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Lin Liu
Shandong University of Science and Technology, Qingdao, China.

Wanwu Li
Shandong University of Science and Technology, Qingdao, China., liwanwuqd@126.com

Yumeng Cui
Shandong University of Science and Technology, Qingdao, China.

Guanghui Hu
Shandong University of Science and Technology, Qingdao, China.

Hang Li
Shandong University of Science and Technology, Qingdao, China

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RESEARCH ARTICLE

Simulating and Predicting Offshore Oil Spills by Using Cellular Automata

Lin Liu [a], Wanwu Li [a,*], Yumeng Cui [a], Guanghui Hu [a,b], Hang Li [a]

[a] Shandong University of Science and Technology, Qingdao, China
[b] Nanjing Normal University, Jiangsu, China

Abstract

In recent years, offshore oil spill accidents have caused substantial damage to both marine organisms and marine ecology. Accurate simulation and prediction of oil spills could provide a scientific basis for assessing losses due to oil spills and provide support for emergency decisions regarding oil spills. We analyzed the advantages and disadvantages of existing oil spill models and constructed an offshore oil spill model based on cellular automata (CA). By considering both the flow field and wind field, we formulated new CA rules for the diffusion and drift of a pollution zone, and in our model, the cellular state in eight-neighborhood mode is updated in accordance with these rules, which makes the model suitable for dynamic simulation of offshore oil spills. We also constructed a model on the basis of fuzzy comprehensive evaluation for evaluating the oil spill grade. Finally, we developed a software system, the Ocean Oil Spill Information System (OOSIS), which includes all necessary functions such as basic operations, data management, information query, oil spill analysis, and oil spill assessment. OOSIS is used to verify the constructed oil spill model, and the sea breeze and current data from the National Oceanic and Atmospheric Administration were used to realize the dynamic simulation and prediction, grade evaluation, and cleanup plan generation for offshore oil spill.

Keywords: Offshore oil spill, Cellular automata, Assessment model, Simulation and prediction

1. Introduction

Offshore oil spill accidents occur frequently; thus, characterizing the trajectory and result of oil spills is of great significance. On April 22, 2010, British Petroleum caused an oil spill in the Gulf of Mexico. According to statistics from relevant agencies, the daily leakage of crude oil in this accident was approximately 12,000−100,000 barrels, and the oil pollutant covered over 2500 km^2 of the sea area [1]. In China, typical oil spill accidents include an oil spill caused by the collision of two container ships, “HYUNDAI ADVANCE” and “MSC ILONA”, the oil spill of the Penglai 19-3 oilfield platform, and the “11.22” Huangdao oil spill [1].

Existing oil spill models are typically categorized as numerical [2] and non-numerical [3] models. Numerical models are typically categorized as physical expansion models [4] and chemical change models [5]. Physical numerical models are better suited to practical applications than chemical models, and representative physical models include the Fay theoretical model [6] and the stochastic oil particle based model [7,8]. Wu [9] analyzed the Fay formula with numerical examples and discovered that the spreading time of an oil slick at each stage strongly depends on the oil spill volume. Sriwichien et al. [10] developed a mathematical model for predicting oil spill diffusion on the basis of the Fay hypothesis and Lehr formula, and simulated oil spill diffusion by using wind speed as the main factor. Tian et al. [11] developed a new method of determining the position of an oil spill on the basis of stochastic particle movements, and combined the method with an improved Lagrangian model to

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* Corresponding author.
E-mail address: liwanwuqd@126.com (W. Li).

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determine the origin and trajectory of an oil slick. Drouin et al. [12] used the Monte Carlo method to comprehensively parameterize the weathering process of oil particles and established a Lagrangian oil slick trajectory model to simulate a continuous oil spill on the ocean surface. Fraga Filho [13] proposed a Lagrangian stochastic oil particle based model to predict the diffusion of oil slicks on the ocean surface.

The lattice Boltzmann method (LBM) [14] is another type of physical numerical model. Theoretically, it is based on statistical mechanics and kinetic theory and is also called the kinetic lattice Boltzmann based model (KLBM). Li and Huang [15] proposed a coupled LBM for a flow−pollutant system to directly simulate shallow water dynamics and pollutant transport. The model could solve complex convection and diffusion problems in shallow water. Sol et al. [16] proposed a model for predicting oil film movement and diffusion; the model was based on the LBM and advection diffusion equation (ADE) and simulated simple oil slick conditions without including external environmental factors such as wind speed or sea currents. Maslo et al. [17] used an LBM to simulate the Lebanese oil spill and suggested that the combination of nine discrete particle velocity and two-relaxation time models was the most effective approach for modeling oil spills on a large scale. Kristiansen and Faltinsen [18] used an LBM with nine discrete particle velocity and a multi-relaxation-time collision model to construct a numerical model; the model was then combined with the phase field model of two-phase flow. The results revealed that the numerical model was suitable for simulating the viscous flow of immiscible fluids. Zhang et al. [19] verified the feasibility and effectiveness of the lattice Boltzmann advection diffusion equation (LBM-ADE) for simulating the movement of oil on the ocean surface under various sea currents by conducting a comparison with the GNOME results for the Gulf of Mexico oil spill.

In recent years, non-numerical models have gradually become dominant; the most widely used models are based on cellular automata (CA). Karafyllidi [3] first proposed an offshore oil spill model based on CA in 1997; the model included the effects of sea breezes, currents, the coast, and other factors on oil spill diffusion. The experimental results revealed that the model improved on conventional numerical models. In 2006, Rusinovic et al. [20] created an improved CA oil spill model based on Karafyllidis' model by including the occurrence of sedimentation, emulsification, dissolution, and other factors. Shyue et al. [21] substantially improved the model again in 2007 by including evaporation, convection and other factors, and by applying the principle of conservation of mass. Zodiatis et al. [22] established an oil spill prediction service that combined multiple models by using the Monte Carlo method; the service could simulate the movement, diffusion, and aging of oil spill particles. Bozkurtoğlu et al. [23] combined velocity data with advection, spreading, and evaporation processes to develop an oil spill trajectory model. By including the effects of wind, sea currents, evaporation, emulsification, natural dispersion, and seashore interaction, Glug et al. [24] proposed a model based on the discrete particle method and CA for simulating offshore oil spills. Arkhipov et al. [25] included weather processes and proposed an oil spill diffusion model based on ordinary differential equations describing the balance of forces acting on an axially symmetric oil slick. Sung [26] proposed a model for predicting the movement and diffusion of oil slicks with CA by considering the effects of wind, surface currents, oil evaporation, shoreline deposition, land boundaries, and vertical dispersion. Vourkas et al. [27] considered the effects of water depth, shore waves, shoreline deposition, and oil dissolution in water to propose an algorithm based on CA for predicting oil slick movement and diffusion. Due to the difficulty of obtaining the parameters required for a conventional oil spill model, Zhang et al. [28] constructed a new oil spill model—namely, the neural network oil spill CA model. Zhang [29] used a logistic regression method to obtain the parameter values and established a CA model through logistic regression to simulate the evolution of an oil slick. Chinese scholars have also made various contributions. Li et al. [30] combined intelligent agents to visualize the concentration of oil pollutants and established a diffusion model for river basins. Wang [31] analyzed a numerical model of oil spill drift and diffusion based on conditional simulation, developed a dynamic simulation model of offshore oil spills, and applied this model to an offshore information management and early warning system to obtain accurate and dynamic oil spill predictions in real time. Man et al. [32] and Zhang et al. [33] adopted a CA model for simulating oil slick evolution by including the influences of evaporation, vertical diffusion, shore adhesion, dissolution, emulsification, and other factors.

In summary, in conventional numerical simulation models of oil spills, differential equations are typically used for describing the physical and kinetic processes occurring during oil spills [34]. These equations are critical for studying the nature of oil spill changes and understanding the rules underlying the evolution of oil slicks. However, the influences of the marine environment, climate, and characteristics of the spilled oil increase the complexity of the evolution of an offshore oil spill; expressing these effects accurately by using equations is challenging, and the necessary parameters for simulation formulas are difficult to obtain [35]. The stochastic oil particle based model includes an expression for randomness in the oil spill process and thus is more suitable for simulating the random diffusion and drift in oil spills. These characteristics somewhat ameliorate the deficiencies of conventional numerical models. However, effectively expressing the expansion process of an oil film and the nonrandom drift process of an oil spill by using the stochastic oil particle based model is difficult. In the stochastic oil particle based model, the oil film is assumed to comprise numerous particles, and the oil spill is simulated by calculating the random movements of these particles. Therefore, expressing the evolution of an oil spill in real time is essentially impossible. Moreover, a physical numerical model based on kinetics, such as the KLBM, cannot completely overcome the defects of physical numerical models in essence, such as complex calculations.

An oil spill model based on CA is a promising alternative method. The model has the same framework as a kinetic system, and various algorithms can be used to express the kinetic factors of an oil spill by defining conversion rules [3]. Moreover, cells can be used to model actual oil spills more accurately than stochastic oil particles can. In addition, the cellular grid and oil spill raster data obtained from remote sensing images have a natural fit, and the grid is suitable for management and processing with a GIS system, improving the practical usability of the system's results.

In conclusion, simulated data instead of real data have been used for processing in most models to date. Moreover, the time scale of the data used in some studies is excessively long and not representative.

To overcome these deficiencies, we propose a new CA-based oil spill model by improving the transformation rules. The model integrates the expansion, diffusion, and drift processes of an oil spill, resulting in better simulation of the overall oil spill process. Moreover, high-accuracy sea breeze data, sea current data, and actual oil spill data from Bohai Bay were used to test the CA oil spill model in an online real-time dynamic simulation of an entire oil spill process.

2. Data

2.1. Overview of the study area

The research area is the Bohai Sea. Numerous large ports are located in the Bohai Rim area and are primarily used for transportation of foreign goods, energy and raw materials; these ports and resources are critical for economic and social development in China and are a key link between China and other countries [36]. However, the large number of port groups and complex navigation routes in the Bohai Sea mean that the risk of oil spill accidents in this area is high. For example, the probability of an oil spill accident is very high in busy ports such as Tianjin and Dalian [37,38]. Moreover, the Bohai Sea is a peninsular sea and thus has low self-purification ability. If the marine ecology of the Bohai Sea is destroyed by an oil spill, the environment would not recover easily [39].

2.2. Data acquisition and processing

Sea breeze and current data for the Bohai Sea area were acquired from the National Oceanic and Atmospheric Administration (NOAA). The sea breeze data provided by the NOAA are blended sea winds, including vector winds on the ocean surface and wind stresses. The blended sea breeze dataset is global gridded data with a spatial resolution of 0.25 and time resolution of 6 hours, 1 day or 1 month. The dataset used in our research is the gridded data with a spatial resolution of 0.25° and a time resolution of 6 hours. The data are in the netCDF format (e.g., files such as *uv20110618.nc* or *uv20110619.nc*). The dataset integrates observations from multiple satellites to fill temporal and spatial data gaps in the observations of individual satellites to reduce subsampling aliases and random errors. The dataset was developed in response to demand for increasingly high-resolution global datasets.

The sea current data for the Bohai Sea area were obtained from the Naval Oceanographic Office (NOO) Global Navy Coastal Ocean Model. The model is managed by the NOO and used as the Naval Global Ocean Forecasting System before its replacement with the global HYbrid Coordinate Ocean Model system in 2013. The model is a Princeton Ocean Model with a mixed (σz) vertical coordinate system. The NOO divides the global sea area into 13 major regions and interpolates outputs to regular horizontal latitude and longitude grids and a series of vertical standard depths to generate a dataset. The sea current dataset for the Bohai Sea used in our research is located in Region 5, as shown in Fig. 1. The sea current data includes the east and north components of the current, which are interpolated to a 0.125° Cartesian grid in the horizontal and to standard depth grades in the vertical. The data model cycle is 1 day, and the output time step is 3 hours. The data type is GRID, the data format is netCDF, and the size of each dataset is approximately 579.5 MB; the datasets included files such as *ncom_glb_regp05_2011061700.nc* and *ncom_glb_regp05_2011061800.nc*.

3. Oil spill diffusion model based on CA

3.1. Principles of CA

The CA model was first introduced by von Neuman [40] and has been widely used as a model for complex systems [41]. A CA model is a model of a physical system in which space and time are discrete and interactions are only local. CA models have been applied to several physical problems that involve local interactions [42–46]. Although the structure of a CA model is simple, the models reveal complex kinetic behavior and can describe numerous physical systems and processes. A CA model comprises regular and uniform n-dimensional grid points (or arrays). At each position in the grid (at each cell), a physical quantity takes a value. This physical quantity is the global state of the CA, and its value in each cell is the local state of the cell. Each cell is limited to interactions in its local neighborhood; the cells cannot perform immediate global communication [40]. The neighborhood of a cell is defined as the cell itself, its adjacent cells, and some or all of its diagonally neighboring. At discrete time steps, the state of each cell is simultaneously updated on the basis of the state of its neighborhood in the previous time step. The algorithm used to calculate the next cellular state in CA is called the CA local rule. Generally, the same local rules apply to all cells in CA. In CA, each part determines the whole, local simplicity becomes global complexity, and numerous cells interact to achieve dynamic evolution.

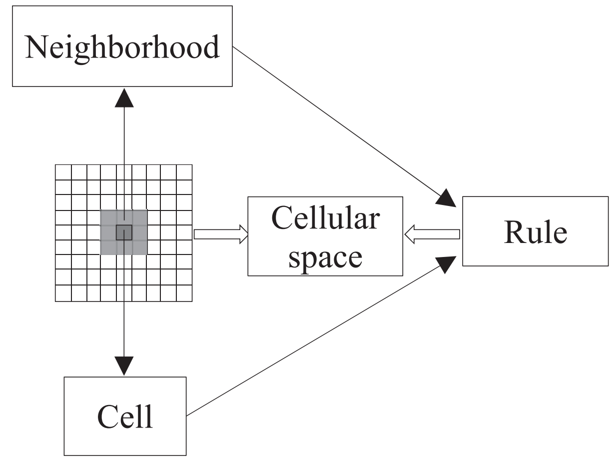


Fig. 2. Cellular space.

The CA model can be described mathematically as follows:

$$S_{t+1} = f(S_t, N) \quad (1)$$

In this formula, S is the finite set of cellular states, N indicates the neighbors of a cell, t is the

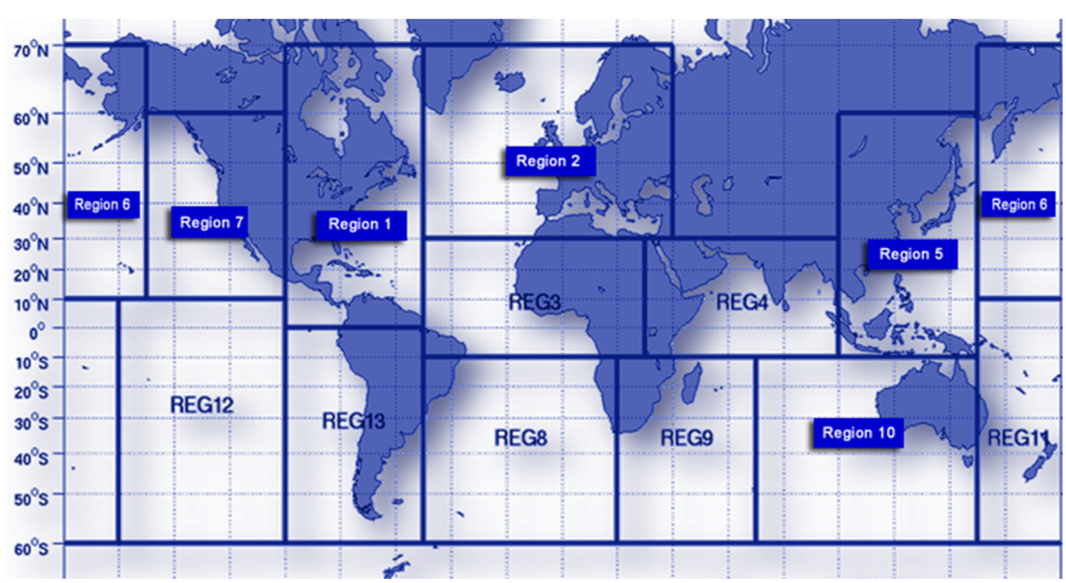


Fig. 1. Global sea division according NOO.

time step, and f is the conversion rule. The principle of CA is illustrated in Fig. 2.

3.2. Oil spill model based on CA

Cellular space is similar to the raster data structure of GIS. The cellular space can be combined with the raster grid space to define a spatial scale for each cell, that is, each cell has a spatial resolution. Spatial resolution data are critical for CA models. In this study, the grid transformation of the cell is the action of covering the sea surface with a grid (Fig. 3).

For an oil spill, within the initial distribution range of the oil, a Gaussian distribution is adopted to assign a mass of oil pollutant to each cell in the area to obtain the initial oil pollutant mass of each cell. The cellular state threshold M_{th} is then set in accordance with the attributes of the oil pollutant. For each time step t, the oil pollutant in the cell (X_i, Y_j) is transmitted to adjacent cells in eight directions in accordance with its mass from large to small, as presented in Fig. 4.

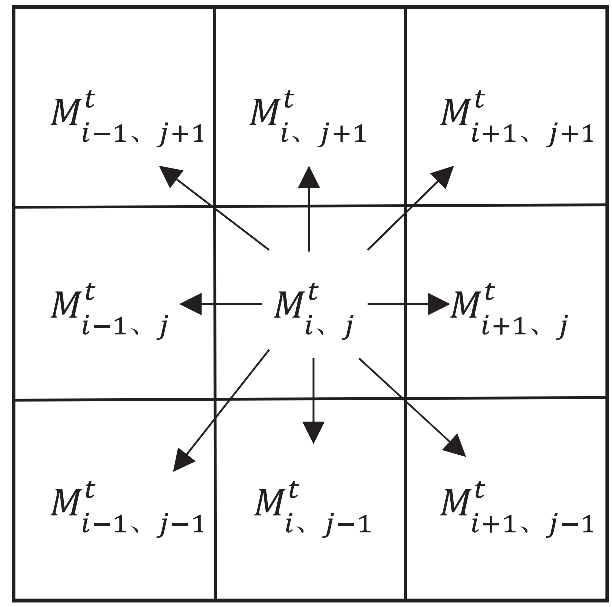


Fig. 4. Oil pollutant transmission.

The mass of oil pollutant in the cell is reassigned and recalculated. At the t+1 time step, the mass of oil pollutant in the cell (X_i, Y_j) can be calculated as follows:

$$M^{t+1}_{i,j} = M^t_{i,j} + \left\{ m\left[\left(M^t_{i-1,j} - M^t_{i,j}\right) + \left(M^t_{i+1,j} - M^t_{i,j}\right) + \left(M^t_{i,j+1} - M^t_{i,j}\right) + \left(M^t_{i,j-1} - M^t_{i,j}\right)\right]\right\} + \left\{ md\left[\left(M^t_{i-1,j+1} - M^t_{i,j}\right) + \left(M^t_{i-1,j-1} - M^t_{i,j}\right) + \left(M^t_{i+1,j+1} - M^t_{i,j}\right) + \left(M^t_{i+i,j-1} - M^t_{i,j}\right)\right]\right\} \quad (2)$$

In the equation, m is the transfer coefficient of oil pollutant in the four positive directions of east, west, south and north, and d is the oblique angle correction coefficient.

According to the law of conservation of mass, the outflow mass of oil pollutant must be less than or equal to the original mass of the oil pollutant in cells; therefore, the relationship between m and d satisfies the following equation:

$$m + md \leq 0.25 \quad (3)$$

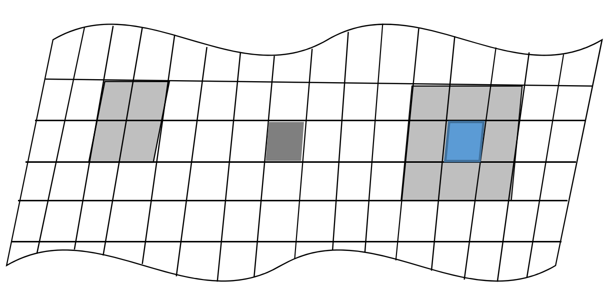


Fig. 3. Celluar grid on the sea surface.

After each evolution, the mass of the oil pollutant in each cell in the cellular space must be checked so that the cell's pollution status can be updated. If the mass of oil pollutant in a cell meets the condition $M^t_{i,j} \geq M_{th}$, the cell is said to be in the polluted state; otherwise, the cell is unpolluted. After updating the status of each cell, the process is repeated in the next time step to dynamically model the evolution of diffusion.

3.3. Expression of factors affecting diffusion

On the basis of an analysis of the characteristics of the study area, this study selected wind speed, wind direction, water flow velocity, and water flow direction as the factors affecting the diffusion of oil pollution. To express these factors, influence coefficients were introduced to reflect the effects of sea breezes and currents. Eq. (2) is thus modified to obtain Eq. (4):

$$\begin{aligned} M_{i,j}^{t+1} = M_{i,j}^{t} + \Big\{ m\Big[\Big(\big(1+W_{i,j}^{t}\big)M_{i-1,j}^{t} - \big(1-W_{i,j}^{t}\big)M_{i,j}^{t} \Big) + \Big(\big(1+E_{i,j}^{t}\big)M_{i+1,j}^{t} - \big(1+E_{i,j}^{t}\big)M_{i,j}^{t} \Big) + \\ \Big(\big(1+N_{i,j}^{t}\big)M_{i,j+1}^{t} - \big(1+N_{i,j}^{t}\big)M_{i,j}^{t} + \big(1+S_{i,j}^{t}\big)M_{i,j-1}^{t} - \big(1+S_{i,j}^{t}\big)M_{i,j}^{t} \Big) \Big] \Big\} + \\ \Big\{ md\Big[\Big(\big(1+NW_{i,j}^{t}\big)M_{i-1,j+1}^{t} - \big(1+NW_{i,j}^{t}\big)M_{i,j}^{t} \Big) + \Big(\big(1+SW_{i,j}^{t}\big)M_{i-1,j-1}^{t} - \big(1+SW_{i,j}^{t}\big)M_{i,j}^{t} \Big) + \\ \Big(\big(1+SE_{i,j}^{t}\big)M_{i+1,j+1}^{t} - \big(1+SE_{i,j}^{t}\big)M_{i,j}^{t} \Big) + \Big(\big(1+NE_{i,j}^{t}\big)M_{i+1,j-1}^{t} - \big(1+NE_{i,j}^{t}\big)M_{i,j}^{t} \Big) \Big] \Big\} \end{aligned} \tag{4}$$

In the equation, $W_{i,j}^t$, $E_{i,j}^t$, $N_{i,j}^t$, $S_{i,j}^t$, $SW_{i,j}^t$, $NW_{i,j}^t$, $SE_{i,j}^t$, and $NE_{i,j}^t$ are the sums of the correction coefficients of the sea breeze and current from each direction; for example, $NW_{i,j}^t$ is the sum from northwest to southeast and $E_{i,j}^t$ is the sum from east to west. An additional correction coefficient is introduced:

$$W_{i,j}^t = WW_{i,j}^t + WF_{i,j}^t \tag{5}$$

Here, $WW_{i,j}^t$ and$WF_{i,j}^t$ are the correction coefficients for the sea breeze and current, respectively, from west to east; the entire W coefficient is jointly determined by two parts. $WW_{i,j}^t$ is the correction coefficient due to the west wind on the system at time t:

$$WW_{i,j}^t = \alpha * cos\theta * \omega_{10}^t \tag{6}$$

In this equation, ω_{10}^t is the wind speed at a height of 10 m from the water surface, and α is the wind drift factor, which is directly proportional to the wind speed and water surface width and inversely proportional to the water depth. Its value is calculated with the following equation:

$$\alpha = \beta^2 * \delta * \nu \tag{7}$$

In Eq. (7), $\delta = B/h$ is the aspect ratio; however, the present research was focused on the ocean surface. Thus, δ was set to 1. Additionally, ν is the average wind speed and $\beta = 0.03$ is an empirically derived constant.

In Eq. (6), the value of θ is related to the wind speed as follows:

$$\theta = \begin{cases} 40^\circ - 8\sqrt{\omega_{10}^t} & 0 \le \omega_{10}^t \le 25m/s \\ 10 & \omega_{10}^t > 25m/s \end{cases} \tag{8}$$

$WF_{i,j}^t$ is the correction coefficient for the system due to water flow from west to east at time t:

$$WF_{i,j}^t = V^t \Big/ V_{max} \tag{9}$$

V^t is the water flow velocity of the flow field at t, and V_{max} is the maximum flow velocity observed in the sea area.

4. Oil spill evaluation modeling based on fuzzy comprehensive evaluation

An index system was constructed to evaluate the grade of pollution duo to an oil spill. Fuzzy comprehensive evaluation (FCE) methods were used, and oil spill quantity, oil spill position, the meteorological environment, the hydrological environment, and oil properties were used as the primary indexes for the evaluation system. A new membership function of the factors affecting the oil spill quantity and location was analyzed and constructed (Fig. 5 and Fig. 6).

Let q be the oil spill quantity, and μ_{q1}, μ_{q2}, and μ_{q3}, respectively, represent the membership functions of light, moderate, and heavy oil spill pollution for an oil spill quantity q as defined in Eq. (10), Eq. (11), and Eq. (12).

$$\mu_{q1} = \begin{cases} 1 & q \le 0.3 \\ \frac{1}{0.7} - \frac{1}{0.7}q & 0.3 < q \le 1 \\ 0 & q > 1 \end{cases} \tag{10}$$

$$\mu_{q2} = \begin{cases} 0 & q \le 1 \\ \frac{1}{9}q - \frac{1}{9} & 1 < q \le 10 \\ 1 & 10 < q \le 50 \\ 2 - \frac{1}{50}q & 50 < q \le 100 \\ 0 & q > 100 \end{cases} \tag{11}$$

$$\mu_{q3} = \begin{cases} 1 & q \le 50 \\ \frac{1}{200}q - \frac{1}{4} & 50 < q \le 250 \\ 0 & q > 250 \end{cases} \tag{12}$$

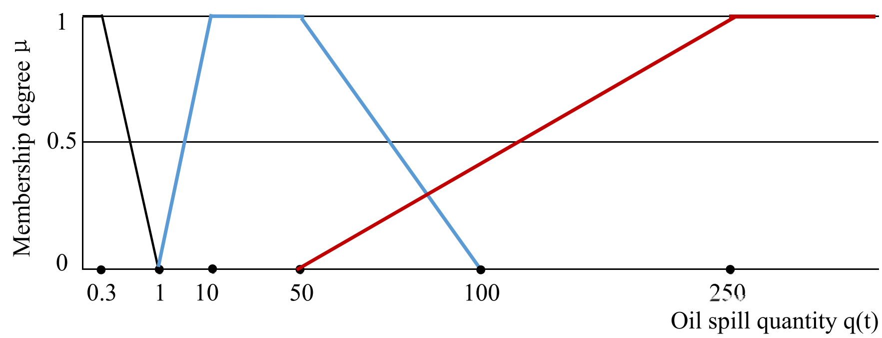


Fig. 5. Membership functions curve of oil spill quantity.

The constants in these formulas were determined through experience and on the basis of the author's previous research work in accordance with the classification standard for the grades of actual oil spill volume and pollution [33,47].

Let r be the distance between the oil spill point and a key area, such as a marine protected area, breeding area, or important facility. At the distance r, μ_{r1}, μ_{r2}, and μ_{r3} respectively represent the membership functions of light, moderate, and heavy oil spill pollution as defined in Eq. (13), Eq. (14) and Eq. (15).

$$\mu_{r1} = \begin{cases} 1 & r > 50 \\ \frac{1}{45}r - \frac{1}{9} & 5 < r \le 50 \\ 0 & r \le 5 \end{cases} \tag{13}$$

$$\mu_{r2} = \begin{cases} 0 & r > 10 \\ 2 - \frac{1}{5}r & 5 < r \le 10 \\ 1 & 1 < r \le 5 \\ \frac{1}{0.5}r - 1 & 0.5 < r \le 1 \\ 0 & r < 0.5 \end{cases} \tag{14}$$

$$\mu_{r3} = f(x) = \begin{cases} 0 & r > 1 \\ 1 - r & 0 < r \le 1 \end{cases} \tag{15}$$

The constants in these formulas were again determined through experience and on the basis of the author's previous research work in accordance with the actual distance range of oil spill point and the classification standard for the grade of oil spill pollution [33,47].

The FCE method was employed to evaluate the degree of oil spill pollution. The comment set is F = {light, moderate, heavy}, and the single factor evaluation index could be obtained using the membership function of these two indexes.

$$R_1 = \left[\mu_{q1}, \mu_{q2}, \mu_{q3}\right] \tag{16}$$

$$R_2 = [\mu_{r1}, \mu_{r2}, \mu_{r3}] \tag{17}$$

Similarly, the single factor evaluation indexes R_3, R_4, and R_5 of the other three indexes were determined. On the basis of these indexes, the fuzzy vector matrix was obtained:

$$R = \left[R_1^T, R_2^T, R_3^T, R_4^T, R_5^T\right]^T \tag{18}$$

Let the weight vector be as follows:

$$W = [w_1, w_2, w_3, w_4, w_5] \tag{19}$$

The fuzzy transformation must then be performed:

$$M = W \circ R \tag{20}$$

In Eq. (20), $\circ$ represents the fuzzy matrix synthesis operator. Here, the model $M(\bullet, \oplus)$ is adopted; that is, ordinary real number multiplication and the bounded sum operator. Because the sum of all components of the weight vector is 1, this operation becomes general real number addition; namely $M(\bullet, \oplus) \to M(\bullet, +)$. By using this operator, the result can take into account the influence of various factors. Substituting Eq. (18) and Eq. (19) into Eq. (20) results in the following equation:

$$M = [w]_{1\times5} \circ [R]_{5\times3} \tag{21}$$

Data on an oil spill, including the oil quantity, distance, surface velocity, surface water temperature, type of sea area, and main components of the oil pollution were collected for calculations. The result $[M]_{1\times3}$ was the comprehensive evaluation result for the corresponding comment set F = {light, moderate, heavy}, that is, the result of the evaluation of the oil spill pollution grade.

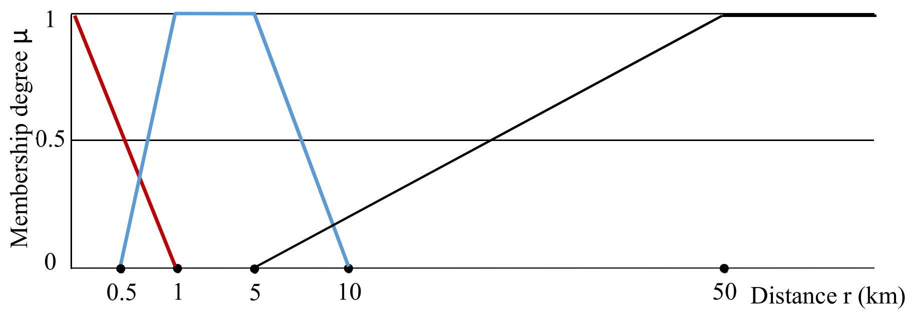


Fig. 6. Membership functions versus offshore distance.

5. Oil spill diffusion simulation and prediction

5.1. Development of the Ocean Oil Spill Information System

To verify the applicability of the constructed CA-based oil spill model, the WebGIS architecture was adopted to develop an Ocean Oil Spill Information System (OOSIS). The system has various basic functions and modules for data management, queries, oil spill analysis, and oil spill evaluation among others. The interface is presented in Fig. 7. The function menu is located on the left side of the interface.

(1) Basic function module

The basic modules of the OOSIS are the user module and basic tool module. The user module is used for user login, registration, and permissions management. The basic tool module is a set of frequently used system tools independently developed with the secondary development interface for ArcGIS, (black border on the upper part of Fig. 7). From left to right, these tools are as follows: switch map, clear map, eraser, restore with the mouse, zoom in, zoom out, pan, previous view, next view, initial map, bookmark, layer management, measurement tool, map export, eagle eye view, Google Maps, and contact customer service. Among these, "switch map" enables the users to switch between three maps streets, topographic, and satellite maps. Local and online maps can be overlain in the key research area.

(2) Query function module

The query function module provides three query functions: attribute, spatial, and comprehensive queries. The system provides multiple query tools as displayed in the black-bordered box on the left in Fig. 8. Fig. 8 presents the results of a query for the oil spill point, and Fig. 9 presents the comprehensive query interface.

(3) Oil spill analysis module

The oil spill analysis module has five functions: layer addition, boundary extraction, diffusion

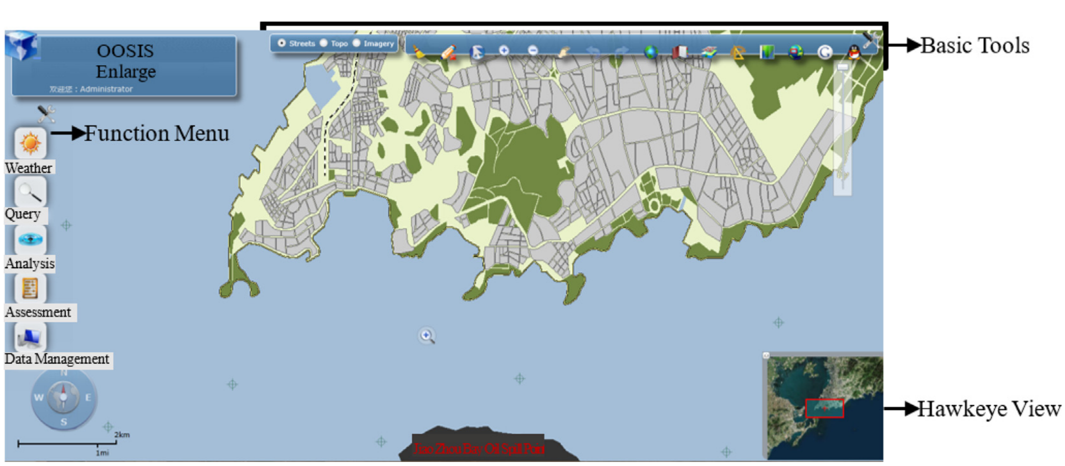


Fig. 7. OOSIS interface.

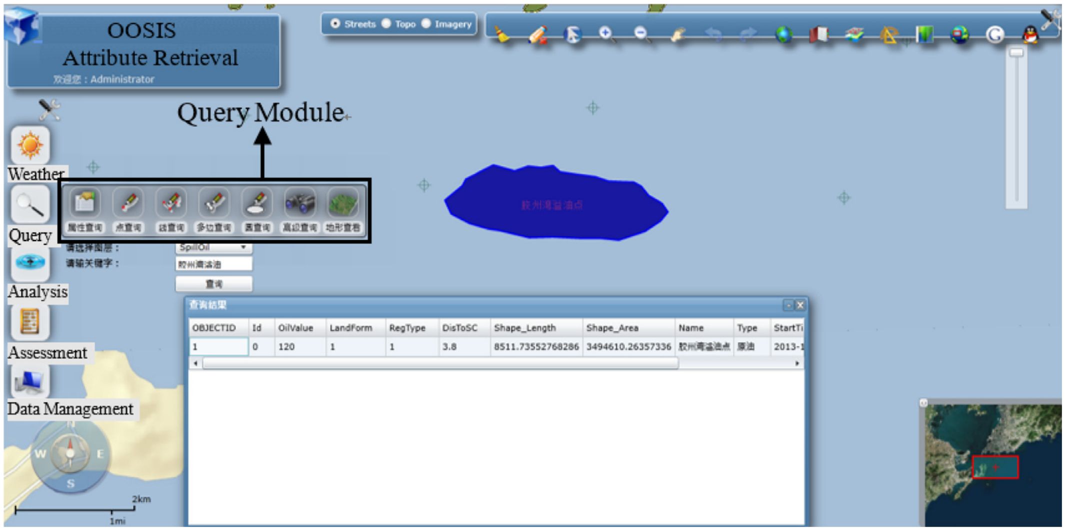


Fig. 8. Property search results.

analysis, thickness analysis, and thickness query (left toolbar, Fig. 10). Oil spill diffusion analysis includes two analysis modes. In the first, oil spill diffusion is simulated on the basis of the assumed oil spill point; in the second, future diffusion is predicted on the basis of the existing oil spill area. The function of layer addition obtains remote sensing images of an oil spill point and adds them to the system, as displayed in Fig. 10. After a patch has been added, its boundary can be extracted to facilitate the subsequent diffusion analysis, as illustrated in Fig. 11.

(4) Oil spill evaluation module

The functions of the oil spill evaluation module are presented in the black-bordered box on the left

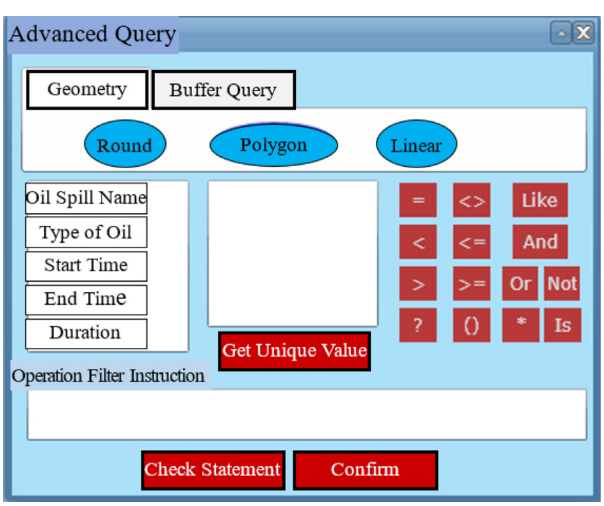


Fig. 9. Comprehensive query interface.

in Fig. 12; these functions are grade evaluation, ship plan, isolation plan, and loss statistics. In the oil spill grade evaluation tool, the FCE-based model detailed in Section 4 of this paper is used to evaluate the grade of the oil spill hazard, as shown in Fig. 12. The ship plan tool generates the optimal path for a cleanup ship to reach the oil spill accident given the ship's position, wind direction, sea waves, distance, and expansion of the oil spill area. This path is then displayed on the map, as shown in Fig. 13. The isolation plan tool analyzes the sea area around the oil spill area to determine the optimal isolation plan and then displays it on the map, as shown in Fig. 14.

(5) Data management module

The data management module provides system administrators with management tools such as storing, updating, and deleting of oil spill data, as shown in Fig. 15. The data types are divided into raster data, ocean current field data, ocean wind field data, and others.

5.2. Oil spill accident simulation

The oil spill accident at the Penglai 19-3 oilfield in 2011 caused the water quality of 840 km^2 of seawater to decrease from its initial grade of Class I, indicating optimal seawater, to Class IV, a grade equivalent to that of sewage from an outlet. The economic losses of marine farms were enormous.

The model constructed in our research was adopted to simulate the Penglai 19-3 oilfield spill event in the developed OOSIS. The oil spill lasted for the 5 days of June 17–21, and the total mass of

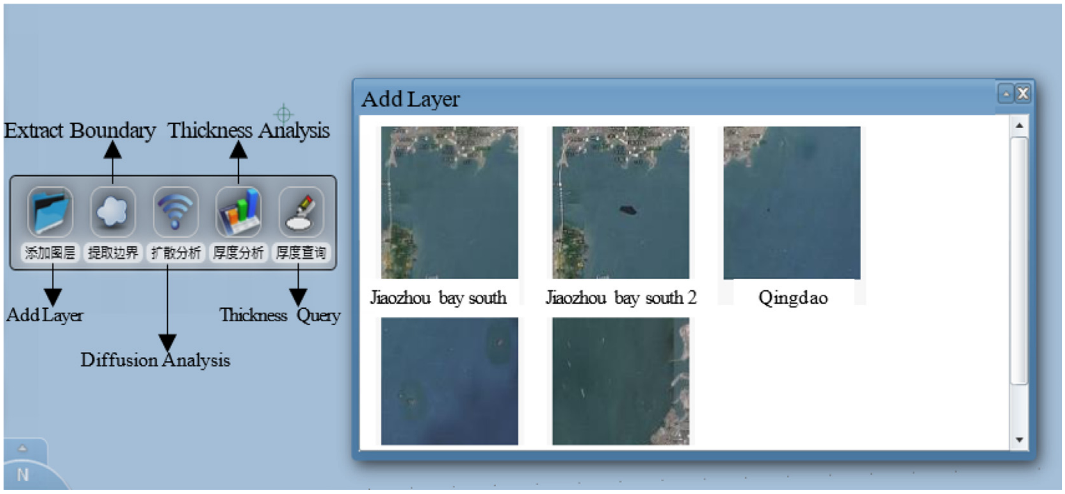


Fig. 10. Oil spill analysis tools.

the oil spill was approximately 100 tons. Due to the size of the grid and other factors, the threshold value was set to 70 kg. The sea breeze and current data for the Bohai Sea area during the 5 days were input to the model for calculation. The system provides a time selector, as shown in Fig. 16. Any interval during the five days can be chosen for viewing. The simulation result for the 5-day period of the oil spill is presented in Fig. 17.

5.3. Oil spill events prediction

The oil spill prediction module is a core function module in the system. Its primary function is to dynamically predict the heat map of an oil spill by selecting the location of the event on the map and setting various parameters.

The oil spill event simulation and prediction process is as follows:

(1) Select the location of the event on the map.
(2) In the pop-up dialog box, input the number of days to be predicted, the total mass of the oil spill, and the threshold value. The subsequent parameter-setting window differs in accordance with the number of simulation days, as shown in Fig. 18.
(3) Input the specific values of wind direction, wind speed, current direction, current speed and other parameters, and click OK, as presented in Fig. 19.

The developed OOSIS is used to predict oil spills. The parameter settings are presented in Table 1, and the prediction results are shown in Fig. 20.

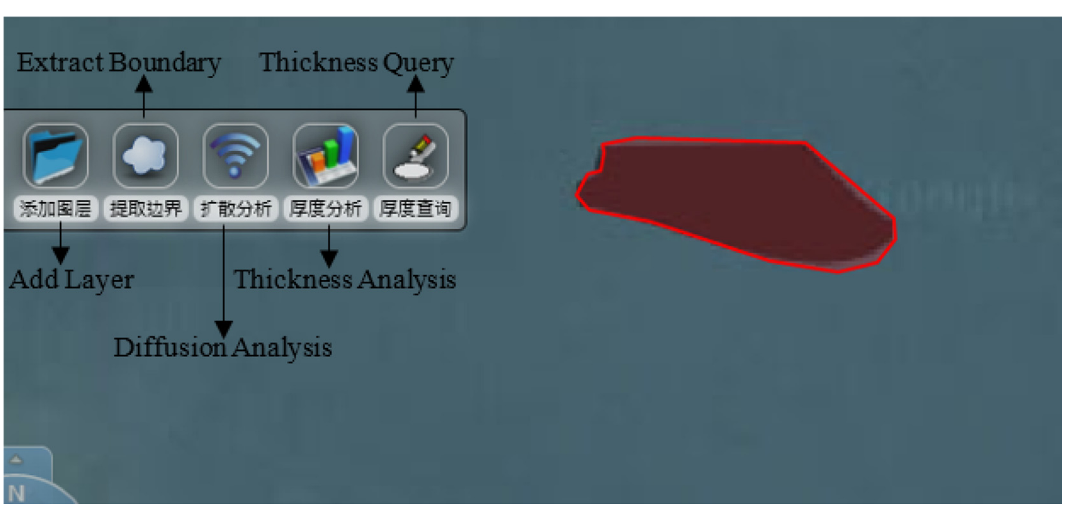


Fig. 11. Boundary extraction.

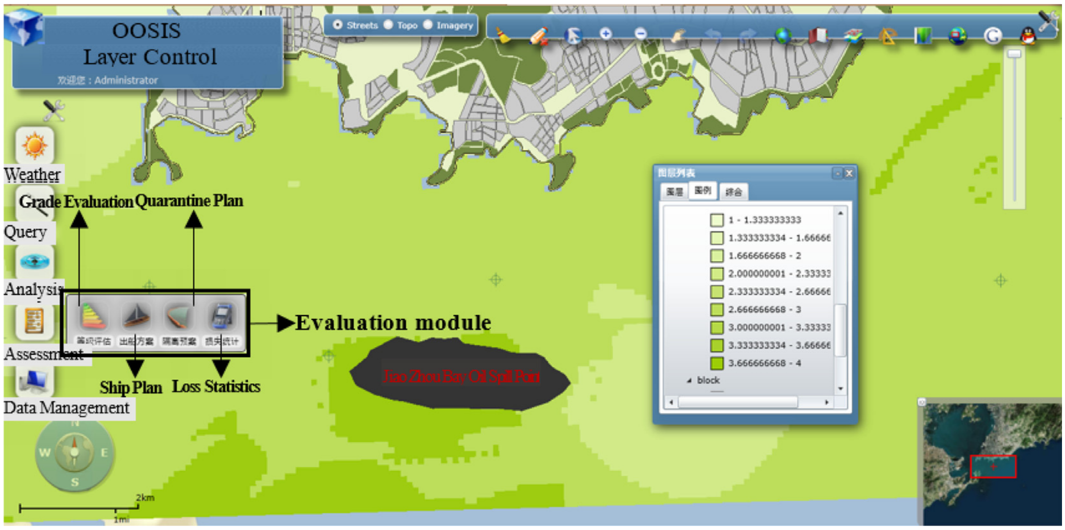


Fig. 12. Oil spill grade assessment.

Fig. 13. Ship plan.

The physical numerical model of an oil spill, represented by Fay theory, simulates the evolution process of the oil spill by using kinetic equations. However, due to the influence of various factors in the marine environment and the characteristics of the oil product, accurately expressing the complex evolution process of an offshore oil spill by using equations is difficult, as is obtaining the parameters for these equations. The stochastic oil particle based model has improved expressions for stochastic diffusion and stochastic drift in the oil spill process; the model is more advanced than conventional numerical models such as Fay theory. However, effectively expressing the expansion process of the oil film and the non-stochastic drift process for the oil spill is challenging with the stochastic oil particle

Fig. 14. Isolation plan.

Fig. 15. Data management function.

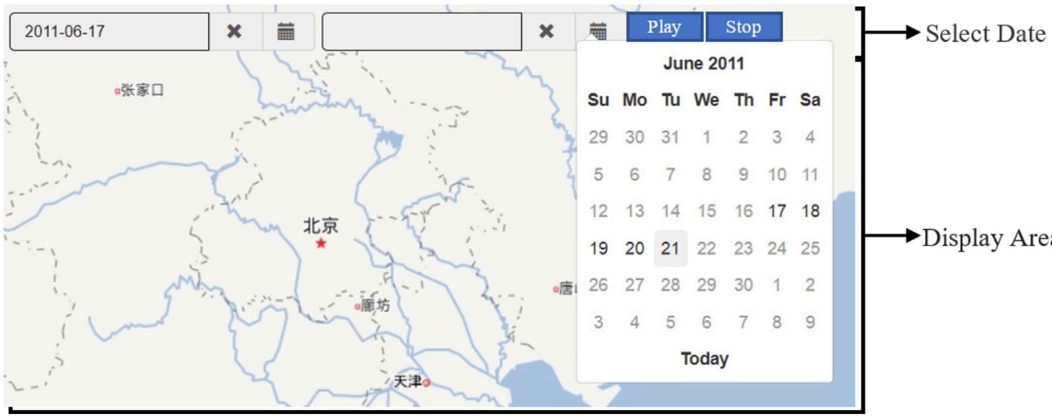


Fig. 16. Date selection in the system.

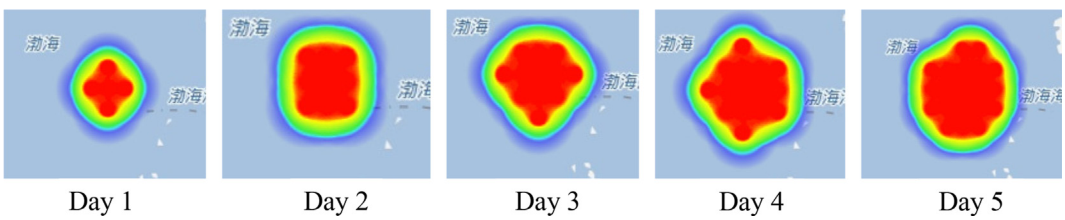


Fig. 17. Simulation results for the 5-day oil spill.

based model. In the stochastic oil particle based model, the oil film is assumed to be composed of numerous oil particles; thus, performing real-time simulation of the oil spill process, including the stochastic process and kinetic processes, is essentially impossible. By using CA, we set up random transformation rules based on kinetic conditions, and constructed a new simulation and prediction model for oil spills. By contrast with conventional numerical models, the constructed model does not require complicated equations or parameters, and simulating and predicting the oil spill is simple. Compared with the stochastic oil particle based model, the CA model has natural conformance with GIS grid data for oil spills and thus is better suited for application to real-world oil spills. Unlike the KLBM, the constructed model integrates the expansion, diffusion, and drift processes of oil spills to achieve superior overall oil spill simulation. Compared with the existing oil spill simulation results, the constructed model uses actual oil spill data

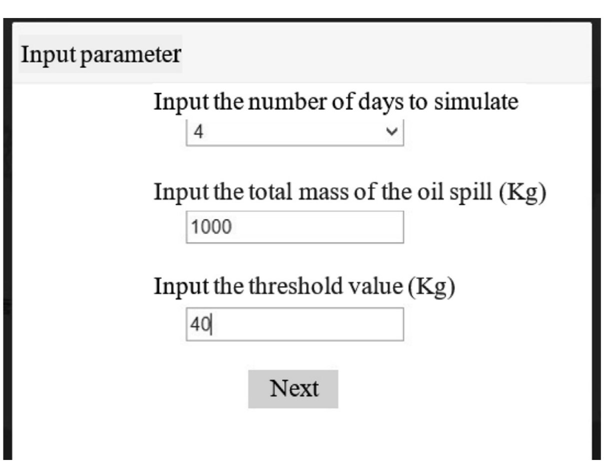


Fig. 18. Dialog box for inputting prediction days.

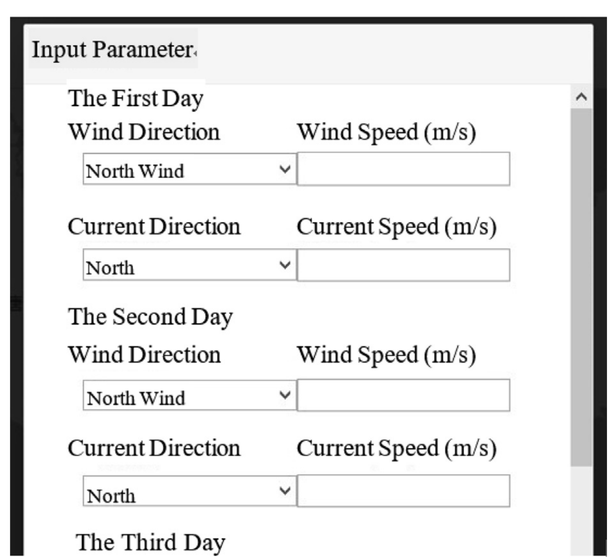
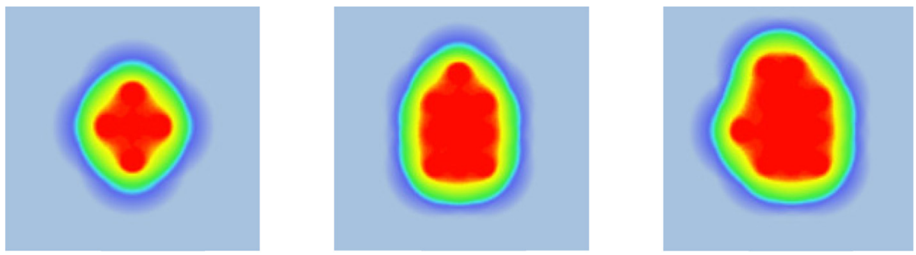


Fig. 19. Dialog box for inputting parameters.

Table 1. Parameter settings.

Parameter / Time	Wind direction	Sea current direction	Wind speed m/s	Flow rate m/s	Total mass of oil spill (Kg)	Threshold (Kg)
The first day	North	North	2	0.5		
The second day	East	Northeast	6	0.7	1200	70
The third day	Northeast	East	3	0.2		



Day 1 Day 2 Day 3

Fig. 20. Prediction result.

with high accuracy, simplifying calculations and improving the real-time performance of the simulation and prediction of oil spills. Moreover, the oil spill assessment based on FCE has a balance between simulation accuracy and real-time performance, increasing the potential for the system to be used in real-world applications.

6. Conclusions

An offshore oil spill event is a typical "unconventional emergency", that is, it has few precursor signs and requires complex incident resolution. In this research, we established an oil spill model based on CA by considering both the kinetic characteristics and uncertainty of oil pollutant diffusion in the ocean. First, the cellular space is established; the sea area space is divided into square grids combining the structure of GIS raster data; each square grid is a cellular space. Second, the general CA model is extended from the aspects of evolution rules and cellular states. A value is then assigned to the cell in accordance with obtained sea breeze and current data. The cellular state is then altered on the basis of the evolution rules. Finally, each cellular state is categorized in accordance with the calculated mass of oil pollutant contained in the cell, and the diffusion and migration processes of the oil pollutant are dynamically evolved. The OOSIS was developed to realize simulation and prediction of oil spills based on CA and evaluation of oil spills based on FCE. This evaluation can be used to determine a cleanup plan for oil spills, and the route of the incident response ship and a layout for an oil fence can be designed.

On the basis of the CA framework, the oil spill simulation and prediction model constructed in this paper integrated the processes of oil spill expansion, diffusion, and drift to set new rules in the model. Compared with the conventional Fay theory model and stochastic oil particle based model, the constructed model has superior overall simulation and prediction results for oil spills. Moreover, the model can balance the simulation accuracy and calculation speed. Finally, OOSIS software was developed to realize online real-time dynamic simulations of oil spills; the software was tested using real-time oil spill data from the Bohai Bay incident.

Conflict of interest

The authors declare no conflict of interest.

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