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Ecosystem health assessment in coastal waters by considering spatio-temporal variations with intense anthropogenic disturbance

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ABSTRACT

In this research, factors that influence ecosystem health assessment (EHA) in coastal waters were grouped into three categories: natural causes, direct human causes, and indirect human causes. Statistical analysis based on previous researches was utilized to determine EHA indicators of the first two categories. For the third category, spatio-temporal patterns of potential EHA indicators are prevalent due to the variations of anthropogenic activities in their spatial and temporal distribution across seascape and over timescales. Various Geographic Information System (GIS) analysis methods were hence incorporated to translate and visualize anthropogenic activities into ecosystem-specific impacts. The most adequate indexes were identified to establish a holistic EHA framework. Case study in the northern coastal waters of Zhejiang Province from 2005 to 2014 excellently highlighted ecosystem health changes over the years and revealed the advantage of visualization efficiency and the superiority of considering intense human disturbance of our EHA method over traditional ones.

1. Introduction

Human existence intimately relies on the health of ecosystems and their resources (Depledge and Galloway, 2005). Ecosystem health assessment (EHA) has therefore gained increasing concerns and been conducted in a lot of ecosystems to facilitate environmental management, including rivers, forests, cities, soils, sediments, etc. (Maher et al., 1999; Su et al., 2010; Ishtiaque et al., 2016; Yang et al., 2016; Wu et al., 2015). Simple EHAs assess the performance of a few species identified as indicators (Karr and Dudley, 1981), while detailed EHAs assess the performance of several ecosystem parameters (Karydis, 2009; Pantus and Dennison, 2005).

The ocean is crucial to human survival for providing food, livelihoods, recreation etc., and plays a vital role in regulating the global climatic (Halpern et al., 2012). However, the booming marine economy and the growing human footprint on coastal areas over the last century has polluted and eroded the ocean, affecting ocean biota as well as marine resources (Doney, 2010; Halpern et al., 2008; Duan et al., 2014). With nearly half of the world's population living near coast, we urgently need a new EHA method that can translate human influence and provide support and reference for balancing the human development and ocean's capacity.

In reality, coastal ecosystem health is influenced by anthropogenic activities and natural factors; but the former is more intense, and furthermore can influence the latter (Wu et al., 2009). Hence, frequent anthropogenic activities are considered as the main factors that impact marine ecological environments, especially in more developed coastal waters (Wu and Wang, 2007). Due to the fact that human impact varies in their spatial distribution across the seascape and over timescales (Fukami and Wardel, 2005), spatial-temporal variations of potential EHA indicators are observed in ecosystems with intense human disturbance (Bierman et al., 2011; Wu and Wang, 2007).

In the construction of a comprehensive EHA model, besides referring to previous researches for the identification of regular EHA indicators, a new methodology was required to express human activities as ecosystem-related impacts and visualize their

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manifestation over time (Halpern et al., 2008). Geographic information system (GIS) is widely used to analyze spatio-temporal visualizations and perform spatial analysis (Nagendra, 2001). Based on these studies, GIS tools were employed in the selection of EHA indicators in this research.

In this paper, various GIS methods were utilized to visualize and analyze the spatio-temporal variations of potential EHA indicators that were significantly influenced by human activities. Suitable parameters were identified and selected to establish a holistic EHA framework after comprehensive consideration. The northern coastal waters of Zhejiang Province were assessed and evaluated for the period 2005–2014. Comparison between the proposed method and traditional method were conducted to verify the effectiveness and superiority of the new method.

2. Material and methods

2.1. Study region

In this paper, northern coastal waters of Zhejiang Province, which experiences intense human influence, was selected for our study. Located in East China Sea, this coastal zone is used for aiquculture with China's biggest fishery in Zhoushan waters. Over the past few decades, this area has gained economic predominance due to the booming offshore shipping industry and rapid development of three major cities referred to as the “golden triangle,” namely, Shanghai, Hangzhou, and Ningbo. In addition, it is located near the Yangtze River and the Qiangtang River estuaries with numerous islands, which further complicates the ecosystem. Extensive urban construction and marine engineering projects such as the Qinshan Nuclear Power Plant, Daishan oil terminal, and Hangzhou Bay Bridge have significantly influenced the marine ecosystem. High population density and economic activity have contributed to severe eutrophication in this area (Liu et al., 2013). The highly complex and nonlinear characteristics of the marine ecological environment of the study area make EHA both urgent and challenging.

2.2. Data sources

Statistical data for potential EHA indicators in the northern Zhejiang coastal waters such as harbors, sewage outlets, sea level change, administrative divisions, and others for the period 2005–2014 were collected and summarized from previous references and published bulletins such as “*Marine Environment Bulletin of China*”, “*Marine Environmental Bulletin of Zhejiang Province*” and “*Bulletin of China Sea Level*”, etc.

From 2005 to 2014, annual marine ecological monitoring data of 102 sampling points, organized by Marine Monitoring & Forecasting Center of Zhejiang Province during spring and summer, mainly on water, sediment quality and biodiversity, were collected. The sampling locations are shown in Fig. 1. In addition, annual monitoring data of sewage outlets and red tides were also collected. The detailed analysis methods of marine parameters could be found in “*The Specification for Marine Monitoring*” (GB17378-2007, 2007).

Detailed sources of various indicator data from 2005 to 2014 are listed in Table 1.

Besides regular sampling variables, some composite indicators were introduced in this research to ensure an effective EHA.

2.2.1. Eutrophication index

Eutrophication is a huge challenge for ecosystem health protection in coastal areas. The northern coastal waters of Zhejiang province is known as the most frequent area of red tides in China, and its eutrophic state is therefore essential and requires more attention in EHA (Liu et al., 2013). Eutrophication index, a widely used indicator by the State Oceanic Administrative of China (SOA) to demonstrate the trophic state of the ecosystem, is therefore adopted in this research (Wells, 2003).

$$E = \frac{COD \times DIN \times DIP}{4500} \times 10^6 \qquad [1]$$

where COD is the value of chemical oxygen demand, DIP is the value of dissolved inorganic phosphorus, and DIN is the value of dissolved inorganic nitrogen, which is the sum of NH_4-N, NO_3-N, and NO_2-N.

According to E value, the trophic status can be categorized into four levels as oligotrophic ($0 < E < 1$), mesotrophic ($1 \le E \le 3$), eutrophic ($3 < E \le 9$), or hypereutrophic ($E > 9$).

2.2.2. Organic pollution index

Organic pollution index, which represents the concentration of organic matter and the pollution states of the ecosystem, plays a very important in the monitoring, comparison and control of water quality (Wong and Hu, 2014). It is calculated as follows:

$$Y = \frac{BOD_i}{BOD_0} + \frac{COD_i}{COD_0} + \frac{NH_{3_i}}{NH_{3_0}} - \frac{DO_i}{DO_0} \qquad [2]$$

where BOD_i, COD_i, $NH_{3i,}$ and DO_i are the values of biochemical oxygen demand (BOD), COD, NH_3, and dissolved oxygen (DO) at point i, while BOD_0, COD_0, $NH_{30,}$ and DO0 are their standard first class values classified in the “sea water quality standard” (GB 3097-1997, 1997).

2.2.3. Potential ecological risk index

Potential ecological risk index is an effective way for evaluating the hazards of heavy metals on the ecosystem by considering toxicity of different metals, regional sensitivity, and various background values (Hakanson, 1980). Its calculation is shown in Eq. (3).

$$RI = \sum_{i=1}^{n} E_r^i = \sum_{i=1}^{n} T_r^i \times W_f^i = \sum_{i=1}^{n} T_r^i \times \frac{W_s^j}{W_n^j} \qquad [3]$$

where, E_r^i is potential ecological risk index of the heavy metal i, T_r^i is its toxic response factor, W_f^i is its pollution index, W_s^j is its concentration, W_n^j is its background value, and n is the number of heavy metals in calculation. The toxic response factors and background values of different heavy metals are listed in Table 2S.

2.2.4. Biodiversity index of the intertidal zone

Species loss is closely related to the degeneration of community structure, and biodiversity is hence regarded as the single indicator in simple EHAs (Karr and Dudley, 1981). The most widely adopted index to evaluate biodiversity is the Shannon-Weaver biodiversity index (H), which demonstrates the stability and complexity of ecosystem (Shannon, 1997). Intertidal zone is the intermediate zone between the sea and land with relatively high productivity and great importance in marine ecosystems. However, the booming offshore development enormously degenerates the species diversity of this area (Wang et al., 2007). Therefore, the biodiversity index of the intertidal zone is considered in our research as follows:

$$H = -\sum_{i=1}^{S} N_i \log_2 N_i \qquad [4]$$

where N_i is the proportion of individual *i* in the community and S is