Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)

A graphics processing unit-based robust numerical model for solute transport driven by torrential flow condition

Keywords: Solute transport; Shallow water equations; Godunov-type scheme; HLLC Riemann solver; GPU acceleration technology; Torrential flow

Cite this as: Jing-ming Hou, Bao-shan Shi, Qiu-hua Liang, Yu Tong, Yong-de Kang, Zhao-an Zhang, Gang-gang Bai, Xu-jun Gao, Xiao Yang, 2021. A graphics processing unit-based robust numerical model for solute transport driven by torrential flow condition. *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)*, 22(10):835-850.

https://doi.org/10.1631/jzus.A2000585

Introduction

- In cities, flood events can destroy chemical plants and wastewater treatment plants. Such an event may threaten the water safety of urban and rural residents and affect the water quality of downstream rivers and lakes.
- It is not easy to design an accurate and efficient numerical model for solving shallow water and solute transport equations. At the same time, the problems of a large amount of calculation and a low calculation efficiency must be faced. Efficient and accurate numerical modelling thus provides a significant tool for environmental impact management and water project design for water pollution incidents.

Fig.1 (a) Dam-break flood flushes coal yard, (b) The black flood enters the street.

Numerical model

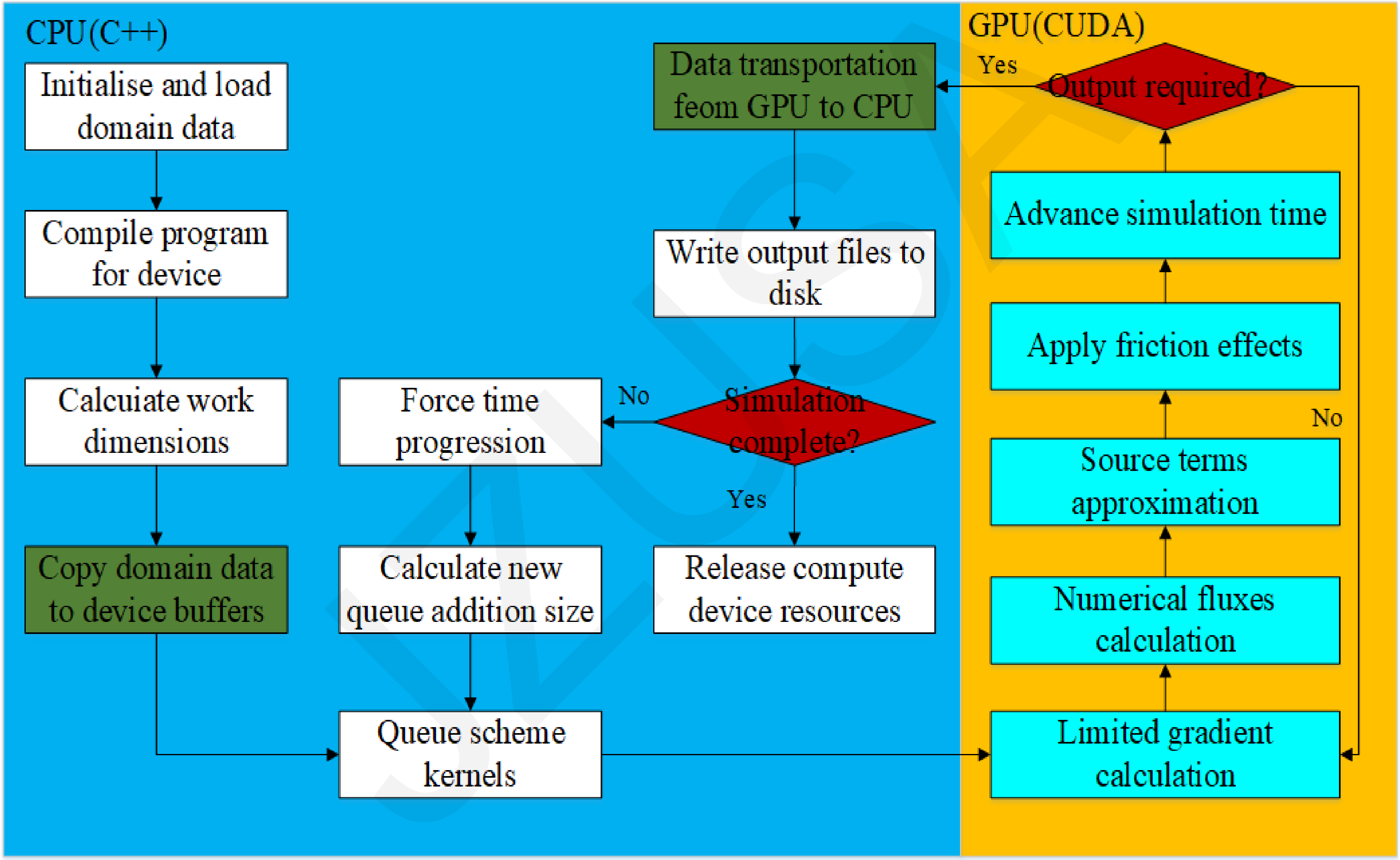
■ Governing equations

$$\frac{\partial \boldsymbol{q}}{\partial t}+\frac{\partial \boldsymbol{F}}{\partial x}+\frac{\partial \boldsymbol{G}}{\partial y}=\boldsymbol{S},$$

$$\boldsymbol{q}=\begin{bmatrix} h \\ q_x \\ q_y \\ hC \end{bmatrix}, \boldsymbol{F}=\begin{bmatrix} q_x \\ uq_x+gh^2/2 \\ uq_y \\ uhC \end{bmatrix}, \boldsymbol{G}=\begin{bmatrix} q_y \\ vq_x \\ vq_y+gh^2/2 \\ vhC \end{bmatrix}, \boldsymbol{S}=\begin{bmatrix} 0 \\ -gh\partial z_b/\partial x-C_f u\sqrt{u^2+v^2} \\ -gh\partial z_b/\partial y-C_f v\sqrt{u^2+v^2} \\ \frac{\partial}{\partial x}\left(D_x h\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_y h\frac{\partial C}{\partial y}\right)+q_{in}C_{in} \end{bmatrix},$$

where t is time; x and y are the Cartesian coordinates; $\boldsymbol{q}$ is the flow variable vector; $\boldsymbol{F}$ and $\boldsymbol{G}$ are the flux vectors in the x and y directions, respectively; and $\boldsymbol{S}$ denotes the vector of the source terms; h is the water level; u and v are the depth-averaged velocity components in the x and y directions, respectively; C represents the solute concentration; q_x and q_x are the unit-width discharge in the two Cartesian directions; g represents the acceleration due to gravity; z_b is the bed elevation; C_f is the bed roughness coefficient determined by the Manning coefficients n and h; D_x and D_y are the x and y components of the solute diffusion coefficient; q_{in} is the flow intensity of the point-source solute; and C_{in} is the average concentration of the solute perpendicular to the point-source. In addition, the water level η , which equals $h+z_b$, is also used in this work.

Flowchart of the computation using GPUs



Results

- The current model has been verified against test cases, and the results show that the numerical dissipation of solute in transport is very small and it can effectively simulate the dry and wet boundary area.

- The Godunov-type scheme is observed to correctly capture the complex flow patterns induced by the dam-break wave (shock) interacting with the three humps and the domain boundaries. The numerical results are the same as those reported by Liang (2010) on a uniform grid and those reported on the adaptive grid by Zhang et al. (2015).

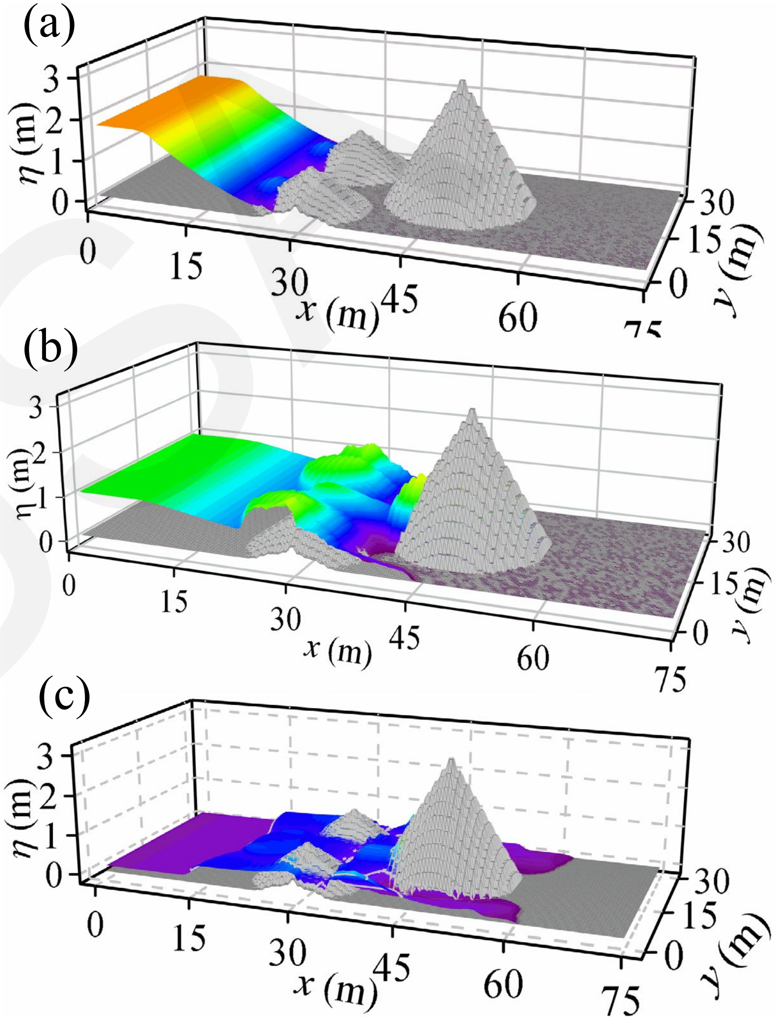


Fig.2 Dam break flood evolution: numerical results at (a) t=2s、(b) t=6s and (c) t=12s.

Results

Point-source solute transport driven by the Malpasset dam break

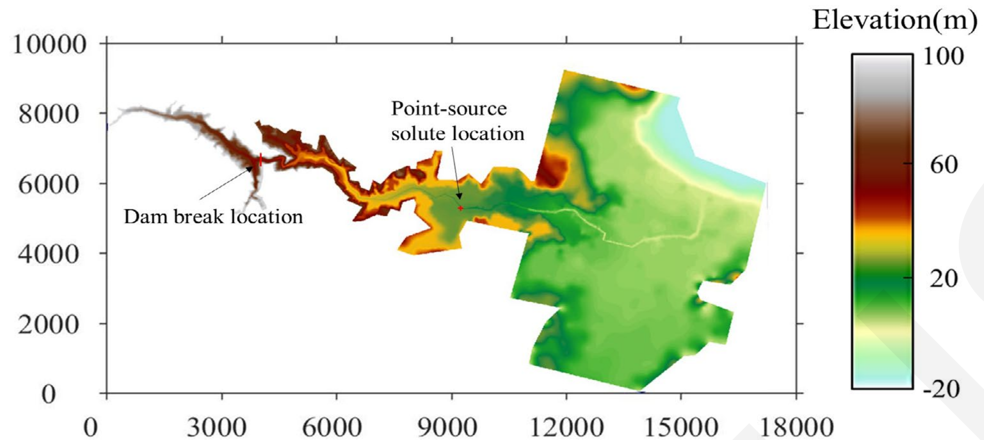


Fig.3 The topographic numerical elevation, dam break position and solute point-source position.

- Realize large-scale high-resolution simulation while ensuring simulation accuracy.
- The GPU computing performance is higher than CPU, and different types of GPU computing performance are different.

Table 1 Total execution time and speedup ratio by CPU and GPU.

Resolution	Cells	Intel Xeon E5-2609/CPU (4 cores) (s)	NVIDIA Tesla M 1080/Singe GPU (s)	NVIDIA Tesla P 100/Singe GPU (s)	CPU/GPU speedup ratio/1080	CPU/GPU speedup ratio/P100
2 m	39,542,850	——	——	17,941.5	——	——
5 m	6,326,856	34,494	2,684.29	1,202.33	12.8	28.7
10 m	1,581,714	7,661.78	382.49	171.79	20	44.6
15 m	703,188	1,334.75	136.19	59.59	9.8	23.4

Table 1: '——' indicates that the number of grids exceeds the calculation limit of the device.

Conclusions

- This paper introduces a robust model based on GPU acceleration for simulating shallow flow-driven solute transport processes.

- The current model has been verified against test cases, and the results show that the numerical dissipation of solute in transport is very small and it can effectively simulate the dry and wet boundary area. The numerical prediction and analytical solution are better than in previously obtained results.

- Using different types of GPU and CPU computing models to simulate the same event shows that GPU acceleration technology can achieve large-scale and high-efficiency calculations while ensuring simulation accuracy.

- The current model is also directly applicable to the practical application of solute transport driven by shallow flows, e.g., the transmission of pollutants in sudden water pollution accidents.