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DEM AGGREGATION FOR WATERSHED MODELING[1]

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ABSTRACT: The widely available USGS 7.5-minute Digital Elevation Model (DEM) has a cell size of approximately 30 m x 30 m. This high resolution topographic information is impractical for many applications of distributed hydrologic and water quality models. In this study, cells were aggregated into coarse-resolution areal units, termed grids, and a method to approximate flow direction for coarse-resolution grids from 30 m DEM cells was developed. The method considers the flow path defined from the fine-resolution DEM in determining a grid's flow direction and makes flow directions for grids closely follow the flow pattern suggested by the DEM. The aggregation method was applied to a DEM of Goodwater Creek, a nearly flat watershed that is located in central Missouri. The drainage networks derived for different levels of cell aggregations showed that grid aggregates of the Goodwater Creek watershed provided an adequate representation of the landscape topography.

(KEY TERMS: digital elevation model; DEM aggregation; flow direction; watershed properties.)

INTRODUCTION

In distributed-parameter models, watersheds are often subdivided into squares with unique characteristics. For these models, flow direction and other drainage properties are required for each square. Manual processing of such data is tedious, time consuming, and error prone. The development of automated techniques to determine watershed drainage properties from DEMs greatly expedites this data preparation task. In previous investigations, a number of algorithms for automated evaluation of fine resolution DEMs have been proposed (O'Callaghan and Mark, 1984; Jenson and Dominigue, 1988; Martz and De Jong, 1988; Fairfield and Leymarie, 1991; Martz and Garbrecht, 1992, 1993; Garbrecht and Martz, 1993).

The widely available USGS 7.5-minute DEMs have a horizontal resolution of 30 m x 30 m. Applying distributed models to large watersheds and using topographic information at this resolution requires extensive computational and memory resources that are often not available. In our previous study (Wang and Hjelmfelt, 1998), a physically based, distributed rainfall-runoff model was developed and applied to a subcatchment of Goodwater Creek watershed established by USDA Agricultural Research Service in 1971. The Goodwater Creek watershed has a drainage area of 72.6 km^2 and the sub-catchment has an area of 12.2 km^2. At the DEM resolution of 30 m x 30 m, the watershed and the sub-catchment have 80,000 and 13,566 cells, respectively. For watershed-level simulation, modeling 80,000 or 13,566 cells is time consuming, sometimes even impracticable. Wang and Hjelmfelt (1998) applied their model based on coarse-resolution areal units, termed grids. The grid size for the simulation is 150 m x 150 m. Typical grid sizes for AGNPS, Agricultural Non-Point Source Pollutant model (Young *et al.*, 1987) are 4 ha (about 10 acres or 200 m x 200 m) for small watersheds and 10 ha (40 acres or 310 m x 310 m) for large watersheds. The primary objective of this study is to develop a method to aggregate flow directions from fine-resolution DEM cells into coarse-resolution grids, each of which may consist of several DEM cells.

Kao (1992, 1996) presented eight methods for approximating the flow directions of fine-resolution cells in coarse-resolution grid aggregates: (1) vectorial

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average, (2) major vector, (3) weighted vectorial average, (4) elevation average, (5) variant elevation average, (6) stream network, (7) drainage direction, and (8) neural network. Kao tested these methods by manually creating flow directions of coarse-resolution grids from topographic maps and comparing that data with the results obtained from each method. His study indicated that the drainage direction method and the neural network method were superior to the others, and that the neural network method gave a better performance than the drainage direction method. The result from the neural network method, however, was based on training sets that were very carefully selected from the manually determined drainage directions. Creating appropriate training sets is time consuming and subjective. On the other hand, the drainage direction method treats each coarse-resolution grid as a small watershed and takes the drainage direction of its outlet cell as the drainage direction of the coarse-resolution grid. This method does not consider the flow path, defined from the fine-resolution DEM, beyond a grid in determining the grid's flow direction. This omission results in coarse-resolution flow directions that deviate from the fine-resolution flow paths and that may become loops. This is a problem that can have significant consequences, especially for large resolution aggregations. To overcome the problem, a new DEM aggregation method was developed based on the drainage direction method. The numerical steps of the method are presented first, and are then followed by an application to the Goodwater Creek watershed and a discussion of the results.

NUMERICAL STEPS

The DEM aggregation method presented in this study consists of three steps: (1) processing the fine-resolution DEM to determine flow direction, (2) determining outlets of coarse-resolution grids, and (3) approximating flow direction of coarse-resolution grids. The method treats each coarse-resolution grid as a small watershed and computes flow direction of the coarse-resolution representation of the landscape topography.

DEM Data Processing

Flow direction of the DEM cells was determined based on the D8 method (Fairfield and Leymarie, 1991), in which the flow direction of a cell points towards the adjacent neighbor with the elevation that forms the steepest downward slope with that cell. Because depressions and flat areas exist in most DEMs and the flow directions of cells in these areas cannot be determined using the D8 method, additional techniques were used. Martz and De Jong (1988) presented an algorithm to search for the contributing area of a depression and to fill the depression to form a flat area with an elevation equal to the lowest "overflow" elevation on the depression perimeter. Martz and Garbrecht (1992, 1993) presented a numerical approach that adds relief to flat areas to determine the flow directions for cells in a flat area. The D8 method and the two algorithms presented by Martz and De Jong (1988) and Martz and Garbrecht (1992, 1993) were combined to determine the flow direction of cells in this study. The flow direction is represented using one of the integer numbers from 1 to 8, which indicate eight neighboring cells as shown in Figure 1. As an example, when the flow direction of the center cell, labeled 0, points to the neighboring cell in the upper left corner, the flow direction value of the center cell is coded as 1.

1	2	3
4	0	5
6	7	8

Figure 1. Number System for 3 x 3 Cell Window.

Grid Outlet Determination

A coarse-resolution grid aggregates several DEM cells. Because a coarse-resolution grid may drain from more than one point, an outlet determination algorithm was developed to find all drain points and select the drain point with the largest contributing area as the outlet of the grid. The outlet is assumed to drain all flow from the coarse-resolution grid.

The outlet determination algorithm is based on the flow accumulation concept introduced by O'Callaghan and Mark (1984). The algorithm develops the flow path for each fine-resolution cell within a coarse-resolution grid by advancing down slope from one fine-resolution cell to the next, following the flow directions defined from the DEM. As the flow path is advanced down slope, the contributing area for each fine-resolution cell along the flow path is incremented by one. This processing stops when the flow path reaches the coarse-resolution grid edge. Once all cells in the coarse-resolution grid are processed, all drain points of the coarse-resolution grid are identified and the contributing area of each point is determined. If only one drain point exists, then it is chosen as the outlet. If more than one drain point cell exists, the point with the largest contributing area is selected as the outlet of the coarse-resolution grid. If there is more than one drain point with the same largest drainage area, the one with the steepest slope is taken as the selected outlet. The selected outlet is assumed to drain the flow from all cells in the coarse-resolution grid.

Flow Direction Approximation

An algorithm was developed to determine the flow direction of a coarse-resolution grid using the flow path that drains from the outlet cell of a grid. The flow direction of the coarse-resolution grid cannot simply be defined as the flow direction of the outlet cell selected in step 2 because of the redirection of flow from a contributing grid due to a drainage divide through the downstream grid. In Figure 2, grid 0 is the contributing grid and grid 7 is the next downstream grid to which the outlet of grid 0 directly points. Water draining from grid 0, although it enters grid 7, does not flow through the outlet of grid 7 according to the DEM. The flow path of water leaving grid 0 is affected by a divide in grid 7 and is routed into grid 6. Thus, grid 6, not 7, receives water draining from grid 0. If grid 7 were to be defined as the receiving grid, the outlet of grid 7 would drain water from grid 0 in the wrong direction. Therefore, the flow direction of a contributing grid should be determined by the flow path from the grid's outlet, but not by the flow direction at the outlet cell. The determination procedures are described in the following paragraphs.

The flow path from the outlet cell of a contributing grid is advanced one cell at a time until an outlet of one of the eight neighboring grids is reached. The neighboring grid with that outlet is defined as the receiving grid. In Figure 2, the flow path from the contributing grid 0 reaches the outlet cell of grid 6 when it is advanced four cells beyond the outlet cell of grid 0. The flow direction value of the contributing grid is defined to be 6.

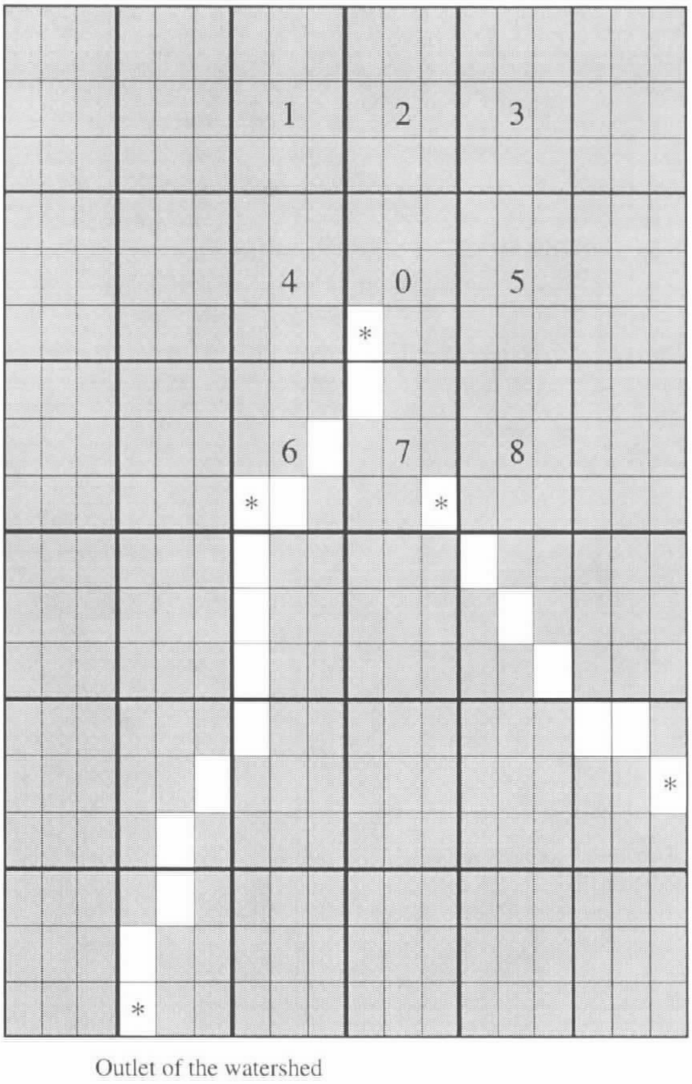

Fig. 2 An example of a contributing grid diverted into a small portion of the down slope grid.

* -- outlet of a grid. ☐ - cell in flow path

In the case of a flow path that fails to pass through the outlet of any neighbors, the flow direction cannot be determined solely on the basis of information in the eight grids neighboring the contributing grid 0. The flow path from the outlet of the contributing grid needs to be advanced beyond the boundaries of grid 0's eight adjacent neighbors until eventually merging with the flow from the outlet of one of grid 0's eight adjacent neighbors. If only one such downslope grid exists, the down slope grid whose flow merges with flow from grid 0 is defined as the receiving grid. Grid 6, as shown in Figure 3, is defined as the receiving grid. If the flow from grid 0 merges with flow from more than one down slope grid, the down slope grid whose flow merges with the flow from grid 0 the furthest upstream is defined as the receiving grid. Figure 4 is an example of this case in which flows from both grid 6 and grid 7 merge with the flow from grid 0. The flow from grid 7, however, merges with the flow from grid 0 first. Grid 7 is defined as the receiving grid. This processing approach makes the flow direction of coarse-resolution grids closely follow the flow direction of the fine-resolution DEM cells.

In the case that grid 0's flow fails to merge with the flow path from any of grid 0's eight adjacent neighbors, there is not enough information to properly determine a flow direction for the contributing grid. The contributing grid 0 is assumed to have the flow direction value of its outlet cell.

APPLICATION

The DEM aggregation method developed in this study was applied to Goodwater Creek watershed, located in central Missouri, to determine flow directions of DEM cells and to approximate them for coarse-resolution grids. Goodwater Creek watershed, which has a drainage area of 72.6 km^2, was established as a research catchment by the USDA, Agricultural Research Service, in 1971.

A DEM, consisting of 360 rows x 500 columns – total of 180,000 cells, was used for this study. The horizontal and vertical resolutions of this DEM are 30 m and 1 m, respectively. From this DEM, the flow directions for fine-resolution cells were determined and were used to generate the watershed drainage network. A minimum drainage area of 9×10^5 m^2 and a

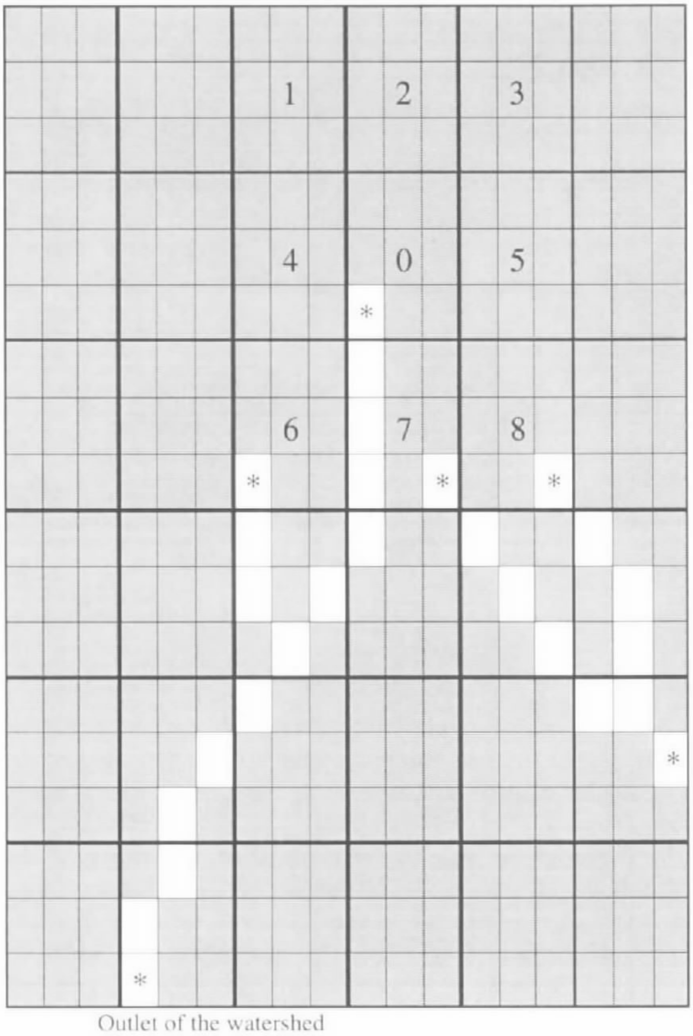

Fig. 3 A contributing grid whose flow merges with flow from one down slope grid.

* -- outlet of a grid. ☐ - cell in flow path

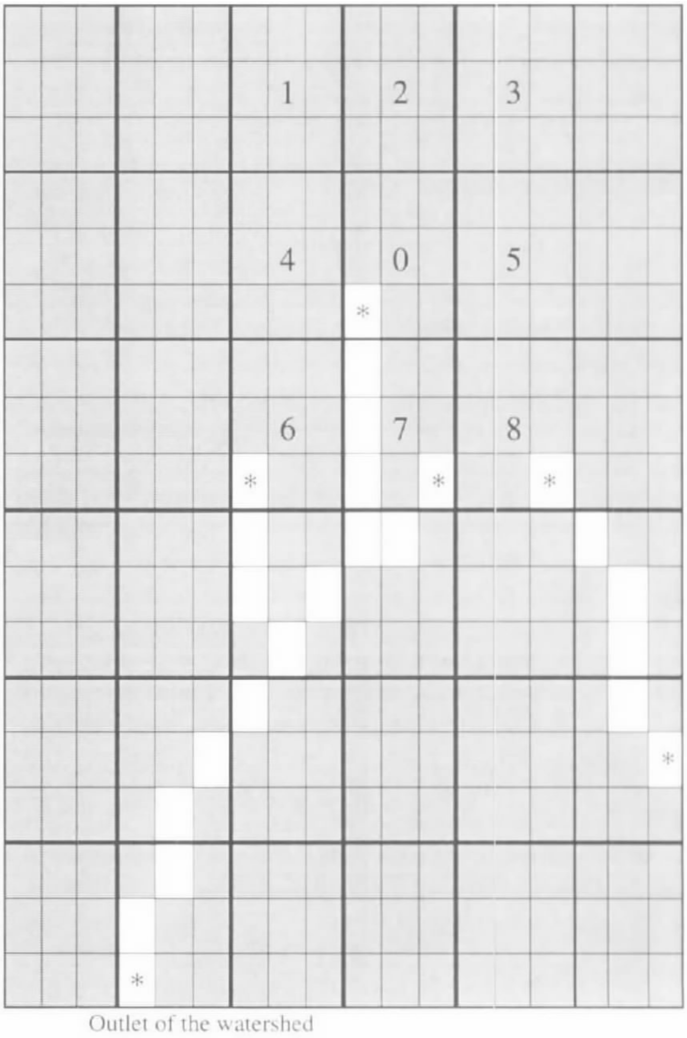

Fig. 4 A contributing grid whose flow merges with flow from more than one down slope grid.

* -- outlet of a grid. ☐ - cell in flow path

channel length of 450 m were used to delineate the drainage network. The generated drainage network is shown in Figure 5A. Flow directions, channel links, and watershed boundaries are needed for distributed watershed models.

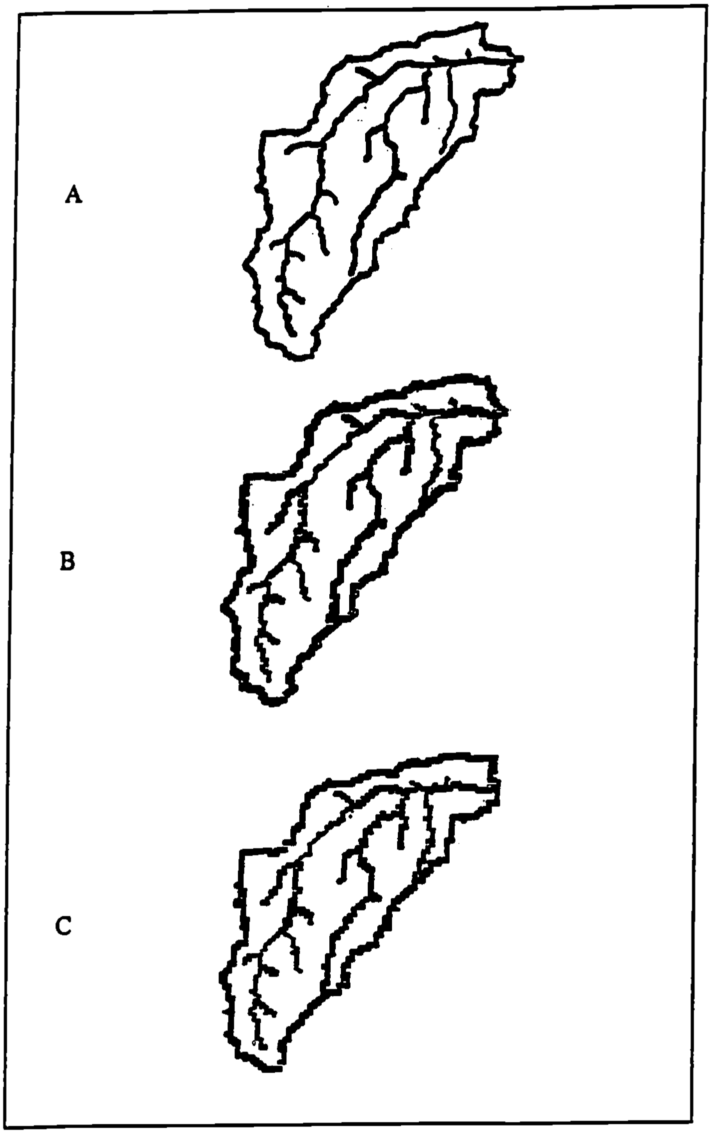

Figure 5. Drainage Networks of Goodwater Creek Watershed Generated From Different Scale Data (A = 30 m x 30 m; B = 120 m x 120 m; C = 150 m x 150 m).

To apply distributed-parameter models, such as AGNPS (Young *et al.*, 1987), for watershed-level hydrologic and water quality simulations based on 80,000 cells is impractical. DEM aggregation is often needed. In this study, the 30 m x 30 m cells were aggregated into two levels: grids with sizes of 120 m x 120 m (1.4 ha) and 150 m x 150 m (2.25 ha), or 16 and 25 cells. After the aggregations, the flow directions for the two resolutions of grids were calculated, and the number of elements in Goodwater Creek watershed was reduced from 80,000 to about 5,000 and 3,000, respectively. Figure 5 shows that the drainage networks generated from the three different resolutions of data under the same threshold values of catchment area and channel length are consistent.

SUMMARY AND CONCLUSIONS

The widely available USGS 7.5-minute DEMs have a horizontal resolution of 30 m x 30 m. In this study, a DEM aggregation method was developed to approximate the flow directions of DEM cells at this resolution into corresponding data for grids at coarse resolutions. Such an aggregation of topographic information is often necessary for many applications of grid-based hydrologic and water quality models to large watersheds. The DEM aggregation method considers the flow trends suggested by fine-resolution DEM cells in computing flow directions of coarse-resolution grids.

The DEM aggregation method was applied to the Goodwater Creek watershed located in central Missouri. The DEM with size of 30 m x 30 m was aggregated into coarse-resolution grids with sizes of 120 m x 120 m and 150 m x 150 m. The drainage networks generated from the three different resolutions of data were consistent.

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