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Flood inundation extent mapping based on block compressed tracing

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ABSTRACT

Flood inundation extent, depth, and duration are important factors affecting flood hazard evaluation. At present, flood inundation analysis is based mainly on a seeded region-growing algorithm, which is an inefficient process because it requires excessive recursive computations and it is incapable of processing massive datasets. To address this problem, we propose a block compressed tracing algorithm for mapping the flood inundation extent, which reads the DEM data in blocks before transferring them to raster compression storage. This allows a smaller computer memory to process a larger amount of data, which solves the problem of the regular seeded region-growing algorithm. In addition, the use of a raster boundary tracing technique allows the algorithm to avoid the time-consuming computations required by the seeded region-growing. Finally, we conduct a comparative evaluation in the Chin-sha River basin, results show that the proposed method solves the problem of flood inundation extent mapping based on massive DEM datasets with higher computational efficiency than the original method, which makes it suitable for practical applications.

1. Introduction

Flood inundation analysis is an important component of both hydrologic forecasting and flood hazard evaluation (Sanyal et al., 2006; Garcia, 2004), while it also plays an essential role in the design of the three-dimensional (3D) simulations (Ghazali et al., 2008) used in water conservation projects. Quick and accurate measurements of the submerged extent, depth, and duration of floods have been the focus of research into flood inundation analysis. Digital elevation models (DEMs) are the most important data source (Sanders, 2007; Umitsu et al., 2006) in flood inundation analysis and their spatial resolution has major effects on the results of these analyses (Horritt et al., 2001; Li and Wong, 2010). The use of DEM data with a low spatial resolution usually leads to distortions in geographical details, where rugged terrain appears even and smooth, and significant topographic details such as ditches, banks, and ridges in fields are simplified and ignored. Thus, the inevitable topographic errors caused by low spatial resolution DEMs means that flood inundation mapping has proved unsatisfactory in previous applications (Merwade et al., 2008b). However, the current availability of sophisticated topographical techniques, such as LiDAR, means that rapid access to high spatial resolution DEM data is now possible, which makes a significant contribution to water conservation projects (Cobby et al., 2001; Raber et al., 2007). In recent years, the application of high spatial resolution DEM data in flood inundation mapping and analysis has attracted much attention from researchers (Haile et al., 2005; Marks and Bates, 2000; Matgen et al., 2007; Archambeau et al., 2004; Zwenzner et al., 2008).

There are two different types of flood inundation analysis: 'zero-side rule inundation' and 'four-side or eight-side rule inundation' (Poulter et al., 2008). The former is used mainly to simulate areas affected by heavy rainfall, where the accumulated rainwater can cause flooding in low-lying sites, whereas the latter case is used mainly to simulate floods caused by overflows from breached dams, reservoirs, or local rainstorms. The flood inundation measurements used for 'zero-side rule inundation' are relatively simple, where DEM grid cells with elevation values lower than the water level are counted as submerged grid cells and this process is iterated for all the DEM grid cells to determine the flood extent but without considering the connection between grid cells. In analyses of 'four-side or eight-side rule inundation', the connections between DEM grid cells must be considered because of possible blockages in the flood stream such as ring structures, dams, and other barriers. Thus, the measurement of 'four-side or eight-side rule inundation' is relatively more complex and this is

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the focus of our flood inundation algorithm. At present, the flood inundation algorithm is based mainly on the seeded region-growing algorithm and its deformation during image processing (Adams et al., 1994; Mehnert et al., 1997; Fan et al., 2005). The algorithm begins by setting a point that represents the start of submersion and diffusion occurs around the given point according to four-side or eight-side rule in the DEM grid cells. In this process, the flood routing can be simulated and the inundated area is mapped automatically. The crucial point of the seeded region-growing algorithm is determining the submersion of each seed point by comparing the elevation value of the DEM grid cell and the surface of the flood water level. The water surface can be a preset horizontal water level, e.g., the water level when measuring the submerged extent in large reservoirs as the water rises or in coastal waters when the seawater level rises (Wang et al., 2002; Webster et al., 2004). Alternatively, it can be the dynamic water level surface obtained by interpolating the actual measurements obtained by hydrologic monitoring stations or the flood routing model, which is similar to the water level used when analyzing inundations of flooded areas caused by heavy rain, or when measuring the downstream flood duration and water depth when dams or dikes break (Bates and De Roo, 2000).

The rapid development of surveying and mapping techniques has facilitated the acquisition and application of high spatial resolution DEM data, but there is a huge disparity between the soaring volume of DEM data and the low computational processing capacity that is available. If we use DEM data with a spatial resolution of 1 m as an example, the overall DEM data volume can be 20 GB (50,000 rows $\times$ 50,000 columns $\times$ 8 bytes $=$ 20 GB) if the total research area is 50 km $\times$ 50 km, whereas the available memory in the majority of current personal computers is only about 4 GB. The general flooded area cannot be evaluated before making comparative measurements using the conventional seeded region-growing algorithm, so the entire DEM dataset must be placed in the memory initially, which requires sufficient memory space in the computer. The DEM required data for topographical graphic analyses in a regular 3D simulation system often reaches several GB, or even dozens of GB, which cannot be read completely in the currently available memory space of personal computers. Furthermore, the limited computer memory space often disrupts the continuity of the calculations during flood inundation analysis. If there is a large submerged area and a huge volume of DEM data, the numerous recursive operations required by the seeded region-growing algorithm disrupt the calculation efficiency and the large volume of data tends to cause stack overflows. These disadvantages restrict the application of the seeded region-growing algorithm to flood inundation measurements.

To address this problem, we propose a block compressed tracing algorithm to facilitate mapping of the inundation extent using massive DEM datasets. The computer memory space requirements can be reduced by dividing the DEM data into blocks and reading the data within the range one block at a time. Run-length encoding is also used inside the block to compress the grid cells in the raster rows with elevation values lower than the water level, which allows the data that correspond to the flood inundation extent to be stored in the computer memory. In addition, the combination of run-length encoding and raster boundary tracing makes the computation of flood inundation extent mapping more efficient than the seeded region-growing algorithm because it only needs to search a small number of grid cells on the boundary of the flood inundation extent.

2. Research background

2.1. Flood inundation analysis

Flood inundation is a dynamic process because the water level in the flooded area changes with time, and at any given time there is a fluctuating water level in the inundated area. Flood inundation mapping make a comparison with the elevation value of each DEM grid cell and its corresponding water level at a given time. Thus, the submersion of each grid cell can be evaluated and the sum of the areas below the flood water level is the flood inundation extent (Noman et al., 2001). Therefore, determining the flood water level is the basis of flood inundation analysis and there are three main methods for obtaining such measurements.

1. Spatial interpolation of hydrodynamic model results. In the field of hydraulic calculation, one-dimensional (1D) or two-dimensional (2D) hydrodynamic models are usually constructed for flood routing simulations. In 1D models, the river channel is segmented by cross-sections perpendicular to the flow direction (Samuels, 1990; Gichamo et al., 2012; Merwade et al., 2008a) and an accurate calculation of the water level in the cross-sections at different times is crucial for the model construction. The cross-sections need to be superimposed on the DEM to map the flood inundation extent, and linear interpolation (Merwade et al., 2008a; Masood et al., 2012) and inverse distance weighted (IDW) interpolation (Werner, 2001) are applied along the river channel between the cross-sections to calculate the actual water level in each DEM grid cell. In 2D models, the river channel is subdivided into nonstructural or structural grids and the water level can be measured from the center of each grid or from the nodes of the grids. To fully exploit the high spatial resolution of DEM data and to obtain more accurate determinations during flood inundation extent mapping, spatial interpolations such as linear interpolation or IDW interpolation (Apel et al., 2009) can be applied to the modeling results, which allows the water level to be calculated in each DEM grid cell and the inundation extent can be extracted.
2. Spatial interpolation of water level measurements obtained by hydrological stations. The impossibility of measuring the actual flood water level at every point in a flooded area is usually solved by setting up hydrological stations along the river channel. Based on the data collected by hydrological stations, the water level at any point can be measured by spatial interpolations such as IDW and Kriging interpolation (March et al., 1990; Zheng et al., 2006), which is then used to compute the actual water level in every DEM grid cell, thereby facilitating an evaluation of the grid inundation extent.
3. Preset fixed water level surface. In this case the flood water level can be regarded as a horizontal water surface, an approximate flood simulation is achieved by setting a specific water level in advance (Ding et al., 2004). Setting a fixed water level in water level surface simulations actually simplifies the issue by transforming the fluctuating water surface into a horizontal plane, which is suitable when measuring an inundation upstream of a dam when the water in a reservoir rises to a certain level after a sluice gate is lowered to store water in hydropower stations, or for measuring the submersion in coastal areas caused by rising seawater (Wang et al., 2002; Webster et al., 2004; Demirkesen et al., 2007; Dobosiewicz, 2001).

The first and second methods apply spatial interpolations to compute the water level in each grid cell in the DEM data, whereas the third method directly sets a fixed water level in each grid cell.