Risk assessment for the benzene leakage from a sunken ship
(沈没船からのベンゼン流出のリスク評価)

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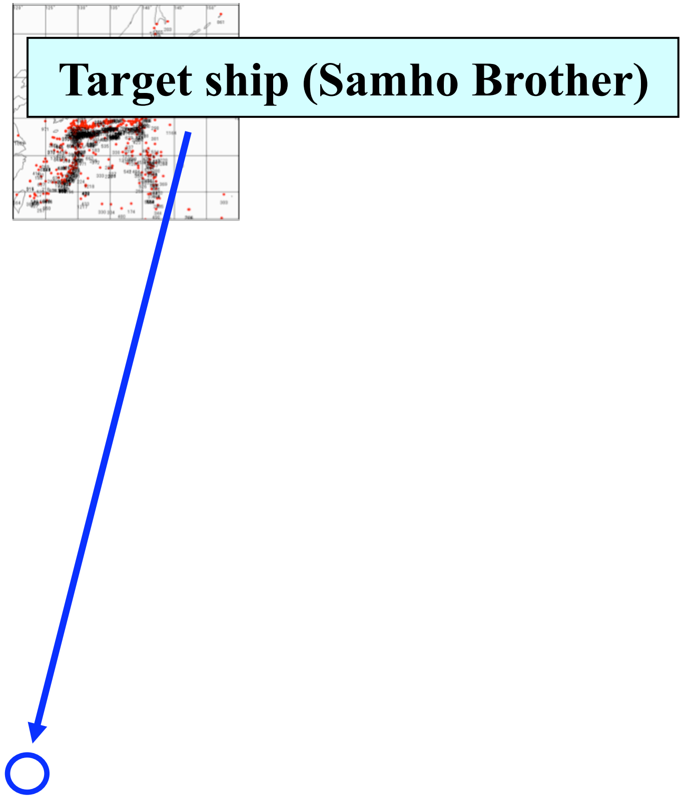
1. Introduction

1.1. Hazard map of wrecks around Japan



There are about 1,200 wrecks (over 100 tons) around Japan . In USA, 150,000 wrecks are reported.

Fig. 1. Wreck data around Northeast Asia (Kuroda 2006)

Notes: 1. Red circle: Position , 2. Black number: Hazard rank

1.2. An accident outline

1. **10th Oct, 2005**
   Samho Brother (Chemical Tanker: 3,100 tons of Benzene, UN1114) capsized off the coast of Taoyuan after collision with another ship.

2. **27th Oct, 2005**
   Military actions to burn off the benzene by firing missiles at the ship → Failed → Benzene spilled from the vessel at unknown rate

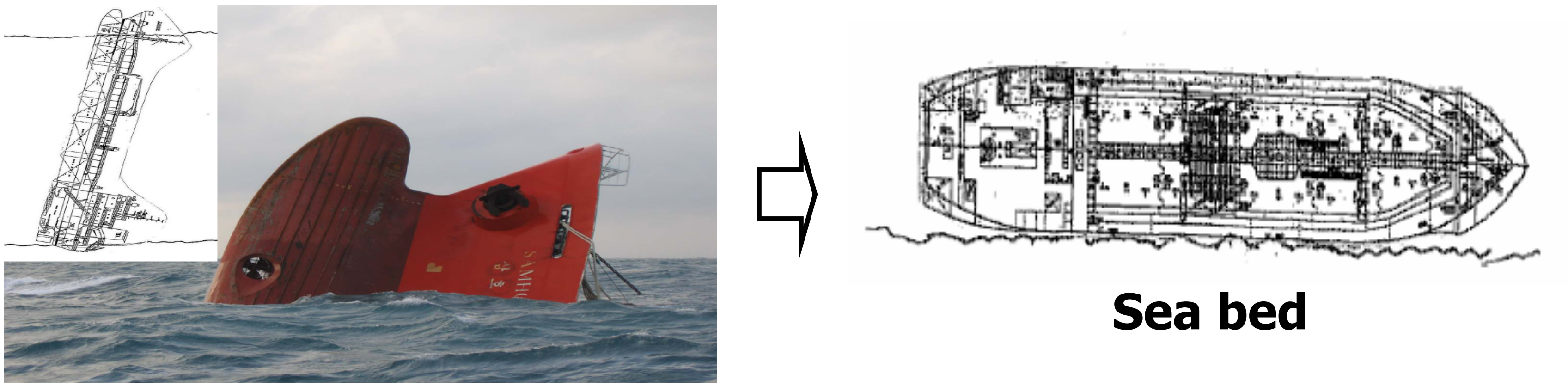
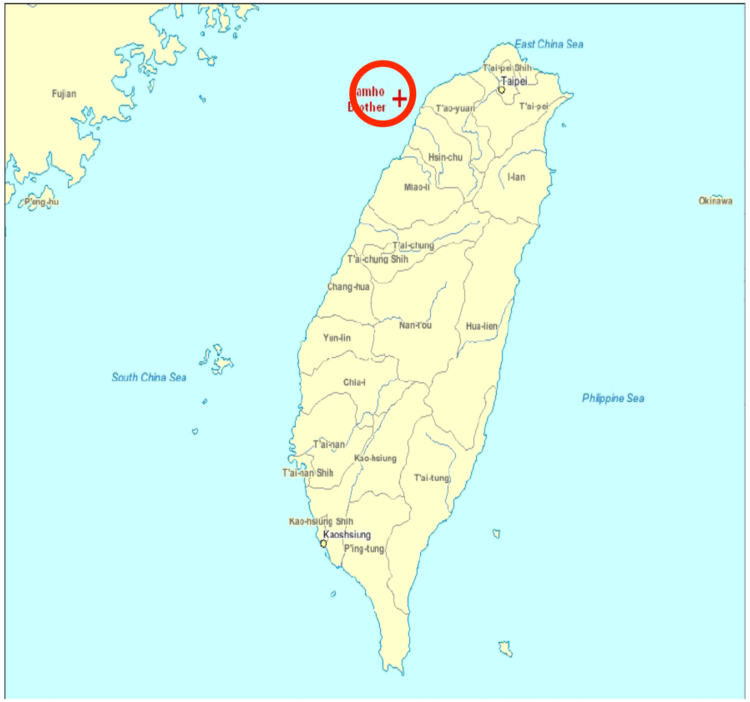


Fig. 2. Before and after military actions

1.3. Location



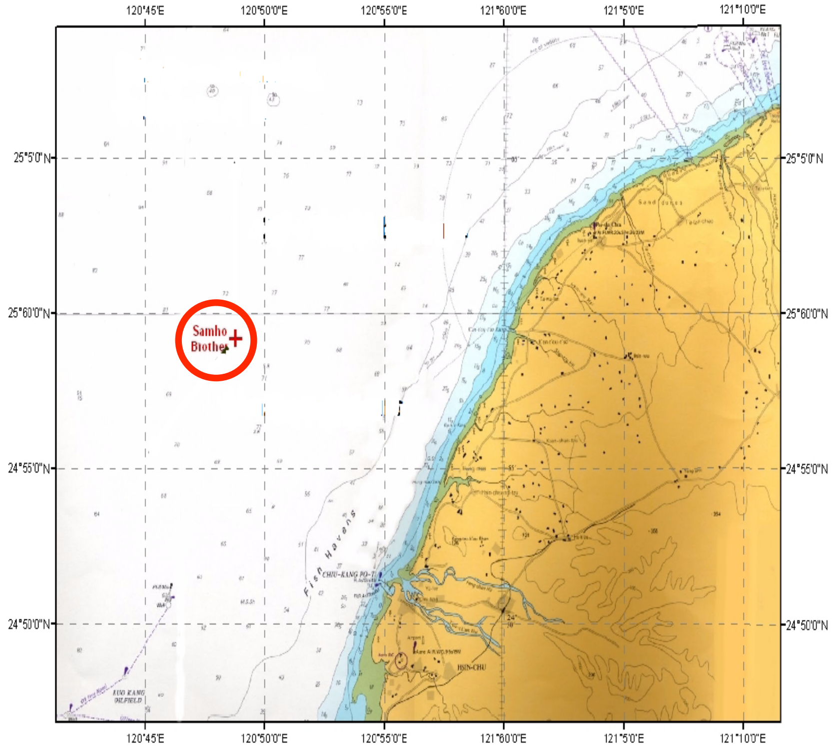


Fig. 3. An accident position: 24.57N-120.48E

(70 kilometers offshore and 75 meters depth)

1.4. A field research in Taiwan Strait

(a)

- On 26th April, 2007, research teams from Japan and Taiwan launched to measure benzene → Failed or not leaking ?

♪

(b)

(c)

Fig. 4. (a) Injured fish (b) Installing ADCP (c) Water sampler

1.5. The purpose of this research

- **Obtaining the useful data for the planning of the optimal observation**
- **To support fundamental data for Risk Evaluation and Risk Management**

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Forecasting model for benzene spills transport and fate

2. MEC Ocean Model

- **Continuity equation**

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \qquad (1)$$

- **Momentum equations in the x and y directions**

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial p_s}{\partial x}+fv+A_M\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+\frac{\partial}{\partial z}\left(K_M\frac{\partial u}{\partial z}\right) \qquad (2)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{1}{\rho}\frac{\partial p_s}{\partial y}-fu+A_M\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\frac{\partial}{\partial z}\left(K_M\frac{\partial v}{\partial z}\right) \qquad (3)$$

- **Hydrostatic pressure equation**

$$0=-\frac{1}{\rho}\frac{\partial p_s}{\partial z}-g \qquad (4)$$

3. Benzene Model

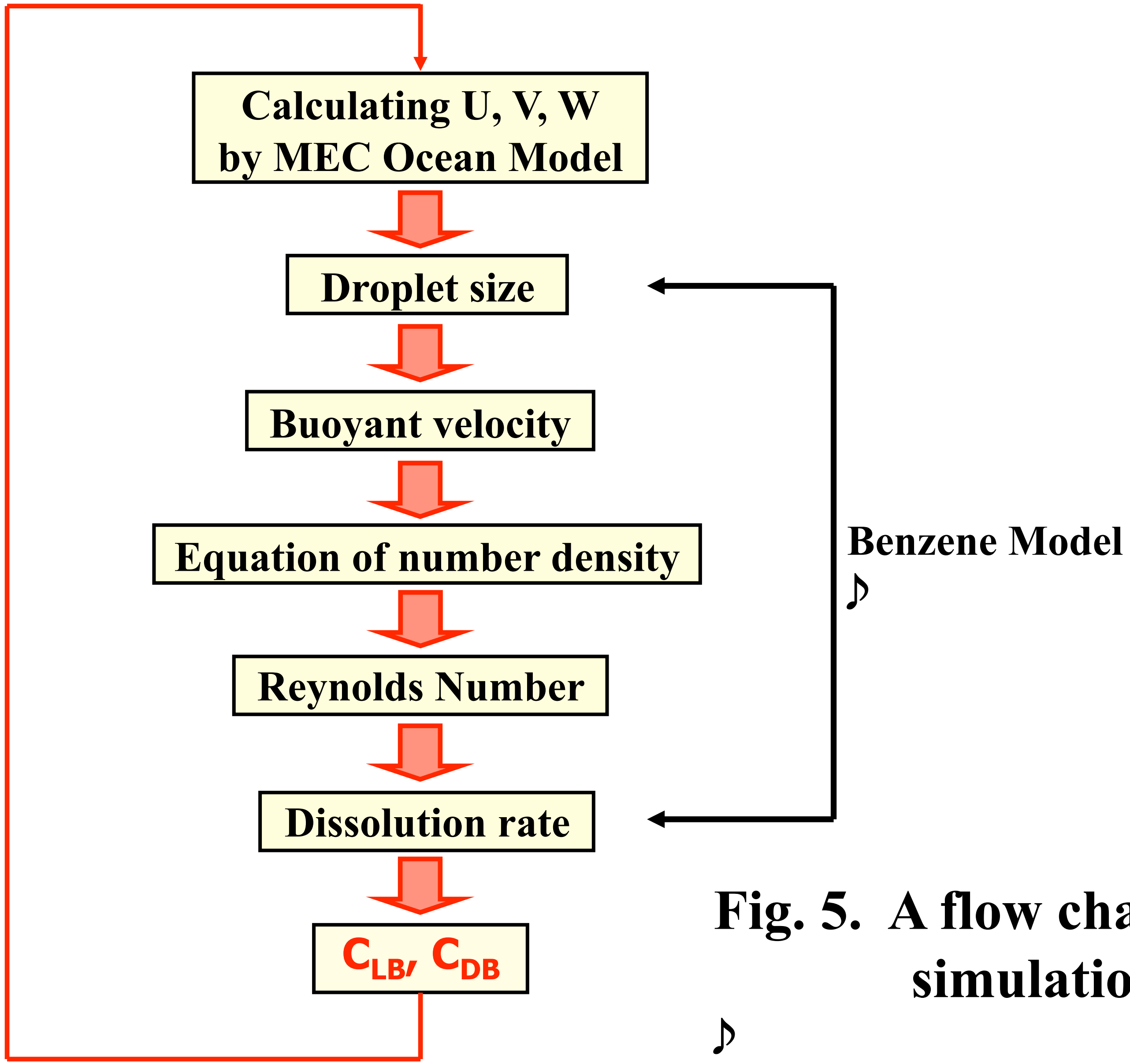

Fig. 5. A flow chart of simulation

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3.1. Equations

- **Dissolution rate**

$$S_{mass} = \frac{dV}{dt} = -\frac{1}{\rho_B}\left(A\frac{ShD}{d}(B_s - B_o)\right) \tag{5}$$

- **Buoyant velocity**

$$\frac{dZ}{dt} = \omega = \sqrt{\frac{4d(\rho_s - \rho_B)g}{3C_D\rho_s}} \tag{6}$$

- **Equation of number density**

$$\frac{\partial n}{\partial t} + \frac{\partial (un)}{\partial x} + \frac{\partial (vn)}{\partial y} + \frac{\partial (wn)}{\partial z} =$$

$$\frac{\partial}{\partial x}\left(Dx\frac{\partial n}{\partial x}\right) + \frac{\partial}{\partial y}\left(Dy\frac{\partial n}{\partial y}\right) + \frac{\partial}{\partial z}\left(Dz\frac{\partial n}{\partial z}\right) + \dot{n} \tag{7}$$

3.1. Equations

• **Evaporation rate (Mackay, D. et al., 1983)**

$$N = K_{OL} \cdot \left(C_{DB} - \frac{p}{H} \right) \qquad (8)$$

$$\frac{1}{K_{OL}} = \frac{1}{K_L} + \frac{R \cdot T}{H \cdot K_G} \qquad (9)$$

$$K_G = 1.0 * 10^{-3} + 46.2 * 10^{-3} * U^* * Sc_G^{\ -0.67}$$

$$K_L = 1.0 * 10^{-6} + 34.1 * 10^{-4} * U^* * Sc_L^{\ -0.5} (U^* > 0.3)$$

$$= 1.0 * 10^{-6} + 144 * 10^{-4} * (U^*)^{2.2} * Sc_L^{\ -0.5} (U^* < 0.3)$$

$$U^* = U_{10}(6.1 + 0.63 U_{10})^{0.5}, \text{ outside}$$

• **Benzene transport equation**

$$\frac{\partial C_{LB}}{\partial t} + \frac{\partial (uC_{LB})}{\partial x} + \frac{\partial (vC_{LB})}{\partial y} + \frac{\partial (wC_{LB})}{\partial z} = A_M \left(\frac{\partial^2 C_{LB}}{\partial x^2} + \frac{\partial^2 C_{LB}}{\partial y^2} \right) + \frac{\partial}{\partial z} \left(K_M \frac{\partial C_{LB}}{\partial z} \right) - \frac{\partial (\omega C_{LB})}{\partial z} + \sum S_{LB} \qquad (10)$$

$$\frac{\partial C_{DB}}{\partial t} + \frac{\partial (uC_{DB})}{\partial x} + \frac{\partial (vC_{DB})}{\partial y} + \frac{\partial (wC_{DB})}{\partial z} = A_M \left(\frac{\partial^2 C_{DB}}{\partial x^2} + \frac{\partial^2 C_{DB}}{\partial y^2} \right) + \frac{\partial}{\partial z} \left(K_M \frac{\partial C_{DB}}{\partial z} \right) + \sum S_{DB} \qquad (11)$$

where C_{LB} and C_{DB} are concentrations of the liquid and dissolved benzene, respectively

3.2. Model verification

These are the first and only known field experiments for subsurface oil jet/plumes (Rye et al., 1997).

Method

1. Comparing with time that the first droplet reaches the surface
2. The position comparison of oil jet/plume at a depth of 3 meters after 12 min 30 sec

A result of Method 1.	
Yapa's model	636 sec
Field experiment	600 sec
Present model	618 sec

A result of Method 2.	
Field experiment	40m from an origin
Present model	50m (Fig. 6.)

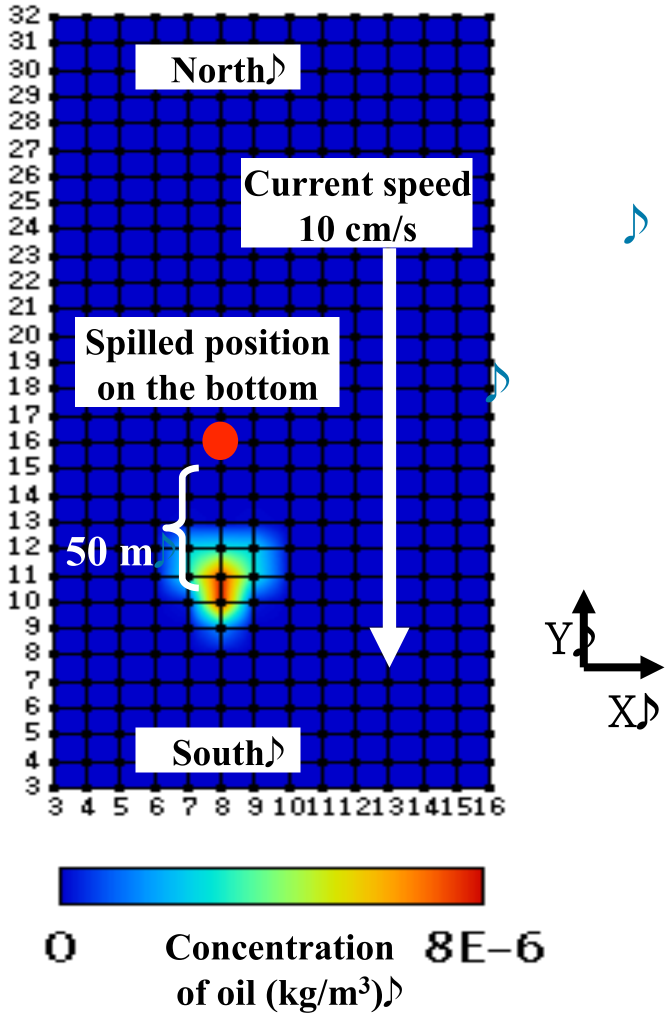


Fig. 6. Result of the position comparison

3.3. Computational and boundary conditions

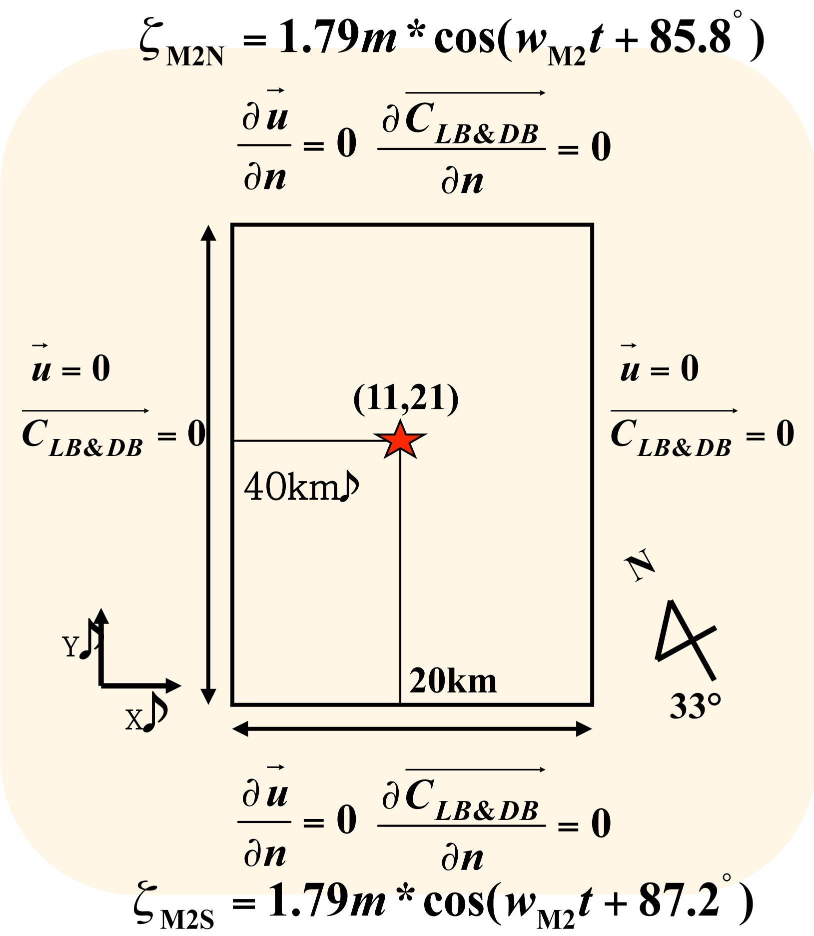


Fig. 7. A schematic view of calculation domain

Parameters for computation

1. Grid size: 1000m
2. Time step: 5sec
3. Calculation time: 24days
4. Beginning of leaking: 3rd to 4th day
5. Number of grids: 20 * 40 * 17
6. Water depth: 75m (Uniform)
7. Calculation area: 20km by 40km

Table 1 Benzene release scenarios

♪	Wind speed (m/s)	Leaking rate (kg/s)	Droplet size (m)	Duration per iod (day)
1	5 (Summer)	10	0.01	1
2	10 (Winter)	10	0.01	1
3	5	10	0.005	1
4	10	10	0.005	1
5	5	1	0.005	1
6	10	1	0.005	1
7	5	1	0.01	1
8	10	1	0.01	1

3.4. Simulations of benzene spill behavior

- **Changes of droplet size, buoyant velocity, and dissolution rate with 8 cases (Table 1)**

(a) Droplet size **(b) Buoyant velocity** **(c) Dissolution rate**

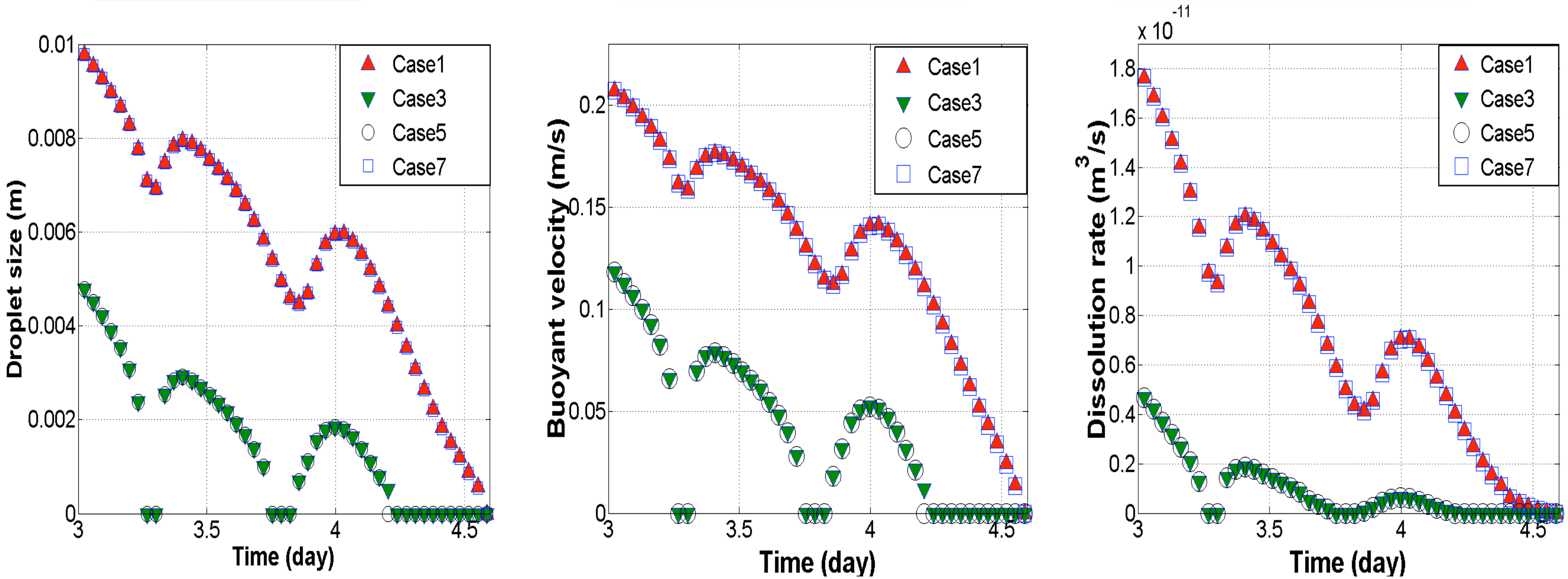
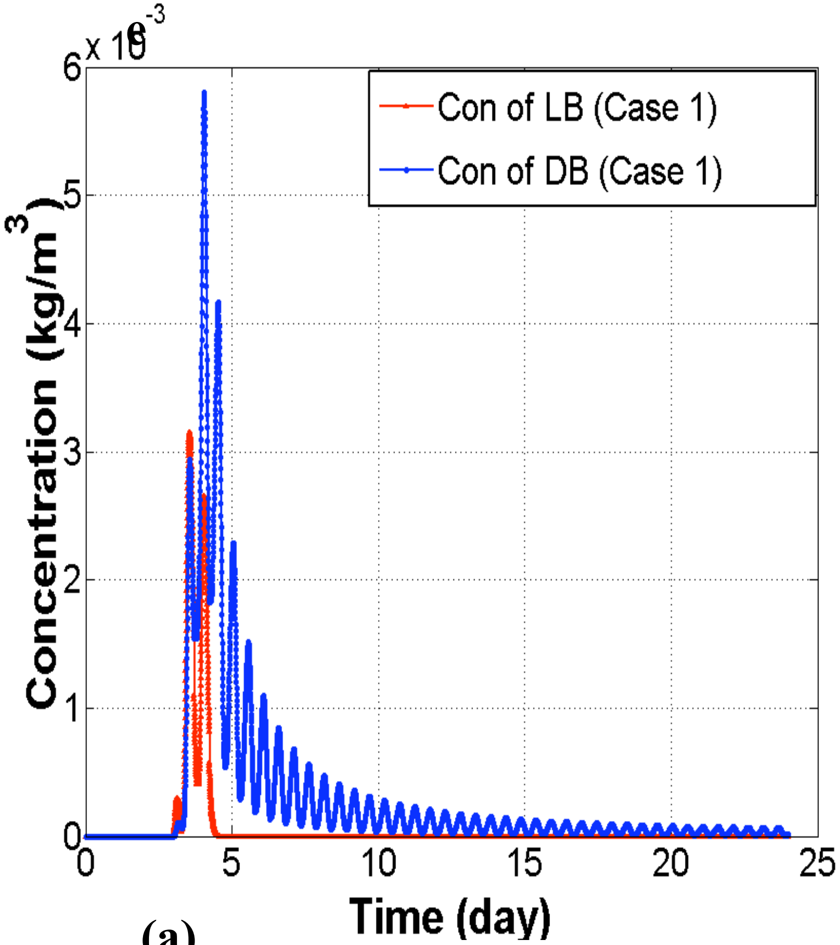


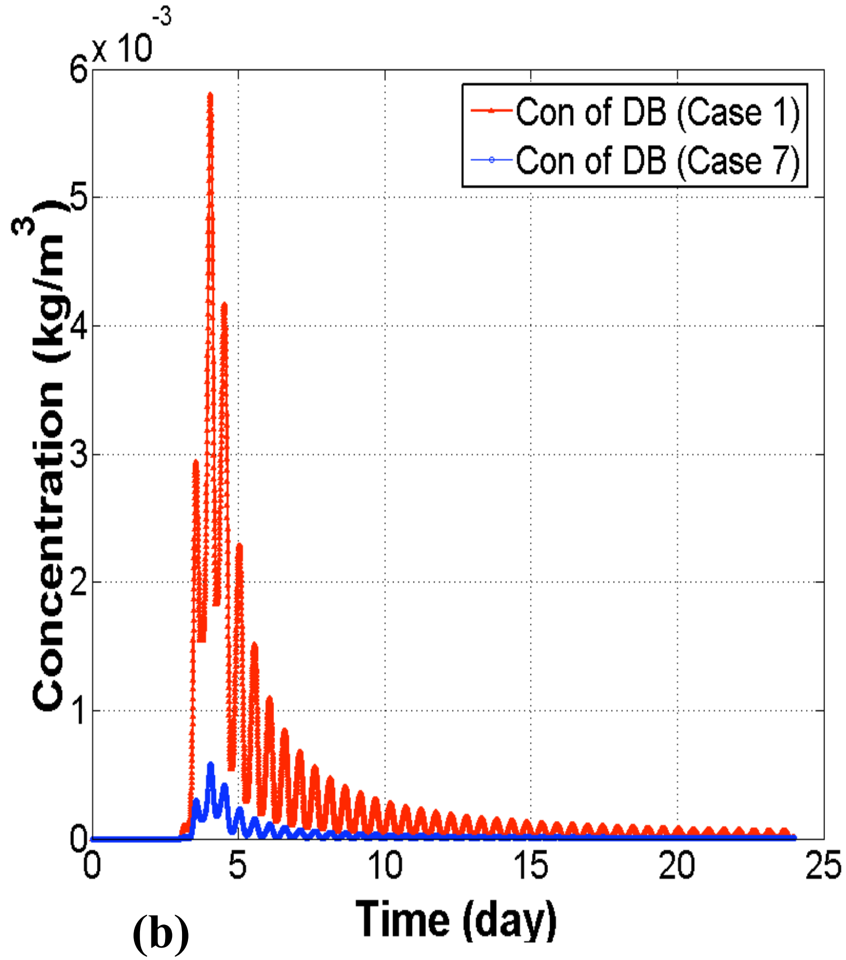
Fig. 8. Time history profile in an accident position at 3 m depth: grid point (11,21)

3.4. Simulations of benzene spill behavior

• Changes of concentrations of the liquid and dissolved benzen



(a)



(b)

Fig. 9. Time history profiles of concentrations of the liquid and dissolved benzene in Case 1 (a) and concentrations of the dissolved benzene in Case 1(10kg/s) and Case 7(1kg/s) in an accident position at 3 m depth: grid point (11,21)

3.4. Simulations of benzene spill behavior

- **Results of Case 1 (leaking rate: 10kg/s, droplet size: 0.01m)**

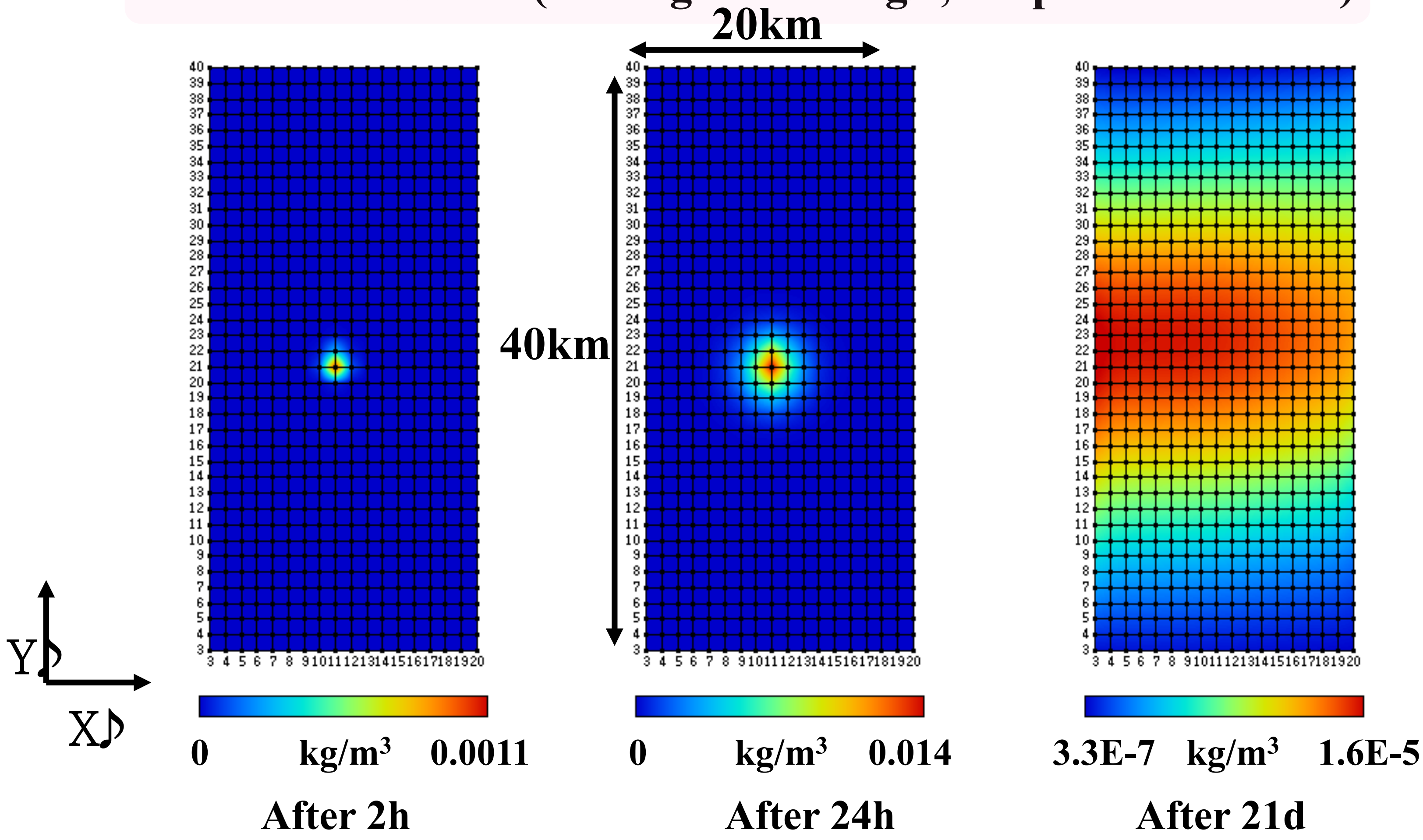


Fig. 10. Horizontal distributions of concentration of the dissolved benzene at 3 m depth

Note: Color bar: Concentration of the dissolved benzene (kg/m^3)

3.4. Simulations of benzene spill behavior

• Results of Case 1 (leaking rate: 10kg/s, droplet size: 0.01m)

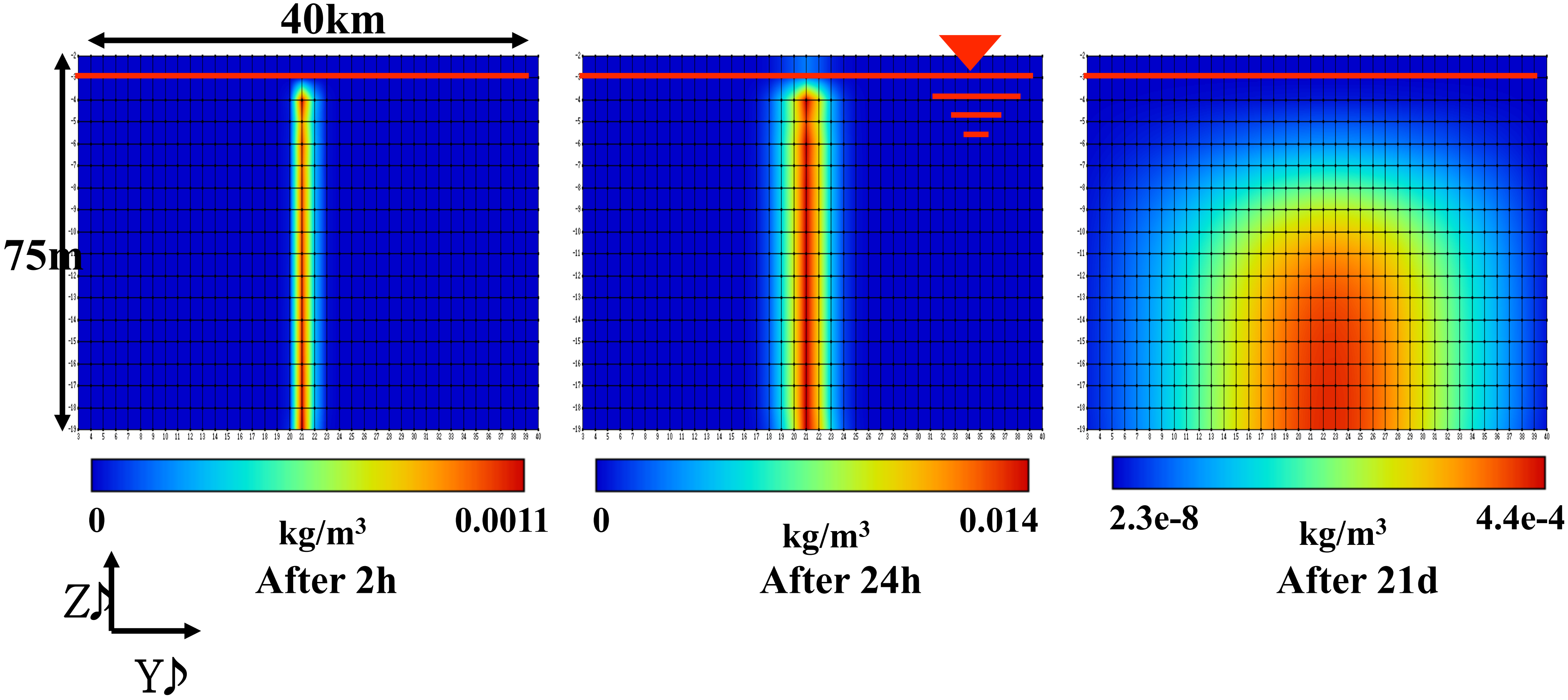


Fig. 11. Cross-sectional views of concentration of the dissolved benzene at 3 m depth
Note: Color bar: Concentration of the dissolved benzene (kg/m^3)

3.4. Simulations of benzene spill behavior

• **Tidal effects on the subsurface benzene spills**

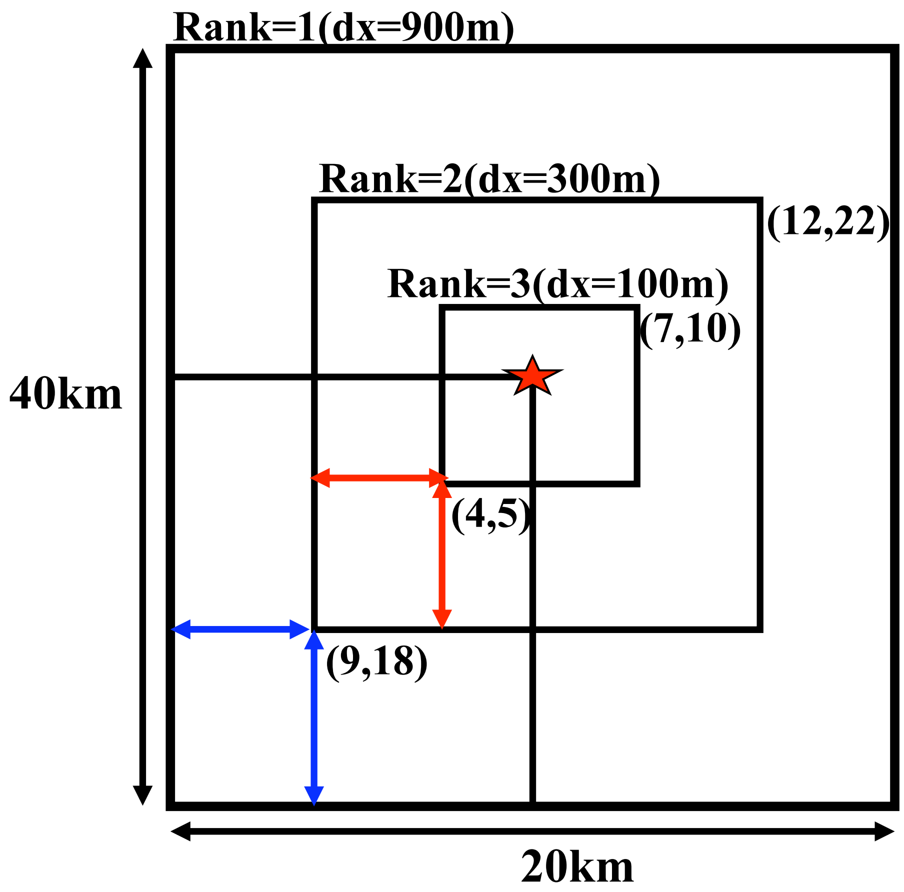


Fig. 12. A nested grid system

3.4. Simulations of benzene spill behavior

- **Tidal effects on the subsurface benzene spills**

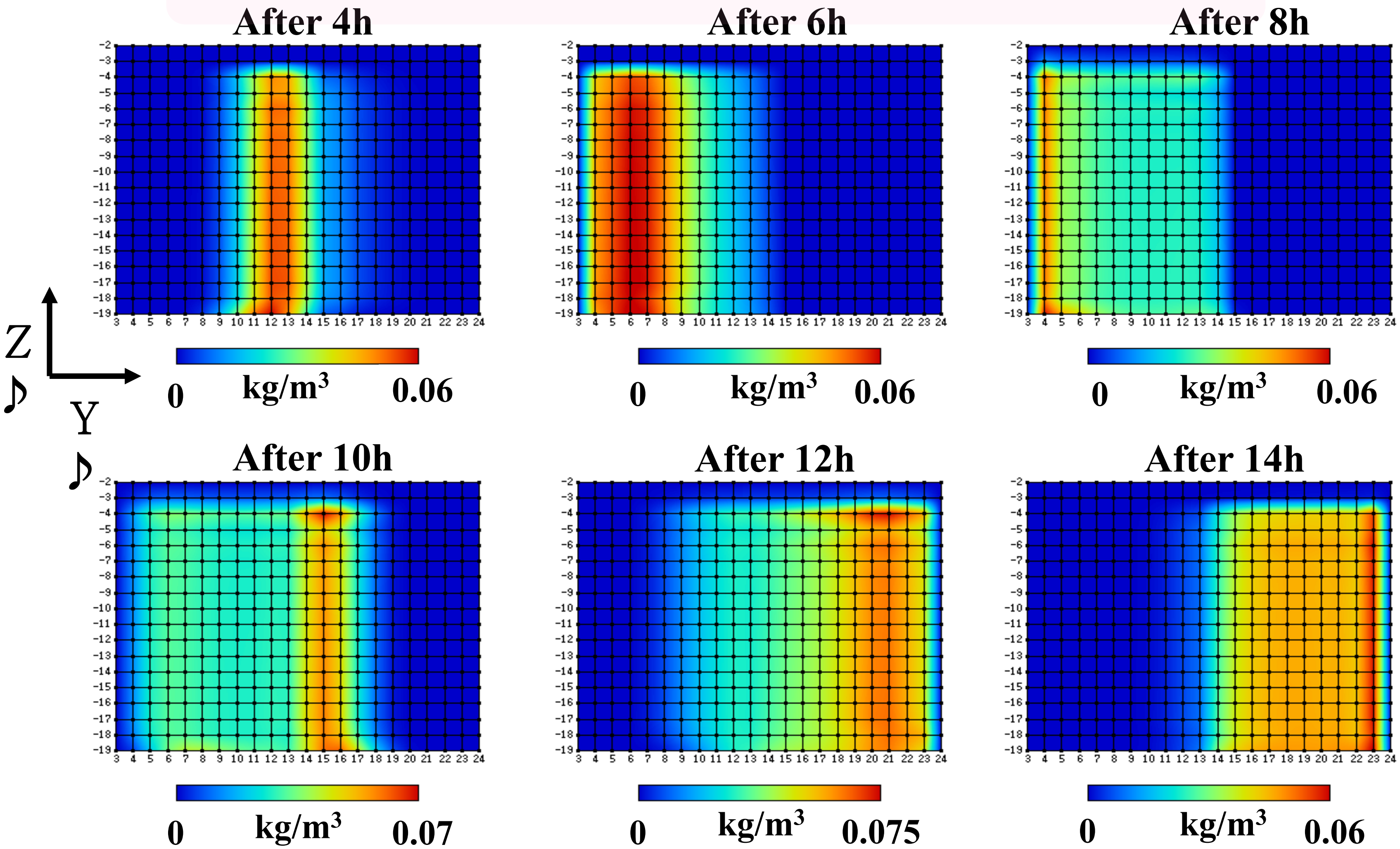
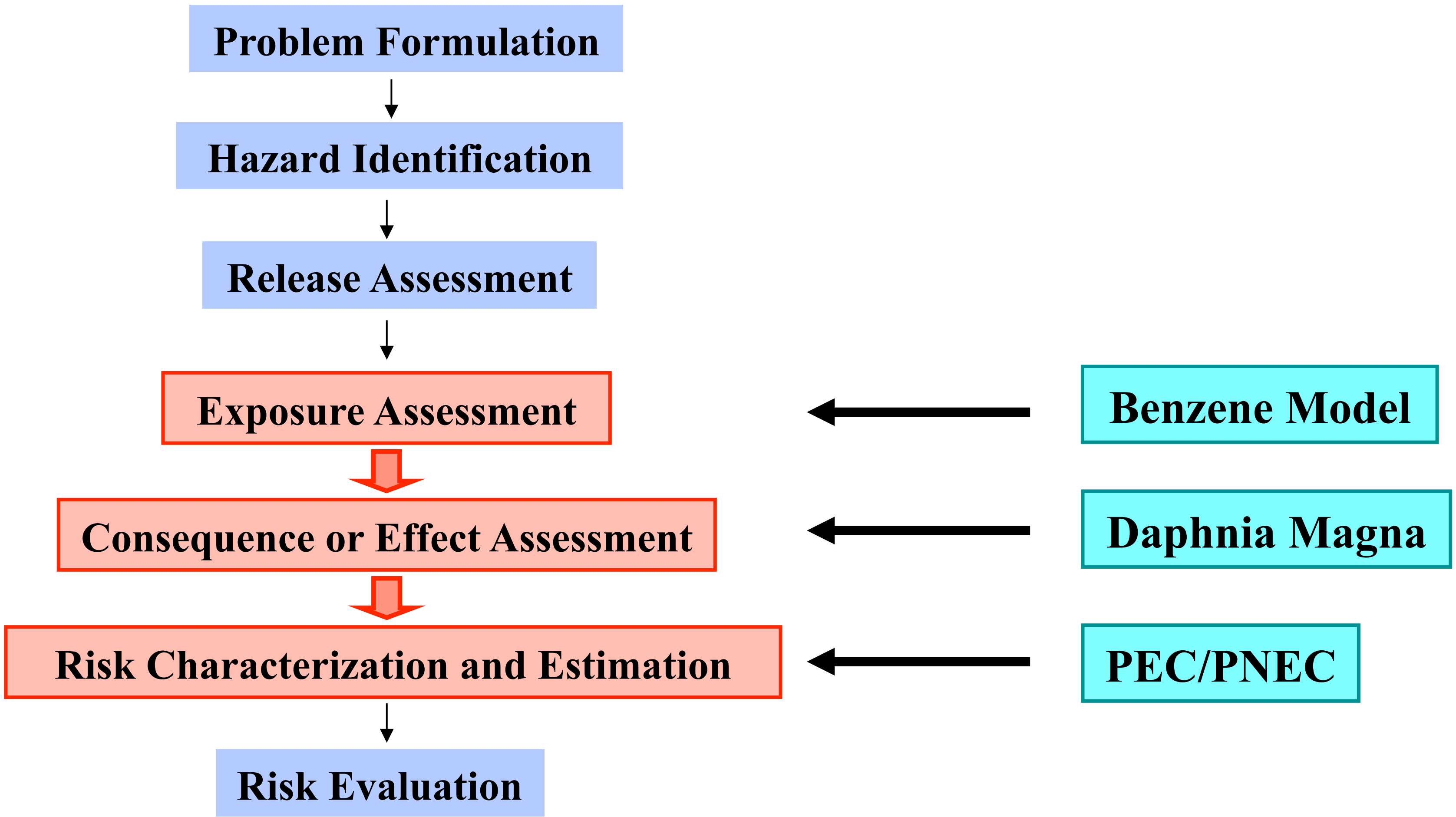


Fig. 13. Cross-sectional views of the concentration of the dissolved benzene

4. Risk assessment

4.1. Introduction

In general seven steps can be identified addressing the key questions in an Ecological Risk Assessment (ERA) (Fairman R. et el., 1999)



4.2. Methods

• The **4th** step: Exposure Assessment

PEC ⟵ Benzene Model

• The **5th** step: Consequence or Effect Assessment

PNEC values with Assessessment Factors(AF) of 100(OECD) or 1000(EU) (Tabel 2)

Daphnia Magna is chosen for ecotoxicity tests.

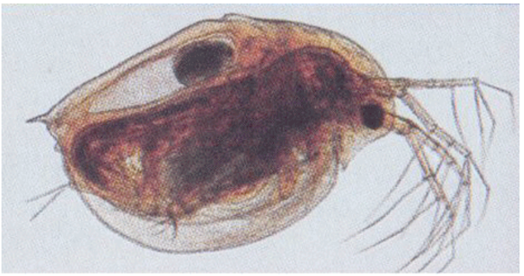


Fig. 14. A photo of Daphnia Magna

Table 2 Defined PNEC values [9]

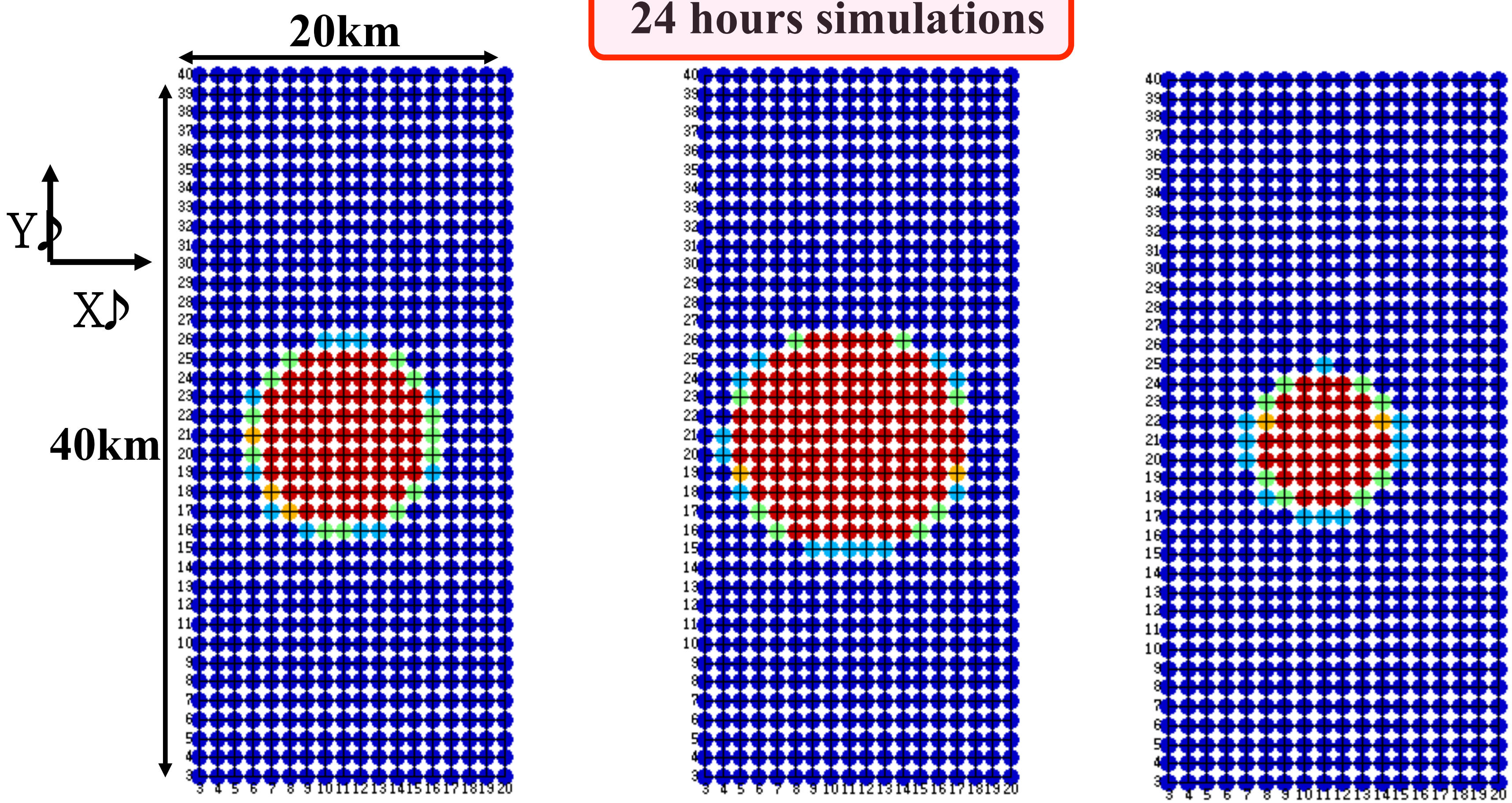
	24hr (acute)	21d (chronic)
100 (AF)	0.08 (mg/l)	0.01 (mg/l)
1000 (AF)	0.008 (mg/l)	0.001 (mg/l)

• The **6th** step: Risk Characterization and Estimation

$$\frac{\text{PEC (Predicted Exposure Concentration)}}{\text{PNEC (Predicted No Effective Concentration)}} > 1$$

4.3. Results of numerical simulations

24 hours simulations



(a) An assessment factor of 100, Case 1 (10kg/s)

(b) An assessment factor of 1000, Case 1 (10kg/s)

(c) An assessment factor of 100, Case 7 (1kg/s)

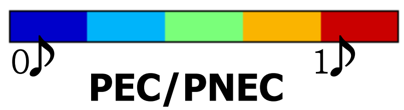
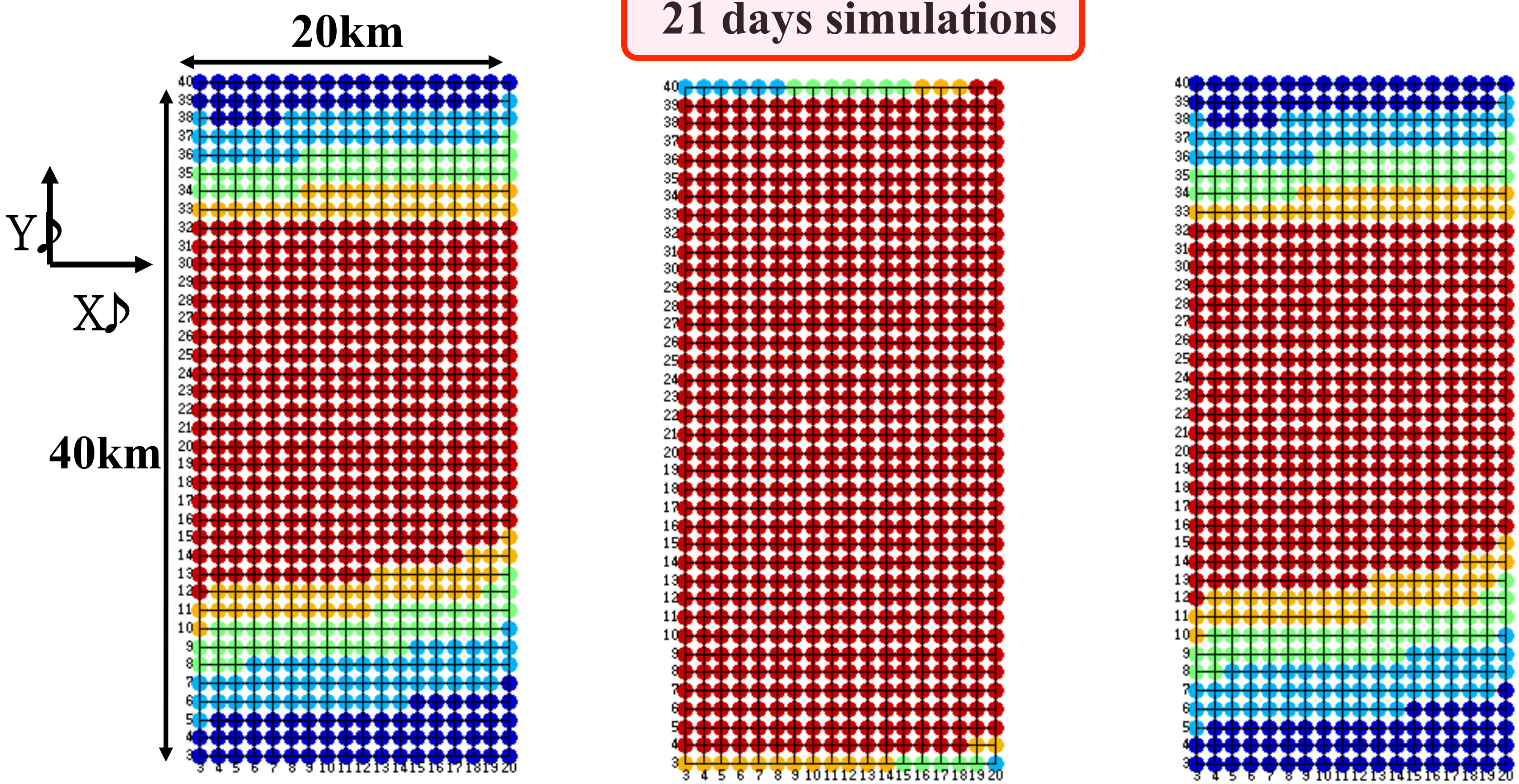


Fig. 15. Horizontal distributions of the PEC/PNEC ratio at 3 meters depth, 24 hours after benzene spills

Note: Color bar: PEC/PNEC ratio

4.3. Results of numerical simulations

21 days simulations



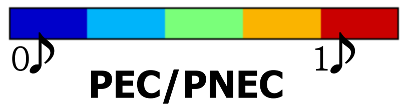
(a) An assessment factor of 100, Case 1 (10kg/s)

(b) An assessment factor of 1000, Case 1 (10kg/s)

(c) An assessment factor of 1000, Case 7 (1kg/s)

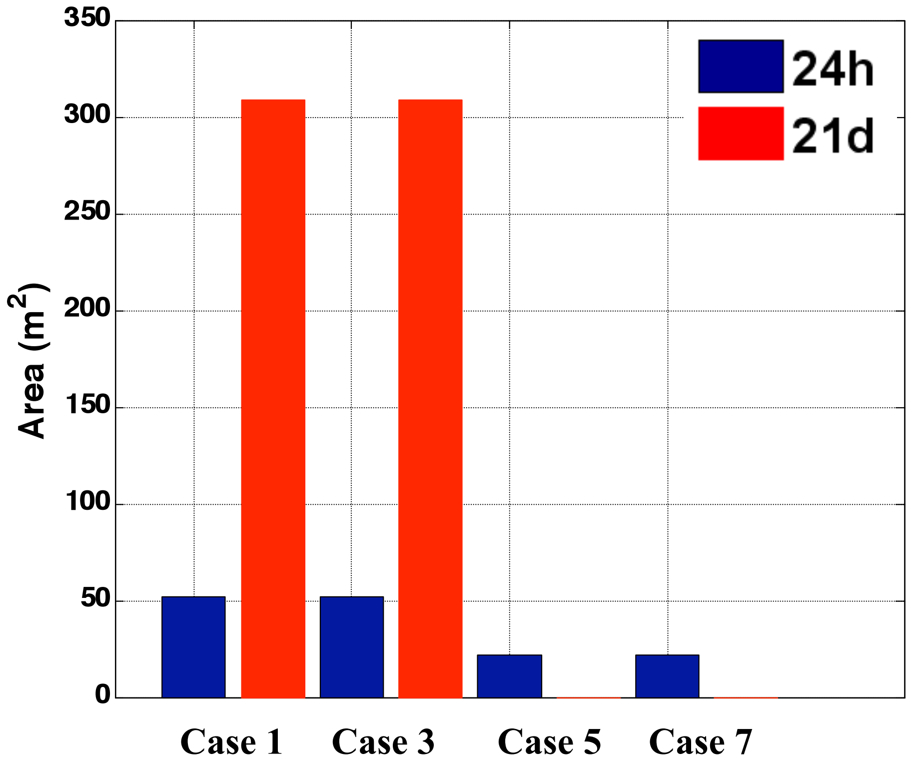
Fig. 16. Horizontal distributions of the PEC/PNEC ratio at 3 meters depth, 21 days after benzene spills

Note: Color bar: PEC/PNEC ratio



4.3. Results of numerical simulations

(a) With an assessment factor of 100



(b) With an assessment factor of 1000

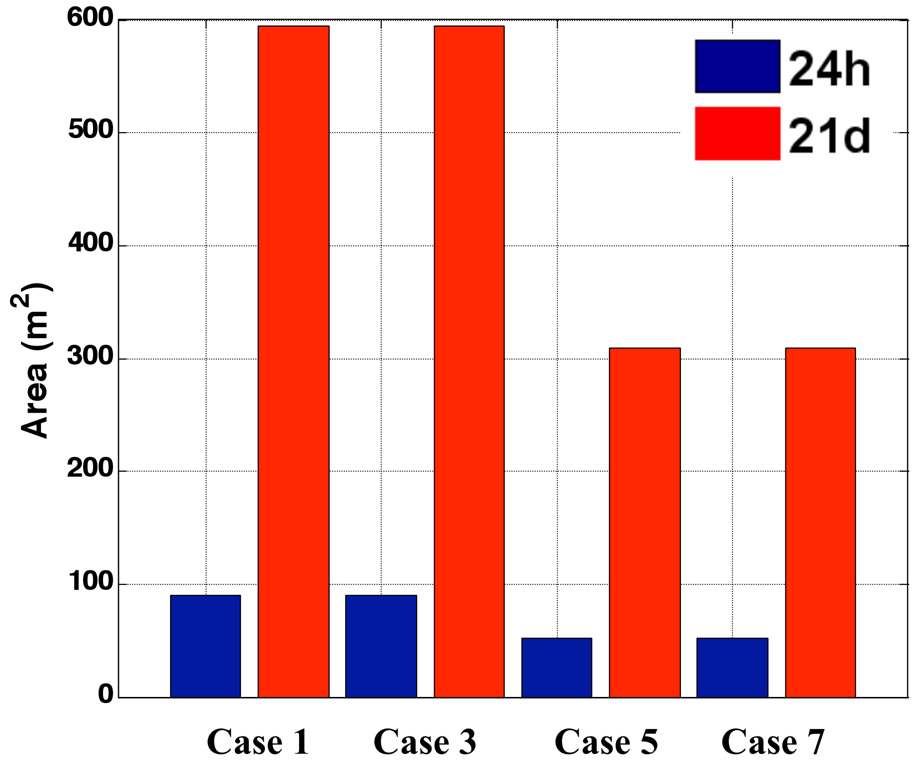


Fig. 17. Histogram of polluted areas which PEC/PNEC ratio is over 1 at 3 meters depth

5. Conclusions

- **In order to simulate benzene diffusion in Taiwan Strait, Benzene Model is developed.**
- **Comparing with observation data of oil jet/plume, the present model agrees well.**
- **An important factor to determine buoyant velocity, dissolution rate, and Reynolds number is the initial droplet size.**
- **Leaking rate and spill duration time strongly affect the concentration of the dissolved benzene in water.**
- **Through the results of the risk assessment, the casualties would be tremendous.**

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Thank you for your attention!!!