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RESEARCH ARTICLE

Eco-environmental vulnerability assessment for large drinking water resource: a case study of Qiandao Lake Area, China

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Abstract The Qiandao Lake Area (QLA) is of great significance in terms of drinking water supply in East Coast China as well as a nationally renowned tourist attraction. A series of laws and regulations regarding the QLA environment have been enacted and implemented throughout the past decade with the aim of negating the harmful effects associated with expanding urbanization and industrialization. In this research, an assessment framework was developed to analyze the eco-environmental vulnerability of the QLA from 1990–2010 by integrating fuzzy analytic hierarchy process (FAHP) and geographical information systems (GIS) in an attempt to gain insights into the status quo of the QLA so as to review and evaluate the effectiveness of the related policies. After processing and analyzing the temporal and spatial variation of eco-environmental vulnerability and major environmental issues in the QLA, we found that the state of eco-environmental vulnerability of the QLA was acceptable, though a moderate deterioration was detected during the study period. Furthermore, analysis of the combination of vulnerability and water quality indicated that the water quality showed signs of declination, though the overall status remained satisfactory. It was hence concluded that the collective protection and treatment actions were effective over the study period, whereas immediately stricter measures would be required for protecting the drinking water quality from domestic sewage and industrial wastewater. Finally, the spatial variation of the eco-environmental vulnerability assessment also implied that specifically more targeted measures should be adopted in respective regions for long-term sustainable development of the QLA.

Keywords eco-environment, vulnerability assessment, drinking water source, fuzzy AHP, GIS, Qiandao Lake Area

1 Introduction

Water scarcity has been affecting China's food security, economic development, and quality of life for years, largely due to the insufficient and disproportionate distribution of water resources as well as deteriorating water quality (Zhu et al., 2001; Liu and Diamond, 2005; Chen et al., 2012). The Chinese government has given a lot of attention to water scarcity and has taken various measures to alleviate the crisis in recent years (SC, 2006; MWR, 2007). However, the severity of water shortages and degraded water quality still prevails and the problem has become more acute in many regions of northern and eastern China (Jiang, 2009). It is very important to be able to better address water resource issues and to provide practical and effective suggestions to authorities of various levels for mitigation of water scarcity.

The eco-environment plays a significant role in water purification and conservation, the evaluation of which provides useful information for further policy making (Popp et al., 2000; Eisele et al., 2003; Isidori et al., 2004). Therefore, assessment and analysis of the eco-environmental situation surrounding water bodies is significant for proper protection of the water quality and eco-environment (Li et al., 2009). Eco-environmental vulnerability assessment (EVA), as a new technique of environmental evaluation, has been rapidly developing recently, and has become a popular topic in the field of sustainability

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research as well as in environmental resources research (Villa and McLeod, 2002; Adger, 2006; Eakin and Luers, 2006; Ford et al., 2006). Studies of eco-environmental vulnerability (EV) help to grasp the eco-environmental characteristics and particular problems of a study area and formulate measures and policies.

Conducting an eco-environmental vulnerability study has been a big challenge in the absence of a unified theoretical and methodological system for an EVA . Many methods have been developed and employed in previous studies, such as the comprehensive evaluation method (Gowrie, 2005), the grey evaluation method (Yang et al., 2013) and the principal component analysis (PCA) method (Li et al., 2006), among which the analytic hierarchy process (AHP) is the most widely used method in ecological assessment studies (Mendoza and Prabhu, 2000; Li et al., 2007). However, the AHP is fatally limited by its imprecision due to the quantification of the decision maker's judgment with discrete values (Jessop, 2004; Li and Huang, 2009). The ways of human thinking may not be fully reflected by using AHP. Fuzzy AHP (FAHP), as an evolution of AHP, can better identify the ambiguity of appraisal by the use of fuzzy numbers instead of discrete numbers (Levy, 2005; Sadiq and Tesfamariam, 2009; Su et al., 2010), and thus can be more effective and appropriate for vulnerability assessment than AHP in practice. Numerous methods and applications of FAHP have been proposed in various investigations. Van Laarhoven and Pedrcyz (1983) initiated triangular fuzzy numbers to express the decision maker's opinion, which was the first application of fuzzy logic principle to AHP. Buckley (1985) first used trapezoidal fuzzy numbers alternatively. Chang (1996) applied triangular fuzzy numbers for pair-wise comparison and introduced the extent analysis for the integrated extent values of the pair-wise comparisons. Chou and Liang (2001) developed a fuzzy multi-criteria model for performance evaluation of shipping companies by integrating concepts of fuzzy set, entropy theory, and AHP. Enea and Piazza (2004) considered the constraints within FAHP, and proposed a constrained FAHP in project selection. Ertuğrul and Karakasoglu (2009) provided a framework utilizing both FAHP and TOPSIS methods for cement firm performance assessment. The FAHP method proposed by Li et al. (2009) and Su et al. (2010) was employed in this study.

Given the characteristics of the local eco-environment and the advantages of adopted FAHP method, this paper presents a case study of eco-environmental vulnerability assessment in the Qiandao Lake Area (QLA), China. In detail, our objectives were to: 1) develop a method integrating FAHP and GIS for assessment of eco-environmental vulnerability of a large drinking water source, 2) identify the main influential factors of eco-environmental vulnerability in the QLA, 3) characterize the temporal and spatial distributions and variations of eco-environmental vulnerability in this region from 1990–2010 and evaluate the effect of the protective policies in the past, 4) establish the relationship between eco-environmental vulnerability and water quality of Qiandao Lake, 5) provide decision makers a useful reference for better protection of Qiandao Lake.

2 Methodology

2.1 Study area

The QLA with complicated topography is located in Chun'an County, Hangzhou City, Zhejiang Province, China (Fig. 1), covering an area of 4,402.4 km^2. Low mountains and hills account for 80% of the total area, water areas accounts for 13.5%, and the rest are small basins and valleys (Guo et al., 2001). Characterized by subtropical monsoon climate, the region is warm and humid with plenty of rainfall, distinct seasons, and sufficient sunshine. The annual average temperature is 17°C, ranging from 5.8°C to 28.9°C, and the annual average precipitation is 1,430 mm.

Qiandao Lake is the largest artificial freshwater lake and the fifth largest reservoir in China, and serves as the most important drinking water source for Zhejiang Province. Moreover, it is a renowned place of interest, enjoying high prestige for beautiful scenery. Maintaining good water quality of Qiandao Lake and protecting the eco-environment of the QLA is particularly important for both water security and economic development. Although various protective measures, such as afforestation, forest protection, and restriction of highly polluting factories have been implemented in this area for years, the eco-environment in the QLA has been undergoing increasing pressures due to rapid urban expansion and industrialization as well as the tourism boom in the recent past. Therefore, it is urgent and important to characterize the eco-environment conditions and to implement appropriate countermeasures.

2.2 Data

The comprehensive data used in sequential evaluation were listed as follows: 1) digital land use map for year 1990, 2000, and 2010 were provided by the Chinese Ministry of Environmental Protection. The dataset was retrieved from remote sensing interpretation and field survey with a validated overall accuracy surpassing 90%; 2) Digital Elevation Model (DEM) with 30 m resolution was used for topographic calculation; 3) historical water quality monitoring records were supplied by Zhejiang Environmental Protection Bureau; 4) annual socio-economic data were extracted from Zhejiang Statistical Yearbook (1990–2010).

Source data was further processed with the following steps: 1) Create sub-watersheds in the study area for calculating assessment indices. The terrestrial regions were

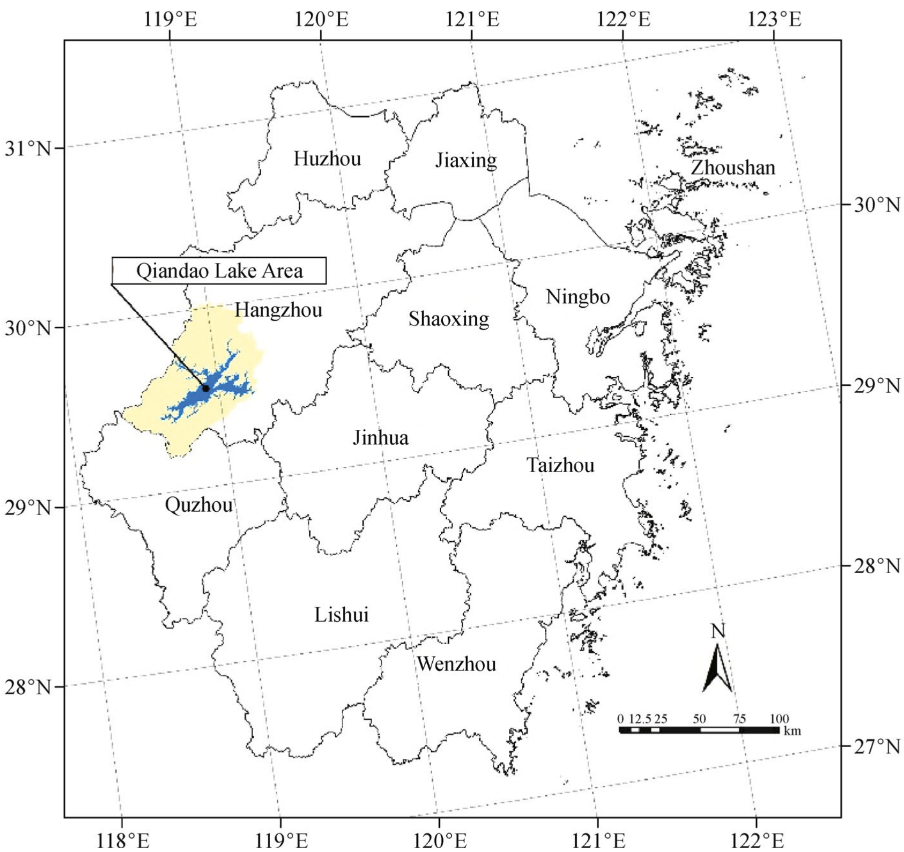

Fig. 1 Location of the study area in Zhejiang Province

segmented into 500 sub-watersheds based on the DEM data using the Hydrology module of ARCGIS9.3 software in which the parameters of flow accumulation for segmentation was 4,000, the minimum number of cells for a stream was 1,000, and the minimum number of cells for a basin was 2,000; 2) Establish subjects for an EVA; 3) Unify the geo-reference of layers with Universal Transverse Mercator (UTM) grid system,WGS_1984 geodetic datum; 4) Rasterize all the vector data to 30 m×30 m units, on which spatial logical and algebraic operations were carried out at each layer.

2.3 Assessment indices and weight assignment

It is a big challenge to select operational, indicative, and representative evaluation criteria in a regional eco-environment assessment (Zhao, 1999) since the eco-environment is a dynamic balanced system (Bockelmann et al., 2004) and can be influenced by many factors (Su et al., 2010). In accordance with previous studies (Li et al., 2006; Li and Huang, 2009; Li et al., 2009; Su et al., 2010), as well as combining expert opinions and practical limitations of case study, the evaluation index system in this study was finally divided into four layers. The first layer was the assessment target, eco-environmental vulnerability. The second layer was a criterion layer composed of ecological pattern, ecological function, and ecological pressure. The third layer consisted of the concrete indices. Following the principles of integrity, geographical accuracy, dynamic response, and data availability (Zhao et al., 2006), altogether thirteen factors were selected and denoted by C1−C13 in sequence: vegetation coverage, slope gradient, elevation, degree of fragmentation, water conservation index, soil conservation index, population density, number of tourists, road density, proportion of ⩾20°cultivated land, proportion of < 20° cultivated land, industrial output value per unit area, and proportion of construction land. The fourth layer referred to the assessment unit (cell). Part of the indices was specifically explained as the following.

The water conservation index (*WCI*) is a universal and important indicator of ecosystem health condition which reflects the ability to retain precipitation and adjust the runoff amount. It is calculated as

$$WCI = \sum\nolimits_{i=1}^{n} H_i \omega_i, \tag{1}$$

where, H_i is the value of component i, ω_i is the weight of component i, i = 1,2,3. The components, weights and standardized measurements are shown in Table 1. The membership degree is applied to assign values for vegetation coverage and impervious area, as is described in Section 2.4. The vegetation types were correspondingly rated as number 1–5.

The soil conservation index is the ratio of the area with moderate or above soil erosion intensity to the regional total area, indicating the soil conservation ability of ecosystem. Soil erosion modulus was calculated by using the revised universal soil loss equation (RUSLE) (Jiang et al., 2012). The corresponding intensities in terms of soil erosion modulus are described in Table 2.

A standardized assessment system for factors is necessary in the process of an EVA (Locantore et al., 2004). All variables should first be standardized into a uniform rating scale for further comprehensive evaluation. In this study, the assessment standards were classified into five levels ranging from 1 to 5 which were assigned to vulnerability levels of slight, light, medium, heavy, and extreme, respectively (Table 3). Most of the employed division boundary values of the decision rules were determined by consulting corresponding national standards (the *Technical Guide for Basin Ecosystem Health Assessment*, compiled by the Ministry of Environmental Protection of China) and relevant literatures (Mendoza and Prabhu, 2000; Krivtsov, 2004; Li and Huang, 2009; Li et al., 2009; Su et al., 2010), as well as taking the practical situation of Zhejiang Province into consideration.

The FAHP method was finally employed to determine the weights of indices. The detailed description of FAHP can be found in (Li et al., 2009b; Su et al., 2010). The derived weights of indices were listed in Table 4.

2.4 Membership value standardization for indices

The fuzzy membership function was used to assign a new

Table 1 Standardized rates of components of *WCI*

Components	Weights	Rating				
		Slight	Light	Medium	Heavy	Extreme
		1	2	3	4	5
Vegetation coverage/%	0.4	80–100	60–80	40–60	20–40	0–20
Vegetation types	0.4	Wetland	Forest, thicket	Grassland	Cultivated land	Others
Impervious area/%	0.2	0–3	3–5	5–10	10–20	⩾20

Table 2 Relationship between soil erosion modulus and intensities

Soil erosion intensity	Potential	Light	Moderate	Heavy	Extreme
Soil erosion modulus/($t/km^2 \cdot yr$)	< 500	500–2,500	2,500–5,000	5,000–8,000	> 8,000

Table 3 Standardized rates of assessment indices

Criterion	Index	Rating				
		1	2	3	4	5
Ecological pattern	Vegetation coverage/%	> 75	65–75	55–65	45–55	< 45
	Slope gradient/(°)	< 6	6–15	15–25	25–40	> 40
	Elevation/m	< 400	400–800	800–1,200	1,200–1,700	> 1,700
	Degree of fragmentation (Standardized)	< 0.2	0.2–0.4	0.4–0.6	0.6–0.8	> 0.8
Ecological function	Water conservation index (Standardized)	1–1.8	1.8–2.6	2.6–3.4	3.4–4.2	4.2–5
	Soil conservation index/%	< 10	10–20	20–30	30–40	> 40
Ecological pressure	Population density/($person \cdot km^{-2}$)	< 2	2–50	50–100	100–250	> 250
	Number of tourists/(10,000 $person \cdot yr^{-1}$)	< 10	10–100	100–200	200–300	> 300
	Road density/($km \cdot km^{-2}$)	< 0.3	0.3–0.4	0.4–0.5	0.5–0.6	> 0.6
	Proportion of ⩾20° cultivated land/%	< 1	1–2.5	2.5–7.5	7.5–12.5	> 12.5
	Proportion of < 20° cultivated land/%	< 4.5	4.5–10.5	10.5–30.5	30.5–48.5	> 48.5
	Industrial output value per unit area /(million $CNY \cdot km^{-2}$)	< 1	1–2	2–5	5–10	> 10
	Proportion of construction land/%	< 10	10–20	20–30	30–40	> 40

Table 4 Weight of each assessment index for the eco-environment

Target	Criterion	Weight	Index	Weight
A	B1	0.2573	C1	0.0769
			C2	0.0493
			C3	0.0365
			C4	0.0546
	B2	0.1812	C5	0.0739
			C6	0.0773
	B3	0.5615	C7	0.1082
			C8	0.0787
			C9	0.0597
			C10	0.0862
			C11	0.0697
			C12	0.1085
			C13	0.1205

value to each index at each layer (Li et al., 2009). For positive indices, the calculation formula is as follows:

When $j = 1$,

$$r_{ij} = \begin{cases} 1, \ C_{ki} > P_{i1} \\ \dfrac{C_{ki} - P_{i2}}{P_{i1} - P_{i2}}, \ P_{i2} \leqslant C_{ki} \leqslant P_{i1} \\ 0, \ C_{ki} < P_{i2} \end{cases}; \tag{2a}$$

when $j = 2,3,\ldots, m-1$,

$$r_{ij} = \begin{cases} \dfrac{P_{ij-1} - C_{ki}}{P_{ij-1} - P_{ij}}, \ P_{ij} \leqslant C_{ki} \leqslant P_{ij-1} \\ \dfrac{C_{ki} - P_{ij+1}}{P_{ij} - P_{ij+1}}, \ P_{ij+1} \leqslant C_{ki} \leqslant P_{ij} \\ 0, \ C_{ki} > P_{ij-1}, \ C_{ki} \leqslant P_{ij+1} \end{cases}; \tag{2b}$$

when $j = m$,

$$r_{ij} = \begin{cases} 0, \ C_{ki} > P_{im-1} \\ \dfrac{P_{im-1} - C_{ki}}{P_{im-1} - P_{im}}, \ P_{im} \leqslant C_{ki} \leqslant P_{im-1} \\ 1, \ C_{ki} < P_{im} \end{cases}, \tag{2c}$$

where r_{ij} represents degree of membership of index i to level j, C_{ki} is the practical attribute value of index i, P_{ij} ($i = 1, 2,...,n, \ j = 1, 2,...,m$) is standard attribute value of positive index i at level m.

The degree of membership of negative indices was calculated in the same manner. In this study, C1 is positive index, while C2−C13 are negative.

2.5 Fuzzy comprehensive evaluation

Weight was multiplied by the degree of membership within different levels of different indices to compute the total degree of membership for different values of eco-environmental vulnerability:

$$V_j = \sum\nolimits_{i=1}^{n} CC_i \times r_{ij}, \tag{3}$$

where V_j is the vulnerability at level j, CC_i represents the weight of index i, r_{ij} is the degree of membership of index i to level j, n is the number of indices.

The comprehensive eco-environmental vulnerability was defined and computed based on the principle of maximum degree of membership. The classification of vulnerability is j when $V_j = V_{\max}$. Supported by ArcGIS, the sub-indices and integrated eco-environmental vulnerability of QLA ultimately was divided into five levels: slight, light, medium, heavy, and extreme conditions.

3 Results

3.1 Eco-environmental vulnerability of the sub-indices

Based on the method introduced above, ecological environment vulnerability in the QLA were assessed and classified into 5 levels: slight, light, medium, heavy, and extreme (Fig. 2). The evaluated results of the vulnerability sub-index for 1990, 2000 and 2010 are further shown in Table 5.

Fig. 2(a) shows the temporal and spatial distribution of ecological pattern sub-indices which presented a tiny change. The ecological pattern situation in the southeast and east were obviously better than those in the other sections. It was indicated in Table 5 that the ecological pattern areas of the three years with slight, light, and medium levels accounted for 92.36%, 93.90%, and 95.35% respectively which denoted a favorable ecological pattern situation for the QLA. Most of these optimistic areas were located at the southeast and the east of the QLA, where an abundance of vegetation existed. The southwest

Table 5 Area percentage of eco-environmental vulnerability sub-index at each level

Eco-environmental vulnerability sub-index	Year	Vulnerability level/%				
		Slight	Light	Medium	Heavy	Extreme
Ecological pattern	1990	31.75	35.56	25.05	5.19	2.45
	2000	33.26	40.43	20.21	4.58	1.52
	2010	34.80	38.72	21.83	3.59	1.06
Ecological function	1990	40.35	34.45	19.51	4.14	1.55
	2000	39.04	30.77	16.85	9.98	3.36
	2010	37.40	29.88	19.46	8.79	4.47
Ecological pressure	1990	61.86	29.20	5.46	2.55	0.93
	2000	54.89	31.54	4.79	6.34	2.44
	2010	46.44	29.79	10.31	9.88	3.58

and north of the QLA, with more distribution of agricultural land, exhibited lower vegetation cover and higher fragmentation, namely worse pattern situation. On the whole, the ecological pattern vulnerability experienced an improvement from 1990 to 2010, mainly attributed to the evolution of vegetation growing which benefited from the vigorous forest protection and afforestation efforts by local government.

The spatio-temporal distribution of ecological function situation was further illustrated in Fig. 2(b). As was presented in Table 5,regions classified as slight, light, and medium level accounted for 94.31%, 86.66%, and 86.75% of the total terrestrial area for 1990, 2000, and 2010. Heavy and extreme level covered 5.69%, 13.34%, and 13.25% respectively, indicating deterioration from 1990 to 2000, and a relatively stable status from 2000 to 2010. It was displayed that the ecological function worsened from southeast to northwest. The most optimistic conditions occurred in the southeast and east of the QLA where forests and shrubs prevailed. Regions classified as heavy or severe ecological function were focused in the southwest of the QLA due to the abundant arable land with high slope which can easily lead to soil loss. The environmental protection department carried out positive measures for soil erosion prevention and treatment over the last decade. According to the assessment result, soil and water loss within the QLA were generally well controlled.

The ecological pressure revealed the influence degree of chosen indicators to the QLA ecological environment. The total area rated as slight, light, and medium type decreased from 96.52% of the total terrestrial area in 1990 to 91.22% in 2000 and 86.54% in 2010. Heavy and extreme levels increased from 3.48% in 1990 to 8.78% in 2000, and to 13.46% in 2010 (Table 5), indicating a continuous intension from 1990 to 2010. The result of ecological pressure distribution was displayed in the Fig. 2(c) which shows a distinct temporal and spatial pattern. The south and north were better than the west and middle. Most of the best conditions occurred in the south of the QLA due to the lower population densities, lower road densities, smaller proportion of construction land and cultivated land. The regions suffering degradation during the study period were mostly distributed in the midwest and northeast of the QLA, and resulted from the expansion of cultivated land and the development of economy and tourism.

3.2 Analysis of eco-environmental vulnerability

The assessment results of eco-environmental vulnerability were presented in Fig. 2(d). Areas with slight, light, and medium level amounted to 97.80%, 92.72%, and 91.85% for 1990, 2000, and 2010 respectively, and heavy and extreme level covered 2.20%, 7.28%, and 8.15% of the total terrestrial area (Table 6),indicating a moderate deterioration during 1990–2010. The areas with heavy and extreme level expanded from 1990 to 2010, while the overall eco-environment of the QLA was acceptable. Moreover, the deterioration of vulnerability during 2000–2010 was less severe than that during 1990–2000, from which it can be concluded that the degradation of eco-environment of the QLA has slowed down in recent years. Fig. 2(d) shows the temporal and spatial transformation of the integrated vulnerability of QLA in 1990, 2000, and 2010. Most of the areas with slight and light eco-environmental vulnerability were located in the south and part of north of the QLA due to the higher vegetation coverage and lower intensity of human activities.

There existed three main regions with worsened eco-environmental vulnerability status: the severest condition on the southwest of Qiandao Lake, and on part of the north and northeast of the Lake. For the southwest and part of north of the QLA regions, the main reason was the expansion of the cultivated land with high slope ($>20°$). The third degraded region in the northeast where Qiandao Lake town is located, experienced rapid urbanization process during which higher densities of construction land and roads, as well as more intensive human activities had greatly challenged the eco-environmental vulnerability .

Table 6 Area percentage of eco-environmental vulnerability at each level

Year	Slight/%	Light/%	Medium/%	Heavy/%	Extreme/%
1990	47.67	32.32	17.81	1.48	0.72
2000	44.49	32.57	15.65	5.74	1.54
2010	42.49	32.74	16.62	6.58	1.57

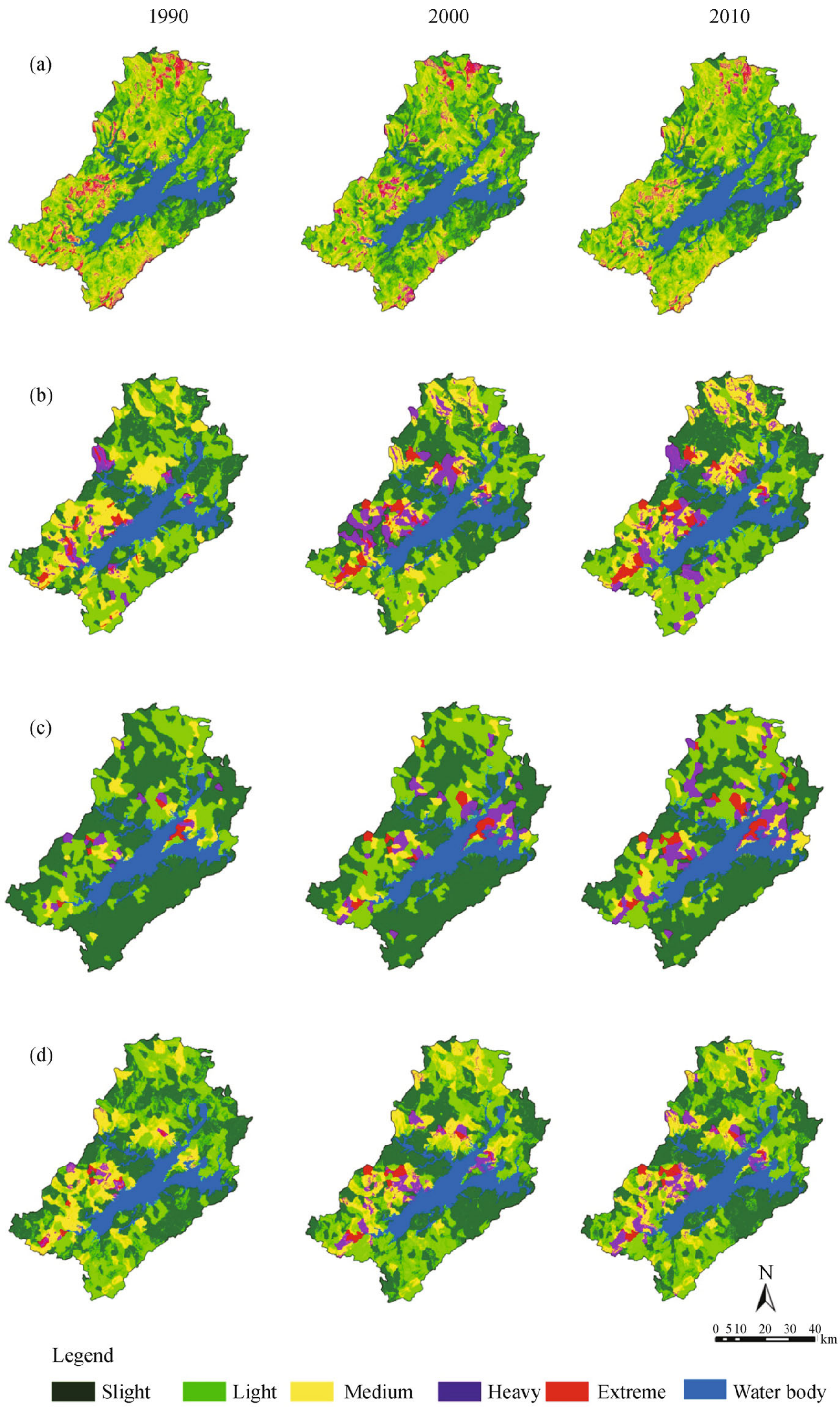

Fig. 2 Mapping of the (a) ecological pattern, (b) ecological function, (c) ecological pressure sub-indices and (d) integrated eco-environmental vulnerability of the QLA in 1990, 2000, and 2010.

4 Discussion

4.1 Assessment of the protective actions

In the past decades, various robust measures, such as shutting down heavily polluting enterprises and limiting industrial development, have been taken to protect the Qiandao Lake. A series of laws and regulations regarding the QLA environment were enacted and implemented. The government tried to restrict the construction land expansion and the population growth. Landfills and sewage treatment plants were constructed to help reduce pollution. Data from statistical yearbooks reflected the protective efforts. As we can see from Fig. 3, population density, proportion of the secondary industry output, and proportion of construction land of the QLA were obviously lower than that of Hangzhou City and Zhejiang Province in 1997, 2000, 2005 and 2010,which reflected that the population growth, industrialization, and urbanization were under strict control in the QLA.

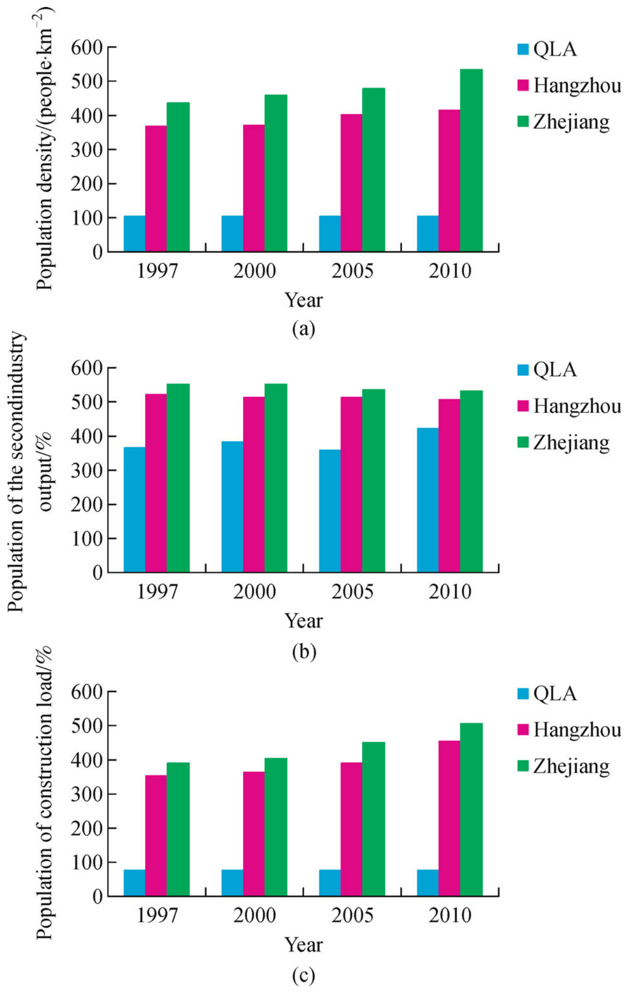

Fig. 3 Comparison of the (a) population density, (b) proportion of the secondary industry output, (c) proportion of construction land between QLA and Hangzhou City and Zhejiang Province in 1997, 2000, 2005, and 2010.

Previous studies showed that industrialization and urbanization were the biggest threats to the eco-environment (Liu et al., 2005). According to our results, the overall eco-environment of the QLA was acceptable, which can mostly be ascribed to the protection and treatment actions.

4.2 Water quality issue in the region

Serving as one of the most important sources of drinking water in eastern China, central and local governments have paid great attention to the regulation and protection of the water quality in Qiandao Lake Reservoir. Up to now, Qiandao Lake is rated as one of the reservoirs with high water quality in China according to constant monitoring data. Four representative indices (transparency (SD), total nitrogen (TN), total phosphorus (TP), and chlorophyll-a (Chl-a)) were chosen to depict the water quality of the Qiandao Lake during the period of 1990–2010 (Fig. 4). Following the national quality standards for surface waters in China (GB3838-2002), they all reached Level II standard, excepting that the total nitrogen was in Level III. However, a slight deterioration occurred during the study period. As we can see from the histogram, all the indicators appeared to decline especially from 2000 to 2010.

Although strict controls were adopted, rapid urbanization, and the development of industry as well as tourism have unavoidably caused environmental pollution to some extent. There continued to be domestic sewage and industrial wastewater directly emitted into Qiandao Lake without any processing. Organic pollutants emerged as a ubiquitous and serious problem (Chen and Ji, 2007). Soil erosion and agricultural non-point source pollution were important contributors of nitrogen and phosphorous which dominantly cause eutrophication (Wen, 2004). The terrain of the QLA is characterized by higher elevation in perimeter and lower in the middle, and land with a slope of more than 25 degrees accounts for 29.18% of the total area (Hu, 2005),which poses high risk of soil and water loss. Large amounts of fertilizers, pesticides, etc. without degradation are transferred from surface sources into Qiandao Lake, raising the concentration of nitrogen and phosphorus in the water and accelerating the eutrophication.

4.3 Major problems of the QLA eco-environment

Inappropriate land use was widespread in the QLA from the 1960s when the reservoir was built to the end of the 20th century. The construction of the Qiandao Lake reservoir led to the occupation of 20 thousand hectares of arable land and immigration of more than 0.12 million farmers, resulting in a strain on the amount of arable land. Immigrants and the original villagers made use of hillsides for cultivation to supplement food, which could destroy the

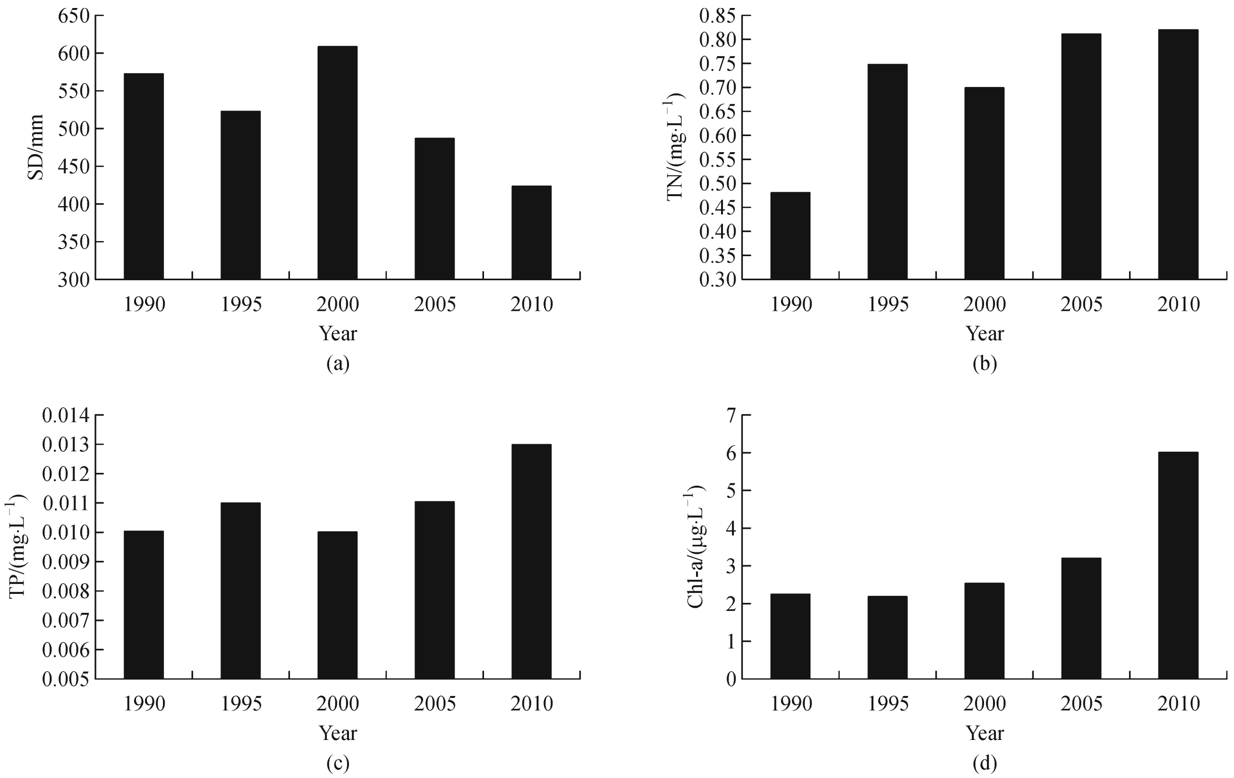

Fig. 4 Variation of main water quality parameters (a) SD, (b) TN, (c) TP, and (d) Chl-a of Qiandao Lake during 1990–2010 with a five-year interval. They are all annual average results calculated by records from state-controlled and province-controlled monitoring points.

vegetation and give rise to soil erosion and agricultural non-point source pollution. Construction had taken up a portion of cultivated land, intensifying the contradiction between limited farmland and food production. As a result, a large amount of gradient land was reclaimed into arable land. Agricultural non-point source pollution caused by soil erosion has posed a great threat to the water quality (Lv et al., 2004).

Rapid economic growth and accelerating urbanization had a profound impact on the eco-environment and water resource (Shao and Chen, 2013; Meng et al., 2014). Domestic sewage and industrial wastewater negatively impacted the water quality of Qiandao Lake. Despite strict regulation, pollution from urbanization and industrialization still has not been fully controlled. The increasing floating population associated with the development of tourism raised the sewage and other pollutants (Fang, 2000). The construction of tourism projects also affected the structure and function of the original ecosystem. Soil conservation and environmental protection were overlooked during the resource exploitation and economic development, threatening the vegetation cover and water body.

4.4 Conservation implications

Owing to the protective actions mentioned above during the past years, the overall eco-environment of the QLA was still decent. However, a moderate deterioration of eco-environment along with a similar trend in water quality of Qiandao Lake was found. According to the recent works regarding water resource (Chen and Chen, 2009; Chen and Chen, 2013; Shao et al., 2013), the QLA could be considered as a socio-economic-ecological integrated system. The social investment, economic development, and ecological status should be incorporated into one combined system for sustainable development of the QLA.

The regions with heavy and extreme ecological vulnerability, most of which are sloping farmland in the southwest and north, must be paid high attention. Soil and water loss as well as agricultural non-point source pollution are great threats to water quality of Qiandao Lake. Immediate prevention and control measures are necessary. For slight, light, and medium vulnerable regions, the significance of environmental protection should also be strongly emphasized. Sustainable utilization and management policies for resources should be adopted to enhance the ecological function for preventing and controlling soil erosion and agricultural non-point source pollution.

Environmental protection in human activities in terms of urbanization, industry, and tourism should be stressed, as always. The planning of residential land use and industrial construction, and the development of tourism should involve full consideration of environmental and water protection. Emissions of domestic sewage and industrial waste water must be strictly regulated to prevent direct pollution to water. It is also important to raise the public awareness of environmental protection as well as scientific understanding. It is not just a matter of government, but a practical issue that is closely related to the living and health of each individual person, which needs the joint efforts of the decision makers and residents.

5 Conclusions

Selecting Qiandao Lake, an important large-scale drinking water reservoir in eastern China, as a case study, this research integrated remote sensing, GIS spatial-analysis and FAHP techniques for comprehensive eco-environmental vulnerability assessment of 1990, 2000 and 2010.

The evaluated results indicated that the state of the QLA's overall eco-environmental vulnerability was satisfactory during the whole study period, although a moderate deterioration was observed. The further analysis of historical water quality records showed the water quality was overall acceptable, with a slight declination trend. In summary, this study demonstrated that the protection and treatment actions in the past years were collectively effective. Nevertheless, more targeted and stricter measures are required to ensure the sustainable development of the QLA. Immediate measures should be conducted for containing the emerging deterioration of the water quality, especially the drinking water sources. The variation in spatial distribution of the eco-environmental vulnerability implied that specifically targeted measures should be established in respective regions.

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