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Numerical modelling of temporal and spatial patterns of petroleum hydrocarbons concentration in the Bohai Sea

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ABSTRACT

The discharge of petroleum hydrocarbons (PHs; ~10,000 tons annually) into the Bohai Sea, a shallow inland sea in China, presents a serious threat to the marine environment. To evaluate the effects of PHs pollution and estimate the corresponding environmental capacity, we have developed a genetic algorithm-based coupled hydrodynamic/transport for simulating PHs concentration evolution and distribution from July 2006 to October 2007, with the predicted values being in good agreement with monitoring results. Importantly, the mean PHs concentrations and seasonal concentration variations were primarily determined by external loading, i.e., currents were shown to drive PHs transport, reconfigure local PHs patterns, and increase PHs concentration in water masses, even at large distances from discharge sources. The developed model could realistically simulate PHs distribution and evolution, thus being a useful tool for estimating the seasonal environmental capacity of PHs.

1. Introduction

The Bohai Sea (BS; area ≈77,000 km^2) is a shallow inland sea in China that is plagued by environmental problems caused by agricultural and industrial development as well as urban population growth along its shores. Some of the most severe problems are caused by contamination with petroleum hydrocarbons (PHs), which are toxic to aquatic organisms, pose danger to human health and disturb the ecological balance. Although the PHs concentration in most coastal and offshore areas is below the limit imposed by the marine water quality standard (500 μg/L) for insensitive regions, it exceeds the limit imposed by the strictest standard (50 μg/L) in many parts of the BS. Zhang et al. (2007) monitored water samples from 16 main rivers around the BS, claiming PHs as a chief pollutant of this water body. Moreover, in some gulfs, the PHs concentration of surface sediments exceeds the limit imposed by the most stringent marine sediment quality standard of China (Zhou et al., 2014). PHs have been shown to accumulate in marine organisms up to the trophic level and thus contribute to the decrease fish population (Xu et al., 2011). No matter where they exist, the transport and transformations of PHs in the water column require additional characterization.

Although oil spills caused by accidental discharge from tankers or leakage from well-drilling platforms receive widespread public attention, the PHs distribution in the BS is mainly determined by continuous long-term emission sources, i.e., accidental spills account for only ~10% of the total PHs influx, whereas river inflow and marine sewage discharge account for 60%,and shipping emissions and offshore platform extraction of wastewater have a share of 30% (Wang and Li, 2006).

During the past thirty years, several numerical oil spill models have been developed for short-term tactical forecasting, facilitating the control and cleanup of spilled oil (ASCE, 1996; Afenyo et al., 2016; Spaulding, 2017). More, some long-term simulation models of PHs distribution were constructed for persistent damage assessment after accidental spills (Afenyo et al., 2017; Blanken et al., 2017). When faced with conventional hydrocarbon contamination from runoff input as the primary pollution source, public authorities can seldom rely on dedicated tools to predict pollutant distribution. Thus, numerical modelling of PHs sources, transport, and fate in the marine system is important for assessing the impact of these contaminants on human health and the marine ecosystem as well as for estimating their environmental capacity.

Fig. 1 depicts the behavior of PHs in marine environments is influenced by a number of processes, e.g., passive transport with moving water masses, volatilization into the atmosphere, chemical/biological degradation, adsorption onto/desorption from particulate matter, and

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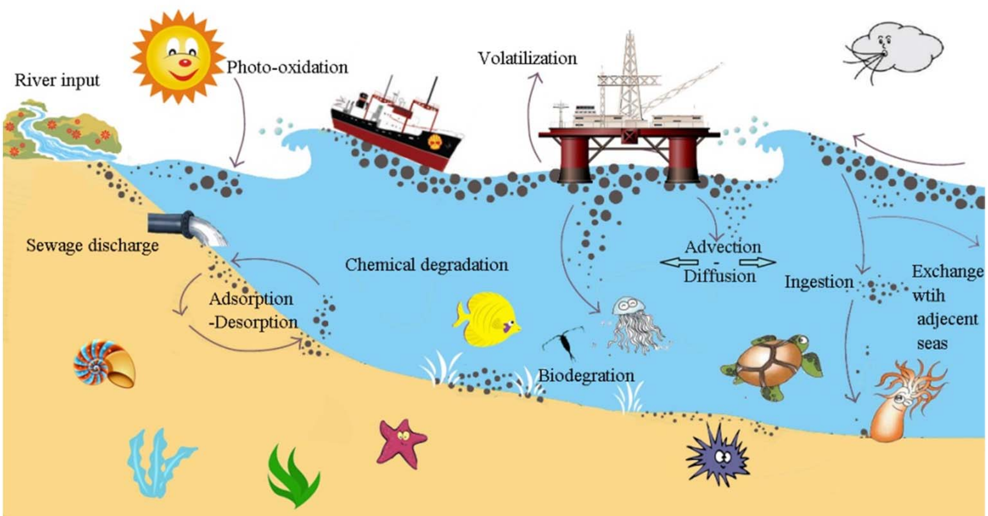

Fig. 1. Transport and fate of PHs in marine environment (after Zadeh and Hejazi, 2012).

ingestion by living organisms. These processes are so complex that simplifications are essential for prediction purposes. Notably, the environmental fluid dynamics code (EFDC) lacks a specific sub-model for simulating PHs transport and transformation processes (Ji, 2007), partly due to the complex chemical components. Thus, it seems more practicable to regard PHs as a single component instead of estimating the total PHs mass transfer rate by calculating the contribution of individual components.

The levels and distribution of PHs in the BS have been first predicted using box-models, which provided built-in piecewise integrated results rather than discrete values for each fine hydrodynamic grid. Thus, Wang et al. (2004) constructed a two-dimensional box model framework for predicting summertime PHs dynamics in the BS ignoring the effect of currents on transport and distribution balances. Li et al. (2013) employed a box model to simulate the seasonal variations of PHs levels in the Jiaozhou Bay, achieving good agreement with field survey data. The box model is only valid for an instantaneously mixed water body, whereas, th BS is characterized by a significant spatial gradient, with the evident shift observed not only in the east-west but also in the north-south direction.

The general trend of ecosystem modelling, i.e. the improvement of spatial resolution by shifting from rough-box models to fine-grid models (Ménesguen et al., 2007), requires hydrodynamic and transport models of the same high resolution to be linked. Guo et al. (2007) computed the environmental capacity of PHs in consideration of self-purification in the BS, neglecting the seasonal variations in the survey data. Shang et al. (2015) used annual mean river inputs to simulate PHs transport in the BS, obtaining overestimated values for spring and autumn, which was explained by the intra-annual cycle of external sources and seasonal variations of degradation kinetics.

The lack of high-resolution data has been recognized as the most important factor limiting the prediction of PHs distribution in the BS. To overcome the shortage of realistic field data on the distribution of these pollutants over a wide sea area, the Chinese government implemented a national project for surveying the marine background in the marginal seas of China, namely Project 908, i.e., Project of Chinese Coastal Waters for Comprehensive Marine Survey and Evaluation (Hong, 2012). A large amount of data on the water quality of the BS as the sole inland sea has also been acquired for fundamental research and future ocean exploitation. The following issue is how to develop numerical model by means of these data for water-quality management. In comparison to hydrodynamic simulations, pollutant distribution modelling is faced with a more challenging task of calibration (i.e., the processes of identifying appropriate model parameter values) due to uncertainties in the mathematical description of the system and filed data (Mulligan and Brown, 1998). To avoid manual trials, a large number of calibration methods have been proposed for attaining optimal agreement between model output and actual observations (Haupt et al., 2009). Specifically, genetic algorithms, based on the principles of genetics and natural selection, are robust search techniques successfully applied in models for water quality modelling (Chau, 2006; Mulligan and Brown, 1998).

The work aimed to improve our understanding of PHs concentration evolution and distribution in the BS and describing the dynamic model and PHs status in the study area, taking advantage of in-situ data and numerical tools. The paper is structured as follows. The dynamic model and PHs status in the study area are described in Section 2. The developed model was calibrated and validated utilizing the available measured data, and the relations between distribution characteristics and environmental factors were analyzed in detail in Section 3. The study's conclusions and a sound basis for further research are presented in Section 4.

2. Method description

The transport and fate of PHs were represented by an advection-diffusion equation that was solved based on the hydrodynamic model, meteorological data and input loads. A genetic algorithm (GA) was used to optimize parameters representing complex PHs complex reaction processes, with a flow diagram describing the proposed methodology shown in Fig. 2.

2.1. Study area

Being a shallow enclosed sea, the BS is affected by numerous PHs emission sources, including both crude oil terrestrials and offshore activities (Fig. 3). Dozens of rivers empty into the BS, with most of them being quite small and exhibiting season-dependent water discharge volumes. Hence, we focused on the 17 highest-capacity rivers, inluding the Yellow River, the Liao River, the Hai River, and the Luan River, which together account for over 80% of the runoff and approximately 70% of PHs contaminant loads. More information on the considered major rivers is provided in Table 1. The combined annual PHs input of all rivers, i.e., the principle source of BS pollution, is approximately equal to 8400 tons. A total of 30 effluent outfalls around the BS discharge 810 tons of PHs per year, i.e., contaminants entering the BS mainly originate from industrial activities. In addition, over 20 offshore oil and gas fields have been built in the BS, ejecting 1600 tons of PHs into the surrounding sea-water each year. Moreover, the heavy marine traffic in the BS also results in accidental oil spills and regular ship