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Assessing the total maximum allocated load of jurisdiction petroleum pollutants in the Bohai Sea

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ABSTRACT

A method for calculation of total maximum allocated load (TMAL) of petroleum in Bohai Sea was established based on jurisdictions by linking land and sea. The TMALs of petroleum pollutants for 51 sea-sink source regions, 356 jurisdictions, and 6 petroleum drilling platforms (PDPs) around the Bohai Sea were calculated. Results showed that the TMALs of petroleum pollutants in 51 sea-sink source regions and 6 PDPs amount to 1.9×10^4 tons/year. The largest TMAL is from the rivers, followed by that of PDPs and wastewater treatment plants (WWTPs), at about 0.22×10^3, 0.13×10^3, and 0.11×10^3 tons/year on average, respectively. The maximum values are 3.05×10^3, 0.47×10^3, and 0.65×10^3 tons/year respectively, while the minimum values are 0.18, 0.10, and 0.31 tons/year respectively. The TMAL of petroleum pollutants on source producing and TMAL on source emission are 11.9×10^4 tons/year and 1.9×10^4 tons/year in 356 jurisdictions, respectively. The TMAL is high in upstream of each basin and the areas of marine water exchange rapidly. Taking Laizhou Bay as an example, 19 jurisdictions are overloaded with petroleum pollutants, and its overload rate is 670% on average.

1. Introduction

The risk of marine petroleum pollution, which causes considerable harm to marine ecosystems, has increased remarkably with the rapid economic development of coastal and offshore oil exploitation. Petroleum pollution becomes serious because of land-based pollution and marine exploitation, particularly in highly intensive human activities of coastal area. Bohai rim includes 356 jurisdictions over three provinces (Liaoning, Shandong, and Hebei) and two municipalities (Beijing and Tianjin). The sea contains three bays, namely, Liaodong Bay, Bohai Bay, and Laizhou Bay. According to Chinese Marine Environment Bulletin in 2010–2015, petroleum pollutant is one of the main pollutants of Bohai Sea, which is damaging the spawning and feeding grounds. And the most heavily polluted areas are mainly located in Liaodong Bay, Bohai Bay, and Laizhou Bay. The monitoring results in May 2015 in Laizhou Bay also showed that the petroleum pollutants concentration are more than class I/II ($\leq$0.05 mg/l) water quality criteria at all positions. Petroleum contamination from sewage and oil spill has become more severe in recent years because of high onshore and offshore oil exploitation. Monitoring results indicated that terrigenous pollution, shipping, and petroleum drilling platform (PDP) are the important sources of Bohai oil pollution.

The total maximum allocated load (TMAL) management for petroleum should be urgently carried out in Bohai Sea, in accordance with the total amount of pollutants in coastal national control plans from the area of industrialization and urbanization process and overall development goal. To date, the Total Maximum Daily Load plan in USA (Lung, 2001; Linker et al., 2013; Selman et al., 2009), the Total Pollutant Load Control plan in Japan (Takeoka, 2002; Yanagi et al., 1999; Kataoka, 2011), Marine Strategy Framework Directive and Water Framework Directive in Europe (Udovyk et al., 2010; Turner et al., 1999; Vázquez-Suñé et al., 2006; Chen et al., 2007), and Action for the Protection from the Marine Environment from Land-based Activities implemented by United Nations Environment Program are all focusing on the region, specifically the administrative area's differential reduction plans of land-based pollutants, to establish and complete the numerical test relationship between the jurisdictions discharge pressure and

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response of water quality. Researchers on this field also conducted considerable amount of researches (Han et al., 2011; Zhang et al., 2012; Ahiablame et al., 2013; Cui, 2008; Guo et al., 2008; Meng, 2008; Dai, 2015). 3D hydrodynamic water quality model can be used to calculate concentration response matrix, which can couple the pollutant discharge and water quality simulation (Gorelick and Remson, 1982). The total control of pollutants limits the pollutant discharge according to environmental quality standard, which aims to make it less than the environmental carrying capacity (Meng, 2008). Therefore, the carrying capacity should be calculated first before establishing the total control index system. Research regarding the carrying capacity of water environment mainly contains the repair and protection of water environment (Progressive, 2002), reasonable development of the aquatic resources (Duarte et al., 2003) and recreation carrying capacity estimates (Sayan and Atik, 2011). The researches about carrying capacity mainly focus on environmental factor carrying capacity and comprehensive carrying capacity in recent years (Wang et al., 2008; Shi et al., 2012).

TMALs of pollutants can be divided into TMALs on outlets and TMALs on jurisdictions. TMALs on outlets are the maximum allowable pollutant discharge quantity of sea-sink source regions (Zhao et al., 2011; Su, 2014; Ding, 2012; Guo, 2005). TMALs on jurisdictions are the maximum allowable pollutant discharge quantity of administrative jurisdiction, which show maneuverability in management (Zhang et al., 2007). Wang et al. (2009) reported the allocation capacity of chemical oxygen demand according to macroscopical environment-economy model in 13 cities around the Bohai Sea. Dai (2015) studied the TMAL of nitrogen pollutants on 34 sea-sink source regions by using 3D hydrodynamic water quality model and programming model in Bohai Sea. However, no calculation method for TMAL of petroleum was performed by considering jurisdictions and offshore oil exploitation. Therefore, the differential reduction plans, which are implemented according to overload condition of jurisdictions based on land and sea, should be investigated (Savchuk and Wulff, 2007). It should be pointed out that there are petroleum pollutants in sediment, which are characterized by plaque distribution (Chen et al., 1980; Qiao et al., 2010). Because they are mostly around the offshore oil exploitation, the TMAL of sediment was classified to platforms in actual calculation.

In the present study, the TMALs of 51 sea-sink source regions, 356 jurisdictions, and 6 PDPs around the Bohai Sea were calculated by linking land and sea. On this basis, total load control countermeasures for the optimal management of jurisdictions were proposed, which can provide a scientific basis for the realization of “differentiated reduction” in Bohai Sea.

2. Material and methods

2.1. Method

On the basis of water quality simulation mathematical programming method, the TMALs of petroleum for jurisdictions were calculated by the matching relationship between the county jurisdictions and source unit boundary, as well as the riverine transport efficiency or delivery factor in the watershed attenuation, which delivers the pollutants to the estuary by the watershed model (Linker et al., 2013). The former was studied by using 90 m resolution digital elevation data (Computer Network Information Center, 2012) and the division of source units; the latter was investigated mainly through the analysis of attenuation process in the watershed. Relative effectiveness between production quantity of jurisdictions and seawater quality can be established by combining outlets with the water quality response relationship of target area (Fig. 2).

This paper adopts the water quality-based allocated capacity index system of land-based pollutants for the jurisdictions established by Dai (2015). PDP can be equivalent to a sea-sink source region containing one source unit, and the transfer coefficient is 1.

The Yellow River basin covers nine provinces. According to the division result of source units in Bohai rim (Dai, 2015), this study considered the anterior basin as an independent source region when the Yellow River is divided into two parts by the boundary of Shandong province, and a certain amount of allocated load for this region should be reserved when calculating the TMAL of petroleum in Bohai Sea. The TMAL proportion of two parts of Yellow River is simplified as river length proportion of two parts, which is 7.5:1, so the TMAL of jurisdictions in the Bohai rim is 1/8.5 times of the Yellow River's TMAL.

2.2. 3D hydrodynamic water quality model of petroleum

Accurate TMAL results were obtained by combining the 3D hydrodynamic water quality model and linear programming model (Fig. 2). 3D hydrodynamic water quality model was used to simulate petroleum distribution in the Bohai Sea, and linear programming model was then used to calculate the relationship between water quality and TMAL.

Petroleum pollutants are multi-constituents mixture and they can be considered as a state variable if distinction in composition and properties are not considered. Petroleum pollutants may be subjected to physical, biological, and chemical processes for the self-purification of water when they enter the marine multimedia environment. These processes may include bio-accumulation by phytoplankton and other aquatic organisms, volatilization from water to atmosphere, sorption by suspended particulate matter, biodegradation by bacteria, and transport to open seas via water exchange (Wang et al., 2002). Compared with the biodegradation, photo-oxidation is relatively unimportant (Swartz and Lee, 1980), which is not considered in this paper.

Hamburg shelf-ocean model was used in this study. This model is a 3D baroclinic level-type model widely applied in the Bohai Sea (Hainbucher et al., 2004; Wang, 2004; Wei et al., 2004; Zhao et al., 2011; Huang et al., 1996). The model contains 20 layers in vertical direction, and the longitudinal and latitudinal grid resolutions are 2′. The hydrodynamic model use six hourly wind and other meteorological forcing, and five tidal components (M2, S2, N2, K1, and O1) in the open boundary; the time increment is 360 s. Evaporation comes from station observation data, and other meteorological parameters come from the National Center of Environmental Prediction and National Center of Atmospheric Research (Wang, 2004) The temperature, salinity, and hydrodynamic fields were verified (Wang, 2004; Dai, 2015), and the parameters of hydrodynamic process reference to correlational research (Wang, 2004).

Volatilization and biodegradation are two main biogeochemical processes for petroleum pollutants (Li et al., 2014). Petroleum pollutant volatilization process can be described by first-order kinetic equation (Xie et al., 1997):

$$\left(\frac{dc}{dt}\right)_{atm} = k_{atm} \cdot C \tag{1}$$

where k_{atm} is a function of temperature (T) and can be described by the following equation (Wang et al., 1995):

$$k_{atm} = k^0_{atm} \cdot e^{-\frac{\Delta H}{RT}} \tag{2}$$

where k^0_{atm} is the volatilization rate constant at T^0; k^0_{atm} is affected by the depth of the water h and generally expressed as $k^0_{atm} = \lambda/h$,

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