

# Automatic Extraction of Drainage Networks from DEMs Base on Heuristic Search

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**Abstract**—Computer aided automatic Extraction of drainage networks from DEMs can promote the efficiency of regional water resource prospecting and assessment in GIS. Extracting drainage networks from raster DEMs is a necessary requirement in many applications of GIS, and determining surface water flow direction is a fundamental problem. In a raster environment, surface water flow direction of each cell can be directed to the neighboring cell with the steepest downslope drop (The basic D8, deterministic eight-neighbour method), which is inadequate for routing flow over pits and flat areas. Several improved methods are proposed to assign flow direction of pits and flats, which typically use entirely different procedures for processing pits and flats without heuristic information. Being different from others, a method to treat pits and flats is proposed in this paper. The method is based on heuristic search, which can effectively handle both conditions. This method is implemented in Pascal and experiments are carried out on actual DEM data. The experimental results show that this approach are robust, computationally efficient, and avoid many of the problems associated with other methods.

**Index Terms**—GIS, pit, flat areas, drainage networks

## I. INTRODUCTION

Geographic information system (GIS) technology can be used for scientific investigations, resource management, and development planning. For example, a GIS might allow emergency planners to easily calculate emergency response times in the event of a natural disaster, or a GIS might be used to find wetlands that need protection from pollution.

Because it is a fundamental problem in digital terrain analysis, the extraction of extracting drainage networks plays an important role in many applications of GIS, such as hydrologic analysis, mineral deposition, land erosion, pollution diffusion analysis, etc. [1-5]. The basic and important problem of extracting drainage networks is to determine flow direction of every cell in a raster DEM. The most popular and commonly used algorithm is

known as D8 [6-9], but the continuity of drainages does not extend across pits and flats.

DEMs (Digital elevation models) provide us a digital representation of the continuous land surface. Grid DEMs consist of a matrix data structure with the topographic elevation of each cell stored in a matrix node. Grid DEMs are distinct from other DEM representations such as triangular irregular network (TIN) and contour-based data storage structures. Grid DEMs are readily available and simple to use and hence have seen widespread application to the analysis of hydrologic problems. However, they suffer from some drawbacks that arise from their gridded nature. DEMs often contain depressions (pits) and flat areas that result in areas described as having no drainage, referred to as pits and flats. Pit and flat areas are common in gridded DEMs; most of them are the result of mistakes, whereas some represent real terrain features, e.g., quarries and grottoes. The majority are spurious features, which arise from interpolation errors during DEM generation, truncation of interpolated values, and the limited spatial resolution of the DEM grid [10]. Pit and flat areas must be dealt with as a precondition of flow route tracing.

Over the past 20 years, there have been many improved methods for routing flow through pits and flats. The limitation of the methods is the searching process of the methods without heuristic information.

In this paper, we present a method to handle pits and flats with heuristic information. Heuristic information is often applied to finding the shortest path [11-13]. While searching for the outlet, the proposed method not only checks the eight adjacent cells of pit or flat, but also takes the general trend of the DEM into considerations.

## II. OVER VIEW OF THE METHODS USED FOR DRAINAGE DELINEATION

### A. Conventional Methods and Improvement

Numerous methods have been proposed for automated drainage recognition in grid DEMs. The basic D8 (deterministic eight-neighbor method) algorithm is

probably the most popular method. However, it has a number of deficiencies. In this method, the flow direction of each cell in a raster DEM is determined by the comparison between the cell's elevation and its eight adjacent neighbors, the maximum drop direction was identified as the flow direction. The generation of parallel flow lines in flat areas that restricts the formation of concentrated channel flow has been identified as a limitation of this method. In particular, pits and flats, both real and spurious, in raster elevation data present challenges for the automated derivation of fully connected drainage patterns.

Pits and flats are areas where the cell's flow direction cannot be determined with reference to its eight neighbouring cells. A pit is defined as a point none of whose neighbors have lower elevations, flats are areas of level terrain (slope =0). Pits and flats can be naturally occurring but are generally viewed as spurious features that result from elevation data capture errors [14, 15] or errors introduced during DEM generation [16]. Pits and flats can be found in all DEMs but are particularly pronounced in low relief areas or in the case of flats.

For ensure each cell in a raster DEM has flow direction, many methods are proposed to assign flow direction of either pits or flats. One of most common methods is proposed by Jenson and Domingue (1988). The method works in two stages. In the first stages, DEM filling, all pits are identified and filled to their pour points. The pits are thus turned into flats. For flow tracing along both natural and resulting flat areas, iterative flow direction assignment through flat areas, the second stage was used. Cells in the flat areas are assigned flow directions that point to one of its neighboring cells having a flow direction not pointing back to the selected cell, until the entire flat area has been consumed.

Outlet breaching modified DEM filling by assuming that the pits are created by an elevation overestimation at the obstruction [17]. However, DEM filling assumes that pits are created by an underestimation of elevation values within the pits. Outlet breaching involves identifying the breach points for each pit and lowering the elevation values in these areas, subject to user-specified tolerances. An advantage of outlet breaching is that it typically involves making fewer alterations to a DEM than filling and much of the original interpolated elevation values, and therefore flow directions within a pit, are preserved.

Imposing relief across flats is a method for flat areas. Flats in a raster DEM are not exactly level in nature because DEM can't represent elevation difference less than vertical resolution. The method introduces a relief algorithm to impose a finite gradient over the flats [18]. This method requires less computer memory compared to the algorithm proposed by Jenson and Domingue (1988). First, this algorithm searches the perimeter of a flat for valid downslope cells (exit points). These exit points are used as a source and neighboring cells within the flat are assigned a small fixed elevation value slightly higher than the outlet cell(s). The process is repeated iteratively until the entire flat has been consumed, thereby creating a gradient across flats based on Euclidian distance from the

outlets. In more advanced forms of relief imposition, a secondary shallow gradient is imposed to force flow from the higher terrain surrounding a flat [19]. This second gradient ensures that flow within the flat is consistent with the topography surrounding the flat surface and avoids parallel flow paths across flats that can be witnessed in the methods proposed by Jenson and Domingue (1988) and Martz and Garbrecht (1993).

The parallel drainage lines were found to be unrealistic and a new method was developed for flow tracing, in which the pits were handled in a more realistic way [20]. Spurious pits and real pits were identified and treated separately. The method involves defining a main flow path through the flat to an outlet, and directing the flow paths for nearby points in the flat towards the main path. However, because the main flow path is defined as a straight line, it could cut through an area of higher elevation [21].

A unique partial solution to the problem of pits in a raster DEM is to utilize the ANUDEM (Australian National University DEM) thin-plate spline interpolation method (called TOPOGRID in ArcInfo) [22-24]. The method uses a flow-directed, single-line hydrology network as a boundary condition during interpolation, ensuring a downslope gradient for all cells along the hydrology network.

For solve the directional problem of the D8 algorithm, a stochastic approach while determining the flow direction was proposed [25]. The method solved the directional limitation of D8, but it bring new problem, it was less efficient and could introduce undesirable feature in other areas. Multiple flow directions were also a method [26]. Drawbacks of this method were the elimination of the unimodal link between the flow directions and the complications in defining the catchment boundary due to the multiple flow direction from a cell [27].

PFS algorithm can effectively process both pits and flats [21]. This algorithm is based on the priority-first-search weighted-graph algorithm. When processing a flat or pit cell the PFS algorithm searches for a nearest cell with lowest elevation (exit point) and finds a shortest drainage path between the two cells. After finding the exit point and shortest drainage path, the PFS algorithm will lower the elevation of all points along the shortest drainage path to create a consistent gradient downslope drainage path between the original flat or pit point and the outlet point [28]. But in case of very large flat areas, the PFS algorithm was not sufficient to define the unique flow direction.

### *B. Heuristic Search*

The primary search strategy of the methods described above is uninformed search (also called blind search). The term means that they have no additional information about states beyond that provided in the problem definition. All they can do is generate successors and distinguish a goal state from a nongoal state. The uninformed search strategies can find solutions to problems by systematically generating new states and testing them against the goal. Unfortunately, these

strategies are incredibly inefficient in most cases. Informed search (or heuristic search) strategies which use problem-specific knowledge beyond the definition of the problem itself can find solutions more efficiently than the uninformed search strategies. Information about the state space can prevent algorithms from blundering about in the dark [29].

In heuristic search, a node is selected for expansion based on a heuristic function,  $f(n)$ . Heuristic functions are the most common form in which additional knowledge of the problem is imparted to the informed search algorithm. Traditionally, the node with the most suitable evaluation is selected for expansion, because the evaluation measures cost to the goal.

Heuristic function evaluates the importance of the node. It evaluates nodes by combining  $g(n)$ , the cost to reach the current node and  $h(n)$ , the cost to get from the current node to the goal node.

Since  $g(n)$  gives the path cost from the start node to current state, and  $h(n)$  is the estimated cost of the cheapest path from current node to the goal node, we have

$f(n)$  = estimated cost of the cheapest solution through the current node

Thus, if we are trying to find the cheapest solution, a reasonable thing to try first is the node with the most suitable value of  $g(n) + h(n)$ . It turns out that this strategy is more than just reasonable: provided that the heuristic function  $f(n)$  satisfies certain conditions, the search is both complete and optimal.

### III. PROPOSED METHOD

The proposed method is based on heuristic search. The main purpose of the method is to handle pits and flats with heuristic information in one procedure.

#### A. The Basic Method for Extracting Drainage Networks

The basic method consists of a sequence of procedures, which are illustrated in Fig. 1. The procedures operate on the elevation matrix and derive depressionless DEM matrix, drainage direction matrix and drainage accumulation matrix. The basic workflow includes the following steps:

Step 1: Read elevation matrix.

Step 2: Detecting depressions. If there are no depressions in the elevation matrix, go to Step 4.

Step 3: Generating depressionless DEM matrix.

Step 4: Detecting flat areas. If there are no flat areas in the depressionless DEM matrix, go to Step 6.

Step 5: Removing flat areas from the depressionless DEM matrix, go to Step 2.

Step 6: Generating drainage direction matrix. The drainage direction for a cell in the depressionless DEM is computed based on the natural law that surface water flow will be directed to the steepest downslope drop.

Step 7: Generating drainage accumulation matrix. Each cell in drainage accumulation matrix represents the sum of the weights of all cells in the matrix which drain to that

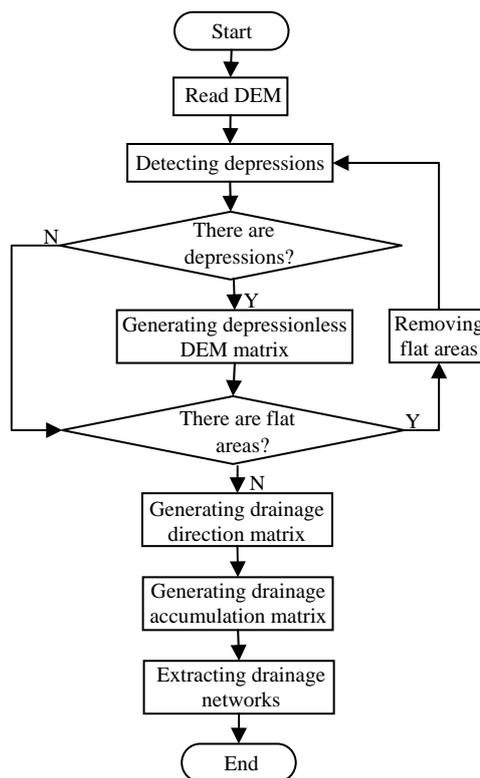


Figure 1. Schematic diagram showing the basic method.

cell. If the weights of all cells are set one, then the resulting values of the drainage accumulation matrix will give the total contributing drainage area, in number of cells. Other weight matrices can be used for specific drainage related applications.

Step 8: Extracting drainage networks. Drainage accumulation data can be used to produce drainage networks when cells with values greater than an assigned threshold value are selected.

#### B. Calculating the Incipient Flow Direction Using the Basic Algorithm

One of the keys to deriving hydrologic characteristics about a surface is the ability to determine the direction of flow from every cell in the raster DEMs. A 3-by-3 moving window is used over a DEM to locate the flow direction for each cell. The elevation difference ( $\Delta E$ ) from the centre cell of the window to one of its eight neighbours is calculated as:

$$\Delta E = \frac{E_0 - E_i}{\phi(i)} \quad (1)$$

Where  $\phi(i) = 1$  for 2, 4, 6, and 8, (E, S, W, and N neighbours) and  $\phi(i) = \sqrt{2}$  for 1, 3, 5, and 7 (NE, SE, SW, and NW neighbours). If  $\Delta E$  is less than zero, a zero flow direction is assigned to indicate that the flow direction is undefined. If  $\Delta E$  is greater than zero and occurs at one neighbour, the flow direction is assigned to that neighbour. If  $\Delta E$  is greater than zero and occurs at more than one neighbour, the flow direction is assigned to the maximum  $\Delta E$ , the lowest neighbour cell. If the flow direction is still undefined, a zero flow direction is

assigned to indicate that the flow direction is undefined. The cell with an undefined flow direction is then processed by the algorithm proposed by this article.

*C. Finding the Optimal Outlet of Depressions and Flat Areas Using the Proposed Method*

After calculating the incipient flow direction, the cells without flow direction (pit and flat cells) need advanced processing with the proposed method. The proposed method is based on heuristic information. The main purpose of the algorithm is to handle pits and flats with heuristic information in one procedure.

The method would require three data structure, closed list, open list and an array. The closed list stores every checked node, the open list keeps the unchecked nodes, and the array stores the cells without flow direction.

The proposed method consists of a sequence of procedures, which are illustrated in Fig. 2. The procedures operate on the elevation matrix, flow direction matrix and flow accumulation matrix. The basic workflow includes the following steps:

Step 1: Read elevation matrix.

Step 2: Detecting nodes without flow direction and put them into the array.

Step 3: If all nodes in the array are processed, go to Step 9.

Step 4: An unprocessed node in the array is put into the open list.

Step 5: Select the node with the minimum value in the open list. Add the selected node into the closed list and remove it from the open list.

Step 6: If the selected node is an outlet, go to Step 8.

Step 7: Check the adjacent nodes of the selected node in the open list. If the adjacent nodes are neither in open list nor closed list, add them into the open list and establish pointers from these nodes to the selected node. Go to Step 5.

Step 8: Traced from the outlet back to the starting node in the closed list, and adjust the elevations. Go to Step 3.

Step 9: Generating flow direction matrix.

Step 10: Generating flow accumulation matrix.

Step 11: Extracting drainage networks.

The proposed method uses the heuristic information value to evaluate the node  $i$ . The heuristic information consists of two elements, actual cost and estimated cost, according to:

$$f(i) = g(i) + h(i) \tag{2}$$

$$g(i) = E_i - E_s \tag{3}$$

$$h(i) = \frac{\sum_{k \in S_i} E_k}{\|S_i\|} \tag{4}$$

Where  $f(i)$  is heuristic information value of node  $i$ ,  $g(i)$  is the difference from the node  $i$  to the starting node,  $h(i)$  is estimated cost, the arithmetic average elevation of the cells in n-by-n ( $n=3, 5, 7, \dots$ ) window centered the node  $i$ , we choose 5 in this article,  $E_s$  is the elevation value of the starting node  $s$ ,  $E_i$  is the elevation value the

node  $i$ ,  $E_k$  is the elevation value the node  $k$ ,  $S_i$  is a set which contains all the nodes in n-by-n window centered

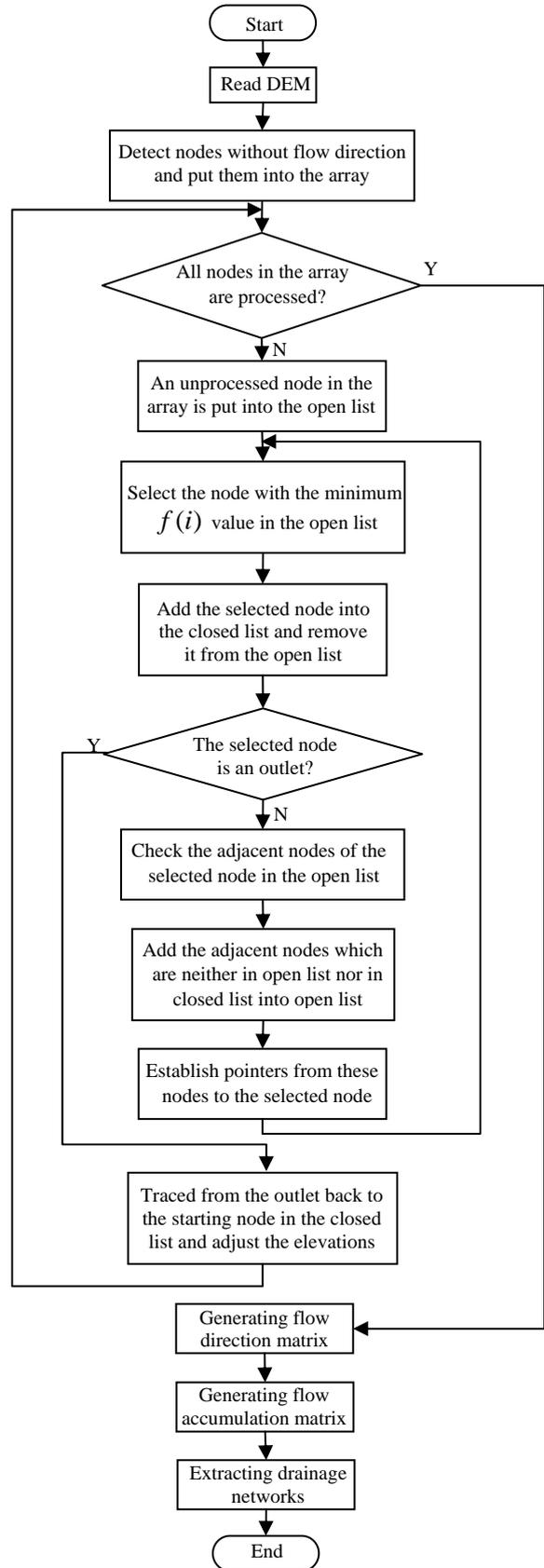


Figure2. Schematic diagram showing the proposed method.

the node  $i$ ,  $k$  is a element of set  $S_i$  and  $\|S_i\|$  is the number of nodes in the set  $S_i$ .

The proposed method executes a single searching procedure on every node without flow direction. The searching procedure try to find an outlet (a node whose elevation is lower than the node with undefined direction) for the node without flow direction. It can be regarded as a path searching problem which start is the node and goal is the outlet.

In turn, the node with the minimum heuristic information value is removed from the open list and added into the closed list, and its adjacent nodes which are neither in the open list nor in the closed list are added into the open list. The iteration continues until a selected node in the open list satisfies the terminating criteria, which is an "outlet" for the drainage. The terminating criteria require the node with the minimum heuristic information value and it has a lower elevation than the starting node. Finally, the nodes in the closed list are traced from the outlet back to the starting node in the closed list, and adjust the elevations in the elevation matrix to create a gradient according to (5).

$$E_i' = E_s - E_s \times \frac{\|Path_{(s,i)}\|}{\|Path_{(s,o)}\|} \quad (5)$$

Where  $E_s$  is the elevation value of the starting node  $s$ ,  $E_o$  is the elevation value of the outlet node  $o$ ,  $E_i$  is the elevation value the node  $i$ ,  $E_i'$  is the new elevation value of the node  $i$  after adjusted,  $\|Path_{(s,o)}\|$  is the path length from  $s$  to  $o$ ,  $\|Path_{(s,i)}\|$  is the path length from  $s$  to  $i$ .

While searching for the outlet of the cell without flow direction, checking only the nearest eight neighbors is not enough. Since a very small area cannot reveal the general trend of the DEM. The proposed algorithm always selects the node in the open list with the minimum heuristic information value as the next node to be checked. This heuristic information ensures the proposed method only tries to select nodes that most likely to lead to the direction towards the outlet. The heuristic information predicates the general trend of the slope, which help find the best outlet with least time.

When all cells with undefined flow direction are processed by the proposed method, we can get the flow direction matrix. Using the flow direction matrix as input, the flow accumulation matrix is determined. The drainage networks can be derived from the flow accumulation matrix by specifying a constant threshold.

#### IV. EXPERIMENT RESULTS

To examine the suitability and performance of the proposed algorithm, we implement it in Pascal and make experiments on actual DEM data. For presentation purpose all raster maps are converted into vector format.

The study area (Fig. 3) is "1-degree" DEM which was provided by the US Geological Survey [30]. The 1-degree

DEM is 1:250,000-scale Digital Elevation Models and covers an area of  $1^\circ$  in longitude by  $1^\circ$  latitude. The basic elevation model is produced by the Defense Mapping Agency (DMA) using cartographic and photographic sources. The 1-degree DEM consists of a regular array of elevations referenced horizontally on the geographic coordinate (latitude/longitude) system of the World Geodetic System 1984 Datum. Elevations are in meters relative to mean sea level. The DEM contains 601 rows by 1201 columns and spacing of the elevations along and between each profile is 3 arc-seconds.

Fig. 4 shows the basic method to extract drainage network from raw DEM data which contains 721,801 points and 140701 pits and flats. Due to the pits and flats, the basic algorithm fail to produce continuous flow lines and larger rivers are not delineated.

Fig. 5 shows the drainage networks generated using ArcGIS 9.2. The major drainage could be delineated satisfactorily but the spurious parallel flow channels can be seen and the detailed information is lost. It is obvious in the selected rectangle and circle region in Fig. 5. It is due to the error in selecting the flow direction of pits and flats when more than one possible direction exists.

Fig. 6 shows the proposed method for extracting drainage network from the same DEM data as Fig. 4. It can be seen from Fig. 6, continuous drainage network and major drainage are delineated. The detailed information can be retrieved and the spurious parallel flow lines can not be found. In order to avoid these cases, the proposed algorithm takes heuristic information for hydrologic analysis and tries to capture the topography and assign the optimal flow direction to the spurious pits and flats. It is more obvious in Fig. 7 and Fig. 8.

#### V. CONCLUSION AND DISCUSSION

This paper presents a new method to assign the direction of the flow through pits and flats by searching for minimum value of heuristic function. The proposed algorithm has been tested with actual DEM data, and the experimental evidence suggests that the proposed algorithm can extract drainage networks better and fully than the basic method. To compensate inadequate searching information of other methods, the proposed method finds the outlet with heuristic information. Furthermore, the proposed method can handle pits and flats effectively in one procedure.

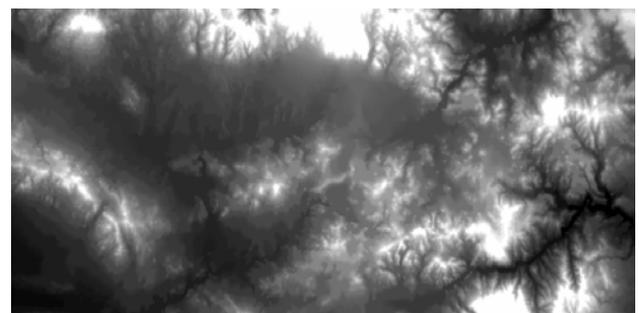


Figure 3. Elevation distribution of the study area.

DEMs digitize continuous and complex three dimensional surfaces at discrete points on regular grid based on sampling data. However, sampling data are limited and DEMs are approximate simulation of real surfaces. Elevation sampling error, discrete sampling error, horizontal resolution, and vertical resolution may cause error of topography. Heuristic information can reveal the general trend of the DEM and help the proposed algorithm find direction of pits and flats efficient and accurately. The proposed algorithm is more appropriate for the processing of large-scale DEMs, which can be used for spatial decision-making with regard to large regional sustainable development projects,

such as the planning of drainage areas, formulating responses to flood disasters, determining borderlines and other applications.

Adding other heuristic information about affecting factor of rainfall, soil, vegetation and others on the surface water flow to the heuristic function, better result may appear. This is the future work.

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Figure 4. Drainage networks generated using the basic method.

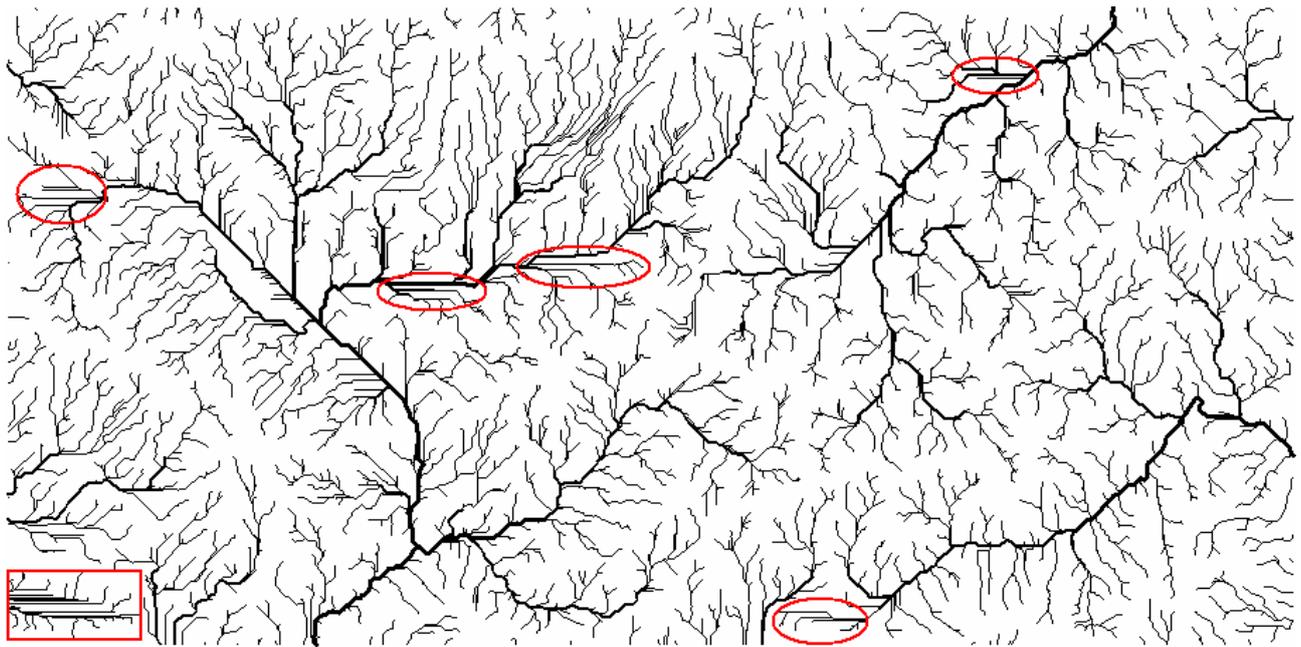


Figure 5. Drainage networks generated using ArcGIS 9.2.

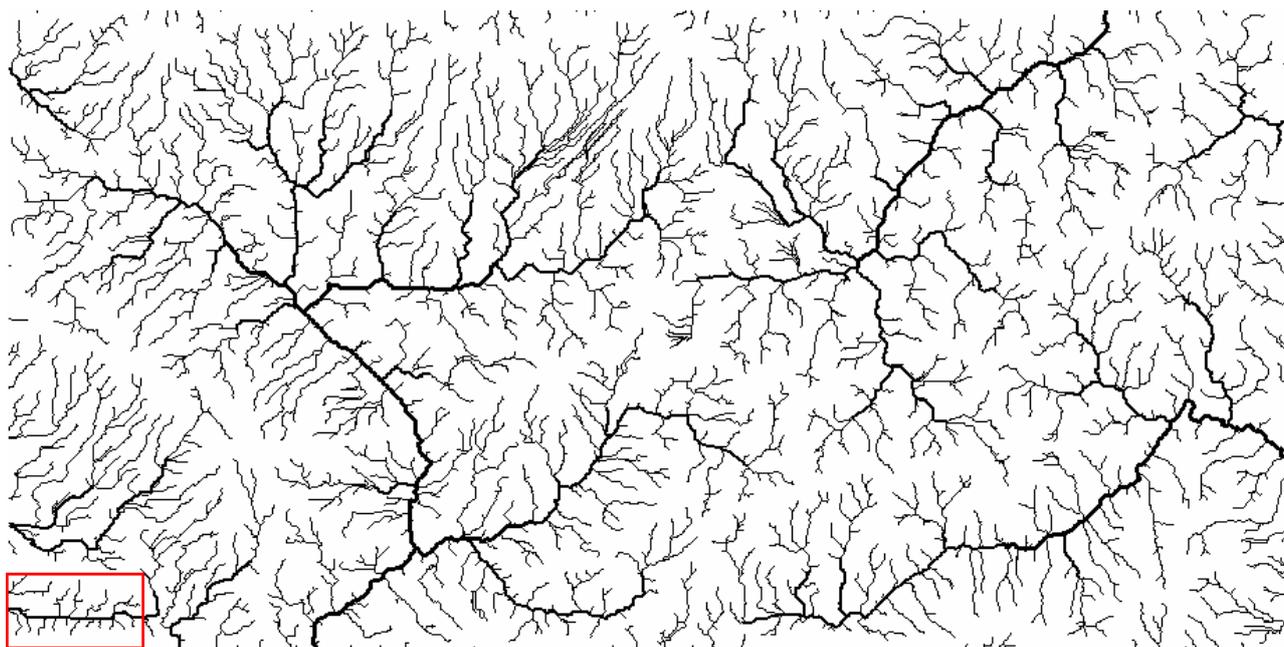


Figure 6. Drainage networks generated using the proposed method.

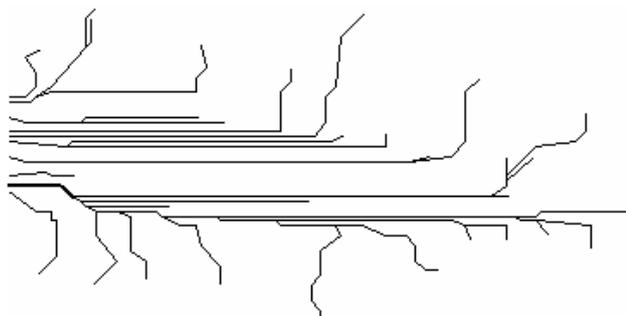


Figure 7. Detail from rectangle region of figure 5.

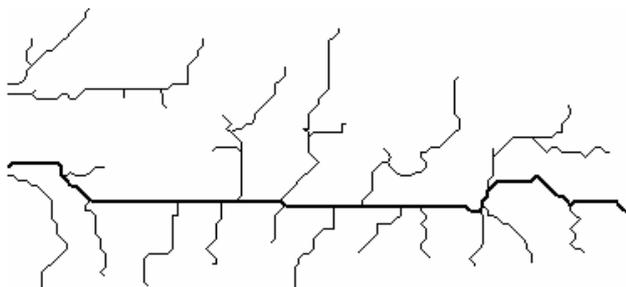


Figure 8. Detail from rectangle region of figure 6.

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