C204

Modeling Urban Flood and Pollutant Transport with Building Flooding Consideration

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1. Introduction

The frequency and intensity of urban flooding have gradually risen due to global climate change, rapid urbanization, and increasing population. While the direct impact of floodwaters, such as structural damage, is commonly recognized, secondary disasters caused by flooding, such as pollutant leakage, can be even more hazardous. For example, during an overtopping flood event in Saga Prefecture, Japan, in 2019, chemical oils leaked from a metal facility, spreading with floodwaters through residential areas and reaching a local hospital, significantly hindering disaster relief efforts.

This research aims to present a stable and efficient two-dimensional coupled flow and mass transport model considering flood intrusion. The proposed model is based on the finite volume method using the HLLC approximate Riemann solver in unstructured grids. A multidimensional slope-limited linear reconstruction method is implemented to achieve second-order spatial accuracy. An improved surface reconstruction method for water depth reconstruction and bed slope term calculation is adopted. The water flow and mass transport into or out of buildings are modeled using Torricelli's theorem, and a splitting semi-implicit scheme is applied to handle friction terms. Hancock's predictor-corrector scheme is utilized for efficient time stepping and second-order temporal accuracy.

2. Research Contents

(1) Governing Equations

In this research, the matrix form of the two-dimensional depth-averaged advection-diffusion equations is as follows:

$$\frac{\partial \mathbf{U}}{\partial t}+\frac{\partial \mathbf{E}}{\partial x}+\frac{\partial \mathbf{G}}{\partial y}=\mathbf{S}$$

where **U**, **E**, **G** and **S** are vectors of the conserved variables, fluxes in the x- and y-directions, and source term, respectively; in which:

$$\mathbf{U}=\begin{bmatrix} h \\ hu \\ hv \\ hc \end{bmatrix},\mathbf{E}=\begin{bmatrix} hu \\ hu^2+gh^2/2 \\ huv \\ huc \end{bmatrix},\mathbf{G}=\begin{bmatrix} hv \\ huv \\ hv^2+gh^2/2 \\ hvc \end{bmatrix},$$

$$\mathbf{S}=\begin{bmatrix} q_{in} \\ -gh\left(S_{bx}+S_{fx}\right) \\ -gh\left(S_{by}+S_{fy}\right) \\ \frac{\partial}{\partial x}\left(D_x h\frac{\partial c}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_y h\frac{\partial c}{\partial y}\right)+c_{in} \end{bmatrix}$$

where h is the water depth; u and v are the depth-averaged velocity in the x- and y-directions, respectively; c is the depth-averaged pollutant concentration; S_{bx} and S_{by} are bed slopes; S_{fx} and S_{fy} are friction slopes; D_x and D_y are the dispersion coefficients; q_{in} is the source/sink; c_{in} is the pollutant concentration of the source.

(2) Numerical Model

To achieve second-order spatial accuracy, the multidimensional linear reconstruction and limiter proposed by Jawahar and Kamath[1] is adopted.

Considering the complex topography and the presence of buildings in urban areas, a novel surface reconstruction method proposed by [2] is employed to reconstruct water depth independently.

The HLLC approximate Riemann solver is employed to calculate the flow-mass transport across inner interfaces. Denoting the water flow fluxes obtained from the HLLC solver as $\boldsymbol{f}=[f_1,f_2,f_3]$, where f_1 is the volumetric flux and f_2, f_3 are the momentum fluxes, the advective flux of mass transport, f^{adv}, is computed as follows:

$$f^{\text{adv}}=\begin{cases} f^1 c_i^{\text{re},k} & \text{if } f^1\geq 0 \\ f^1 c_j^{\text{re},k} & \text{if } f^1<0 \end{cases}$$

where $c_i^{\text{re},k}$ and $c_j^{\text{re},k}$ are the reconstructed concentrations at interface k for cells i and j, respectively. Using the divergence theorem, the diffusion flux of mass transport is expressed as:

$$f^{\text{diff}}=\frac{1}{2}\left(h_i+h_j\right)\left(D_x c_x n_x+D_y c_y n_y\right)$$

This research utilizes Torricelli's theorem to estimate the exchange of water volumes and concentration between the building and its surroundings[3]. Let the greater water depth be h_{out}, the smaller water depth be h_{in}, the opening height be h_a, and the opening area be a. Then the water volume through the opening is calculated as:

$$q_B = \begin{cases} a\sqrt{2g\left(h_{\text{out}} - h_a\right)} & \text{if } h_{\text{in}} < h_a \\ a\sqrt{2g\left(h_{\text{out}} - h_{\text{in}}\right)} & \text{if } h_{in} \geq h_a \end{cases}$$

Similarly, the mass transport through the opening is calculated as $c_B = c_{\text{out}}q$.

This research employs the splitting method and semi-implicit scheme to compute the friction term, ensuring the direction of flow velocity components remains unchanged while improving numerical stability and computational efficiency.

The Hancock predictor-corrector scheme is adopted for time integration to achieve second-order temporal accuracy.

3. Results and Discussion

A hypothetical urban flood and pollutant leakage scenario in Uji Campus, Kyoto University is used to evaluate the proposed model's capability in predicting flow and mass transport. A total of 220 kg of conservative pollutant is assumed to leak from the storage facility once the water depth reaches 0.3 m, with the leakage lasting 1,800 s. Fig. 1 illustrates the study area.

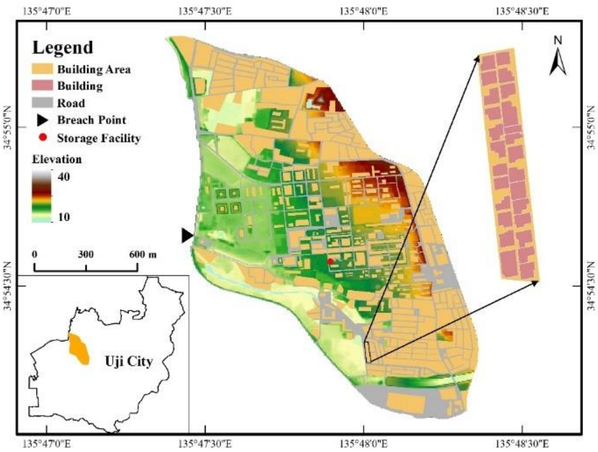

Fig. 1. The study area in Uji City.

Fig. 2 presents the spatial distributions of water depth and pollutant concentration after 30,000 s simulation. Following the breach, water flows along the terrain, initially spreading southward and northward before moving toward higher elevations in the east. As pollutants leak into the water and are driven by advection and dispersion, the initial high-concentration region disperses, reducing its concentration and expanding the affected area. A portion of the pollutants also enter buildings, becoming trapped in them. These processes are consistent with what we expected.

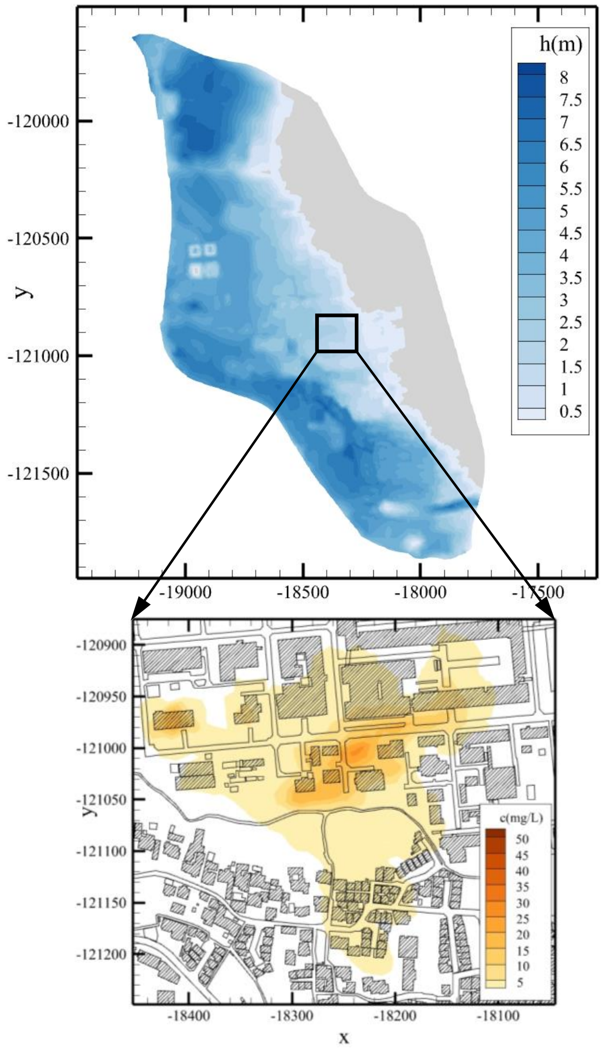

Fig. 2. Spatial distribution of water depth and pollutant concentration following a hypothetical levee breach flood event.

Reference

[1] Jawahar P, Kamath H. A high-resolution procedure for Euler and Navier–Stokes computations on unstructured grids[J]. Journal of Computational Physics, 2000, 164(1): 165-203.

[2] Xia X, Liang Q, Ming X, et al. An efficient and stable hydrodynamic model with novel source term discretization schemes for overland flow and flood simulations[J]. Water resources research, 2017, 53(5): 3730-3759.

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