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Input-output model based ecological risk assessment for ecological risk management of watersheds: a case study in the Taihu Lake watershed, China

Jianchuan Qi[a], Nan Li[b], Ping Yang[a,*] and Bo Lai[a]

[a]*Department of Environmental Science and Engineering, School of Architecture and Environment, Sichuan University, Chengdu 610065, China*

**Corresponding author. E-mail: yping63@163.com*

[b]*School of Information Management, Beijing Information Science & Technology University, Beijing 100192, China*

Abstract

To achieve advanced watershed ecological management, policy-makers have struggled to predict ecological impacts for a long time. As a process of ecosystem analysis, ecological risk assessment (ERA) has been widely adopted to analyse the possibility of adverse ecological effects. ERA has developed from considering only a few indicators in an area to multiple sources and receptors in large-scope regions. However, the transfer of risk in large-scope regions caused by internal interaction has not been deeply analysed, especially in regions with complex internal interaction structures. This would lead to extensive management, where watershed-level policies may not be fit for some subregions, thus leading to limited management efficiency. In this study, we integrate an Input-Output (IO) model into the Relative Risk Model (RRM), and propose an IO model based ERA (IO-ERA) methodology, which would reveal the intensity of ecological risk caused by local sources, direct water flows and indirect transfers. An IO-ERA is conducted in Taihu Lake watershed as a case study, in which we could demonstrate that IO-ERA is capable of providing advanced insights of risk analysis in large-scope regions. The outcome of IO-ERA would support watershed administration to transfer from single standard regulation to diverse, dynamic and lean ecological risk management.

Keywords: Ecological risk assessment; Input-Output model; Relative Risk Model; Taihu Lake watershed; Water habitat risk; Watershed risk management

Introduction

With functional, stable, and identifiable natural boundaries, watersheds have been widely accepted as basic water management units for planning and policy-making (Bohn & Kershner, 2002). Present

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watershed management tends to focus on problems which have caused obvious bad influence. For example, the programmes of land retirement and 'Returning Cropland to Lake' are developed to control non-point source pollution and protect cropland, forest and wetland (Liu *et al.*, 2013; Xu *et al.*, 2016), which are serious ecological problems in corresponding regions. However, especially from an ecosystem perspective, there is always a lag time between the adoption of policy and the improvement of the ecosystem (Meals *et al.*, 2010). The predictive analysis approach to the watershed ecosystem has been exploited to prepare the authority for upcoming ecological risk in advance (Summers *et al.*, 2015; Bennetsen *et al.*, 2016). Watershed ecosystem management would be enhanced if policies were developed considering possible risk, which would reduce adverse effects or even prevent a problem from happening.

Ecological risk assessment (ERA) is a process that evaluates the likelihood that adverse ecological effects may occur or are occurring as a result of exposure to one or many stressors, which are human-induced and undesirable (United States Environmental Protection Agency, 1998). Traditional ERA focused more on the impact of a single stressor to a single receptor, but this approach was limited in revealing the ecological risk of the entire ecosystem. The application of ERA was expanded to large-scale and holistic ecosystems during the 1990s, when researchers started to focus on ecosystem-level risk.

The major challenge to achieving large-scale ecosystem-level ERA is the description of the complex ecosystem which contains multiple stressors and receptors. Landis and Wiegers built the Relative Risk Model (RRM) to solve the problem of regional ERA at spatial scales (Landis & Wiegers, 1997). RRM would divide the region (watershed) into subregions and assess the relative risk states of all the subregions. RRM incorporates multiple sources and stressors, multiple receptors and multiple endpoints of a large-scale ecosystem into the ERA process, and could be used in various scopes of environments. Regional ERA with RRM claims that sources release stressors to the habitat, and impacts may occur if the habitat is ecologically disturbed (Landis & Wiegers, 1997). It has been used in ERA of various types of regions, including river watershed (Chen *et al.*, 2012), bay area (Yu *et al.*, 2015), etc. At the largest scope, an (ERA) of all the freshwater ecosystems in China was conducted with RRM (Zhao & Zhang, 2013a).

These ERA practices with RRM, mentioned above, focused on sources and stressors in the subregions, which is successful for the risk caused by local sources. However, ecological risk of one subregion caused by other subregions has not been paid much attention. The neglect of inter-subregional connection would result in uncomprehensive source identification, especially on the occasions where water was regarded as a habitat, as upstream water would influence downstream through water connections (Alexander *et al.*, 2007). Inter-subregional sources were identified and calculated in ERA of Yellow River watershed (Zhao, 2012) and Haihe River basin estuary area (Chen *et al.*, 2012) of China. Results showed that inter-subregional sources contributed significantly to the ecological risks of downstream subregions.

However, it is relatively explicit to calculate risk caused by upperstream subregions for a river watershed, as generally there are only a few up-downstream relationships among subregions. For more complex situations (e.g. a lake watershed), there may be a comprehensive inter-connecting network consisting of multiple subregions connected with lakes and rivers. It is difficult to identify the up-downstream relationships, as one subregion may be simultaneously both the upstream subregion of some subregions and the downstream one of others. This structure shows a feature of networks, in which the exposure of water habitat may transfer through water flows. In this article, we analysed the process of regional network transfer of water habitat exposure and developed an Input-Output (IO) model based ERA (IO-ERA) method, to conduct ERA of the water habitat in regions with a complex network of exposure transfer. IO-ERA could be an important analytical tool in evaluating regional ecological exposure and risk in the situations where there is a complex network of water flows, such that internal transfer is a critical source of ecological risk.

Methods

Inter-subregional risk model of water habitat

Definition of ecological risk in IO-ERA. RRM defines exposure and effect as the interaction between source, habitat and impact, and exposure represents the effect on habitat from source (Landis & Wiegers, 1997). Definition of risk in RRM is adopted in IO-ERA, which is demonstrated as Equation (1).

$$\text{risk} = \text{exposure} \times \text{effect} \tag{1}$$

Exposure refers to the intensity of stressors caused by sources, which is calculated with a Source Ranking Matrix and a Source-Stressor Filtering Matrix.

Effect is the result of the stressors' impact on habitat and endpoints. In addition, as part of a complex system, the components of the ecosystem would interact with each other, which makes the interaction among them an important factor (Altman *et al.*, 2010). In IO-ERA, we define Stressor-Habitat Filter Matrix, Inner-Habitat Filter Matrix, and Habitat-Endpoint Filter Matrix to represent the relationship between components. Habitat State Matrix is determined by the states of the habitat. The better state an indicator is in, the lower the risk is, as the ecosystem could endure more impacts.

Finally, the total risk could be calculated.

$$\text{risk} = \sum_{k,l,m,n} (\text{SRM}_k \times \text{SSFM}_{k,l} \times \text{SHFM}_{l,m} \times \text{HSM}_m \times \text{IHFM}_{m,m} \times \text{HEFM}_{m,n}) \tag{2}$$

where k represents the sources, l the stressors, m the habitat indicators and n the endpoints.

Inter-subregional exposure transfer and ecological risk. For a watershed, water flow from an upstream subregion could be regarded as a source to the downstream subregions (it may carry substances considered as stressors), and it may also be a stressor itself (flood, drought, etc.). These sorts of risk should be considered, therefore sources could be categorized into subregional sources (local sources of the subregion) and inter-subregional sources (Zhao, 2012).

Based on this categorization, the exposure of one subregion could also be categorized into subregional and inter-subregional. For one subregion, while the water habitat is exposed to subregional sources, it is also affected by water from upstream subregions. Meanwhile, if there are water flows from this subregion to other subregions, it would transfer ecological exposure downstream, which would consequently reduce the exposure of the water habitat in this subregion. In summary, the exposure of a water habitat is the sum of exposure caused by subregional sources and inter-subregional sources from upstream water, excluding exposure of inter-subregional source as upstream water (Figure 1). In a watershed with multiple subregions, the model could describe the process of exposure transfer with water flow, which forms the network structure of the region.

According to the model, the ecological risk of each subregion could be calculated.

$$\text{risk}_i = \left(ex_i^R + \sum_h ex_{h,i}^I - \sum_g ex_{i.g}^I \right) \times \text{effect} \tag{3}$$

Here $risk_i$ indicates the ecological risk of subregion i. ex_i indicates the ecological exposure of subregion i, while ex_i^R indicates the exposure caused by subregional sources. $\sum_h ex_{h,i}^I$ represents the inter-subregional exposure caused by all the upstream subregions h, while $\sum_g ex_{i,g}^I$ represents the inter-subregional exposure of subregions g caused by i.

IO model based ERA

Ecological risk IO table

An Input–Output Table (IOT) is an accounting framework which could be used to mimic the behaviour of a system. As the core of the IO model, the IOT represents the economic and material flows among sectors and is able to provide a systematic view of all activities in a region. The IO model has been introduced into network analysis in ecosystem-related modelling, which has been used as the approach to analyse the network structure and ecological relationships (Fath & Patten, 1999). In lake watershed ERA, subregions and water flow could be regarded as sectors and material flow, respectively. For one subregion, water flows from upstream subregions, the exposure increases (or decreases) by local sources, and then the water flows to downstream subregions (or remains in the subregion to cause ecological risk). This scenario has significant similarity with material flows among sectors. Thus with flows calculated with RRM, the integration of an IOT to ERA would clearly depict the relationships among subregions. The integration of an IOT with ERA would contribute to watershed or other regional management scenarios, as long as there are water flows within the area. An IOT would help ERA with the ability of analysing overall contribution of risk and inner relationships among subregions.

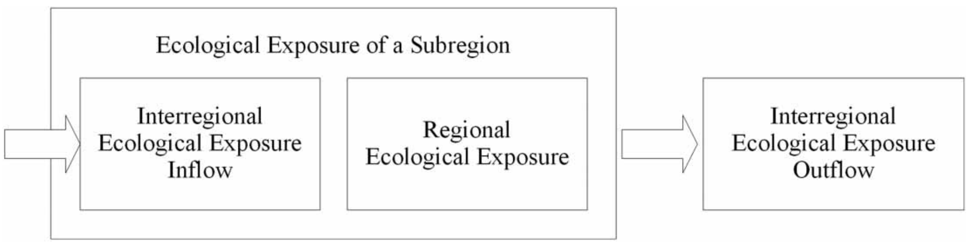


Fig. 1. Exposure transfer model of water habitat.

A major outcome of an IOT is the 'transaction matrix', which represents the inter-sector relationship. Thus, in IO-ERA the matrix would reveal the ecological risk of one subregion caused by others. An IOT divides economic activities into two parts of input and output, and uses the sector as the unit of analysis. The basis of any socio-economic activity is the flow among sectors. Similarly, in IO-ERA, the transfer could be divided into inflow and outflow of exposure, and subregions are regarded as sectors.

There are three quadrants in an IOT. An Ecological Risk Input-Output Table (ER-IOT) is built according to the structure. Introductions to each quadrant and their definitions in an ER-IOT are explained as follows.

The upper left zone in an IOT is the first quadrant, in which rows are categorized as intermediate inputs and columns as intermediate outputs. Data in this quadrant represent the intermediate inputs and outputs between sectors, in which data in each row represent inputs from the sector to others while data in each column represent outputs to this sector from others. In IO-ERA, we define that data in this quadrant represent the risk caused by intermediate inflows and outflows of exposure between subregions. Each row represents a subregion as upstream, and each column as downstream. Consequently, data in this quadrant of IO-ERA are the risk caused by inter-subregional exposure transfer from subregions in the rows to the ones in the columns.

The upper right zone in an IOT is the second quadrant representing the final demand of sectors in the rows of the table. Data in this quadrant demonstrate the final destination of a sector, taking possible items of destinations into consideration, including imports and exports. In IO-ERA, data in this quadrant represent the final destination of risk of the subregions in the rows. Exposure transfer with areas outside the watershed are defined as imports and exports in the second quadrant to describe the relationship of the water habitat between the object region and outside the watershed, which contributes to the calculation of final risk of the subregions, as there are also water flows between subregions and areas outside the watershed.

The left lower zone in an IOT is the third quadrant as the primary inputs of the sectors of the columns. This quadrant serves as demonstrating the origin of the sectors. In IO-ERA, the third quadrant is defined as the risk caused by subregional sources of a subregion, which is calculated with RRM which is similar to that applied in previous researches.

An ER-IOT of IO-ERA is demonstrated in Table 1, where $risk_{i,j}^{I}$ represents inter-subregional risk inflow from subregion i to j, $risk_{i}^{R}$ as subregional risk of subregion i, while $risk_{o,i}^{I}$ and $risk_{i,o}^{I}$ represents inter-subregional imported and exported risk, respectively. The column 'Final Risk' in the second quadrant is the final ecological risk of the water habitat in the subregion.

Three-dimensional ecological risk IO table

Assessment endpoints are an interpretation of the goals of ERA (United States Environmental Protection Agency, 1998), which makes them critical units of the final ERA result and analysis. Consequently, there is an ER-IOT for each endpoint with subregional and inter-subregional ecological risk. To integrate all ER-IOTs of the endpoints, a three-dimensional ecological risk IOT (3D-ER-IOT) is created to support risk calculation and analysis for each endpoint, inspired by the X-Y plane of the three-dimensional physical IO table (Xu & Zhang, 2007).

A 3D-ER-IOT is a three-dimensional model integrated by a series of two-dimensional ER-IOTs. Xu and Zhang regarded material as the third dimension to describe the material flow among sectors (Xu & Zhang, 2007). With subregions as sectors, assessment endpoints are regarded as the third dimension in 3D-ER-IOT, to describe the risk of each endpoint. The 3D-ER-IOT is illustrated in Figure 2, where the

Table 1. ER-IOT.

Inflow/ Outflow	Subregion 1	Subregion 2	…	Subregion i	IM	EX	Final Risk	Total Risk
S1	0	$\mathrm{risk}^{I}_{1,2}$	…	$\mathrm{risk}^{I}_{1,i}$	$risk^{I}_{o,1}$	$\mathrm{risk}^{I}_{1,o}$	$\mathrm{risk}^{R}_{1} + \sum_i \mathrm{risk}^{I}_{i,1} - \sum_i \mathrm{risk}^{I}_{1,i} + \mathrm{risk}^{I}_{o,1} - \mathrm{risk}^{I}_{1,o}$	$\mathrm{risk}^{R}_{1} + \sum_i \mathrm{risk}^{I}_{i,1}$
S2	$\mathrm{risk}^{I}_{2,1}$	0	…	$\mathrm{risk}^{I}_{2,i}$	$\mathrm{risk}^{I}_{o,2}$	$risk^{I}_{2,o}$	$\mathrm{risk}^{R}_{2} + \sum_i \mathrm{risk}^{I}_{i,2} - \sum_i \mathrm{risk}^{I}_{2,i} + \mathrm{risk}^{I}_{o,2} - \mathrm{risk}^{I}_{2,o}$	$\mathrm{risk}^{R}_{2} + \sum_i \mathrm{risk}^{I}_{i,2}$
…	…	…	0	…	…	…	…	…
Si	$\mathrm{risk}^{I}_{i,1}$	$\mathrm{risk}^{I}_{1,2}$	…	0	$\mathrm{risk}^{I}_{o,i}$	$\mathrm{risk}^{I}_{i,o}$	$\mathrm{risk}^{R}_{i} + \sum_i \mathrm{risk}^{I}_{i,i} - \sum_i \mathrm{risk}^{I}_{i,i} + \mathrm{risk}^{I}_{o,i} - \mathrm{risk}^{I}_{i,o}$	$\mathrm{risk}^{R}_{1} + \sum_i \mathrm{risk}^{I}_{i,i}$
Regional Risk	risk^{R}_{1}	risk^{R}_{2}	…	risk^{R}_{i}				
Total Risk	$\mathrm{risk}^{R}_{1} + \sum_i \mathrm{risk}^{I}_{i,1}$	$\mathrm{risk}^{R}_{2} + \sum_i \mathrm{risk}^{I}_{i,2}$	…	$\mathrm{risk}^{R}_{i} + \sum_i \mathrm{risk}^{I}_{i,i}$				

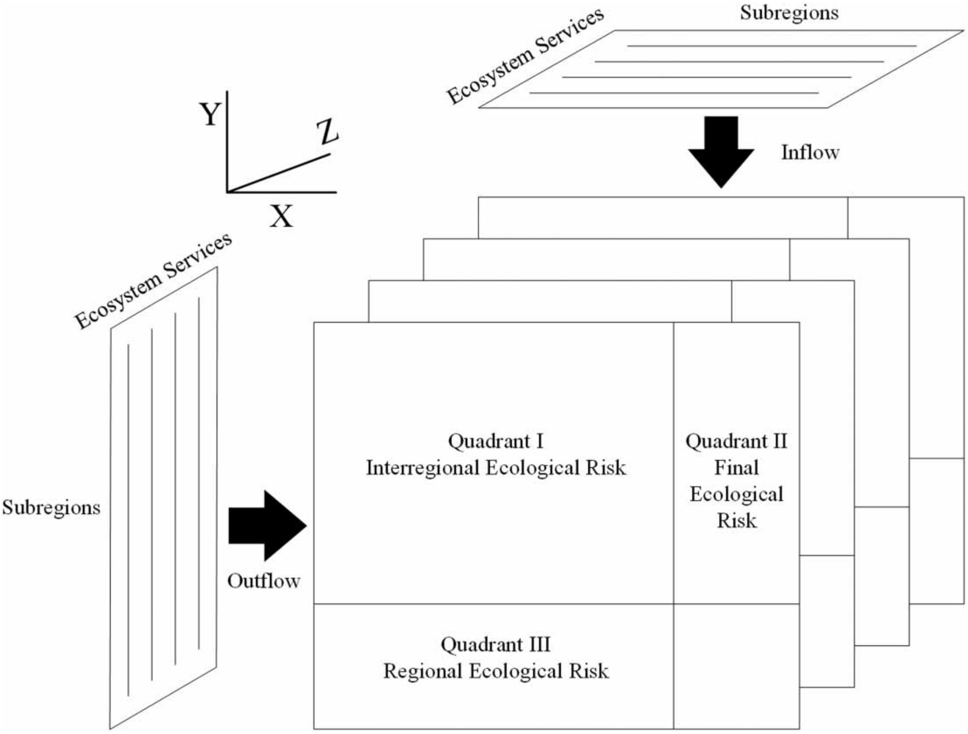


Fig. 2. Structure of 3D-ER-IOT.

X-axis represents the downstream subregions, the Y-axis represents the upstream subregions, and the Z-axis represents the assessment endpoints. Consequently, the X-Y plane is the ER-IOT, representing the subregional, inter-subregional and final ecological risk of one endpoint. The X-Z plane represents the output risk for one subregion as the upstream area of all the endpoints, while the Y-Z plane represents the input risk for one subregion as the downstream area of all the endpoints.

With 3D-ER-IOT, ecological risk for one subregion could be calculated.

$$\mathrm{risk}_i = \sum_n \left({}^n\mathrm{risk}_i^R + \sum_h {}^n\mathrm{risk}_{h,i}^I - \sum_g {}^n\mathrm{risk}_{i.g}^I \right) \tag{4}$$

Here n refers to the endpoints. $risk_i$ indicates the ecological risk of subregion i, while ${}^n risk_i^R$ indicates the risk of endpoint n caused by subregional sources. $\sum_h {}^n\mathrm{risk}_{h,i}^I$ represents the inter-subregional risk of endpoint n caused by all the upstream subregions h, while $\sum_g {}^n\mathrm{risk}_{i,g}^I$ represents the inter-subregional risk of endpoint n of subregions g caused by i.

Outcome of IO-ERA

Direct risk coefficients. Data in the first quadrant of the ER-IOT are all direct inter-subregional risks between subregions. Input and output between adjacent sectors are called direct input in IO models. The direct input coefficient, representing the strength of the connection between adjacent sectors, could be calculated with data of the first quadrant. Direct Risk Coefficients (DRC) could be calculated with the IO model. The DRC matrix A is as follows.

$$A = \begin{pmatrix} 0 & \text{risk}^I_{2,1}/\text{risk}^T_2 & \ldots & \text{risk}^I_{i,1}/\text{risk}^T_i \\ \text{risk}^I_{1,2}/\text{risk}^T_1 & 0 & \ldots & \text{risk}^I_{i,2}/\text{risk}^T_i \\ \ldots & \ldots & 0 & \ldots \\ \text{risk}^I_{1,i}/\text{risk}^T_1 & \text{risk}^I_{2,i}/\text{risk}^T_2 & \ldots & 0 \end{pmatrix} \quad (5)$$

Here $\text{risk}^I_{i,j}$ refers to inter-subregional risk from subregion i to$j$, while risk^T_i represents total risk of subregion i. A three-dimensional DRC table could be created to calculate the DRC for each endpoint.

Total risk coefficients. Total input in an IOT consists of direct input and indirect input. Indirect input represents the input between sectors through a third sector. Similarly, exposure brought into one subregion may be transferred into a third subregion. In this situation, the subregion may transfer exposure to both the adjacent and remote subregions. In the ER-IOT, we define the indirect inter-subregional risk between two subregions without direct water flow as the risk caused by exposure transfer through a third subregion. Consequently, we define the total risk as the sum of direct and indirect risk, and Total Risk Coefficients (TRC) would reflect the risk caused by exposure transfer within the entire watershed.

According to the formula for total input coefficients, TRC could be calculated.

$$B = (I - A)^{-1} - I \quad (6)$$

Here I is the identity matrix, and B represents the TRC matrix. A three-dimensional TRC table could be created to demonstrate the TRC for each endpoint.

Case study

Description of study region

Taihu Lake watershed is the third largest freshwater lake in China. It covers an area of 36,895 km^2 in east China, including 5,551 km^2 of surface water area and 120,000 km of rivers (National Development and Reform Commission *et al.*, 2013). Taihu Lake watershed is one of the most populated and developed areas of China, which also makes it a watershed with severe environmental pollution and ecological crisis. In this study, we choose Taihu Lake watershed as the object region of IO-ERA to assess the ecological risk of the watershed and to analyse the risk caused by exposure transfer among subregions within the watershed.

Various methods of subregion delimitation could be used in RRM and IO-ERA. As delimitation based on administrative boundaries may provide the most effective support to environmental management and policy-making (Jiao *et al.*, 2015), it is more practical in China because of the administration structure of the watershed. Taihu Lake watershed includes Jiangsu Province, Zhejiang Province and Shanghai, and its administration bureau is Taihu Basin Authority (TBA). Consequently, in this study, the region of Taihu Lake watershed is divided into 28 subregions based on administrative boundaries of county (or city, if there was no county level administration unit in the city) (Taihu Basin Authority, 2012a).

Description of risk components

Identification of risk components. Risk components in ERA include sources, stressors, habitats and endpoints.

Sources and stressors. Risk sources and stressors are identified based on previous studies of ecological risk. For subregional sources, 11 sources are selected and categorized into natural sources and socio-economic sources with expert judgement and literature review. For inter-subregional sources, Upstream Water Quantity with Quality (UQQ) and Upstream Flow Rate Change (UFR) are selected to describe the inter-subregional interaction. Selected sources are shown in Table 2. Stressors selected as being consistent with the sources, include COD, nutrients, heavy metals, organic pollutants, sediments, water abstraction, dams, agricultural inning, hydrological change and watercourse diversion.

Habitats. Water habitat is regarded as the habitat of this IO-ERA practice, including both surface water and ground water. In this study, we use Zhao's system to describe the water habitat of Taihu Lake watershed (Zhao, 2012). Table of properties and indicators for water habitat are shown in Table S1 in the supplementary material (available with the online version of this paper).

Endpoints. Ecosystem-level ERA regards the ecosystem as the target, so assessment endpoints should be a representation of the macroscopic ecosystem rather than single indicators or aspects. In this study,

Table 2. IO-ERA sources of risk.

Classification	Source	Criteria	Data Reference	
Subregional	Natural	Hydrologic change	Precipitation change rate (%)	[a]
		Soil erosion	Erosion area (hectare)	[b]
	Socio-economic	Industry	Industrial wastewater quantity (10^4 tons)	[a]
		Crop farming	Cultivated area (10^3 hectare)	[a]
		Livestock breeding	Domestic product (￥10^9)	[a]
		Aquaculture	Domestic product (￥10^9)	[a]
		Tourism	Tourists (10^4)	[a]
		Domestic waste water	Population (10^4)	[a]
		Shipping	Cargo (10^4 tons)	[a]
		Water projects	Water storage (10^9 m^3)	[a]
		Urbanization	Urban population proportion (%)	[a]
Inter-subregional		UQQ	Upstream water quantity (10^9 m^3) Upstream water quality	[c],[d],[e]
		UFR	UFR (%)	[f]

Data references: [a] Statistical yearbook of all subregions; [b] The first bulletin of water resources census of all subregions; [c] Taihu Basin and Southeast Rivers Water Resources Bulletin (Taihu Basin Authority, 2012a); [d] Annual Taihu Lake Water Regimen (Taihu Basin Authority, 2012b); [e] The Health Status Report of Taihu Lake (Taihu Basin Authority, 2012c); [f] China Water Resources Yearbook (Compilation Committee of China Water Resources Yearbook, 2013).

Ecosystem Services (ES) are selected as representative endpoints. ES have been utilized as endpoints of environmental analysis (Millennium Ecosystem Assessment, 2005), and used in ERA (Zhao & Zhang, 2013a, 2013b). With various categorizations of ES, we define the ES for the water habitat based on Millennium Ecosystem Assessment (MEA). ES defined are Provisioning Services (Food Supply, Fresh Water Supply, Genetic Resources and Biochemicals), Regulating Services (Climate Regulation, Water Regulation and Water Purification), Cultural Services (Recreation and Ecotourism, Aesthetic) and Supporting Services (Nutrient Cycling and Primary Production).

Ranking criteria of source, habitat and filter matrix. Conventional RRMs use data segmentation to rank data into nil, low, medium and high levels of intensity. However, we think that this segmentation would be insufficient in representing the relative intensity of sources among subregions due to the existence of range within one level. The min-max data normalization method is introduced to reduce the effect of range.

For ranking of habitat, we follow the ranking criteria of the system of aquatic ecosystem properties and indicators (Zhao, 2012), which rank the indicators of water habitat based on government standards of China and literature review, as Table S2 in the supplementary material shows (available with the online version of this paper). Ranks of the filter matrix, which represent the relationship of sources/stressors, stressors/indicators, and indicators/endpoints are determined with the research of Zhao (2012).

Data

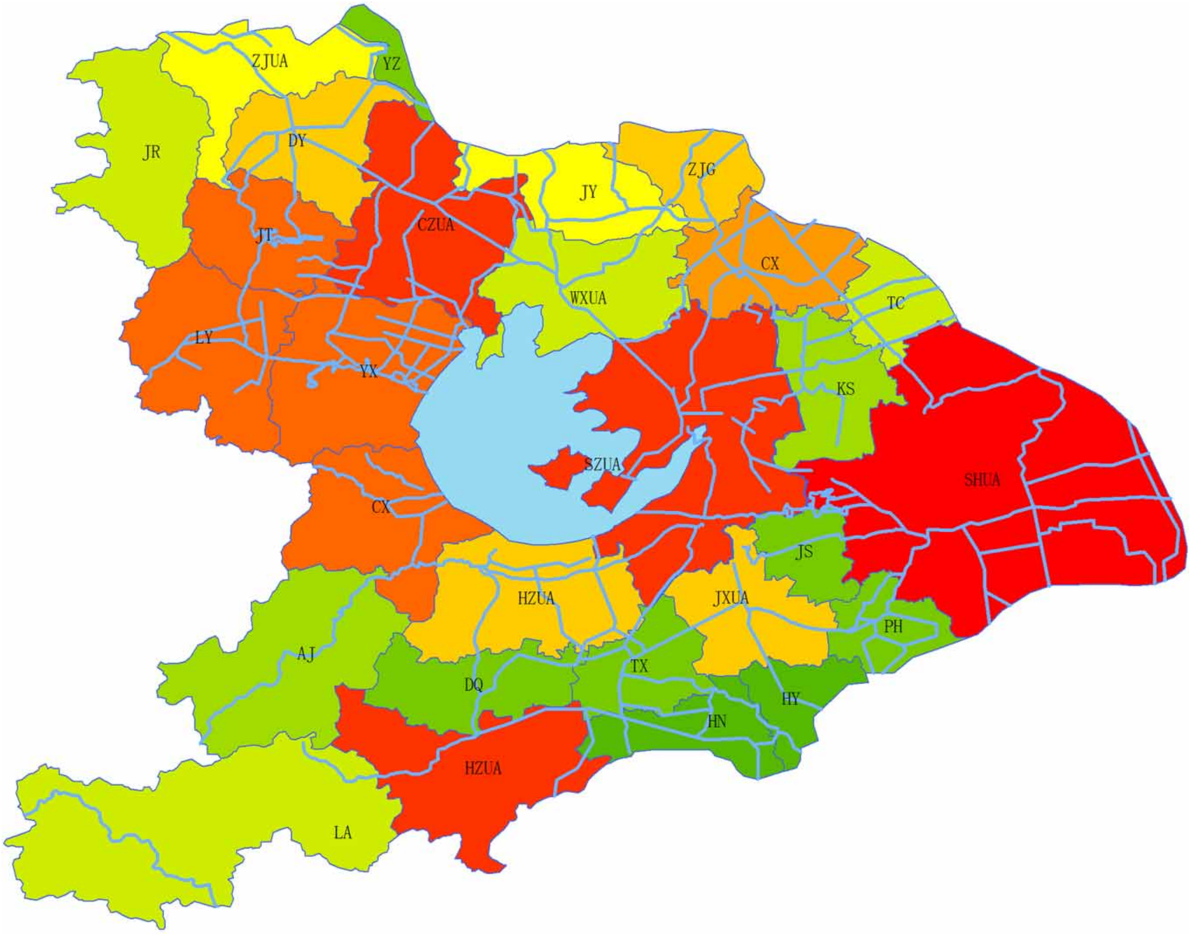
The year 2012 is defined as the time period of IO-ERA in the Taihu Lake watershed. Data used in this study include data of socio-economic activities, data of water habitat indicators and data of inter-subregional water quantity and quality. Data of socio-economic activities are obtained from the Statistical Yearbook and Bulletin of First National Census for Water of the cities in the watershed. Data of water habitat indicators are from the Environmental State Bulletin of the cities. Data from previous research about the indicators are also adopted if the data of the corresponding indicator are not included in the bulletins. Data of inter-subregional water quantity and quality are from the Taihu Basin and Southeast Rivers Water Resources Bulletin, Health Status Report of Taihu Lake and Annual Report of Hydrological Status in Taihu Basin, which are all reported by TBA.

Results and discussion

Subregional ecological risk by conventional RRM

The result of the subregional ecological risk is illustrated in Figure 3 and Table S3 in the supplementary material (available with the online version of this paper), which shows that the top five subregions with the highest subregional ecological risk are Shanghai urban area, Changzhou urban area, Hangzhou urban area, Suzhou urban area and Yixing. The top five subregions with the least subregional ecological risk are Haining, Haiyan, Pinghu, Jiashan and Deqing.

For subregional sources, domestic waste water, water projects, crop farming, urbanization and industry are comparatively important sources in the overall Taihu Lake watershed, contributing 18.28%, 17.76%, 11.60%, 10.03% and 9.80% of the Risk Score (RS), respectively. For endpoints, water



Haining: HN;	Huzhou Urban Area: HZUA;	Liyang: LY;	Changzhou Urban Area: CZUA;
Haiyan: HY;	Jiaxing Urban Area: JXUA;	Taicang: TC;	Danyang: DY;
Deqing: DQ;	Hangzhou Urban Area:HZUA;	Yixing: YX;	Lin'an: LA;
Tongxiang: TX;	Wuxi Urban Area: WXUA;	Changshu:CS;	Shanghai Urban Area: SHUA;
Pinghu: PH;	Changxing: CX;	Jintan: JT;	Jurong: JR;
Anji: AJ;	Kunshan: KS;	Jiangyin: JY;	Zhenjiang Urban Area: ZJUA;
Jiashan: JS;	Suzhou Urban Area: SZUA;	Zhangjiagang: ZJG;	Yangzhong: YZ

Fig. 3. Subregional ecological risk.

regulation, biochemicals and water purification are ES at the highest risk, with 24.82%, 15.57% and 13.92% of the RS, respectively.

This result shows that the urban area of the major cities in the watershed have the highest subregional risk, which is due to the pressure caused by rapid economic development, mainly from the large population and the activities to promote their living conditions. From an ecological services perspective, the ability to provide sufficient water regulation service is severely at risk, endangering the timing and magnitude of runoff, flooding and aquifer recharge. Risk of biochemicals refers to the ability of Taihu Lake watershed to provide biological materials derived from ecosystems, including medicines, biocides, food additives, etc. The results also show that the ability to purify fresh water is at risk, as the ecosystem could help with filtering and decomposing of organic wastes and pollutants.

Inter-subregional ecological risk by 3D-ER-IOT

ER-IOT for each endpoint. For each endpoint, water regulation, biochemicals and water purification are also ES at the highest risk, with 24.54%, 15.24% and 14.05% of the inter-subregional RS, respectively. There is one inter-subregional ER-IOT for each endpoint, which forms the complete 3D-ER-IOT. Table S4, Table S5 and Table S6 in the supplementary material (available with the online version of this paper) are three ER-IOT as subtables of 3D-ER-IOT.

These subtables show that for water regulation, biochemicals and water purification, Pinghu to Shanghai urban area, Jiashan to Shanghai urban area and Kunshan to Shanghai urban area have the highest inter-subregional RS. For the fourth highest RS, risk scores from Zhenjiang urban area to Danyang are high for endpoints of water regulation and biochemicals, while for water purification, Yixing and Wuxi urban area to Suzhou urban area have the most intense inter-subregional risk effect.

Total inter-subregional ER-IOT. Total inter-subregional ER-IOT is the sum of all subtables of 3D-ER-IOT. Table S7 in the supplementary material (available with the online version of this paper) shows the inter-subregional ecological risk in Taihu Lake watershed. Sixty-two inter-subregional ecological risks caused by exposure transfer between subregions with direct water flow are identified. Suzhou urban area and Shanghai urban area are the two subregions with the highest inflowing risk, while Suzhou urban area is the subregion with significant high outflowing risk. The top ten inter-subregional ecological risks caused by exposure transfer are from Pinghu to Shanghai urban area, Jiashan to Shanghai urban area, Kunshan to Shanghai urban area, Zhenjiang urban area to Danyang, Danyang to Jintan, Yixing to Suzhou urban area, Wuxi urban area to Suzhou urban area, Suzhou urban area to Changxing, Suzhou urban area to Jiaxing urban area, and Deqing to Tongxiang.

The high inflowing and outflowing risk in Suzhou urban area is mostly due to two reasons. One is that most of the area of Taihu Lake belongs to Suzhou urban area, which causes all the inflowing water to the Taihu Lake to bring risk to Suzhou urban area, and all the outflowing water from Taihu Lake is calculated as output from Suzhou urban area. Six inflowing and ten outflowing inter-subregional risks are identified in Suzhou urban area, which are all the highest numbers for a single subregion. The other reason is associated with the water quality and quantity. Taihu Lake water is graded as the worst quality grade, while the inflowing and outflowing quantity were in a high position in 2012, being 20% and 33.3% higher than 5 years previously (2007), respectively. The higher quantity with the worst quality makes Suzhou urban area a critical source to other subregions.

Shanghai urban area is the main outflow of Taihu Lake, with 189.6×10^9 m^3 of water inflowing from Taihu Lake (Taihu Basin Authority, 2012b). Inter-subregional risks from Pinghu to Shanghai urban area are through the complex network of rivers. Risks from Jiashan and Kunshan are all outflow from Taihu Lake, which are through Taipu River with rivers nearby, and Wusong River and Dianshan Lake with rivers nearby, respectively. Pinghu and Jiashan together input 70.1×10^9 m^3 of water to Shanghai urban area with low quality, which makes them two critical sources to Shanghai urban area.

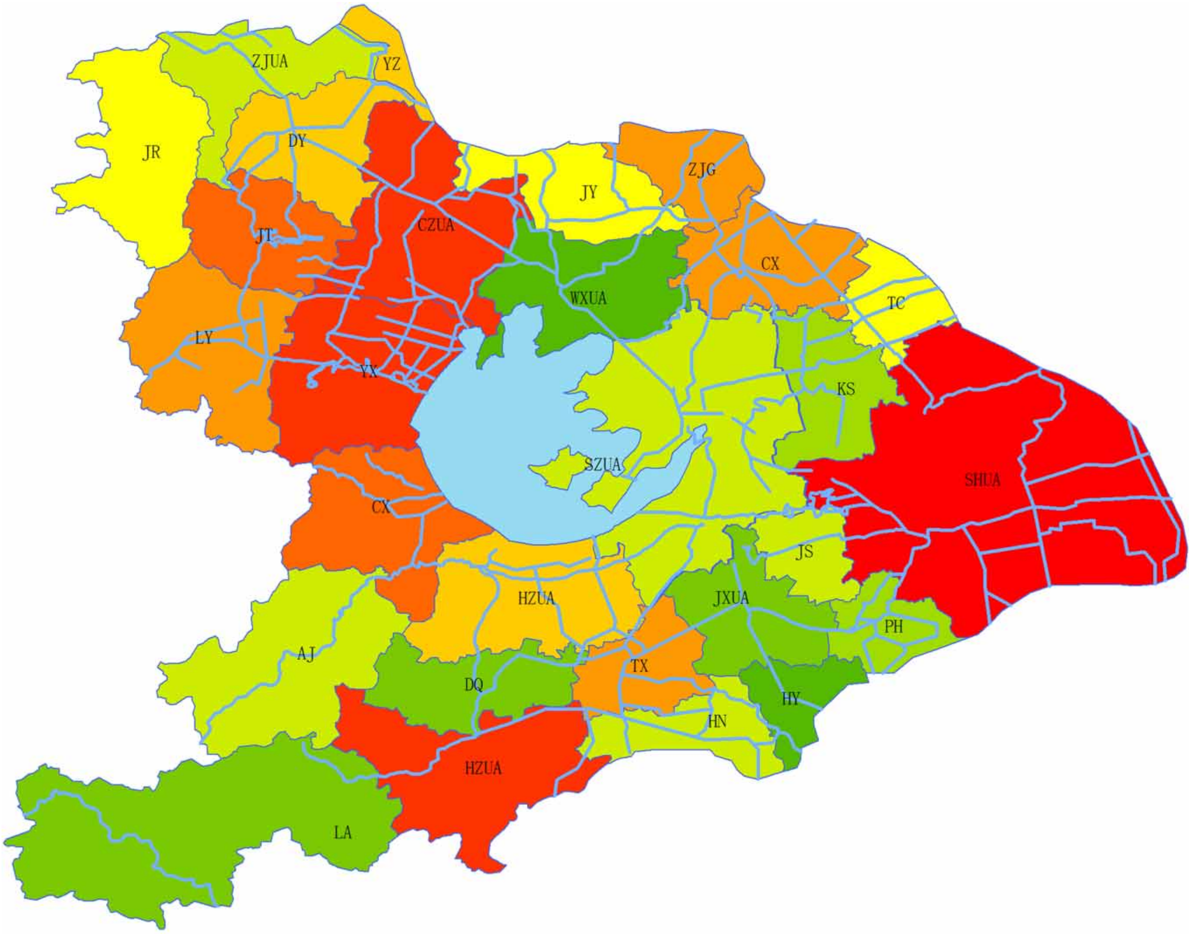
The insight of inter-subregional ecological risk is a critical outcome of IO-ERA, which would reveal the risk caused by inter-subregional water flow among all the subregions. This would help with understanding the relationship between subregions, and analysis of inter-subregional ecological risk would contribute to watershed risk management and decision support by identifying inter-subregional risk responsibilities.

Final ecological risk by IO-ERA

Final ecological risk integrates subregional and inter-subregional risk. As Table 3 shows, the top five subregions with the highest ecological risk are Shanghai urban area, Changzhou urban area, Yixing, Hangzhou urban area, and Changxing. The top five subregions with the least ecological risk are Haiyan, Wuxi urban area, Deqing, Jiaxin urban area and Lin'an. The result of the final ecological risk by IO-ERA is illustrated in Figure 4. If the adjustment by total RS of a subregion is positive, it could be concluded that this area is taking in inter-subregional risks, which increase the risk. If the adjustment is negative, it shows that the water flow may reduce the intensity of ecological risk in the subregion.

Table 3. Final ecological risk and inter-subregional adjustment.

Subregion	Final	Subregional	Inter-subregional Adjustment
Shanghai Urban Area	419,178	602,303	+43.69%
Changzhou Urban Area	287,655	290,449	+0.97%
Yixing	202,430	264,931	+30.88%
Hangzhou Urban Area	236,520	263,697	+11.49%
Changxing	189,136	213,787	+13.03%
Jintan	181,071	207,760	+14.74%
Danyang	149,548	192,467	+28.70%
Changshu	163,454	187,645	+14.80%
Liyang	179,748	184,948	+2.89%
Tongxiang	113,901	184,340	+61.84%
Zhangjiagang	150,584	173,334	+15.11%
Huzhou Urban Area	150,110	155,358	+3.50%
Taicang	137,768	139,263	+1.09%
Jurong	137,046	137,046	0.00%
Jiangyin	144,508	134,467	−6.95%
Yangzhong	114,880	124,612	+8.47%
Jiashan	107,178	117,175	+9.33%
Anji	122,262	112,172	−8.25%
Suzhou Urban Area	227,262	111,681	−50.86%
Haining	84,620	107,503	+27.04%
Zhenjiang Urban Area	146,722	99,195	−32.39%
Kunshan	121,108	95,467	−21.17%
Pinghu	104,610	91,184	−12.83%
Lin'an	130,361	82,099	−37.02%
Jiaxing Urban Area	154,722	81,741	−47.17%
Deqing	113,676	74,239	−34.69%
Wuxi Urban Area	138,844	57,706	−58.44%
Haiyan	95,455	56,626	−40.68%



Haining: HN;	Huzhou Urban Area: HZUA;	Liyang: LY;	Changzhou Urban Area: CZUA;
Haiyan: HY;	Jiaxing Urban Area: JXUA;	Taicang: TC;	Danyang: DY;
Deqing: DQ;	Hangzhou Urban Area:HZUA;	Yixing: YX;	Lin'an: LA;
Tongxiang: TX;	Wuxi Urban Area: WXUA;	Changshu:CS;	Shanghai Urban Area: SHUA;
Pinghu: PH;	Changxing: CX;	Jintan: JT;	Jurong: JR;
Anji: AJ;	Kunshan: KS;	Jiangyin: JY;	Zhenjiang Urban Area: ZJUA;
Jiashan: JS;	Suzhou Urban Area: SZUA;	Zhangjiagang: ZJG;	Yangzhong: YZ

Fig. 4. Final ecological risk.

Comparing subregional RS and final RS, the top five adjustments with inter-subregional ecological risk considered are Tongxiang, Wuxi urban area, Suzhou urban area, Jiaxing urban area and Shanghai urban area, which are +61.84%, −58.44%, −50.86%, −47.17% and +43.69%, respectively. The adjustment results are able to demonstrate the significant influence caused by inter-subregional water flow in these subregions. For example, Tongxiang, ranking 23rd in subregional ecological risk, 5th in inter-subregional ecological risk inflow and 22nd in outflow, becomes 9th in final ecological risk, because of the high RS of inflowing inter-subregional ecological risk. The results are able to demonstrate the actual ecological risk in the watershed, as IO-ERA has an enhanced capability for risk calculation taking inter-subregional flow into consideration.

TRC by IO-ERA

Table S8 in the supplementary material (available with the online version of this paper) reports the TRC of Taihu Lake watershed in IO-ERA, representing the risk caused by exposure transfer including both direct and indirect. A total of 221 TRC are revealed with two decimals kept, representing the connection between subregions. The top ten TRC are all risks caused by exposure transfer between adjacent subregions, which are Suzhou urban area to Jiashan (0.32), Suzhou urban area to Jiaxing (0.27), Jiaxing to Haiyan (0.26), Danyang to Yangzhong (0.25), Jiaxing to Pinghu (0.25), Danyang to Jintan (0.25), Deqing to Tongxiang (0.24), Suzhou urban area to Huzhou urban area (0.24), Suzhou urban area to Changxing (0.24) and Suzhou urban area to Kunshan (0.23). The difference between inter-subregional risks caused by exposure transfer and TRC is that inter-subregional transfer would identify the risk caused by inflowing water, while TRC may assist in analysing the origin of the inflowing risk. For example, the highest inter-subregional ecological risk caused by exposure transfer is from Pinghu to Shanghai urban area, but their TRC is only 0.12. This is explained by the 12 TRC revealed with Pinghu as the inflowing subregion, including a TRC of 0.25 from Jiaxing urban area. This reveals that although Pinghu is transferring a high level of risk to Shanghai urban area, Jiaxing is making a significant contribution, although Jiaxing and Shanghai urban area are not adjacent.

For TRC between subregions without direct water flow, 76 TRC between subregions without direct water flow are revealed. Suzhou urban area to Tongxiang (0.12), Suzhou urban area to itself (0.12), Jiaxing to Haining (0.07), Suzhou urban area to Haiyan (0.07), to Pinghu (0.07) and to Shanghai urban area (0.07) are relatively significant. TRC of one subregion to itself indicates that exposure transfer to other subregions would be transferred back with other inflows. Suzhou urban area, which is relatively high in TRC rankings, is influenced by Wuxi urban area (0.16), Yixing (0.14), Changshu (0.11) and Suzhou urban area itself (0.11). Inter-subregional ecological risk in Wuxi urban area is mainly from Suzhou urban area (0.14) and Yixing (0.12). Inter-subregional risk of Yixing is mainly from Suzhou urban area (0.16), Wuxi urban area (0.16) and Changzhou urban area (0.11), while that of Changshu is heavily influenced by Suzhou urban area (0.15), Wuxi urban area (0.15) and Zhangjiagang (0.13). It could be concluded that Suzhou urban area, Wuxi urban area and Yixing are the most influencing subregions to the entire watershed.

Implication of IO-ERA to lake watershed management

IO-ERA is capable of providing a more accurate result of ERA and revealing the relationships within an entire watershed. The application of IO-ERA in ecological risk management may provide new standpoints of management and explicit support of policy-making, especially in large scales of lake watersheds.

IO-ERA and ecological risk management. Connectivity of the network of water flow should be taken into consideration, as results of IO-ERA in Taihu Lake watershed show that inter-subregional water exchange could lead to a significant difference. From the perspective of risk control, for instance, IO-ERA demonstrates that the ecological risk of Tongxiang (+61.84%) may be underestimated and that of Wuxi urban area (−58.44%) may decrease due to inter-subregional water exchange. Consequently, with IO-ERA applied to ecological risk management, the results of ERA and related analysis would be more accurate and supportive for watershed ecological risk management.

By analysing the lake watershed from the system level, IO-ERA would promote ecological risk management to the new approach of Ecosystem-Based Management (EBM), which has been applied to various management scenarios. EBM regards the ecosystem as a whole, while it also acknowledges the complexity and interspecies relationship within the ecological system (Long *et al.*, 2015). Based on this, EBM allows coupled analysis of socio-economic activities and the ecosystem, which would provide more valuable results to support ecological risk management, as socio-economic activities are critical sources of ecological risk. IO-ERA would support the application of EBM in lake watersheds, where there are complex water flow networks.

Implication for policy-making in lake watershed management. IO-ERA would inspire a new level of elaborate management in lake watershed management by providing a tool to assess ecological risk from the optimization of both the watershed ecosystem and the subregions within it.

Firstly, watershed administration should value both subregional and inter-subregional ecological risk as important indicators of reference to support managerial decision-making. Ecological management, risk control and corresponding policy development should refer to subregional ecological risk, inter-subregional ecological risk and TRC to maximize the managerial effect on the watershed. Taking Suzhou urban area as an example, ecological management policy-making should consider the effect on adjacent subregions including Jiashan, Jiaxing, Huzhou urban area and remote ones like Tongxiang. The achievement of one subregion would not only contribute to its local ecosystem, but also benefit other subregions, and the entire watershed.

Secondly, a diverse and dynamic watershed management mode should be established instead of conventional ecological management of one single standard for a watershed. Policies considering subregional circumstances would help transfer the conventional management mode to lean ecological management. On the one hand, subregions with high ecological risk or critical influence to others could be identified and regarded prior to others. In this case, Suzhou urban area, together with Wuxi urban area, Yixing and Changshu, should be paid more attention in risk management to reduce ecological risk in the downstream area of Taihu Lake watershed. On the other hand, for each subregion, the focus of ecological management should be on controlling critical sources and restoring ES at risk.

Finally, a comprehensive consideration of the inter-subregional relationship of ecological risk would contribute to the macroscopic planning of the watershed management, which would result in an optimal solution for the watershed through collaborative regional management. Inter-subregional relationships within the watershed would support the analysis and decision of collaborative regional management, the core of which is to seek the holistic optimum by conducting diverse and dynamic management for each subregion. Regional management approaches have been exploited in countries like the United States (Rinkus *et al.*, 2016), and regions across countries in rivers of Europe (Pfeiffer & Leentvaar, 2013). In China, TBA has been established to manage Taihu Lake watershed. IO-ERA is able to assist in identifying features of the subregions and differences among them, which may support the socio-economic regulation management of the watershed.

Conclusions

In this study, an IO-ERA methodology has been developed on the basis of an ecological exposure transfer model. It is applied to ERA in Taihu Lake watershed, with both subregional and inter-subregional ecological risks assessed and analysed. IO-ERA is able to describe the exposure transfer in a network structure of water habitat from the ecosystem level. It could meet the requirements of water ecological management and policy-making in most large-scale regional water management situations.

With inter-subregional ecological risk taken into consideration, IO-ERA promoted the accuracy of conventional ERA results. Adjustments of risk assessment results, which could be significant according to the case study, would provide better evidence for watershed managerial policy-making. As IO-ERA results include both subregional and inter-subregional risk, water management policies both for watershed scale and for single subregions could be developed. Water policy-making would benefit from IO-ERA, as authorities may develop different policies for all subregions to achieve large-scale optimization. The outcome of IO-ERA would promote the watershed management to EBM and lean ecological management. Application of IO-ERA would support watershed administration to transfer from single standard regulation to diverse and dynamic ecological risk management.

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