Urban scale flood simulation based on dynamic wave

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Abstract: Currently based on the full 2D shallow water equations (SWEs) model has been widely used in flood simulation, but there are still two problems to be solved in urban inundation simulation: small-scale structure simulation and calculation efficiency of urban scale model. In this paper, the effective representation of small-scale structure and GPU acceleration technology are introduced into the numerical model to establish a high efficiency and high score model. The model is applied to the simulation of urban inundation in Yuhuan. The simulation results show that the model can simulate urban inundation well with a high accuracy.

1. Introduction

With the development of cities and the impact of extreme climate, urban inundation in China is more and more frequent, and the loss is more and more heavy. "Looking at the sea from the city" has become a new normal. Although, more and more models based on full 2D shallow water equations (SWEs) are used in the simulation of overland flow and rainfall-off transformation [1-3], there are still some challenges to apply the model to the large-scale flood simulation of the city scale: first of all, we need a robust flood model that can deal with high irregular topography. In addition to the characterization of small structures such as fences, the other challenge is computing power. In addition, with the rapid development of 3D tilt photography and geographic information technology, it provides necessary conditions for the accurate simulation of urban inundation.

Esteves⁴ Wu⁵ Zhang⁶ and CEA⁷ use dynamic waves to simulate the rainfall and flood in small blocks, but most of them focus on the calculation of rainfall runoff. This work uses a well balanced shallow flow model [⁷-⁸], which can ensure that the calculated water depth is non-negative everywhere [⁹], and introduces parallel calculation of GPU into the model. By solving the calculation efficiency of small-scale structures and urban scale area, we build an efficient, high-resolution and high-precision model, and the model is applied to the simulation of urban inundation in Yuhuan.

2. Governing equation

The two-dimensional nonlinear shallow water equation in conservation form can be written as follows:

\[
\frac{\partial u}{\partial t} + \frac{\partial f}{\partial x} + \frac{\partial g}{\partial y} = s
\]  

(1)
Among them, $\eta$ is the water surface height (m); $h$ is the water depth (m); $z_b$ is the river bed elevation (m); $t$ represents the time (s); $x$, $y$ represents the coordinates of the two directions of the plane (m); $u$, $v$, $g$, $s$ respectively represents the vector containing fluid variables, $x$ directional flux, $y$ directional flux and source term. $q$ is a point source term considering rainfall and other factors, $u$, $v$ is speed in direction $x$, $y$ (m/s), $\frac{\partial z_b}{\partial x}$ and $\frac{\partial z_b}{\partial y}$ represent the slope of the bed in the $x$, $y$ direction and $c_f$ is the roughness coefficient of the bed. According to Manning’s formula: $c_f = \frac{1}{6} \rho g n^2 h^{-1/3}$.

The equation strictly keeps the balance of source term and internal force term, and ensures the accuracy of simulation calculation involving complex terrain.

GPU acceleration technology is used in the model. According to the different construction of GPU and CPU, the model assigns different tasks to GPU and CPU based on CUDA language. The main task of GPU is to obtain the flux of cell interface in prediction step and correction step respectively through MUSCL linear interpolation and HLLC approximate Riemann solution, and its parallel computing ability can complete the flux solution process of multiple cell at the same time; CPU is responsible for the main program of the model, and its main task is to use the interface flux obtained by GPU to obtain the water depth and velocity of the cell. The characteristic quantity is calculated iteratively. The cooperation between GPU and CPU ensures that the model can complete the whole solution process efficiently.

### 3. Weir and dike

In the two-dimensional hydrodynamic model of urban flood inundation simulation, the local water flow caused by key hydraulic structures such as walls and weirs may also play a decisive role in the evolution of the whole simulation. In order to realize the effective simulation and forecast of urban rainwater and inundation, the operation of flood control facilities such as walls should be directly and effectively represented in the model. In the numerical calculation, we regardless of the thickness of structures, the wall and weir are arranged at the cell interface, which is the common surface between two adjacent cell. For example, when the water level is lower than the elevation of the wall or weir, it is treated as a solid wall boundary. When the water level is higher than the water level of the wall, the weir flow formula is used.

1. According to the water level of the grid element, when the water level of the upstream grid element is lower than the elevation of the wall or the crest of the weir, the interface of the element is considered as a solid wall boundary.

2. When the water level of upstream cell is higher than the elevation of wall or weir, the flux through the interface of wall or weir is calculated by weir flow formula:

$$q = cm\sqrt{2gh} \sqrt{h_0 - h}$$
In the formula: \(c\) represents the shrinkage coefficient; \(m\) represents the discharge coefficient, \(h_0\) is the water depth ahead the weir; \(h\) is the downstream water depth above the weir top elevation; \(q\) represents the unit interface flux of the flow through the weir under the condition of free outflow or submerged outflow, among which the discharge coefficient is obtained through physical model experiment. The calculation formula of the numerical flux is as follows:

\[
F_L = \left[ \frac{q}{h_L} + \frac{1}{2} g (\eta_L^2 - 2 \eta_L Z_{bl}) \right] \quad F_R = \left[ \frac{q}{h_R} + \frac{1}{2} g (\eta_R^2 - 2 \eta_R Z_{br}) \right]
\]

(3)

Where: subscripts \(L\) and \(R\) represent the physical state of the left and right sides of the weir or wall interface respectively; \(h_L\), \(h_R\) the water depth value of the shrinkage section and \(q\), \(q\) is the unit interface flux in the direction.

In the model, the dykes (walls) in the calculation area are simulated. Due to the large scale of the grid, the dykes of the river cannot be well characterized. When the dykes are not considered, the water flow in the river channel overflows at the initial stage of rainfall, which is inconsistent with the actual situation. As shown in figure 1 below. But after considering the influence of dike, the water in the river will not overflow basically, and the calculation results are quite consistent with the actual situation.

![Figure 1 Inundation area before and after dike being consideration](image)

4. Study area
Yuhuan city is located in the middle section of the gold coast in the southeast coast of Zhejiang Province (between 121 ° 05 ′ - 121 ° 32 ′ E and 28 ° 01 ′ - 28 ° 19 ′ N), The land area of the county is 378km², which is composed of 136 small islands such as Chumen Peninsula and Yuhuan island. The sea area is 1930km².

The study area is mainly located in the southwest of Yuhuan. Damaiyu street is surrounded by mountains on three sides and the other side is sea, and the water system in the basin is relatively independent. The research area is about 25km². The location of the old city and the location of the flood mark during the rainstorm of Typhoon Morakot in 2009 are shown in the figure below.
5. Model building

5.1. DSM establishment
A large range of terrain, river and house data are mainly obtained by CAD topographic map, but in some areas that are considered to be seriously flooded, we have obtained three-dimensional high-precision data by using three-dimensional tilt photography technology, and will build surface DEM model and DSM model respectively according to the DEM, house, river course and road data in the study area, and at the same time, through the ArcGIS toolbox. The grid calculator function in spatial analyst calculates the grid, so that houses, rivers and roads can be superposed into DEM to get DSM model. Among them, the area of 3D oblique photography is an old urban area of the research area, and its scope and DSM model are shown in the figure below.
5.2. **LANDUSE**

In addition, the impervious rate of different land use types is one of the parameters that have a great impact on the calculation of runoff. The traditional calculation method of impervious area is to calculate the impervious area and permeable area in the land use planning map of the research area, and then calculate the impervious area of each area. However, the actual land use situation of the underlying surface is more complex than the planning map, such as the area marked as residence in the land use planning map, there are still many green land. Therefore, from the perspective of improving the accuracy of the model, with the aid of ArcGIS image classification tools, the research satellite images are interpreted to extract the permeable and impermeable areas of the research area.

According to different land use types, the surface water dynamic model sets different infiltration rates, and sets 9 different land use types, namely, houses, roads, squares (impermeable water), squares (permeable water), bare soil, general green space, trees and water bodies.

5.3. **Establishment of study area model**

The two-dimensional surface model uses a square grid to complete the modeling of the two-dimensional surface model of Damaiyu street. The model has 2701 rows and 2201 columns in total. There are 5971911 grids in the model. The dynamic time step is adopted for the model, and the initial time step is 0.02s.
5.4. Model validation
Influenced by Typhoon Morakot in the year of 2009, Yuhuan city suffered heavy rain in September, 2009. The heavy rain was mainly from September 29 to 30. The total rainfall at Yuhuan station was 383mm. Since there is no water level station in Qinglan river system, the verified water level is obtained through field investigation. Three relatively reliable water level verification points are obtained this time, namely, station 1-3, as shown in Figure 2 and table 1.

Table 1 verification comparison of the highest water level during the rainstorm process on September 29-30, 2009

| Location | Water level/m | Flood marks | Calculated value |
|----------|---------------|-------------|------------------|
| Station 1 | 3.9           | 4.01        |
| Station 2 | 3.3           | 3.29        |
| Station 3 | 3.8           | 3.68        |
6. Application in Yuhuan

For 20-year return period flood in Damaiyu street, the depth and scope of inundation in the old urban area is the largest in the whole process of rainfall, among which the areas with submergence depth more than 25cm are mainly concentrated in point 1 and point 2, the maximum water depth at the point 1 can reach 50cm, and the maximum water depth at the point 2 can reach 63cm. It is analyzed that the main reason for the serious inundation at the intersection of point 1 is that the rainstorm for a 20-year return period flood has exceeded the flow capacity of the underground culvert, resulting in the upstream water unable to be discharged, and finally overflowed to the ground. The area with the submerged depth of 10cm-25cm is mainly concentrated in Point 1 point 2 and the neighbouring regions. When the flooded area is most serious, the motor vehicles are basically unable to pass, which will have a greater impact on the work and life of the people. In addition, in the old urban area, the water level on the weir of XiaoChengAo reservoir is monitored at the same time by the model. The results show that for 20-year return period flood, the maximum water head on the weir is about 9cm, the discharge is small, and the flood discharge has a small impact on the downstream channel.
In addition, the calculation efficiency of the model is analyzed. After GPU parallel calculation, for the calculation area of 25km$^2$, the grid of 6 million, and the actual time of 48 hours of rainfall, the time can be shortened to about 3.4 hours when six Telsa K80 graphics cards are used for parallel calculation.

7. Conclusions
In recent years, with the frequent occurrence of urban inundation, more and more attention has been paid to the simulation of urban rainwater and flood. In this paper, the parallel technology of GPU is introduced into the model, as the same time the weir gate and other structures are introduced into the model by generalizing the enclosure (dike) and other structures into the grid cell edge, it can effectively represent the structures smaller than the minimum grid scale. The model is used to simulate flood in urban scale, and the simulation results are consistent with the measured flood traces and the investigation results. It can provide reference for other similar urban flood simulation.

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