Ecological Indicators xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Ecological Indicators

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

Original Articles

Simulation-based risk analysis of water pollution accidents combining multi-stressors and multi-receptors in a coastal watershed

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ARTICLE INFO

Keywords:
Environmental risk assessment
Numerical simulation
MIKE21
Risk ranking
Near-shore sea
Beihai city

ABSTRACT

As environmentally important ecosystems, coastal watersheds are vulnerable to abrupt water pollution events. Previous researches of accidental pollution in coastal watersheds mostly focused on oil leakages from mobile sources, pipelines, or stationary sources; however few considered chemical pollution accidents from terrestrial stationary sources. The present paper uses one-dimensional and MIKE 21 convection-diffusion models to simulate chemical transport processes in coastal rivers and in near-shore seas. Based on the simulation results, a Coastal Accidental Water Pollution Risk Analysis (CAWPRA) method is proposed. CAWPRA considers acute pollution risk passing from upstream to downstream, and to estuary and near-shore sea areas in a coastal watershed. The method is applied to Beihai City, a typical coastal area of rising economic development, to provide a risk assessment based on simulations of water accidental pollution from terrestrial stationary sources. A leakage event of hydrochloric acid from Wenkehaiyang Co. Ltd is taken as an example. Water quality simulation results indicate that after 6, 12, 18, and 24 h the peak concentrations of hydrochloric acid would be 3.72, 0.91, 0.75, and 0.68 mg/l, respectively, and accordingly, the areas of coastal water exceeding the seawater quality standard would be 5.56, 4.92, 9.71, and 45.01 km^2, respectively. Hydrochloric acid would reach Dangjiang Mangrove Nature Reserve a time 14 h after the leakage event first occurred. The resultant map indicates high, medium, and low risk sub-areas. The map is useful at identifying the most risky sources and the most vulnerable receptors for the Beihai coastal watershed.

1. Introduction

Accidental pollution events, such as structural and marine incidents, collisions, fires, dropped objects, blowouts, risers/pipelines leaks, process leaks and transport accidents, are a significant threat to the coastal watershed in terms of catastrophic release, associated damage, and unpredictability of occurrence (Bai and Jin, 2015). In the U.S.A., water pollution incidents comprised 79% of the total number of environmental emergencies reported in 2014 (NRC, 2015). Over the past decade, the Ministry of Environmental Protection, P.R. China responded directly to 558 water pollution accidents, corresponding to 52% of the total number of environmental emergencies (China MEP, 2006-[China MEP, 2015]2015). Accidental pollution events in the marine environment, such as spills of oils and chemicals, pose a very specific threat (Kirby and Law, 2010). In 1994, a barge in the US spilled a large amount of caustic soda in the Bay of Newark, causing the pH alongside the barge to reach 12 very quickly (USCG, 1999); in 2001, the chemical tanker Balu, transporting 8000 t of sulphuric acid, sank in the Bay of Biscay (Emina et al., 2009). In 2010, the explosion and sinking of the Deepwater Horizon oil rig located about 42 miles off the coast of Louisiana killed 11 people, and its pipe leaked about 3.19 million barrels of oil in 87 days later into the Gulf of Mexico (Crone and Tolstoy, 2010). As for China, approximately 3000 accidental oil spill events occurred from 1973 to 2011 (Ministry of Transport, 1974-[Ministry of Transport, 2012]2012). In 2011, an oil spill accident due to over-exploitation by ConocoPhillips led to an environmental disaster in Bohai Bay, China (Guo et al., 2015). It is very well established that such incidents can cause serious ecological and environmental damage to surrounding areas leading to imbalance of the regional marine ecological system.

In the aftermath of toxic oil and chemicals disasters, numerous studies have been carried out on accidental risk assessment in different coastal areas. Many studies focused on the risk assessment of oil spill accidents (Price et al., 2003; Mestreset al., 2010; Frazao et al., 2013;

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http://dx.doi.org/10.1016/j.ecolind.2017.06.018
Received 13 December 2016; Received in revised form 5 June 2017; Accepted 11 June 2017

Please cite this article as: Dong, L., Ecological Indicators (2017), http://dx.doi.org/10.1016/j.ecolind.2017.06.018

Lan et al., 2015). Fewer studies have considered comprehensively multiple types of risk sources from terrestrial stationary sources and ocean mobile sources. Much effort has focused on accumulative water pollution risk analysis in harbors (Jones et al., 2005; Birch and Olmos, 2008; Chen et al., 2010; Grifoll et al., 2010; Tan et al., 2011; Beyer et al., 2012), and, to the authors' knowledge, few analyses have been carried out (Hayes and Landis, 2004; Lan et al., 2015; Yu et al., 2015) of accidental water pollution risk in coastal watersheds, which considered pathways involving multiple hazards and multiple receptors.

Previously, we developed a watershed-scale risk analysis method, adopting the idea of risk ranking from Relative Risk Assessment (Landis and Wiegers, 1997). The method has been applied successfully to several case studies (Liu et al., 2015, 2017) and progress made in addressing the complicated interactions between multiple stressors and multiple receptors. Using a similar framework, the present research develops a Coastal Accidental Water Pollution Risk Analysis (CAWPRA) method. CAWPRA is designed for coastal-watershed risk analysis, and its advantage over other methods lies in quantifying the exposure possibility from simulations of accidental water pollution events. Water quality models are used to simulate the fate of hazardous pollutants and hence quantify exposure possibility. In practice, many water quality models, such as QUAL (Park and Lee, 2002; Chapra and Pelletier, 2003), WASP (Wool et al., 2001; Kim et al., 2004), MIKE (Xu et al., 2012; Wang et al., 2011), and EFDC (Jin et al., 2006; Seo et al., 2012), have been applied to simulate accidental oil or chemical spills. Here, we select a one-dimensional convection-diffusion model and the MIKE21 model to simulate accidental water pollution in a coastal river and the near-shore zone, respectively. The MIKE21 model was selected because of its user-friendly interface, strong pre-processing and pro-processing functions, and efficient performance. Multi-criteria analysis and a risk-ranking method using GIS tools are incorporated. The proposed method is applied to Beihai, a major coastal city in China. The potential consequences of coastal accidental water pollution on sensitive receptors are quantified in order to obtain sub-watershed risk levels.

2. Methodology and materials

2.1. Water pollution accident simulations in a coastal watershed

Coastal accidental water pollution arises from sudden, massive spills of oil, chemicals, heavy metals, etc., in which hazardous pollutants are released from stationary or mobile sources, transported by a waterway, and cause acute and severe consequences to coastal rivers, estuaries and the near-shore zone. CAWPRA focuses on stationary sources mostly related to industrial enterprises dealing with hazardous chemicals (e.g. acids and bases, insoluble organic matters, oils). The simulation of accidental water pollution requires two steps: (i) analyses of accidental release sources; and (ii) modeling of the fate of accidental chemicals in a river or/and an estuary and near-shore zone.

2.1.1. Analyses of accidental release source

According to China MEP (2014), more than 310 materials can be categorised as high risk. Any enterprise that produces, uses, stores or discharges such materials is classed as a stationary risk source, because it may potentially cause an accidental release of hazardous pollutants. After tank rupture or the initiation of leakage occurs, the leakage rate of hazardous substance though an orifice may be estimated from the Bernoulli equation as (Liu, 2009):

$$Q = C_d A\rho\sqrt{\frac{2(P\text{-}P_0)}{\rho} + 2gh} \tag{1}$$

where Q is the leakage rate of liquid risk substance, kg/s; C_d is the leakage coefficient of liquid risk substance; A is the split area, m^2; ρ is the density of the leaky liquid risk substance, $\mathrm{kg/m}^3$; P is the media pressure inside the container, Pa; P_0 is environment pressure, Pa; g is gravitational acceleration, 9.8 $\mathrm{m/s}^2$; h is the height above the rip of liquid risk substance, m. Furthermore, the concentration of a pollutant after dilution may be estimated from:

$$C = \frac{C_1{\cdot}Q_1 + C_2{\cdot}Q_2}{Q_1 + Q_2} \tag{2}$$

where C is the concentration after dilution, mg/l; C_1 is the concentration of liquid risk substance, mg/l; Q_1 is the leakage rate of liquid risk substance, kg/s; C_2 is the concentration of wastewater, mg/l; Q_2 is the rate of wastewater, kg/s.

2.1.2. Pollutant convection-diffusion modeling in a river

For the sudden spill of hazardous substance into a coastal river, it is usual to adopt a one-dimensional convection diffusion model for an instantaneous point source to simulate the pollutant transport process because of the relatively small transverse dimensions of the river compared to its stream-wise length. An analytic solution of the one-dimensional convection diffusion mode is given by (Fischer et al., 1979):

$$C(x,\, t) = \frac{M}{A\sqrt{4\pi Et}}\exp\left[-\frac{(x-ut)^2}{4Et}\text{-kt}\right] \tag{3}$$

where $C(x,\ t)$ is the concentration of pollutant at x (location) and t (time), mg/l; M is the suddenly leaked amount of the pollutant, g; A is the area of river cross section, m^2; E is the convection diffusion coefficient of pollutant, m^2/s; u is the average flow rate of water, m/s; x is the diffusion distance of the pollutant at the direction of water flow, m; t is the time of the pollution, s; k is the attenuation coefficient or self-purification coefficient of the pollutant, d^{-1}.

2.1.3. Pollutant convection-diffusion modeling in an estuary and near-shore sea

Flows in estuarial and near-shore areas are considerably affected by tide and wind forcing. Such areas are usually wide and shallow in extent, and so MIKE 21, a two-dimensional depth-averaged hydrodynamic and water quality model (Xu et al., 2012; Wang et al., 2011; Yang et al., 2015), is adopted to simulate the sudden leakage of toxic and hazardous substances into an estuary and near-shore sea. MIKE 21 is based on the cell-centered finite volume method implemented on an unstructured flexible mesh (Paliwal and Patra, 2011). It includes hydrodynamic, transport, eco lab/oilspill, mud transport, particle tracking, sand transport, and inland flooding modules. Here we use the hydrodynamic module to predict water motions, the convection diffusion module to predict the transport of non-oils, and the oil spill module to account for oils.

(1) Hydrodynamic module

The Hydrodynamic module is based on numerical solution of the depth integrated incompressible flow Reynolds-averaged mass conservation and Navier-Stokes momentum equations (DHI, 2012a). The governing equations include:

mass conservation:

$$\frac{\partial h}{\partial t} + \frac{\partial h\bar{u}}{\partial x} + \frac{\partial h\bar{v}}{\partial y} = hS \tag{4}$$

momentum conservation:

$$\begin{aligned}&\frac{\partial h\bar{u}}{\partial t} + \frac{\partial h\bar{u}^2}{\partial x} + \frac{\partial h\bar{v}\bar{u}}{\partial y} = f\bar{v}h - gh\frac{\partial \eta}{\partial x} - \frac{h}{\rho_0}\frac{\partial P_a}{\partial x} - \\ &\frac{gh^2}{2\rho_0}\frac{\partial \rho}{\partial x} + \frac{\tau_{sx}}{\rho_0} - \frac{\tau_{bx}}{\rho_0} - \frac{1}{\rho_0}\left(\frac{\partial s_{xx}}{\partial x} + \frac{\partial s_{xy}}{\partial y}\right) + \\ &\frac{\partial}{\partial x}(hT_{xx}) + \frac{\partial}{\partial y}(hT_{xy}) + hu_s S\end{aligned} \tag{5}$$