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A practical tool to support ecosystem-based management in a river ecosystem: a case study of the Yellow River in China

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Abstract

Ecosystem-based management (EBM) is widely applied in marine and coastal ecosystems. However, its implementation in river basins is limited. This limitation is attributed to the lack of practical tools, which combine the general principles of EBM and the unique features of river ecosystems, to provide information for policy-making. A method to support EBM in rivers is proposed in the present study. This method analyzes the ecosystem by quantifying multiple relationships among natural and human components and considering the spatial heterogeneity in external activities and ecosystem resilience. Using this method, policies are prioritized in an EBM plan by systematically evaluating the effects of external activities on the ecosystem services. The application of this method in policy-making in the EBM context is presented in a case study using the Yellow River in China. As a practical tool, this method can help practitioners improve the implementation of EBM in river ecosystems.

Keywords: Coupled social-ecological model; Ecosystem-based management; River ecosystem; River management; Yellow River

Highlights

- Ecosystem-based management (EBM) is widely applied in marine and coastal ecosystems. However, its implementation in river basins is limited. This limitation is attributed to the lack of practical tools, which combine the general principles of EBM and the unique features of river ecosystems, to provide information for policy-making. A method to support EBM in rivers is proposed in the present study. This method analyzes the ecosystem by quantifying

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multiple relationships among natural and human components and considering the spatial heterogeneity in external activities and ecosystem resilience. Using this method, policies are prioritized in an EBM plan by systematically evaluating the effects of external activities on the ecosystem services. The application of this method in policy-making in the EBM context is presented in a case study using the Yellow River in China. As a practical tool, this method can help practitioners improve the implementation of EBM in river ecosystems.

Introduction

The increase in human activities exerts multiple pressures that threaten sustainable ecosystem services (Alcamo, 2003). These problems have compelled policy-makers to adopt ecosystem-based management (EBM) (McLeod *et al.*, 2005). The increasing practices of EBM over the past decades (Pikitch *et al.*, 2004; Barbier *et al.*, 2008; Chan *et al.*, 2009) have evolved with distinguished principles which were different from conventional environmental management (Slocombe, 1998a; Babcock & Pikitch, 2004; Arkema *et al.*, 2006; Leslie & McLeod, 2007; Clarke & Jupiter, 2010; Altman *et al.*, 2011). First, EBM considers both natural and human-induced multiple external activities. Second, EBM focuses on both direct and indirect impacts on the ecosystem. Third, EBM acknowledges the interactions among natural and human components. Fourth, EBM promotes ecosystem services rather than a single species or an issue. Finally, EBM is concerned with the resilience of the ecosystem against certain effects.

In contrast to the practice of EBM in marine and coastal areas, the implementation of EBM in river ecosystems is rare and superficial (Liu *et al.*, 2008; Gurnell *et al.*, 2009; Zhao & Zhang, 2013; Burks-Copes & Kiker, 2014; Gilvear *et al.*, 2016). However, as an important part of aquatic ecosystems, rivers face the continuous degradation of their ecosystem services (Sparks, 1995; Han *et al.*, 2009). Consequently, the urgency of implementing EBM in river ecosystems is great (Craig *et al.*, 2008). There are many difficulties in implementing EBM in rivers, some of which are from political and institutional obstacles, but the most essential reason is lack of practical tools (Leslie & McLeod, 2007). Despite the development of some ecosystem models or ecological methods for river management (Vannote *et al.*, 1980; Nakamura, 2003; Prato, 2003; Helton *et al.*, 2010), they do not fully meet the principles of EBM. The great challenge is to develop a practical tool to promote the implementation of EBM in rivers, which depends on the general EBM principles and unique features of river ecosystems.

As an early attempt to introduce EBM principles into river management, the current study develops a method to systematically prioritize drivers and effects according to their importance and risk in the EBM context. This method quantifies the multiple relationships among natural and human components, indirect impacts, and spatial heterogeneity in external activities and ecosystem resilience. Using the Yellow River in China as a case study, this method is expected to help policy-makers implement EBM in river management.

Methodology and materials

Concepts and framework

Rivers are relatively unique from other aquatic ecosystems because they are asymmetric ecosystems with the ability to transport energy and materials to downstream directions (Alexander *et al.*, 2007).

Large rivers are split into a succession of river reaches, each of which endures the threats from upstream and creates threats to downstream (Thorp *et al.*, 2006). In addition, the spatial heterogeneity of the different river reaches is significant in terms of human activity, ecosystem structure, and ecosystem services (Walker *et al.*, 2004). Therefore, when introducing EBM principles into river management, the basic ecosystem unit needs to be outlined in the whole river basin by building a complete analysis chain with the spatial heterogeneity analysis, which has similar ecosystem indicators' results, border conditions and thresholds for further analysis.

The accessible ecological information is too limited to identify all the interactions among the external activities and ecosystems. Thus, the ecosystem is usually treated as a 'black box', with attention given to the main external activities that cause the changes in the ecosystem. The spatial heterogeneity in external activities and ecosystem resilience, which is the 'capacity of ecosystem to absorb disturbance and reorganize while undergoing change' (Fisher *et al.*, 2009), is usually ignored (Figure 1(a)), and the question of how a specific ecosystem service is affected by a specific activity still remains unsolved. Besides, ignoring the complex interactions within an ecosystem and its spatial heterogeneity can reduce the reliability of the assessment results.

To answer the question, the ecosystem is analyzed by building an analysis chain with the spatial heterogeneity (Figure 1(b)). First, a set of external activities produces a series of threats, which bring perturbations to some particular ecosystem elements. Then, the interactions within the ecosystem induce these perturbations to transmit one part to another, disturbing the original conditions. Finally, the ecosystem services, as the assessment endpoints that enable the evaluation of the ecosystem from an integral perspective (de Groot *et al.*, 2002; Carpenter *et al.*, 2009; Munns *et al.*, 2009), show corresponding changes. The relationships mentioned above are spatial-generic.

The concepts mentioned above can be simplified in the relationship of sources, stressors, ecosystem indicators, and ecosystem services (Figure 1(b)). *Sources* are the natural and human-induced activities that externally release one or more threats to the ecosystems. *Stressors* are the threats of chemical, physical, or biological entities that induce perturbations on the ecosystems. *Ecosystem indicators* are the biotic and abiotic elements. The process of the change of the sources, stressors and ecosystem indicators

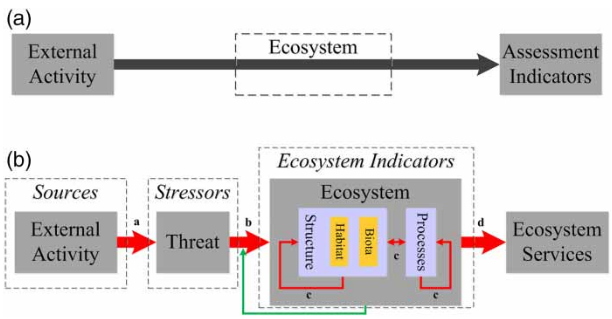

Fig 1. Different ways of linking external activity to ecosystem change. (a) Treating ecosystem as a 'black box'. (b) Considering interactions within the ecosystem and giving successive logic relationships on how external activities affect ecosystem services. (a–e) Five relationships in the framework. a: a set of external activities produces a series of threats; b: threats bring perturbations to some particular ecosystem elements; c: the complex interactions within the ecosystem induce these perturbations to transmit one part to another, disturbing the original conditions; d: the ecosystem services, provided by the components and processes, show corresponding changes; and e: the spatial-specific resilience of ecosystems translates the perturbations to spatial-specific effects of the ecosystem elements, which means the spatial-specific effects the threats on ecosystem elements are b + e.

causes the changes in the ecosystem services. Sources, stressors, ecosystem indicators, and ecosystem services are the model components in the present paper.

Quantification of relationships

According to the framework (Figure 1(b)), the total impact of the external activities on ecosystem services is resolved into a succession of relationships among or within the model components. Five relationships are involved: from sources to stressors, from stressors to ecosystem indicators, from ecosystem indicators to ecosystem indicators, from ecosystem indicators to ecosystem services, and from resilience of ecosystem indicators to stressors. A series of matrices are constructed to evaluate these relationships, which are abbreviated as SSM, SEM, AEM, EEM, and REM, respectively (Figure 2). The SEM, as an example to show the structure of these matrices, has t rows of stressors and e columns of ecosystem indicators, where the cell $SEM_{i,j}$ (i from 1 to t, and j from 1 to e) represents the relationship of a specific stressor and a specific ecosystem indicator.

The relationships fall into two categories: spatial-generic and spatial-specific. The former relationships include SSM, SEM, AEM, and EEM. A hierarchical scoring procedure is adopted to evaluate the strength of these spatial-generic relationships. The partial scores associated with several hierarchical criteria are added to determine the total relative score (Figure 3). The scoring criteria are hierarchical because of the variety of their influence on the total effect score. The spatial and temporal scales are considered as the scoring criteria, and are concerned with two levels of scale. The larger the spatial scale is, the stronger the relationship becomes. The relationship is considered strong if it occurs chronically, whereas it is considered weak if it is acute.

Resilience, in which the ecological status of the ecosystem is located, is related to the ecosystem indicator and stressor. A classification procedure is developed to evaluate the matrix of the REM. First, based on the ecological theories (Prato, 2003), the resilience of the ecosystem depends on its current status, which refers to the water quality and water quantity. Then, the statuses in different locations are ranked, and are assigned a score. The score indicates the condition. Second, the ecosystem indicators are classified into four categories, namely, habitat quality, habitat quantity, biota, and processes. The stressors are categorized into two parts, which are containment and habitat alteration. Third, the resilience of indicators is relative to the status of water quality, or water quantity, or both, as shown on the classification illustrated in Figure 4. Finally, the strength of resilience is evaluated as the score of water quality, or water quantity, or the product of both, according to the assumption in Figure 4. As the status of water quality and quantity in different locations is specific, the matrix of REM is also spatial-specific.

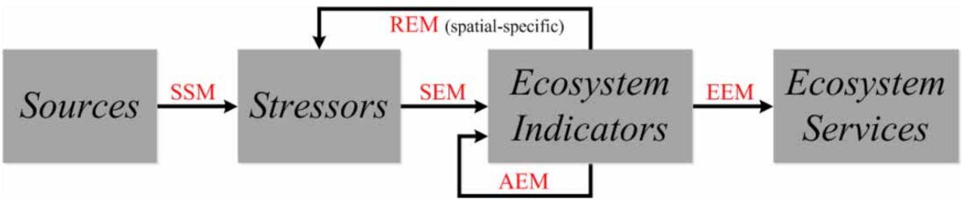

Fig. 2. Five matrices and their relationship with the four model components of sources, stressors, ecosystem indicator, and ecosystem services.

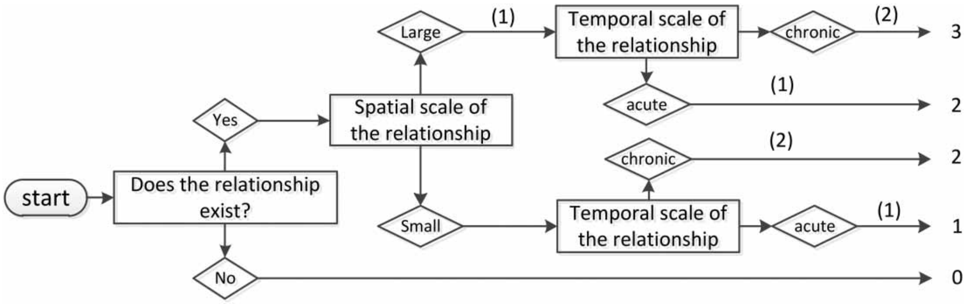

Fig. 3. Schematic diagram of the hierarchical scoring procedure evaluating scores between components. Responses to questions outlined in boxes provide partial scores (in parentheses), and are added to obtain the final effect score (outlined in text at the right).

REM		Ecosystem Indicators			
		Habitat Quality	Habitat Quantity	Biota	Processes
Stresors	Containment	A	B	A+B	A+B
	Habitat Alteration	A	B	A+B	A+B

A: spatial-specific status of water quality B: spatial-specific status of water quantity

Fig. 4. The resilience of indicators is relative to the status of water quality, or water quantity, or both.

Calculation procedure

As the river reach is the basic unit for analysis, the reach-specific intensity of the source is quantified. The ranking method is used to construct a source rank matrix (SRM) to evaluate the source intensity. SRM has r rows of sources and one column, where each cell represents the relative score of the specific source in that river reach. For example, the conditions of a specific source in the five river reaches are 38, 12, 42, 78, and 9, respectively. These numbers are ranked from largest to smallest, giving a proper data segmentation method to divide into three segments, which refers to 0–12, 12–42, and more than 42. Relative scores are assigned as 1, 2, and 3, respectively, for the segmentation. Therefore, the conditions of this source in each river reach are converted to rank scores, which are 2, 1, 2, 3, and 1, respectively in this example.

The complex interaction within the ecosystem causes numerous indirect impacts. For example, in a situation where A affects B, the direct effect of A on B is shown. The relationships A affects C and C affects B show the first indirect effect of A on B. Analogically, many indirect effects exist among ecosystem indicators. When the AEM expresses *direct* effect, it is assessed as a *complete* effect (*direct* and all *indirect*) by constructing a matrix of complete relationships among ecosystem indicators (CEM), presented as follows:

$$\mathrm{CEM} = \mathrm{AEM} + \mathrm{AEM}^2 + \mathrm{AEM}^3 + \cdots + \mathrm{AEM}^\infty \quad (1)$$

As AEM represents the direct effect, AEM^2 represents the first indirect effect, AEM^3 represents the second indirect effect, and so on. Therefore, CEM can represent the complete effect among ecosystem indicators.

Hence, the total effects of external activities on ecosystem services in a river reach can be expressed as follows:

$$\mathrm{FM}_i = \left[\left(\widehat{\mathrm{SRM}}_i \times \mathrm{SSM} \right) \times ((\mathrm{SEM} \cdot \mathrm{REM}_i) \times \mathrm{CEM}) \right] \times \mathrm{EEM} \quad (2)$$

where i represents the river reach; FM_i is a final matrix of river reach i with r rows of sources and s columns of ecosystem services. $\widehat{\mathrm{SRM}}$ denotes the diagonal matrix made by SRM. $\widehat{\mathrm{SRM}}_i \times \mathrm{SSM}$ represents the intensity of stressors introduced by sources in river reach i, $\mathrm{SEM} \cdot \mathrm{REM}$ stands for the reach-specific strength of perturbation induced by stressors on ecosystem indicators. $(\mathrm{SEM} \cdot \mathrm{REM}) \times \mathrm{CEM}$ is the complete effect of stressors on ecosystem indicators. EEM corresponds to the effects of the ecosystem indicators on ecosystem services. $A \cdot B$ means the inner product of matrix A and B, whereas $A \times B$ is the outer product of matrix A and B.

The matrix scores of FM can be analyzed to identify the sources of the strongest drivers of ecosystem change by adding the scores for each source across the column of FM. The ecosystem services that are most threatened in river reaches are derived by adding the scores for each ecosystem service across the rows of FM. This is expressed as follows:

$$a^i_{r\cdot} = \sum_{s=1}^{n} a^i_{rs} \quad a^i_{\cdot s} = \sum_{r=1}^{n} a^i_{rs} \quad (3)$$

where $a^i_{r\cdot}$ denotes the total score for a specific source r in river reach i, and $a^i_{\cdot s}$ denotes the total score for a specific ecosystem service s in river reach i.

The total score of a specific source r and the total score of a specific ecosystem service s from all reaches are added to prioritize the key elements to focus on the entire river. All the scores in the FM of a river reach can be added to obtain a total relative score, which is an integrated reach comparable value. This result illustrates the river reach that faces the higher risk of ecosystem change, and is expressed as follows:

$$a_r = \sum_{i=1}^{n} a^i_{r\cdot} \quad a_{\cdot s} = \sum_{i=1}^{n} a^i_{\cdot s} \quad (4)$$

$$a^i = \sum_{r=1}^{n} a^i_{i\cdot} \; or \; a^i = \sum_{s=1}^{n} a^i_{\cdot s} \quad (5)$$

where $a_r\cdot$ and $a_{\cdot s}$ denote the total score of a specific source r and a specific ecosystem service s, respectively, for the entire river, and a^i denotes the total score of river reach i.

Case study

The Yellow River is the second longest river in China. With a long history of development, the Yellow River faces increasingly serious ecological crises. Multiple threats and spatial heterogeneity in hydrology and economic development in the Yellow River necessitate the adoption of EBM. In the present work, the Yellow River is divided into seven river reaches (RR) according to the Second Watershed District, based on the Water Resources Zoning System of China (Figure 5).

The literature review is used to identify the sources and ecosystem services. Ten indicators of sources from three categories of climate change, socioeconomic system, and upper river are chosen. The stressors are consistent with the sources and contain eleven objectives. Meanwhile, ten ecosystem services have been identified based on a relevant literature review (Slocombe, 1998b; Alcamo, 2003; Nelson *et al.*, 2009).

The limited knowledge of the ecosystem makes the identification of ecosystem indicators difficult. Based on ecological theories, ecosystems are identified by two aspects: structure and processes. Structure is further divided into two parts: biota and habitat. The biota contains spatially heterogeneous species, thus making the selection of particular species as indicators improper. Hence, four systemic indicators are built. They are the stability of the primary producers, trophic level integrity, biodiversity, and species abundance, which reflect the multiple properties of biota. The habitat contains two properties, quality and stability. Quality consists of several traditional physical and chemical indices, and stability contains three indicators: abundance, connectivity, and hydrogeomorphic stability. The ecosystem services of the river are produced during the six processes. The objectives and their relationships are illustrated in Figure 6.

Results and discussion

Risk characterization

The FMs of each river reach in the Yellow River are calculated. The scores of each FM are added according to different sources and ecosystem services (see Table 1).

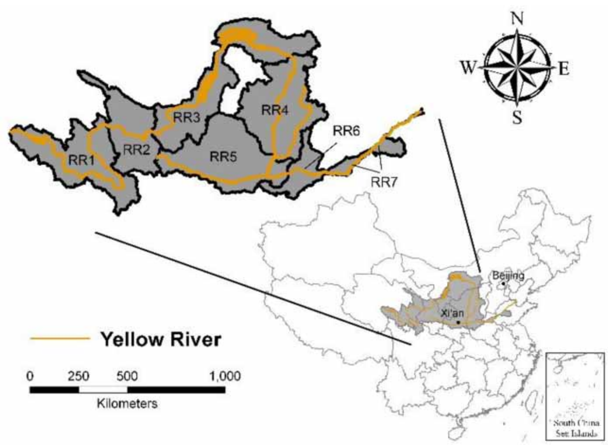

Fig. 5. Study areas and reaches of the Yellow River and its relationship with China.

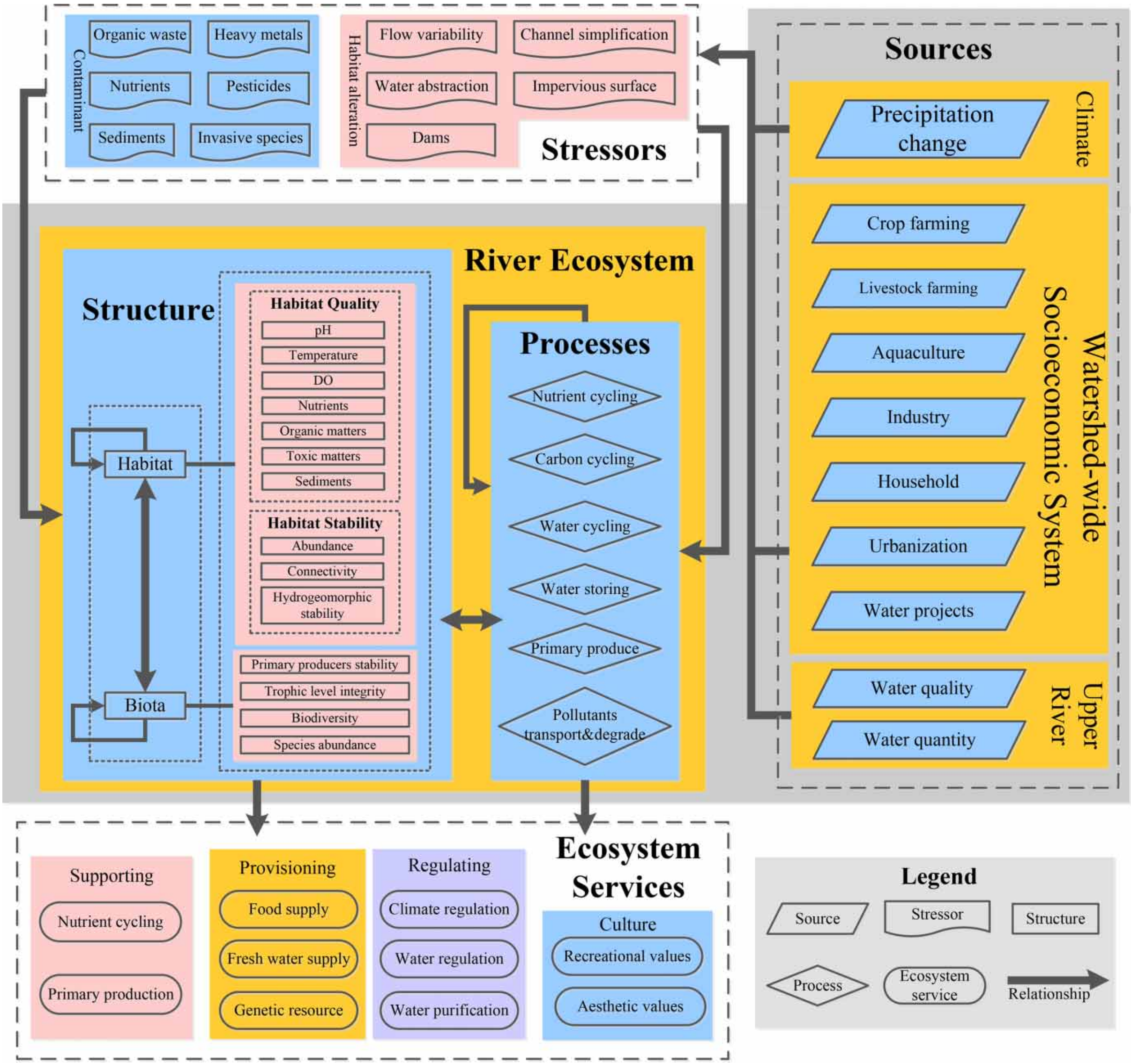

Fig. 6. The detailed components chosen in the case study of the Yellow River and their relationships.

The top three sources that are the strongest drivers of ecosystem change in the entire Yellow River are urbanization, upper river quality, and industry, followed by upper river quantity, crop farming, and precipitation change. The top three ecosystem services that experience the strongest effects are primary production, genetic resource, and water purification. The top three river reaches that face the highest risk of ecosystem changes are RR5, RR3, and RR6.

There are some similarities and differences between the key sources and ecosystem services in a specific river reach, as illustrated in RR5 and RR6. The top sources in RR5 are similar to those of

Table 1. Relative scores of sources and ecosystem services in each river reach.

Categories \ River reaches	RR1	RR2	RR3	RR4	RR5	RR6	RR7	Total per category
Precipitation change	7597	18,595	48,219	23,296	23,548	34,195	17,097	172,548
Crop farming	3576	6664	28,144	29,123	55,181	25,503	25,503	173,694
Livestock farming	2224	4204	27,535	12,564	36,519	16,720	16,720	116,487
Aquaculture	1759	3517	15,514	15,514	20,477	13,652	20,477	90,911
Industry	3239	5989	40,654	18,721	55,089	25,462	25,462	174,617
Household	2197	7809	16,829	11,872	33,652	15,935	15,935	104,228
Urbanization	4849	8366	53,830	25,701	72,010	34,669	34,669	234,093
Water projects	10,130	13,892	8729	7235	23,148	29,516	9839	102,488
Upper river quality	0	7001	31,149	31,149	41,297	41,297	27,531	179,425
Upper river quantity	0	5104	12,574	18,928	54,906	41,472	41,472	174,456
Nutrient cycling	3668	9884	39,613	26,287	57,179	35,569	31,340	203,540
Primary production	4166	11,257	45,279	30,094	65,386	40,542	35,827	232,550
Food supply	3292	8622	33,509	22,389	48,166	30,168	26,489	172,635
Fresh water supply	2982	5865	17,701	12,522	27,593	20,427	16,054	103,144
Genetic resource	5073	12,679	45,116	30,448	63,486	40,300	35,034	232,136
Climate regulation	1661	2573	5935	4649	10,256	9119	6509	40,702
Water regulation	2778	4358	10,006	7840	17,062	15,095	10,837	67,976
Water purification	5643	12,386	40,942	28,294	60,449	41,501	34,354	223,569
Recreational values	2952	6132	19,394	13,746	28,206	19,811	16,449	106,690
Aesthetic values	3357	7386	25,683	17,834	38,043	25,889	21,812	140,004
Total per river reach	35,572	81,141	283,178	19,4102	41,5827	278,421	234,706	

the entire river, whereas the precipitation change turns into a relatively weaker source in RR5. The sources belonging to the categories of the upper river are stronger than the other sources in RR6. Urbanization, industry, and crop farming, which are the strong sources of the entire river and RR5, are relatively weaker in RR6. The key ecosystem services that experience the strongest effects in RR5 and RR6 are the same as those of the entire river.

The results have several implications for river management in the EBM context. First, the results suggest that despite the many sources bringing threats to river ecosystems, as well as the many ecosystem services provided by the river, a few drivers are more important or at a higher risk than others. An EBM management framework in the river should specifically focus on these key natural and human components, and prioritize a systematic solution to the problem. Besides, the ecological risks of the river ecosystem from different spatial reaches in the same river are diverse. In the Yellow River, more attention should be given to the sources of urbanization, the upper river quality and quantity, industry, and crop farming, the ecosystem services of water purification, primary production, and genetic resources, and the reaches of RR5, RR3, and RR6.

Second, the results indicate that EBM plans in rivers should balance the whole river basin level and spatial-specific level, especially in large rivers. The climate, landscape, hydrogeology, and the socioeconomic development in different regions of a large river present significant heterogeneity. These spatial differentiations make the source intensity, ecosystem resilience, and ecosystem services provision spatial-specific. Some sources of ecosystem services, which are the key ones in one river reach, may be considered low priority for inclusion in another reach. Despite these specific factors, the water flow, energy flow, and information flow through the connectivity with the upper and lower reaches areas make the different reaches integrate into a whole system and the threats and the effects can transfer through the river corridor, which make the management plans more complicated. Hence, the prioritization and management procedures should be consistent with both the whole river basin and the spatial-specific features.

Third, we should adopt a system management idea in river management. The sources, influence pathway, and effects are diverse so the policy maker should consider all the potential factors and use a system management method for balance and trade-offs.

Fourth, monitoring should be considered in river management policy. According to the results, monitoring plays a crucial role in the support of effective EBM and rigorous monitoring could verify the theoretical results and evaluate effectiveness of the applied management actions. Monitoring can also provide invaluable knowledge which guides improvements in methodology and the practice of EMB. Hence, sufficient funds and a detailed monitoring program should be considered in river management policy.

Uncertainty analysis

Uncertainty analysis produces Monte Carlo distributions for each risk component. We use RR6 as the case in the uncertainty analysis process of each risk component. The results are shown in Figure 7. Based on the results of Figure 7, we can tell that the means of the distributions of each source and each ecosystem service are similar to the forecast results in Table 1, which means the uncertainty does not change the order of sources and ecosystem service. Besides, from Figure 7(b), the higher the mean of the distribution is, the larger the range between the minimum and maximum scores appears, which means the degrees of confidence in the ecosystem service with higher scores, such as primary production and genetic resource, are relatively lower.

These uncertainties may be caused by two factors: uncertainty in the method, and in the calculation procedure. The former is mostly of a qualitative nature arising from lack of the knowledge of the relationship within the complexity of ecosystems; the latter comes from poor data quality and misunderstanding of the relationship between risk components. Despite these uncertainties, the results are still useful to prioritize the key risk components in Yellow River ecosystem management.

Conclusion

The method introduced in the present research focuses on the magnitude and importance of multiple sources and ecosystem services, and provides a framework to prioritize the most important drivers of ecosystem change and the most risky ecosystem services in different reaches of the river ecosystem. This method can be tailored for various users at different spatial scales and different management demands. For environmental flow management, the ecosystem services can be simplified, which may be focused on the water quantity related indicators. For the restoration management in some rivers mainly influenced by human activities, the source can be emphasized on watershed-wide socioeconomic systems. All the factors of sources, ecosystem services, and ecosystem indicators could be adapted according to the data accuracy and management aspects.

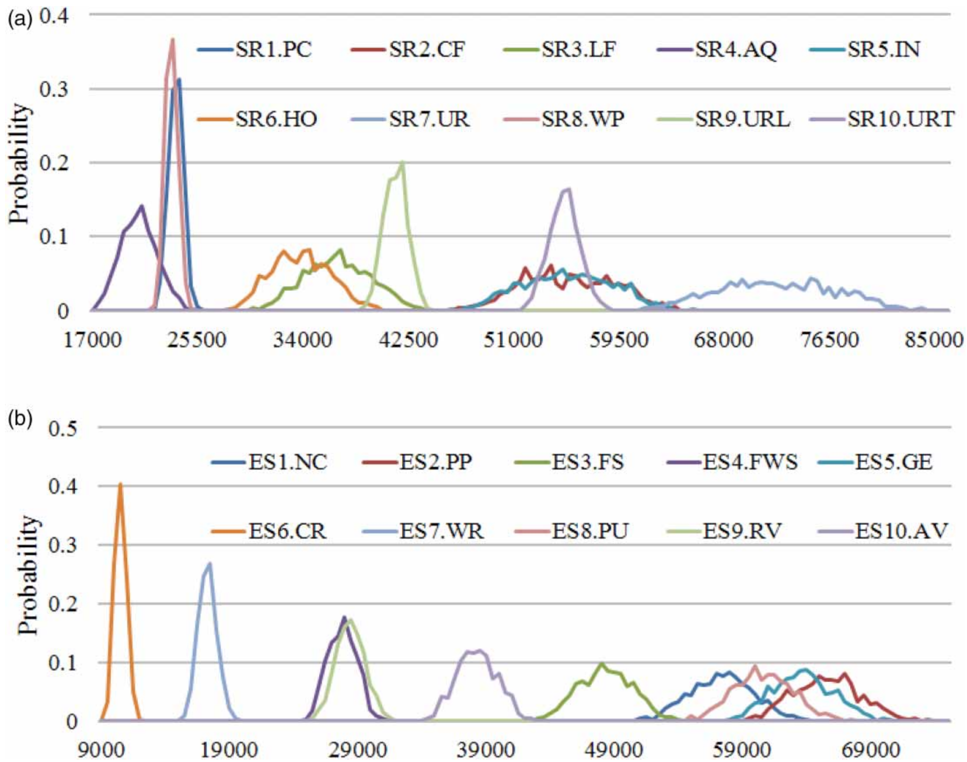

Fig. 7. Monte Carlo simulation distributions of RRS. (a) per source in RR6, (b) per ecosystem services in RR6.

However, the inadequacies of this method should be addressed. First, the quantification of ecosystem resilience is based on some assumptions. Most of them need to be validated along with the ongoing increase of ecological knowledge. Second, the effect strength of one on another is evaluated by a relative score, rather than experimental data. The uncertainties in these scores require the method equipped with analysis, testing, and validation in the future.

The implementation of EBM in rivers should address political, institutional and some other obstacles (Slocombe, 1998a, 1998b). First, the data of the indicators used in this method are from many different departments, the data year, accuracy, and availability may be hugely different from different sources, which make the reliability of the results much lower in some circumstances. Second, in some countries, such as China, the river basin management authorities are usually in the hands of the local governments, which only care for the river reaches within their own jurisdictions, and sometimes it is hard to coordinate with upper and lower reaches within different administrative areas. Third, insufficient funds and myopic guiding thoughts have always made river management eager for quick success and instant benefits, which is against EBM ideals. However, the solutions to these obstacles are not considered in the method. Moreover, the limited implementation of EBM at present cannot reveal a comprehensive picture of the EBM framework in a river. Therefore, the method and operational framework of EBM in river ecosystems should be developed along with its practice.

Despite these obstacles, the implementation of EBM in river ecosystems is moving forward. In this context, the method developed in the present paper is just a trial of the first step, which can serve as a practical tool for practitioners in the field of river EBM. Future research and practices could focus on reducing the uncertainties, especially on how the river ecosystem functions and changes under the outer and inner threats. Besides, how to apply this method under a specific institutional environment should also be considered. Anyhow, the method can help practitioners with better implementation of EBM in river ecosystems, meanwhile incorporating more ecosystem-level thinking into river management.

Data availability statement

All relevant data are included in the paper or its Supplementary Information.

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