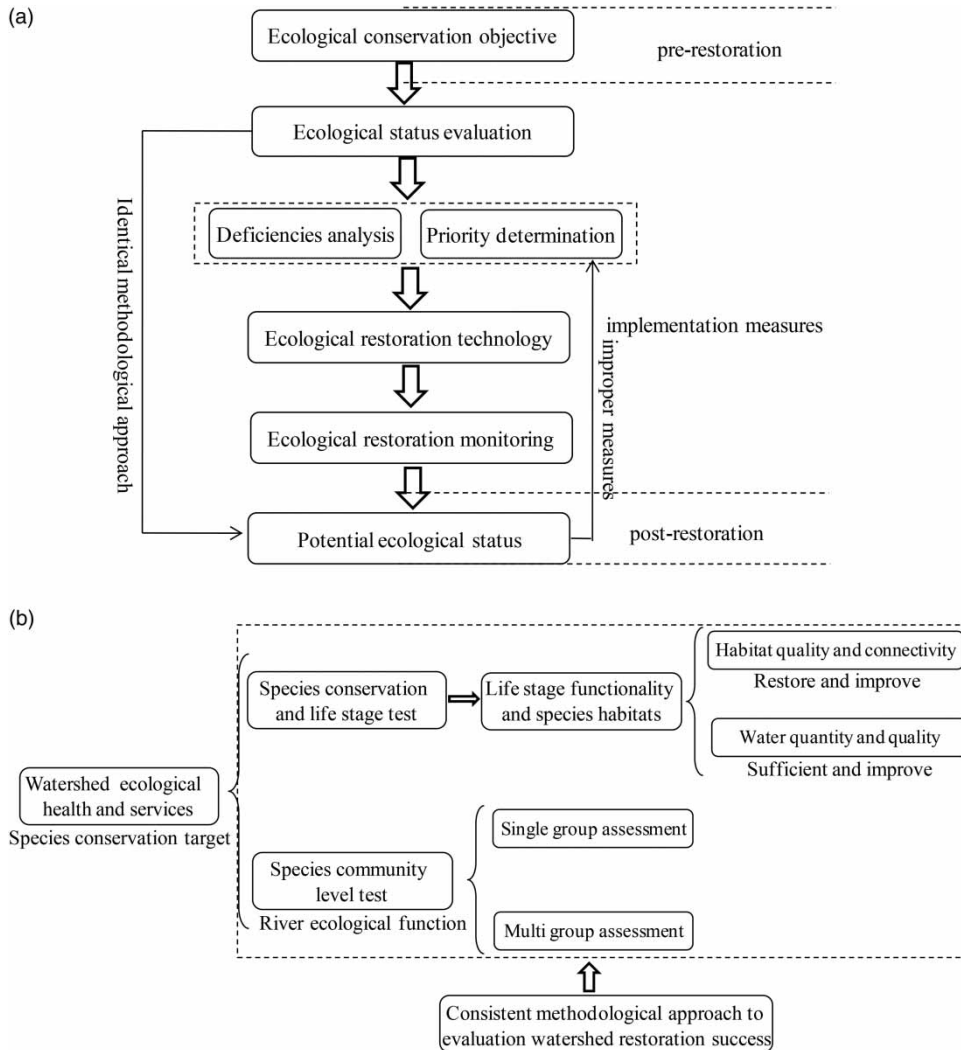


Figure 2 | The proceeding chain of river ecological restoration. (a) The systematic structures of the complex procedure. (b) The frame diagram of integrative control behavior for ecosystem restoration measures.

estimation of the risk of human exposure to pollutants. A probabilistic fuzzy hybrid model to assess river water quality can be proposed. The model has been used to propagate parameter uncertainties in risk analysis, which is an integration of fuzzy arithmetic at each α -cut and Monte Carlo algorithms (Kentel & Aral 2004). The equivalence fate model is written in terms of fuzzy arithmetic operations. The estimations based on concentration, probability and density of pollutant are applied using the kernel smoothing method (Ocampo-Duque *et al.* 2013). Fuzzy inference systems (FIS) have been used to evaluate multiple criteria related to water quality and other environmental conditions. Classical water quality indexes available

worldwide could be computed with the Monte Carlo methods. The FIS output is a fuzzy water quality (FWQ) index using the same indicators as those included in the well-known NSF-WQI and the ICAUCA. When the FWQ index is stochastically computed with the Monte Carlo method, we need a stochastic FWQ index to reflect the uncertainty of the random variables.

ERA

ERA is a process using existing information relevant to cause and effect to estimate the probability of predictive assessments.

The weight-of-evidence methods suggest a useful ERA strategy (Hope & Clarkson 2014). The ecological risk index values, enrichment factors and geoaccumulation indices (I-geo) can be used to estimate the concentrations of arsenic, cadmium, copper, mercury, and zinc along estuarine and coastal areas. Factors like abundance, species richness, and species composition of sessile invertebrate assemblages, including corals, are the focus for assessing the risk of loss and degradation of natural habitats and their biodiversity. Diatoms can be considered as effective indicators to estimate the ecological restoration risk of eco-regional rivers. Microevolutionary effects have been reported in the literature, and different types of microevolutionary effects or investigated eco-toxicological endpoints may influence the conclusions of the suggested comparative approach. Therefore, this suggests that microevolutionary effects on environmental risk assessments of freshwater environments do not need immediate consideration (De Coninck et al. 2014). The quality of watercourses can be influenced by meteorological conditions, and the regional changes of meteorological parameters can affect a diverse set of physical and biological systems in many parts.

ERA is a powerful analytical tool that allows objective comparison of the relative risk contributed by each specific 'threat' to the ecological structures being managed. The assessment process contains the management of natural resources through complete use of available information on potential environmental stressors, and through participative consultation with all stakeholders. So the ERA plays an important role in natural resource BMPs based on adaptive management principles (Figure 3).

The ERA process aims to draw together all the relevant information to identify and quantify the risks associated with the stressor, and provides environmental managers the means to consider scientific information along with other social, political and economic factors in BMP action. The ERA framework has been used effectively to test different management interventions and scenarios under risk assessment.

ASSESSMENT OF ECOLOGICAL SUSTAINABLE DEVELOPMENT

To realize the sustainable development of water ecology in watersheds, we use the energy triangle to infer the degree

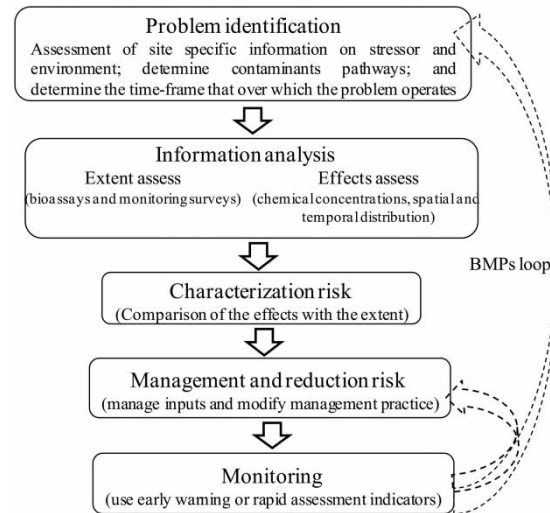


Figure 3 | The basic framework of the ERA process.

of environmental sustainability. R represents renewable resources, N means non-renewable resources and F represents the economic input of environmentally friendly production. ESI is the environmental sustainability index, and $ESI = [(R + N + F)/F]/[(N + F)/R]$. In short, the inputs of ecosystems are classified into three types: renewable resources in the watershed (R), nonrenewable resources in the watershed (N) and economic inputs of environmentally friendly production (F). F is provided by the market or economic flows. In Figure 4, the sustainability lines depart from

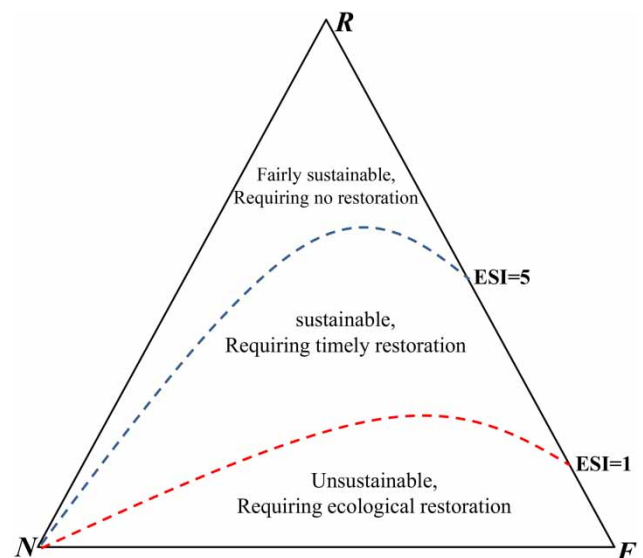


Figure 4 | A schematic diagram of the relationship between ESI and the implementation of eco-compensation.

the apex N which leads to the R and F lines allowing the division of the triangle into sustainability areas. This triangle is useful for the identification and comparison of the sustainability of products and processes. The upper part of the diagram represents the regions ($ESI > 5$) where systems are sustainable, the middle part represents the regions ($1 < ESI < 5$) in which the systems are sustainable for the medium term, and the lower part of the diagram represents the regions ($ESI < 1$) where systems are not sustainable (Almeida *et al.* 2007). The indicator sometimes neglects the role of local non-renewable resources (N). ESI takes both ecological and economic compatibility into account, which evaluates the sustainability of a process or system. The larger the ESI, the higher the sustainability of a system is. The parameters used in emergy calculation are provided in Table 2. For ESI, it would be more sustainable to exploit all the non-renewables in an area (for $N \rightarrow 1$, $ESI \rightarrow R/F$) than to have a relatively important but low amount of exogenous resources (F), so the indicator sometimes neglects the role of local non-renewable resources (N). However, depending on the viewpoint of efficiency, renewability and external inputs, ESI is more efficient (lower transformity) in the case of relatively lower non-renewable inputs (lower environmental loading ratio (ELR)) and higher emergy yield ratio (EYR).

The assessment of ecological sustainable development in a watershed is influenced by a wide range of issues within national and international settings, which may become complex when dealing with spatiotemporal and integrated issues. The framework for water ecological management and its influences in a watershed is shown in

Table 2 | Emergy calculation indices

Symbols	Descriptions	Equations
EYR	EYR: the ratio of the emergy of the output ($Y = R + N + F$) to the emergy of input (F).	$EYR = Y/F$
ELR	ELR: the ratio of non-renewable energy ($N + F$) to renewable energy (R). It is an indicator of the pressure on the ecosystem due to production activity.	$ELR = (N + F)/R$
ESI	ESI: to obtain the highest yield ratio at the lowest environmental loading.	$ESI = EYR/ELR$

Table 3 | Watershed ecology management influencing factors technical framework

Ecological management objectives	Governance measures	Correlation of indexes
Development of Restoration	Watershed strategy regulation	Coupling
Watershed Ecology	General rules of consideration	Coupling
	Responsibility definition	Coupling
	Pollution treatment plan	Coupling
	Water buffer area and ecology reserve program	Coupling
	Nutrient management	Coupling
	Prohibition action tax	Coupling
	Government investment grants	Coupling

Table 3. Based on the analyzing and modeling of actual and future availability and demands of watershed ecology, the optimal and sustainable management strategies of aquatic ecology by virtue of operative optimal control of the technical system are selected. Because of the inherent uncertainty in the future and the epistemic uncertainty of data and models, specific assessment approaches and planning strategies are required. The implementation of the BMPs for watershed ecology may have multiple benefits. Ecological sustainable assessment has been used to reduce or eliminate the costs resultant from pollution, which are also adaptive approaches for controlling and mitigating pollution from diffuse sources.

Feasibility and scientific validity are key preconditions to assess ecological restoration and integrity of a specific watershed. At present, a series of technically feasible practices have been performed in China, including payments for environmental services. The calculation of cost for watershed ecology restoration is necessary for ecological protection. An appropriate control standard for water quantity and quality is an effective reference for degraded aquatic ecology. Besides the technologically feasible methods, a scientifically valid approach should be based on the level of social feasibility. To supply necessary social commitments to restoration, a multivariate analysis is applied to calculate the costs for watershed ecology restoration in terms of cost effectiveness and the probability of exceeding the pollutant concentration limit. Watershed ecology restoration can effectively accelerate ecological protection progress and

facilitate ecosystem conservation, especially in watersheds with water shortages (Fu et al. 2012).

CONCLUSIONS

The paper presents a conceptual framework and typology to describe the assessment of watershed ecology restoration. The integration of the eco-indicators standardized for monitoring management practices and structures is a useful way. According to multiple life stages and habitat properties, the indicators that integrate natural, political and socio-economic dimensions are proposed. The ERA process aims to identify and quantify the risks associated with the stressor. We use the emergy triangle to infer the degree of environmental sustainability. The larger the ESI, the higher the sustainability of a system is.

The method selected to estimate watershed ecological restoration cost is critically important. Technical feasibility and scientific validity are necessary for alleviating ecological damage and supplying positive protection actions to river health assessment. Further research is required on hyporheic watersheds, where meteorological effects might be mixed with pollution due to human activities.

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