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A flooding algorithm for extracting drainage networks from unprocessed digital elevation models

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ABSTRACT

A new method for extracting the drainage network from a digital elevation model (DEM) is presented. It is based on the well-known D8 approach that simulates the overland flow but uses a more elaborate water transfer model that is inspired by the natural behaviour of water. The proposed solution has several advantages: it works on unprocessed DEMs avoiding the problems caused by pits and flats, can generate watercourses with a width greater than one cell and detects fluvial landforms like lakes, marshes or river islands that are not directly handled by most previous solutions.

1. Introduction

Since the early 1980s, a vast amount of research has been devoted to the hydrological analysis of digital elevation models (DEMs) (see Barták, 2009 for an extensive review of existing literature). In particular most attention has been focused on the identification of the river network and catchment boundaries. This data is of extreme importance, since it is necessary for simulation of rainfall-runoff and river basin management among other applications.

Most methods are based on the modeling of the overland flow, as O'Callaghan and Mark (1984) originally proposed. This approach must always work in a hydrological correct DEM, i.e., those which meet the premise that starting out from any cell and following the greatest slope we can reach the edge of the DEM. In practice, diverse anthropogenic features, vegetation, measure and interpolation errors or lack of accuracy generate closed depressions (or pits) where the water flow stops and flat areas where flow directions are difficult to assign. The importance and complexity of these anomalies have motivated the design of many different solutions that share a common approach based on preprocessing the DEM for modifying its topography to resume the circulation of the water flow. However in many cases these modifications can be rather artificial and lead to incorrect drainage networks or even remove real terrain features like volcanic craters or lakes.

We propose a new approach for computing the drainage network of a DEM that avoids the effect of pits or flat areas in an elegant and straightforward way, and therefore works with non-hydrological correct DEMs. It can also generate wide watercourses and detect lakes, reservoirs or marshes, getting results that are closer to the actual shape of the river than other methods. The key of this new approach is extending the classic method of O'Callaghan and Mark by considering the level of water in each cell and enforcing the same level for neighbour cells.

The rest of the paper is organized as follows. Section 2 provides a necessary background and contextualizes our proposal. Section 3 presents our new algorithm and discusses how it handles problematic DEMs, such as those containing flat areas and closed depressions. Section 4 studies the influence of the parameters of our algorithm and its performance. Finally, Section 5 presents the conclusions and outlines some future work.

2. Previous work

The extraction of the river networks from a DEM can be done by different methods. Peucker and Douglas (1975), Douglas (1986), Tribe (1992) determine ridge and valley lines by topographic evaluation. Meisels et al. (1995) proposed an original solution based on performing a skeletonization process on the set of elevations of the DEM. But by far the most widely used approach is based on the work of O'Callaghan and Mark (1984) that uses a simulation of water flow over terrain to extract the drainage information.

The basic implementation of this approach has three stages. In the first stage, one or more drainage directions are assigned

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from each DEM cell to its eight neighbours following the line of steepest slope. In the second stage, a unit of flow is set to each cell, and the DEM is repeatedly scanned row by row. During each iteration, the cells containing a non-zero flow are determined. Next, the flow of these cells is transferred to their neighbours following the drainage directions computed before. In the final stage a threshold is chosen and all cells with an accumulated transferred flow greater than this threshold are included as part of the drainage network.

There are several strategies for assigning the flow direction from a given cell. The simplest one, used by O'Callaghan and Mark (1984) in their seminal paper is choosing the neighbour to which the slope is steepest. This is generally known in the literature as D8 although a more precise designation is SFD8 (Single Flow Direction chosen from 8 options). If the flow is divided among all the neighbours with lower elevation according to their local slope the method is called MFD8 (Freeman, 1991). Subsequently Tarboton (1997) and Seibert and Brian (2007) proposed a more general solution that considers the steepest slope in the 0° to 360° range around the cell, although the direction is finally assigned to one or two neighbours (SFD∞), or more (MFD∞).

The methods described before for assigning flow directions fail in situations where a cell or a group of cells is surrounded by cells of higher elevation (pits). The simplest method for removing a pit proposed by Jenson and Domingue (1988) involves finding the outflow point (i.e., the cell on the boundary of the pit through which the water will overflow when it is filled with water) and filling the pit by altering the height of the cells to the height of the outflow. This solution has two important drawbacks: it can significantly change the real topography of an area leading to incorrect results and also generates flat areas that have to be treated. The alternative approach followed by Rieger (1998) and Jones (2002) is based on decreasing the elevation of the cells in the pour point and its surroundings to ensure a natural outflow of the water. This method does not generate flats and is more adequate for processing large pits than the previous one although again the DEM can sometimes be altered in unrealistic ways.

Treatment of flats is also required as a preprocessing stage before applying a flow transfer approach. The first solution, again described by Jenson and Domingue (1988) is altering the elevations of the flat to construct an inclined plane towards the lower neighbours of the flat. As this approach can result in unrealistic parallel flow lines across the flat, Garbrecht and Martz (1997) and Barnes et al. (in press) subsequently proposed combining the gradient towards lower neighbours with the gradient from higher neighbours. In certain cases this may lead to new small depressions that have to be solved again by using the gradient towards lower neighbours approach. But eventually these two methods are based on assumptions and therefore it is not clear that they will produce a result that resembles the real river morphology in large and complex flats.

Alternatively, a few methods have addressed the problem directly without preprocessing the DEM. The best known is based on the search of the least-cost drainage paths (LCPs) by using the A* search algorithm (see Ehlschlaeger, 1989) and an improved version has been implemented in the *r.watershed* GRASS module by Metz et al. (2011). This method starts at the boundary of the DEM and visits all the cells using a search that follows the least steep uphill slope, or the steepest downhill slope when a depression is encountered. The result of the search is the flow directions for each cell and a standard flow accumulation can then be applied to compute the stream channels. More recently (Magalhaes et al., 2012) have proposed a simple and intuitive approach that starts by considering the DEM as an island and then raises the outside water level step by step until the entire DEM is submerged. As the water level increases, it gradually floods the cells of the DEM, filling the depressions and spreading on flat areas. The order in which cells are reached by water determines the flow directions (as water gets into a cell, the flow directions of its neighbours are set towards it). Again a flow accumulation stage finishes the computation of the drainage network.

3. Flooding algorithm for drainage network determination

The approach described in this work is based on the modeling of the outland flow but is novel in three main aspects:

- A cell is not initialized with a unit of flow but with a water layer of a given height that also contributes to the global height of the cell.
- A SFD8 strategy is used to transfer the water to a neighbour cell, but in contrast with a classic flow-based approach, the neighbour to which the slope is steepest changes from one iteration to the next due to the changes in the height of the water layer. A second difference is that not all the water is transferred to the neighbour; instead, the same water level in both cells is enforced when possible.
- No preprocessing of pits and flats is required, as the water layer fills the pits when required and also runs through the flats to continue its course.

3.1. Algorithm description

Our approach for extracting a drainage network from a DEM can be summarized in the following steps:

1. Simulate a homogeneous rainfall flooding the entire DEM by initializing all cells with a constant water depth value of W.
2. Simulate the water spilling over the DEM by iteratively draining water between adjacent cells. For each cell c of the DEM, compute the neighbour n to which the slope is steepest considering the sum (ZW) of the altitude (Z) of the cell and the height (W) of the water layer (see Fig. 1). Transfer water from the cell c to n to enforce the same level. Update the drainage accumulation (DA) of the cell n. Repeat this procedure while the overall amount of water transferred is greater than 0 (or a small predefined epsilon).
3. Mark as belonging to the drainage network the cells with a drainage accumulation greater than a predefined threshold.

The flow direction determination and water transfer in stage 2 is the key part of the algorithm. Given a cell c, the algorithm first checks whether the cell is in the border of the DEM. If this is the case, the water it contains is drained out of the DEM and the W value of the cell becomes 0. Otherwise, the drainage direction for the cell is computed on the fly as the direction to the 3 × 3

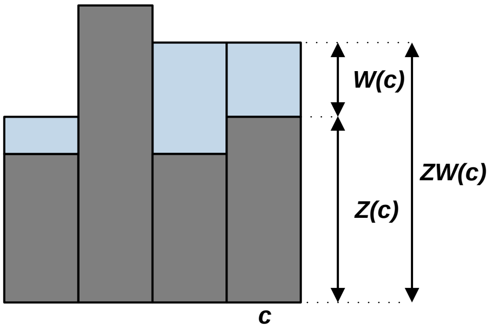

Fig. 1. Example illustrating some cells of a DEM and the notations used in the paper.