Estimating Flow Distribution over Digital Elevation Models Using a Form-Based Algorithm

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Abstract
This paper discusses a new approach to estimate flow distribution over a continuous surface. This approach is based on the analysis of topographic form of a surface facet that dictates the flow distribution. In the case of a raster Digital Elevation Model (DEM), the facet consists of a centre cell and its eight neighbouring cells. If the form of the facet is convex, the water flow is divergent; thus the amount of flow is distributed to all cells that have a lower elevation. In the case of a concave or flat surface, the convergent flow is directed to the main drainage direction. Comparison between the results of this algorithm with the traditional 'eight-move' algorithm, which is widely used in today's commercial GIS software, indicated that the form-based algorithm yielded a more realistic results in estimating flow accumulation over the land surface, but produced less convincing results in deriving a drainage network.

I. INTRODUCTION AND BACKGROUND

Catchment topography is critical for models of distributed hydrological processes. Slope controls flow pathways for surface as well as near surface flow, and influences the surface flow pattern substantially. The key parameter in catchment topography is flow distribution, which tell us how overland flow is distributed over the catchment area.

Stating flow distribution over a land surface is a crucial measurement in hydrological modelling, the use of Digital Elevation Models (DEM) has made it possible to estimate flow on each location over a surface. Based on the flow distribution estimation on each location represented by a DEM, the drainage pattern over an area, as well as various hydrological parameters, such as catchment area and up-stream flow accumulation, can be modelled.

One common approach for measuring flow distribution is the hydrological flow modelling methods that are widely applied to geomorphological and hydrological problems [6]. This method is based on the following basic principles:

- A drainage channel starts from the close neighbourhoods of peaks or saddle points.
- At each point of a channel, hydrological flow follows one or more directions of downhill slopes.
- Drainage channels do not cross each other.
- Hydrological flow continues until it reaches a depression or an outlet of the system.

On critical and most controversial assumption of the hydrological flow modelling method is the determination of flow direction (or drainage path). In the early development, it was assumed that flow follows only the steepest downhill slope. Using a raster DEM, implementation of this method resulted in that hydrological flow at a point only follows one of the eight possible directions corresponding to the eight neighbouring grid cells [5][7][1][2]. Here we call this approach the 'eight-move' algorithm. However, for the quantitative measurement of the flow distribution, this over-simplified assumption must be considered as illogical and would obviously create significant artifacts in the results, as stated by Freeman [3], Holmgren [4], Wolock and McCabe [13], and Pilesjö and Zhou [10]. More complex terrain is supposed to yield more complicated drainage patterns.

Attempts to solve the problem have led to several proposed 'multiple flow direction' algorithms [3][12][4][9][10]. These algorithms estimate the flow distribution values proportionally to the slope gradient, or risen slope gradient, in each direction. Holmgren [4] summarises some of the algorithms as

$$f_i = \frac{(\tan\beta_i)^x}{\sum_{j=1}^{8}(\tan\beta_j)^x}, \text{ for all } \beta > 0 \qquad (1)$$

where i,j = flow directions (1…8), f_i = flow proportion (0…1) in direction i, $\tan\beta_i$ = slope gradient between

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the centre cell and the cell in direction i, and x = variable exponent.

By changing the exponent (x) in Equation 1, two extreme approaches in estimating flow distribution can be observed. While $x = 1$, flow will be distributed to downhill neighbouring cells proportionally to the slope gradients, as suggested by Quinn et al [12]. The other extreme is when $x \to \infty$, which will approach towards the 'eight-move' drainage distribution mentioned above. Holmgren [4] suggested an x value between 4 and 6. This gives a result between a very homogeneous flow distribution when $x = 1$, and a distinctive flow which occurs when x becomes greater than 10.

Pilesjö and Zhou [11] used mathematical surfaces (a cone, a hemisphere and an inverse hemisphere) to test different x values. They concluded that an x value of 1 was optimal, especially on convex surfaces.

However, the constant relationship between slope and flow distribution (the x value) over a terrain surface can also be problematic. On a natural surface, we could expect less concentrated flow on the upper slope, and a more pronounced drainage pattern in the lower part of back slope. This expectation is closely related to the topographical form. On the upper slope, the convex slope forms are dominant, and the flow is divergent so that its distribution is divided between all downhill directions. On the lower part of slope, the concave slope forms are common, which forces the flow converging into the main drainage direction.

Other difficulties relate to 'complicated' terrain, flat surfaces and sinks. 'Complicated' terrain is defined as a surface facet (3x3 cells in a raster DEM) without a homogenous topographic form (convex or concave). If the facet consists of a number of valleys and ridges originating from the centre cell, the estimation of flow distribution from that cell becomes more complex. Flat surfaces are surface facets where all cells have the same elevation value. As long as the flat area has an outlet, water will move over the surface in that direction. Sinks are small depressions (i.e. drainage basins) that can disturb the forthcoming hydrological analysis (e.g. estimation of flow accumulation) if they are not properly handled. Pilesjö [8] discussed this problem, and possible solutions.

This study focused on the estimation of flow distribution over a raster DEM. A raster DEM is by far the most commonly used elevation models for modelling purposes, and is easily integrated with other types of spatial data. Given the limitation and problems of the 'eight-move' algorithm, a 'multiple flow direction' approach based on analysis of individual surface facets was taken in this study to estimate flow distribution over the raster DEM. The results from this form-based algorithm were then evaluated and compared with those from the 'eight-move' algorithm.

II. ASSUMPTIONS

In this study, a number of assumptions were made, mainly in order to isolate the mechanism of overland flow distribution from soil, vegetation and atmospheric impact. The assumptions were:

- The flow from a grid cell to its neighbouring cells is dependent upon the topographic form of the surface.
- Water is evenly distributed over the grid cells (i.e. homogeneous precipitation).
- Every cell in the raster DEM, except sinks, contributes a unit flow and all accumulated flow distributes to its neighbourhood.
- The infiltration capacity over the surface is set to zero.
- The surface is bare (e.g. no vegetation).
- The evaporation is set to zero.
- The topographic form of a cell can be estimated by the use of its eight neighbours (a 3x3 window).

III. METHODOLOGY

The procedure of the proposed method for the estimation of flow distribution, and subsequently the flow accumulation, from a raster DEM is outlined below:

- Examine each grid cell and the surface facet formed by the 3x3-cell window to classify the facet into 'complicated', 'flat' and 'undisturbed' terrain.
- These three categories are treated separately in determining their flow distribution using the algorithms reported below.
- Results from different categories of the facets are then merged to create flow distribution, and flow accumulation, over the entire study area.

Classify Each Facet into 'Complicated', 'Flat' or 'Undisturbed' Category

The classification of the facet into one of the three categories is based on a normal 3x3-cell filtering process, as outlined below.

- If all the cells in the 3x3 window have the same elevation values the centre cell is marked as a flat surface.
- The eight neighbour cells around the centre cell are examined (clockwise) in order to determine if there are multiple valleys. A valley in this context is defined as one, or more, lower (in elevation) neighbour cells surrounded by cells with higher elevation. The centre cells in these facets are

marked as 'complicated' terrain. An example of a facet classified as complicated is presented in Figure 1.

- Cells classified as neither 'flat' nor 'complicated' are marked as 'undisturbed'.

Estimation of Flow Distribution on a 'Complicated' Surface Facet

The estimation of flow distribution on a 'complicated' surface facet is based on the topographic form. For each of the valleys, originating from the centre cell, the topographic form is estimated. If a valley is one, two, or three cells wide, it's treated as a concave surface, and the estimated flow direction equals the main drainage direction (see below). On the other hand, if a valley is more than three cells wide, it's treated as a convex surface, and the water flow will be divided between all the cells in that valley (see below).

The flow distribution between different valleys is split according to the width of the valley (i.e. proportional to the area of the centre cell contributing flow in different directions). In Figure 1, the upper left valley is judged to be concave, and the lower valley is judged to be convex. One-third of the water flow will be distributed to the upper left valley according to the main drainage direction (the concave case, see below), and two-third of the water flow will be distributed to the lower valley according to individual gradient values (the convex case, see below).

Estimation of Topographic Form for 'Undisturbed' Surface Facets

There is no absolute way to determine convexity and

.90	.80	.110
.110	.100	.80
.90	.70	.60

Figure 1. An example of a surface facet to be classified as 'complicated' terrain. The numbers in the cells denote the elevation values of the centre of the cells. The upper and the upper left cell represent one valley, and the four cells below and right of the centre cell represent another valley.

concavity of the centre cell in a 3x3-cell facet. The possible complexity of the surface often implies approximations. One way to approximate is to use a trend surface based on the elevation values of all cells in the facet. Below a method based on a least-squares approximated second-order trend surface (*TS*) was proposed:

$$TS(x_i, y_i) = a_0 + a_1 x_i + a_2 y_i + a_3 x_i^2 + a_4 y_i^2 + a_5 x_i y_i \quad (2)$$

where

$i = 1, ..., 9$ The index numbers of the centre cell and its eight neighbours.

$a_0, ..., a_5$ The constants for the second-order trend surface.

x_i, y_i The cell coordinates (central cell) in a local system.

To simplify the calculations and expressions the process is performed in a local coordinate system, which has its origin [0, 0] at the centre cell with a cell size equal to 1. This gives a range of coordinates between –1 and 1, in both *x* and *y* directions.

The first step is to determine the constants ($a_0, ..., a_5$) by the use of the nine known elevation values in the 3x3-cell window. Then the main drainage direction and a measure of the topographic form as function of these constants are computed. To determine the constants an over-determined equation system needs to be solved:

$$A \cdot \mu = I + v \quad (3)$$

where

$$A = \begin{bmatrix} 1 & x_1 & y_1 & x_1^2 & y_1^2 & x_1 \cdot y_1 \\ \dots & \dots & \dots & \dots & \dots & \dots \\ 1 & x_9 & y_9 & x_9^2 & y_9^2 & x_9 \cdot y_9 \end{bmatrix},$$

$$\mu = \begin{bmatrix} a_0 \\ \dots \\ a_5 \end{bmatrix}, \quad I = \begin{bmatrix} h_1 \\ \dots \\ h_9 \end{bmatrix}, \quad v = \begin{bmatrix} v_1 \\ \dots \\ v_9 \end{bmatrix},$$

v_i denotes the values in the residual vector,
h_i denotes the elevation values of the nine cells, and
x_i, y_i denotes the coordinates in the local system.

Since the equation system is over-determined, there is no 'true' solution. True in this sense implies that the elevation values for the nine points lie on the trend surface. The residuals (v) are the discrepancy between the given elevation values from the DEM and the elevation values computed from the trend surface. The 'optimal' solution minimises these discrepancies according to a certain criterion. In this study, the least-squares method was used to determine the constants of the second order trend surface.

$$\mu = (A^T A)^{-1} \cdot A^T \cdot I = B \cdot I \quad (4)$$

where

A^T is matrix **A** transposed.

Since matrix **A** contains the coordinates in the local systems, the matrix **B** will look the same for all facets during the filtering procedure, if the same indexing (*x* and *y* coordinates) is used for all windows. This implies that we only have to compute **B** once; and the constants (**u**) are then computed using Equation 4. Two examples of the approximation of second-order trend surfaces from nine elevation values are presented in Figure 2 and in Figure 3.

To derive analytical expressions for the topographic form and the drainage direction as functions of the constants determined by Equation 4, the gradient (slope) of the trend surface at the centre cell is computed:

$$\mathrm{grad}(TS(x,y))\Big|_{\substack{x=0\\y=0}} = \left[\frac{\partial TS}{\partial x}, \frac{\partial TS}{\partial y}\right]_{\substack{x=0\\y=0}} = [a_1, a_2] \quad (5)$$

The next step is to compute the main drainage direction (φ; see Figure 4). This value equals the aspect value at the centre cell of the surface facet, and varies between zero and 360 degrees. φ is undefined if both a_1 and a_2 are equal to zero. This is the case for e.g. a flat area, a symmetric hilltop or a symmetric sink.

$$\varphi = \begin{cases} \arctan\left(\frac{a_1}{a_2}\right) + 180^0, & a_2 > 0 \\ \arctan\left(\frac{a_1}{a_2}\right), & a_2 < 0, \quad a_1 \le 0 \\ \arctan\left(\frac{a_1}{a_2}\right) + 360^0, & a_2 < 0, \quad a_1 > 0 \\ 270^0, & a_2 = 0, \quad a_1 > 0 \\ 90^0, & a_2 = 0, \quad a_1 < 0 \\ \text{not defined}, & a_2 = a_1 = 0 \end{cases} \quad (6)$$

.90	.110	.90
.80	.100	.80
.60	.70	.60

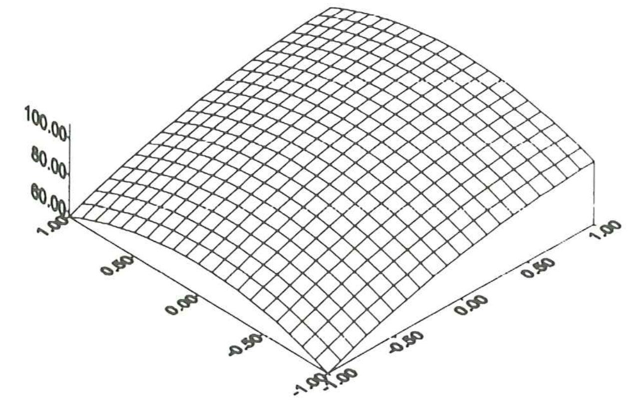

Figure 2. An example of the approximation of a second-order trend surface from nine elevation values in a 3x3-cell window. The raster on the left shows the nine elevation values from the surface facet, and the approximated trend surface is illustrated on the right. The topographic form of the centre cell is convex.

.130	.110	.130
.110	.100	.110
.90	.70	.90

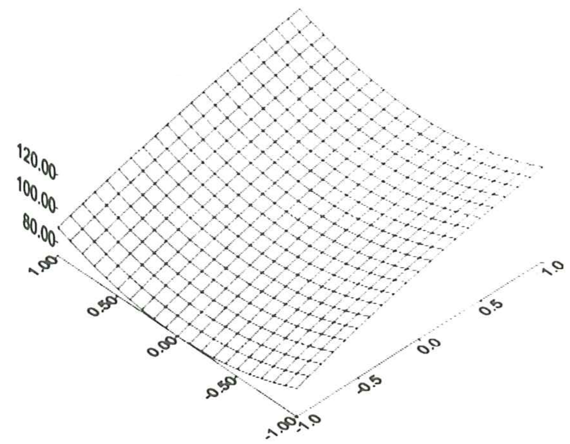

Figure 3. An example of the approximation of a second-order trend surface from nine elevation values in a 3x3-cell window. The raster on the left shows the nine elevation values from the surface facet, and the approximated trend surface is illustrated on the right. The topographic form of the centre cell is concave.

The topographic form now can be determined along a line (l), which is perpendicular to the main drainage direction and contained by the centre cell (see Figure 4). When the elevation values along the line are evaluated, the form can be estimated. Figure 5 shows a section of the trend surface, created by cutting the trend surface with a vertical plane (containing the line l).

To measure the form of the trend surface exemplified in Figure 5, the first step is to calculate the elevation values along the line (l). Using the main drainage direction (φ), there is:

$$l = [x(t), y(t)] = [t \cdot \cos\varphi, -t \cdot \sin\varphi], \quad t \in [-0.5, 0.5] \qquad (7)$$

where the absolute value of t is equal to the Euclidean distance from point b in Figure 5.

Given the known elevation values on the trend surface along the line l (from point a to point c, see Figure 5), we can express the trend surface along the line (l) as a function (TS') of t. Thus:

$$TS'(t) = a_0 + cc\_measure \cdot t^2 \qquad (8)$$

The value of the *cc_measure* (which represents the concavity-convexity measure) describes the topographic form. By combining Equation 2, 7 and 8, there is:

$$cc\_measure = a_3 \cos^2\varphi + a_4 \sin^2\varphi - a_5 \cos\varphi \sin\varphi \qquad (9)$$

where φ is given by Equation 6.

If $a_1 = a_2 = 0$ the *cc_measure* is not defined (cf. Equation 6). This is, for example, the case over a flat surface, where the derivatives (a_1 and a_2) are zero and we have neither a convex, nor a concave form. Since

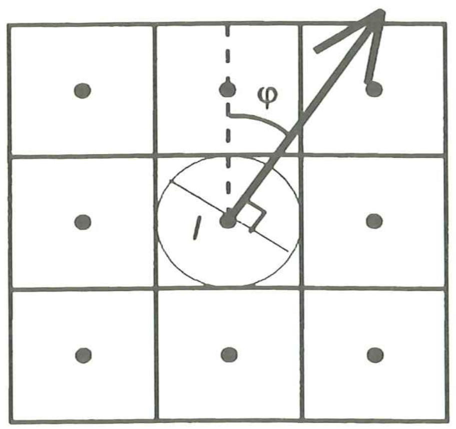

Figure 4. When the main drainage direction (ö) from the centre cell has been estimated, the elevation values along a line (l), perpendicular to the drainage direction, is examined in order to obtain the topographic form of the centre cell in the surface facet.

Figure 5. The form of the line (l) reveals the topographic form of the sub surface. a and c denotes the end points of the line (l), and b denotes the mid point of the centre cell.

the *cc_measure* is the constant for the second order term in Equation 8, we obtain:

cc_measure > 0 → the topographic form of the centre cell is concave.

cc_measure < 0 → the topographic form of the centre cell is convex.

Estimation of Flow Distribution on Convex and Concave Surface Facets

Depending on the topographic form of a surface facet, the flow distribution from the centre cell either fully contributes to the main drainage direction (concave case), or is divided between all lower neighbouring cells.

The Concave Case

When the topographic form of the centre cell in the facet is judged as concave, the flow is distributed fully to the main drainage direction. If the main drainage direction (calculated by the use of Equation 6) is not equal to the direction to one of the eight neighbouring cells, the flow distribution has to be split between two cells. This is done by splitting the drainage vector (**b**, see Figure 6) into two diagonal (i.e. 45^0apart) vectors.

In the example presented in Figure 6, the drainage vector is calculated to approximately 35^0, and split into one vertical (0^0) and one diagonal (45^0) vector. The length of the vertical vector describes the amount of water draining into the cell above the centre cell. As shown in Figure 6, let **A** denote the aspect of the estimated drainage vector (approximately 35^0). Since **B** = $180^0 - 45^0 = 135^0$,
then **C** = $180^0 - 135^0 -$ **A** = $45^0 -$ **A**.

Let **a** denote the vector that represents the amount of water flowing into the cell above and right of the centre cell, and **c** denote the vector that represents the amount of water flowing into the cell directly above the centre cell (this amount is initially set to 1.0). Since directions of all vectors and the length of **c** are known, it is relatively simple to calculate the unknown length

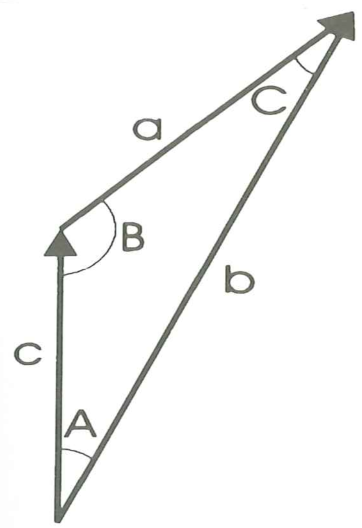

Figure 6. An example of how the main drainage vector is split in order to calculate flow distribution to neighbouring cells. The drainage vector (**b**) is divided into one vector directed up (**c**), and one vector directed up/right (**a**). The estimated flow distribution is directly proportional to the lengths of the vectors.

of vector **a**:

$$a = \frac{\sin A}{\sin(45 - A)} \qquad (10)$$

The amount of water (W, in percent) that each neighbouring cell (up and up/right cell in this case) receives from the centre cell is distributed according to different ratios between **a**, **c** and (**a** + **c**), i.e.:

$$W_a = \frac{a}{a+c} \quad \text{and} \quad W_c = \frac{c}{a+c} \qquad (11)$$

Similar calculations as above can be carried out for all drainage vectors, independently of direction.

The Convex Case

When the topographic form of the centre cell in the facet is judged as convex, the flow is distributed according to Equation 1, with an exponent (x) of 1.0. This x value is also recommended by Pilesjö and Zhou [11].

Methods for Estimating Flow Distribution on Flat Surface Facets

The flow distribution over flat surfaces is initially set to zero. However, since it is assumed that water will flow over all cells in the DEM except sinks (assumption c), drainage directions have to be assigned on these flat surfaces. This is done based on defined flow distribution values in the surroundings. If a flat area consists of more than one surface facet, the order of the estimation is related to the number of neighbours with defined flow distribution values. The flat facet with the highest number of defined neighbours is treated first, then the one with the second highest number of neighbours, and so on, until the flow distribution for all the facets has been defined. If the flat area turns out to be a bottom of a sink, the centre cell of the flat area is not allocated any drainage direction. No contradictory drainage directions are ever allowed.

The flow distribution from a cell on a flat area is estimated by vector addition of defined flow directions of the neighbours. In order to calculate the flow distribution to the neighbouring cells from the centre, the summed drainage vector may be split, using the method in the above concave case.

Estimation of Flow Accumulation

The flow accumulation is computed by tracing the waterway downstream from cells not receiving water from any neighbour cell. These cells are situated on hilltops in the landscape. When these cells in the DEM have been found, the program will 'step down' the hills in order to estimate the flow to all cells lower down in the drainage basins. For an individual cell, the flow out from the cell is:

$$F_{out} = F_{in} + F_{local} \qquad (12)$$

where F_{out} denotes the flow output from the cell, F_{in} denotes the flow received by the cell, and F_{local} denotes the flow produced in the cell, which is set to 1.

The F_{out} is then distributed to the cell(s) which receive the flow from the centre cell according to its drainage distribution. All cells in the DEM contribute in the same way until the whole area, traced down to outlet cells or sinks, is examined.

IV. EXPERIMENT AND RESULTS

The proposed algorithms have been tested in comparison with some commonly-used algorithms. Elevation sample points were acquired in a 10-metre interval in the area of Bredbo, New South Wales, Australia using aerial photographs that is processed by a digital photogrammetry workstation. The sample points were then converted into a raster DEM, using ARC/INFO Triangulated Irregular Network (TIN) and linear interpolation functions. This resulted in a DEM of 745 columns and 687 rows with a 5 ¥ 5 metre grid cell size.

The proposed algorithm was tested against the commonly-used 'eight-move' algorithm represented by ARC/INFO's hydrological modelling functions, namely *flowdirection* and *flowaccumulation*, to produce flow accumulation grid from the DEM. Figure 7 shows the comparison between the results. As shown in Figure 7, the flow accumulation produced by the 'eight-move' algorithms has shown a clear weakness for only allowing one of the eight possible flow directions for each cell. As a consequence of this limitation, the trend of distribution of flow accumulation in relation to land surface was not clearly simulated in the result (Figure 7a). The proposed algorithm, on the other hand, has demonstrated its ability to produce a more realistic simulation result (Figure 7b) by allowing more complicated scenarios in its simulation of flow direction.

However, the form-based algorithm has also demonstrated its weakness in delineating drainage networks as it shows broken drainage lines (shown by cells with high flow accumulation values) (Figure 7b). Since the DEM from digital photogrammetry maintained a high accuracy, landscape features such as trees were also recorded as the surface elevation. As the consequence, the test surface is 'noisy' with some 'unwanted' features. Although this would create minimal impact on the flow distribution on the slope, the DEM 'noise' could affect local trend surfaces in determining flow directions, which in turn may create problems in connecting drainage lines.

V. DISCUSSION AND CONCLUTION

The proposed method for estimating flow distribution on a raster DEM consists of processes normally not included in other methods. The two new main suggestions are:

- To treat different part of the surface differently, depending on if the surface is judge as 'complicated', 'flat', or 'undisturbed' terrain.
- To use the topographic form to assist in determining how flow is distributed over a surface.

This study presents an argument that different forms of surfaces should not be modelled in the same way in terms of flow distribution. Complicated terrain, characterised by a number of valleys and ridges, has to be investigated mainly in order to obtain different possible water channels from the centre cell to its neighbours. The flow distribution over flat areas is obviously dependent upon the surrounding topography.

The presence of 'complicated' terrain and flat areas is relatively rare. In most surface facets on a DEM the topography can be classified as 'undisturbed'. This means that the surface is characterised by one single topographic form: concavity or convexity. Convex forms normally occur in the higher parts of the terrain, while the valleys are characterised by concave topographic forms. Since the flow distribution over a convex surface is divergent, and the flow converges over a concave surface, it seems more appropriate to include the topographic form when estimating flow distribution.

The proposed method has demonstrated its ability to produce a better simulation for flow accumulation compared with the 'eight-move' algorithm which is commonly used in today's GIS. However, the results have to be statistically tested, by applying the new algorithm to mathematically generated surfaces. Another challenge in future research will be focused on appropriate algorithms for generating drainage network, appropriate treatment of sinks, and introduction of more environmental variables into the hydrological modelling processes.

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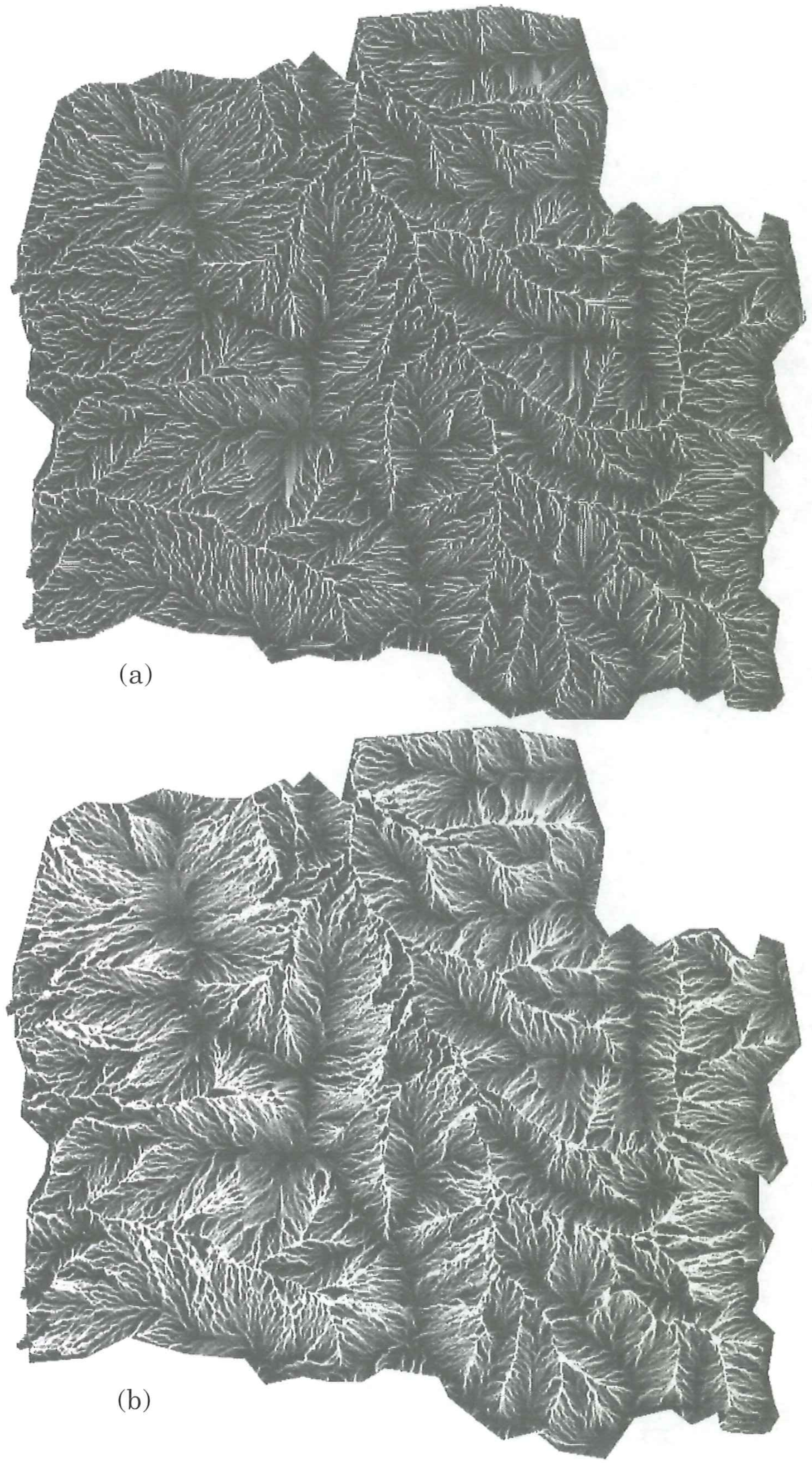

(a)

(b)

Figure 7. Comparison between computed flow accumulation: a) top: flow accumulation estimated by ARC/INFO; b) bottom: flow accumulation estimated by the form-based algorithm.