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DEVELOPMENT OF A GIS-BASED OIL SPILL MODEL AND ITS APPLICATION IN THE THREE GORGES RESERVOIR

Jiaxing Chen[1]
He Chen[2]
Hong Geng[3]
Hua Li[3]
Jun Qi[4]

[1]College of Chemical and Environmental Engineering, Jiaozuo University, Jiaozuo, China
[2]State Key Laboratory of Environment Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing, China
[3]China Academy of Transportation Sciences, Ministry of Transport, Beijing, China
[4]Beijing Municipal Research Institute of Environmental Protection, Beijing, China

A GIS-aided oil spill model was developed to simulate currents and oil transportation in rivers, lakes and reservoirs. The model is a two-dimensional hydrodynamic/oil spill model based on GIS. The use of GIS facilitates and improves communication of the spill behavior. A finite element solution of the Reynolds form of the Navier-Stokes equations for turbulent flows was used to simulate the currents in rivers. Mass conservation theory and wind functions were integrated into an oil spill model. The model was applied to the Three Gorges Reservoir where a 50 ton light oil spill was simulated.

INTRODUCTION

Transportation in rivers and lakes has increased the risk of oil spill accidents. Oil spill accidents are very harmful to ocean environments and human health. To prepare for such accidents, many government agencies have prepared oil spill contingency plans (Fingas, 1995; Chao et al., 2001). Numerical modeling of oil spills plays an important role in the environmental monitoring and prediction of environmental pollution (Spaulding et al., 1994; Varlamov et al., 2000; Chao et al., 2001).

Many oil spill dispersion models have been developed and published (Garcia-Martinez and Flores-Tovar, 1999; D'Asaro, 2000; Zhu and Strunin, 2002; Korotenko et al., 2003; Liu and Wirtz, 2005; Wang et al., 2005; Alvarez et al., 2006; Tkalich, 2006; Eide et al., 2007; Elhakeem et al., 2007; Kankara and Subramanian, 2007; Perianez, 2007). Most of these papers describe spill models for marine systems and have no convenient interface with a GIS. We adopted a 2D hydrodynamic model and oil dispersion model to simulate oil spills in rivers and reservoirs. A GIS interface was used to display results and give environmental managers a useful tool.

The Three Gorges Reservoir is one of the largest reservoirs in the world and a "golden passage" for water transportation in China. There will be oil film floating on the surface and moving downstream if boats in the Three Gorges Reservoir spill oil. The model developed in this paper will improve the efficiency of oil spill prediction and remediation.

METHOD

The oil spill model consists of two parts: a hydrodynamic model and an oil dispersion model. A 2D hydrodynamic model was used to obtain flow currents in rivers and reservoirs. Oil dispersion was solved using a particle tracking method. Oil spill was simulated by a number of particles, each of them equivalent to a number of units, whose paths are followed in time.

Hydrodynamic Model

We used RMA2 to compute a finite element solution of the Reynolds form of the Navier-Stokes equations for turbulent flows (Donnell et al., 2003). Friction is calculated with the Manning's or Chezy equation, and eddy viscosity coefficients are used to define turbulence characteristics. Both steady and unsteady (dynamic) problems can be analyzed.

The governing equation solves the depth-integrated equations of fluid mass and momentum conservation in two horizontal directions. The forms of the governing equations are

Continuity equation:

$$\frac{\partial h}{\partial t}+h\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)+u\frac{\partial h}{\partial x}+v\frac{\partial h}{\partial y}=0 \tag{1}$$

x-wise momentum equation:

$$h\frac{\partial u}{\partial t}+hu\frac{\partial u}{\partial x}+hv\frac{\partial u}{\partial y}-\frac{h}{\rho}\left(E_{xx}\frac{\partial^2 u}{\partial x^2}+E_{xy}\frac{\partial^2 u}{\partial y^2}\right)+gh\left(\frac{\partial a}{\partial x}+\frac{\partial h}{\partial x}\right)$$
$$+\frac{gun^2}{\left(C_0 h^{1/6}\right)^2}\left(u^2+v^2\right)^{1/2}-\xi V_a^2\cos\psi-2hv\omega\sin\Phi=0 \tag{2}$$

y-wise momentum equation:

$$h\frac{\partial v}{\partial t}+hu\frac{\partial v}{\partial x}+hv\frac{\partial v}{\partial y}-\frac{h}{\rho}\left(E_{yx}\frac{\partial^2 v}{\partial x^2}+E_{yy}\frac{\partial^2 v}{\partial y^2}\right)+gh\left(\frac{\partial a}{\partial y}+\frac{\partial h}{\partial y}\right)$$
$$+\frac{gvn^2}{\left(C_0 h^{1/6}\right)^2}\left(u^2+v^2\right)^{1/2}-\xi V_a^2\sin\psi+2hu\omega\sin\Phi=0 \qquad (3)$$

where h is water depth; u, v are velocities in the Cartesian directions; x, y are cartesian coordinates; t is time; ρ is density of fluid; E is Eddy viscosity coefficient; E_{xx} is normal direction on x axis surface; E_{yy} is normal direction on y axis surface; E_{xy}, E_{yx} are shear directions on each surface; g is acceleration due to gravity; n is Manning's roughness n-value; ξ is empirical wind shear coefficient; V_a is wind speed; a is elevation of bottom; ψ is wind direction; ω is rate of earth's angular rotation; Φ is local latitude; C_0 is conversion from SI (metric) to non-SI units.

Equations 1, 2, and 3 are solved by the finite element method using the Galerkin Method of weighted residuals. The elements may be one-dimensional channel reaches, or two-dimensional quadrilaterals or triangles, and may have curved sides. The shape functions are quadratic for velocity and linear for depth. Integration in space is performed by Gaussian integration. Derivatives in time are replaced by a nonlinear finite difference approximation. Variables are assumed to vary over each time interval in the form

$$f(t)=f(t_0)+at+bt^c \quad t_0\le t<t_0+\Delta t \qquad (4)$$

which is differentiated with respect to time, and cast in finite difference form. Letters a, b, and c are constants.

The above equations are appropriate for far-field problems in which vertical accelerations are negligible and velocity vectors generally point in the same direction over the entire depth of the water column at any instant of time. It expects a vertically homogeneous fluid with a free surface.

Oil Spill Governing Equations

The oil film is made up of a series of slicks floating on the water surface, as can be seen in Figure 1.

The movement of oil film is influenced by flow and wind.

$$U_{\text{slick}}=\alpha_{\text{vel}}U+\alpha_{\text{drift}}U_{\text{wind}} \qquad (5)$$

where U_{slick} is velocity of oil centroid, U is flow velocity, U_{wind} is wind velocity, α_{vel} is emendation index of velocity, α_{drift} is excursion index of wind. Influence of wind in curving rivers is greater than that in straight rivers.

Mass conservation equation

$$\frac{dm}{dt}=\int_{\text{length of slick}}\left[-k_{\text{dis}}W\left(X_{\text{o}}C_{\text{W}}^{\text{sat}}-C_{\text{W}}\right)-k_{\text{evap}}W\left(\frac{X_{\text{o}}P^{\text{o}}M_i}{RT}\right)\right]dx+r \qquad (6)$$

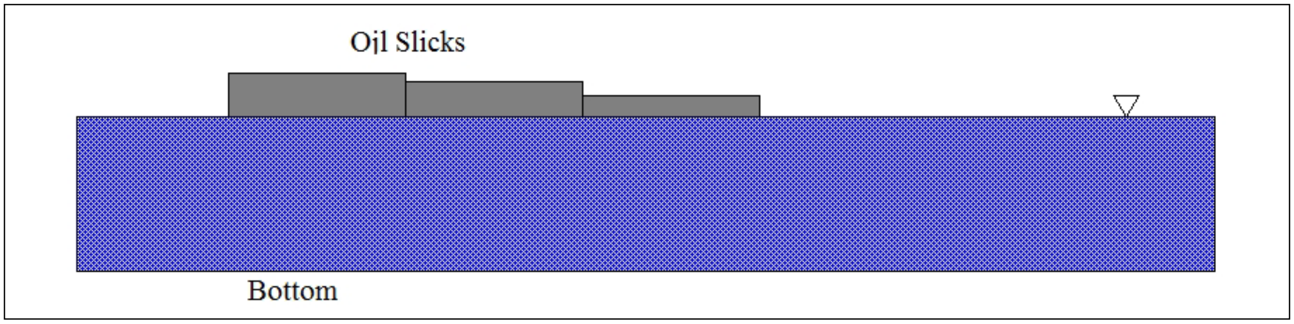

Figure 1. Oil structure on water surface.

where, m is mass of oil film, k_{dis} is dispersion index, W is width of oil film, X_o is mol, C_W^{sat} is saturation, C_w is soluble concentration in water, k_{evap} is evaporation index, P^o is atmospheric pressure, M_i is molecular weight, x is length of river, r is release rate.

RESULTS

Assumed Oil Spill Scenario

The oil spill site is located in the Chaoyang River of Chongqing, where a boat is assumed to have spilled oil when it moved from position (106.624E, 29.620N) to position (106.625E, 29.619N).

Type of spilled oil: Gasoline.

Amount of spilled oil: 50 tons, oil spill lasts for ten minutes.

Wind: Velocity is 1.5 m/s, wind direction is north.

Flow rate: 3500m^3/s

Water depth: 2.5 meters.

The oil spill site and the Three Gorges reservoir are shown in Figure 2.

Hydrodynamic Simulation

River shape and terrain in .shp format was read and meshed, as is shown in Figure 3.

Flow velocities and vectors are shown in Figures 4 and 5.

Oil Spill Simulation

Oil spill dispersion in ten hours was simulated, as is shown in Figure 6. After 1 hour the center of oil film moved to position 106.648E, 29.593N and its head moved to position 106.658E, 29.592N). Part of oil adhered in the banks.

After 2 hours the center of oil film moved to position 106.688E, 29.567N and its head moved to position 106.700E, 29.570N. Part of oil adhered in the banks from 106.628E, 29.617N to 106.700E, 29.570N. After 6 hours the oil film dispersed and most of the oil adhered in the banks. The center of oil film moved to position 106.528E, 29.527N and its head moved to position 106.700E, 29.570N. Most of oil adhered in the banks from 106.535E, 29.400N to 106.528E, 29.527N.

CONCLUSIONS

Hydrodynamic simulation models linked to GIS technology will enhance model performance and ultimately improve decision making. This advanced oil spill model will work to provide the

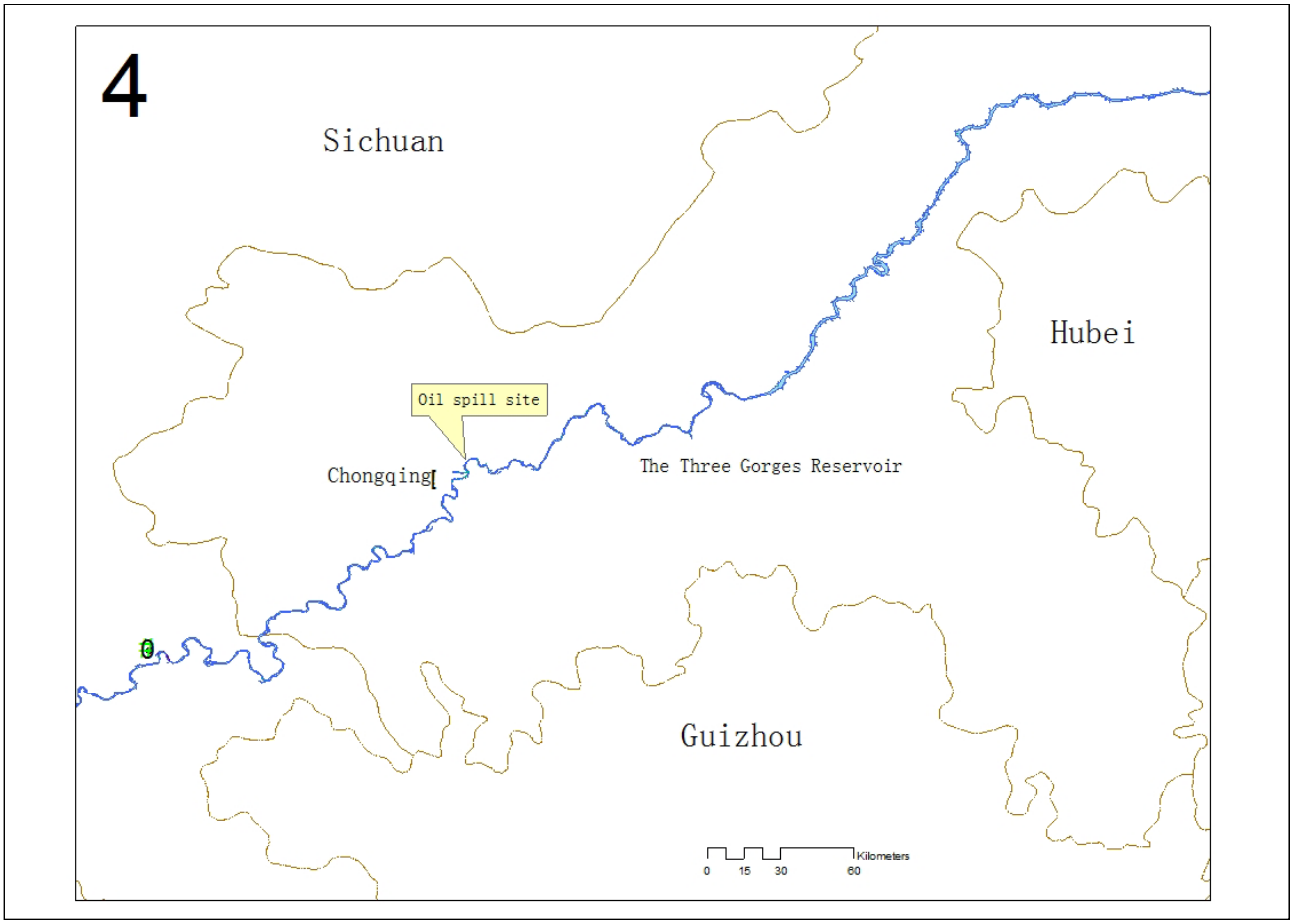

Figure 2. Map of the Three Gorges Reservoir.

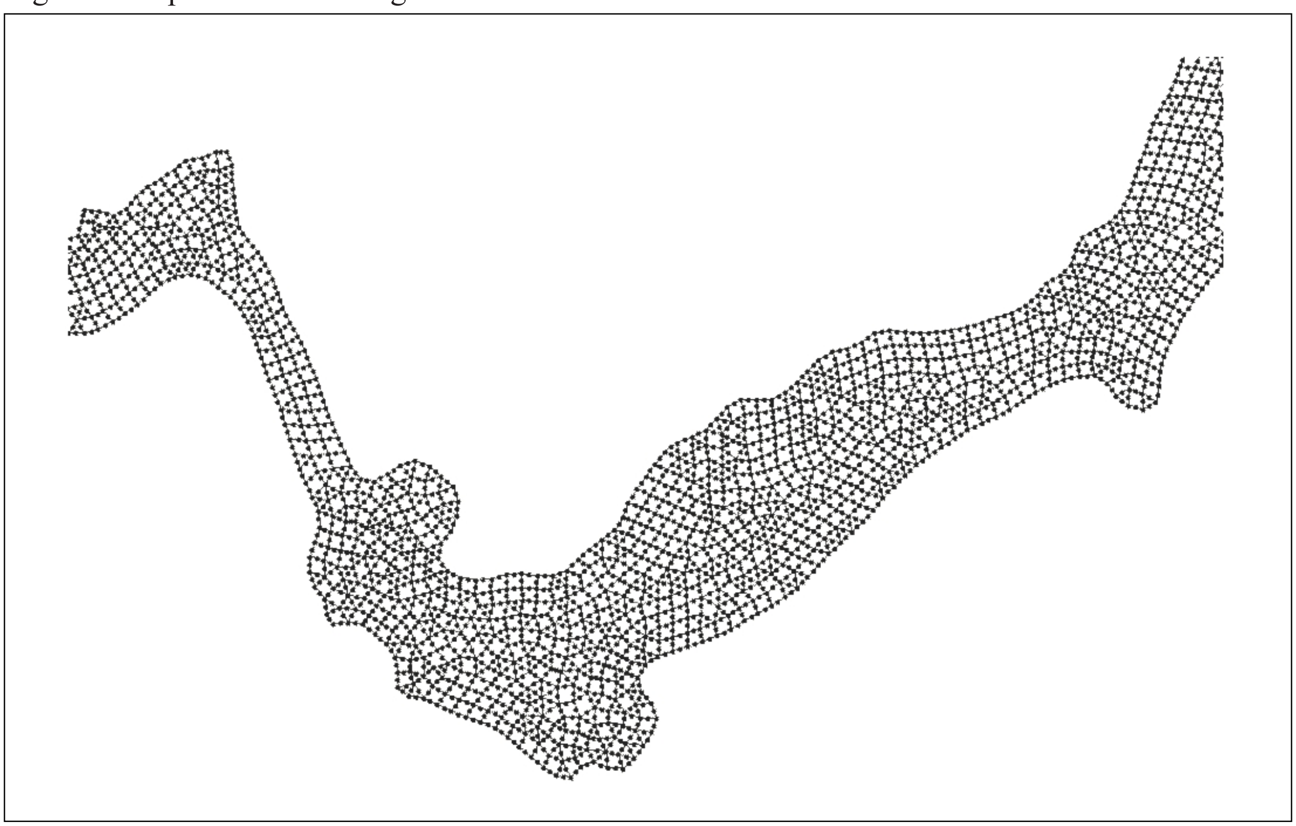

Figure 3. Part of the mesh.

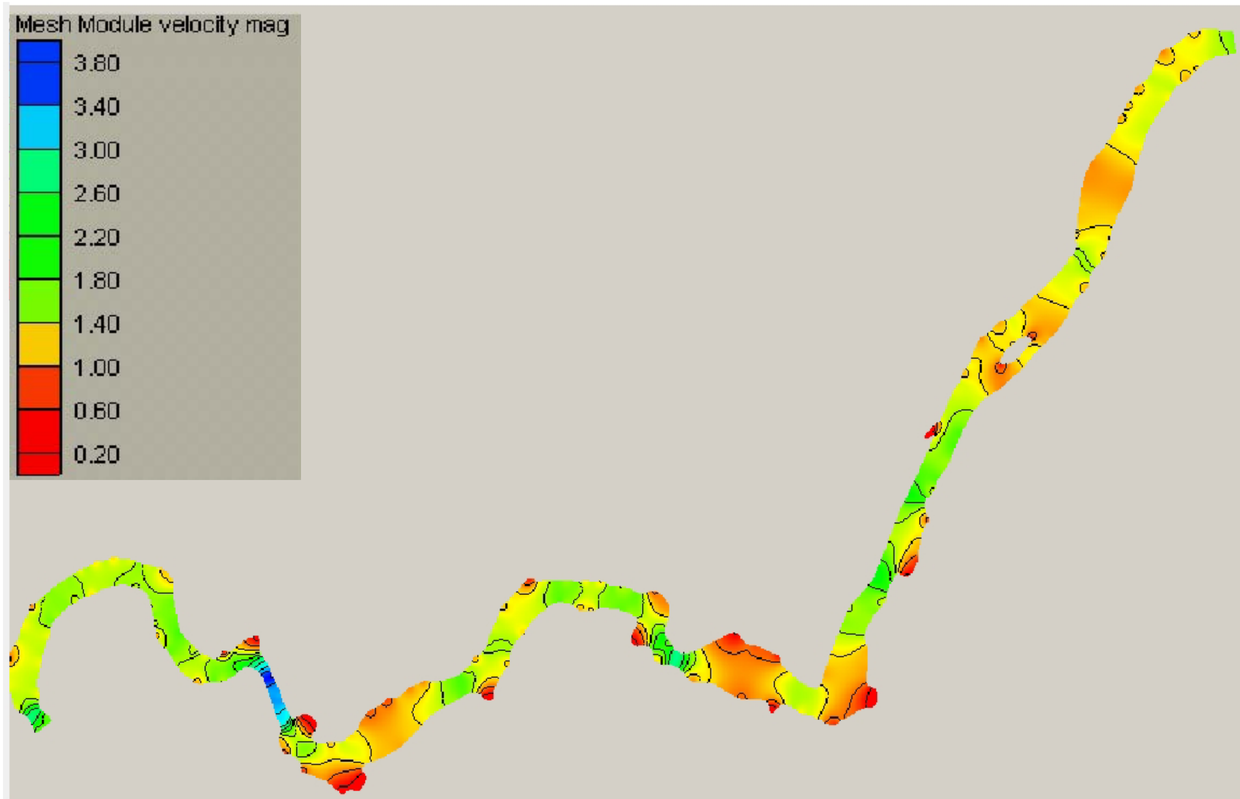

Figure 4. Flow velocity.

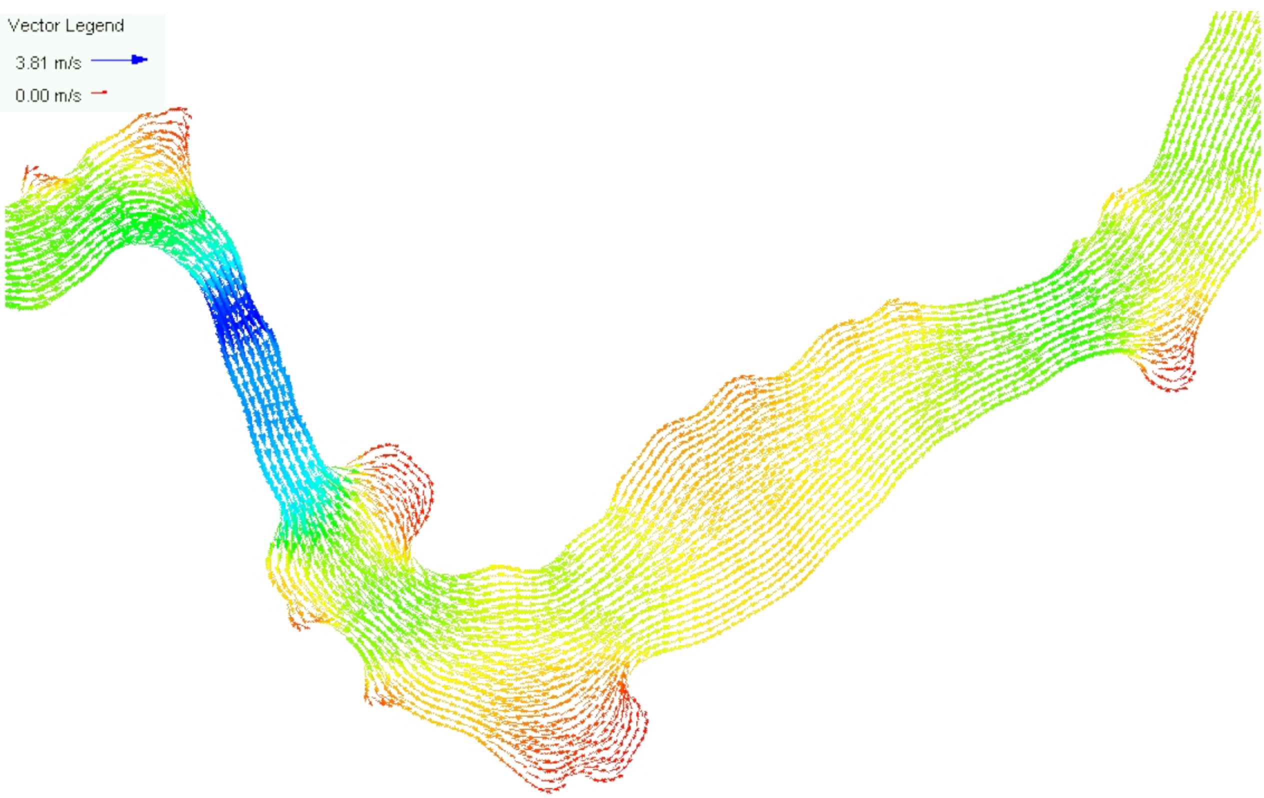

Figure 5. Velocity vector.

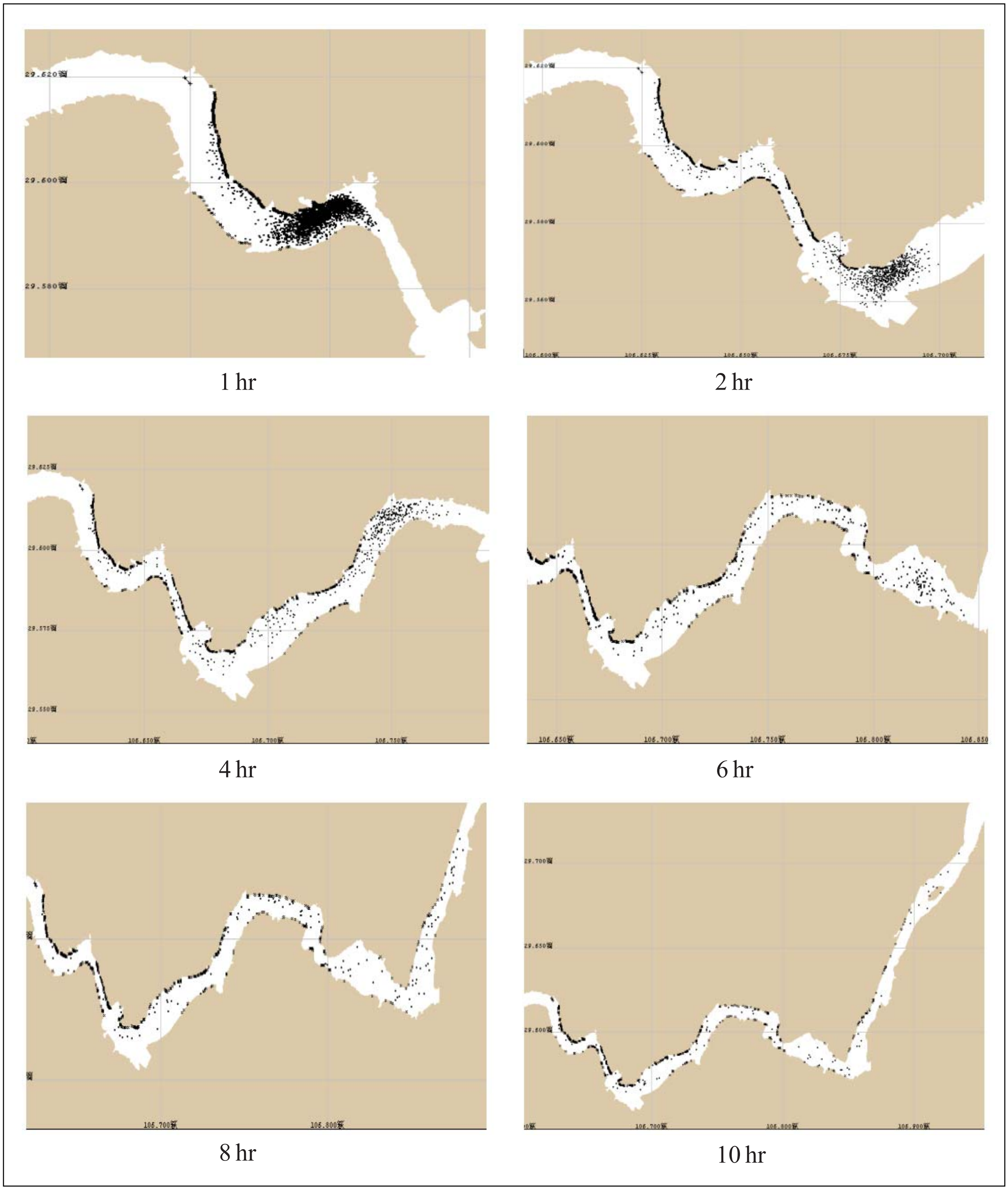

Figure 6. Dispersion of oil over time.

necessary understanding required in controlling oil spill pollution, helping environmental agencies to set and monitor regulations and prioritize remedial work. The model developed in this paper is a 2D model and its numerical precision is limited. Numerical precision can be improved by coupling with the 3-D multi-level turbulence model in which flow currents in every layer are obtained. In the next work oil spill experiment should be made to verify the results of oil spill model.

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ADDRESS FOR CORRESPONDENCE
He Chen
Laboratory of Environment Simulation
School of Environment
Beijing Normal University
Beijing 100875, China

Email: chenhe@bnu.edu.cn