Ocean & Coastal Management 142 (2017) 90–97

Contents lists available at ScienceDirect

Ocean & Coastal Management

journal homepage: www.elsevier.com/locate/ocecoaman

An integrated method for the control factor identification of resources and environmental carrying capacity in coastal zones: A case study in Qingdao, China

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A R T I C L E I N F O

Article history:
Received 11 January 2017
Received in revised form
22 March 2017
Accepted 26 March 2017
Available online 31 March 2017

Keywords:
Factor identification
Carrying capacity
Control factor
Environmental remediation
Qingdao

A B S T R A C T

Large amounts of pollution in coastal waters have placed marine ecosystems under stress. In relation to this, socio-economic development can only be considered sustainable when the ecosystem is under normal carrying capacity. However, accurately evaluating the environmental carrying capacity and efficiently remediating related problems are difficult to carry out in the absence of systematic methods to identify the influencing factors. Hence, this study established an integrated identification method, including the selection and horizontal independence test of potential factors as well as the identification of control factors and water quality effects. We identified the control factors and proposed a series of remediation measures based on the survey and statistical data from 1982 to 2015 in Qingdao and its coastal area. Results indicated 21 control factors, five of which were high-level control factors in Qingdao offshore, namely, wastewater discharge, livestock production, ammonia nitrogen emission, river runoff, sewage treatment. In addition, reclamation area was identified as significant pollution contributors in the Jiaozhou Bay. These control factors showed that the carrying capacity for land-based pollutant emissions and shoreline destruction in the Qingdao offshore is generally overloaded, especially in Jiaozhou Bay. The reduction of land-based pollutants and watershed restoration projects, such as the removal of artificial dikes and the rehabilitation of its natural shoreline, are thus needed to resolve this problem in Jiaozhou Bay. Meanwhile, only differential reduction approaches on land-based pollutants are needed for other coastal waters in Qingdao, such as adjusting the industrial structure, enhancing investments in sewage treatment facilities.

1. Introduction

With the increase of human population and rapid commercial and industrial development since the 1970s, the coastal waters of Qingdao, especially in the Jiaozhou Bay, have been heavily polluted, causing critical and rigid constraints to the sustainable socio-economic development of the region (Li et al., 2002; Sun et al., 2007; Han et al., 2011; Liang et al., 2015). The overall degradation of environmental quality, which is derived from the interaction of anthropogenic pressure and marine natural processes, is a concrete indication that the resources and environmental carrying capacity in the coastal area are already saturated or overburdened. If the coordination of the two types of process fails, then environmental disasters may occur (Simeonov et al., 2003; Borja et al., 2006; Wei et al., 2014). Therefore, we must establish efficient environmental remediation measures to prevent marine water pollution and improve the environmental quality in the Qingdao offshore, especially in Jiaozhou Bay (Juwana et al., 2012).

A quantitative analysis of resources and the environmental carrying capacity in the coastal area is needed to determine the control factors. This analysis should include a scientific evaluation of the carrying capacity and a systematic identification of the influencing factors of coastal environmental quality (Han and Luo, 2010). The concept of "carrying capacity" can be traced back to human statistics theory in the late 1890s (Malthus, 1798), and was later used in ecology studies in 1921 (Park and Burgess, 1921). Subsequently, the theory was extended to socio-economic, resource, environmental and regional fields of research (Daily and

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http://dx.doi.org/10.1016/j.ocecoaman.2017.03.024
0964-5691/

Ehrlich, 1996; Bishop and Crawford, 1997; Leopold, 1941; Liu and Borthwick, 2011; Wei et al., 2014). However, research on marine resources and environmental carrying capacity, which is generally considered from the universality of regional carrying capacity and the particularity of the marine resources, is still in the exploratory stage. This condition refers to the rational development of marine resources and the marine ecological benign cycle in a certain period, it also refers to the capacities and limitations of efforts to initiate a coordinated development of the economy and the environment through self-regulation and self-sustainment (Carver and Mallet, 1990; Arrow et al., 1995; Di and Han, 2005). Comprehensive research on marine resources and environmental carrying capacity is rare in foreign countries, and domestic research only began in the early 21st century. Di and Han were the first to conduct research on marine carrying capacity in China (Han and Luan, 2008; Di and Han, 2005). Subsequently, many methods have been adopted to calculate carrying capacity: the coastal pollutant capacity, index evaluation, state space, the ecological footprint, the system dynamics model, single factor analysis, and fuzzy comprehensive evaluation, among others (Wackernagel and Rees, 1998; Mao and Yu, 2001; Ren et al., 2012; Gu et al., 2015; Dai et al., 2015; Ye et al., 2016; Wang, 1998; Wang and Xu, 2015). The coastal pollutant capacity method, a concentrated reflection of multi-factor interaction, can express the pollutant carrying capacity of open systems. The single-factor evaluation method can only investigate a single factor and is unable to quantify control factors of carrying capacity. Although other methods can characterize the quantitative relationship between carrying capacity and multiple factors, several disadvantages have emerged (e.g., the index evaluation method has a complex calculation process, the ecological footprint method deviates from the actual situation analysis because of factor attributes, the system model method can only predict future trends and cannot judge the current carrying status, and the state space fails to effectively determine an ideal value). The state space, coastal pollutant capacity, and the system dynamics methods have been widely used in the calculation of coastal resources and environmental carrying capacity.

Index system research originated in the 1970s, and the earliest of its kind was applied in evaluating the carrying capacity of land resources (Carneiro, 1960; Brush, 1975). Research on the influencing factors of environmental quality in the coastal area began in the early 21st century, and nearly 200 factors have already been discussed in the literature. The European Union (EU) proposed a list of basin pressure and influencing factors, which was divided into the pollutant discharge of point and non-point sources, hydrological conditions, land morphology, biology and resource utilization, and other characteristics, according to the pressure-state-response framework (Borja et al., 2006; Lanz and Scheuer, 2001). Similarly, the State Oceanic Administration of China (SOA) proposed a list of marine resources and environment monitoring and warning index systems, this list is divided into three sets of factors, namely, socio-economic development pressure, marine resource supply, and marine ecological environment support (Fan et al., 2015; Miao et al., 2006). However, the lists provided by the EU and SOA have a “fixed list” attribute, which limits partially influencing factors and cannot systematically reflect vertical and horizontal relationships between factors and water quality. Moreover, the lists might have also ignored the regional characteristics of influencing factors. With the lack of systematic research on the theoretical system and framework, the vertical and horizontal relationships of influencing factors remain vague. Meanwhile, differences among the regional socio-economic and environmental structural systems give rise to the regional characteristics of influencing factors (Sun et al., 2009). Consequently, an accurate identification method is essential in determining the influencing factors and analyzing the control elements of marine resources and environmental carrying capacity. However, even if objective identification methods are adopted, factor identification is subjective and causal and may be limited to the selected influencing elements (Juwana et al., 2012).

Therefore, the current paper investigates the problems related to the overall degradation of environmental quality in the Qingdao coastal area, especially in Jiaozhou Bay, and proposes a comprehensive quantitative evaluation index system based on the natural relationships among the source, sink, transport, and transformation of pollutants in coastal areas. An integrated method is established to systematically clarify and quantitatively analyze the control factors of the resources and the environmental carrying capacity in Qingdao, China. The results are expected to provide insights regarding the integrated remediation of the water quality environment in coastal areas.

2. Material and methods

2.1. Study area

Located at the west coast of the Yellow Sea, Qingdao is a typical coastal city with 12,200 km^2 of sea area under its jurisdiction, which has a subtropical monsoon climate, characterized by mild temperature, moderate humidity and distinct seasons. Its total land area is 10,654 km^2, and comprises six districts (Shinan, Shibei, Licang, Laoshan, Chengyang, Huangdao), four county-level cities (Jiaozhou, Jimo, Pingdu, Laixi). In 2016, the total population of Qingdao was 9.09 million and the gross domestic product (GDP) of Qingdao was 1.01 trillion RMB. It has a mainly hilly topography with an average elevation of 17 m; farmlands occupy 68% of the city. It has 224 rivers from three main river networks (Dagu, North Jiaolai and coastal river networks), and 50 of these rivers flow into the sea. Seventy percent of the total population lives in the urban areas, which are located along the coast, especially, Jiaozhou Bay (Fig. 1).

2.2. Construction of the correlation of influencing factors

The vertical and horizontal relationships of the influencing factors were arranged according to the natural relationships among the source, sink, transport, and transformation of pollutants in the coastal area. Based on the related conceptual model, the influencing factors of the coastal water quality were divided into four clusters, namely, coastal zone, land-sourced pollutant emissions, hydrodynamic transport, and biogeochemical migration transformation processes (Zhang et al., 2017; Borja et al., 2006; Cormier et al., 2000). Coastal zone and land-sourced pollutant emissions are called “anthropogenic pressure.” Hydrodynamic transport and biogeochemical migration transformation process are called “marine natural processes.” Each cluster consists of several groups that comprise hierarchical factors, and significant differences exist among different clusters. For example, the coastal zone cluster is divided into coastal wetlands, coastline, sewage outfalls, runoff, sediment, and coastal engineering, whereas the hydrodynamic transport cluster is classified as tide, flow field, island, boundary, and meteorological conditions. The biogeochemical migration transformation process cluster is divided into biological, suspended particles, seafloor sediments, environmental conditions, and others. Meanwhile, combined with the transport path of pollutants into the sea, land-sourced pollutant emissions include pollutant production, watershed reduction pollution, and project emission reduction pollution. Pollutant production is subdivided into industrial and population pressure factors according to the type of pollutant source, the former comprises agriculture, industry, and services, whereas the latter comprises urban and rural life. The agricultural source is subdivided into planting, animal husbandry,