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DEM Based Multi-Directional Flow Path Mapping Using the Raft Method

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ABSTRACT: Digital elevation models (DEM) are extensively used in hydrological analysis to obtain the direction of flow on a topographical surface. Knowing the direction of flow helps in determining channel networks, and in obtaining the distributed specific catchments, which are important hydrological attributes in a DEM based analysis. There are certain demerits in the known methods of DEM-based flow-path mapping, despite the ease of handling the DEM in present generation computational capacity. A major demerit is the problem of accounting multidirectional flow path mapping efficiently. In this study, a new approach of assigning the flow direction is proposed. This approach considers the flow as a vector component and argues that the direction of flow can be different from the direction of steepest slope on a planar surface depending on surface roughness and flow vectors. The direction of flow, if assigned to the direction of the maximum flow tendency, gives a better flow path mapping. In this case, the direction is not necessarily restrict either on grid or across diagonal of the grid-centers, which enables to assign the flow direction toward multiple downstream cells. This method is named as the Ranked Flow Tendency (RAFT) method. This method was tested using the DEM of Kamishiiba Reservoir Site (210 km2) as the case. The results show the RAFT method is better than the conventional D8 method and modified D8 method. The RAFT method identifies the network of channels and lakes and can incorporate the flow dispersion properly. These abilities show higher possibility of yielding a better result while used this method in sediment and pollutant flow simulation and water quality modeling.

1 INTRODUCTION

Many studies in hydrological science use Digital Elevation Model (DEM) for describing the catchment topography and obtaining topographical attributes. A network of flow channels, which the DEM can produce easily, is the most widely used product of DEM in hydrological studies. In addition to that, the DEM provide the basic data for calculating the upslope area, specific catchment, and slope driven parameters in flow routing and sediment and contaminant movements (Beven *et al.* 1984;Beven and Kirkby 1979;Costa-Cabral and Burges 1994;Moore *et al.* 1991;Tarboton *et al.* 1991;Wood *et al.* 1990). It is therefore understandable the significant importance of the method, which calculated the flow direction from the DEM.

The earliest and simplest method for specifying the directions of flow in a catchment using the DEM is the D8 method (O'Callaghan and Mark 1984). This method assigns the direction of flow same to the direction of steepest downward slope. For each cell the direction is assigned toward one of its eight neighbors. This method has been widely used in hydrology for flow direction mapping and to evaluate hydrological attributes

Several disadvantages and limitation are reported while using D8 method (Costa-Cabral and Burges 1994;Moore *et al.* 1991;Tarboton 1997). Alternatives to D8 method have been investigated and tried by several researchers. Following methods can be listed as the sequential advancement in this direction. Multiple flow direction method (Quinn *et al.* 1991) (usually termed as MS method) recognizes Multiple Slopes (MS) to allocate fraction of flow proportional to slope downstream. Another similar method presented by (Freeman 1991) uses the slope to an exponent. The MS methods are criticized for drawbacks of too much dispersed flow. Associating a probability which refers to an aspect angle as same as that of expected flow direction, Rho8 method (Fairfield and Leymarie 1991) is suggested to obtain the flow direction, which is criticized on its disability to reproduce the result and random wiggles. Improved Rho8 method (Lea 1992), called Lea's method, has routed the flow as a rolling ball released on a plane from the center of each grid cell. DEMON (Costa-Cabral and Burges 1994) has advanced the Lea's method. Both Lea's method and DEMON are questioned on plane fitting technique that may mislead the determined flow direction.

A triangular facet based D∞ method (Tarboton 1997) calculates steepest descent for the triangular facets same as that of triangular irregular network (TIN) surface slope (Tachikawa *et al.* 1994) by constructing facet from DEM (Douglas 1986). The distribution weights are evaluated on the basis of surface angle of the steepest descent to shift the steepest flow line to nearby edge of triangular facet. This method is asserted as compromise between D8 and Lea's method.

(Shiiba *et al.* 1999) presented a method to trace flow direction from two sides by tracing the steepest descending lines and steepest ascending lines. Overlaying the layers of steepest descending lines and opposite of ascending lines, the flow-diverging grid-cells are traced. The flow is distributed to multiple downstream cell receivers where the descending line and opposite of ascending line do not overlap each other. This method can be said as further development of the multidirectional approach (Freeman 1991) and pure stream lines(Douglas 1986).

MS methods (Freeman 1991;Quinn *et al.* 1991) have included all the down stream cells. (Costa-Cabral and Burges 1994) commented these multiple flow direction methods for their discontinuous nature while suggesting DEMON. (Tarboton 1997) illustrated an erroneous result from the Lea's method with an example, which may appear with DEMON too and argued that MS methods are free from grid bias. In D∞ method, the receiver two cells are always together. Proposed method of (Shiiba *et al.* 1999) gives freedom to the receiver cells such that they should not necessarily be connected as that of the D∞ method.

Most of the alternate methods apply strategy of recognizing multiple downstream receiver cells, if they exist, unlike recognizing a single downstream receiver cell in D8 method. The flow direction is then utilized to obtain some distribution factors that represent the fractions of flow from the source to receiver cells either adjacent or diagonal. It is therefore clear that, flow representation by using the distribution factors is the generally accepted method for using the grid DEM surfaces to determine flow direction. However, the approaches to evaluate the distribution factors are different and have prime concern.

Demerits, those the hydrologists want to remove, are still there even after developing many methods. Search of an efficient method that attempts to address the encountered weaknesses preserving the strengths has inspired to think of a new method to define the flow direction.

A new method, named as ranked flow tendency (RAFT) method, to define the flow direction is presented in this paper. This is a multi-directional method, which has attempted to consider the flow mechanism referred to land surface slope to obtain the flow directions. The proposed method is tested at Kamishiiba reservoir with 210 sq. km. catchments in Kyushu, Japan. The results are compared against conventional D8 method (O'Callaghan and Mark 1984) and modified D8 method.

2 RANKED FLOW TENDENCY METHOD

2.1. Basic Concept

While the slope drives to cause flow, the non-linear relation between flow and slope represents the tendency of flow along the direction of slope, but the magnitude of the tendency is non-linearly dependent. The flow tendency may be quantified to represents the possibility to occur flow on each infinite strip of slope direction, which is termed here as "Virtual Flow Tendency" (VFT). The VFT has its own magnitude and direction; therefore, it is a vector.

An area with variable sloped surfaces, divided into multiple infinite strips of uniform sloped surfaces, has many VFTs for each of these strips. A resultant vector of the multiple strip VFT vectors should represent the resultant VFT vector for that area, which is given by

$$F_R = \frac{\int_{\phi} f_i \, d\phi}{\int i} \tag{1}$$

Here, f_i is ith strip VFT, which is a function of surface characteristic and slope. f is spread angle of the surface and F_R is a resultant VFT. The orientation of F_R vector on horizontal plane represents the gross flow direction on that area.

Chezy's relation $Q \propto S^m$ may be referred to define the nonlinear dependency of slope S with discharge Q. An exponent m = 0.5 to the slope thus represents the VFT magnitude, which may be generally applicable. However, a different m value, for example 0.55, 0.6, etc., may sometime suit to some specific topographies (Freeman 1991).

Manning has introduced the surface roughness coefficient recognizing the effect of surface characteristic on flow velocity. The surface characteristic affects the VFT too. However, in the present experiment, this part is omitted assuming uniform surface characteristic.

2.2 Flow direction within triangular facet

Using a DEM, infinite numbers of strips cannot be involved in calculation. Inside a 9 grid cells' window, one can easily form 8 planar triangular facets by connecting the center point of all 8-neighbor grid cells to the center of central grid cell (see Fig.1). Adopting the triangular facets as primary regions of flow surface, their edge strip VFTs give the resultant VFT vector F_R as a cross product of the two VFTs for the triangular surface. The orientation of resultant slope S_R may differ from that of F_R (see Fig.2 and 3) Thus in a 9 grid cells' window, 8 directions of F_R vectors are obtained. The F_R vector which when drawn outward from the center may be at an angle that lies within or outside of the facet angle of 45^o range at center point. If the VFT angle q is within the facet angle, it represents the resultant flow direction on that facet. If the VFT angle q is outside the facet, the direction associated with that facet is taken along the steepest edge.

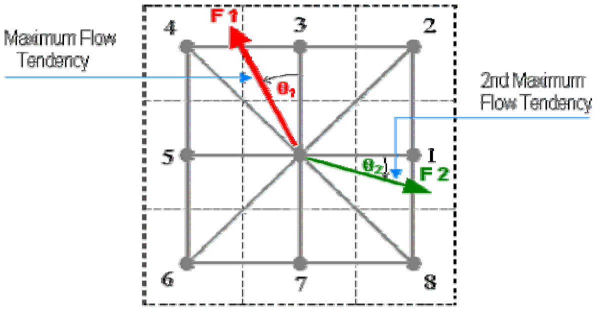

Figure 1. Ranked Flow Tendency search

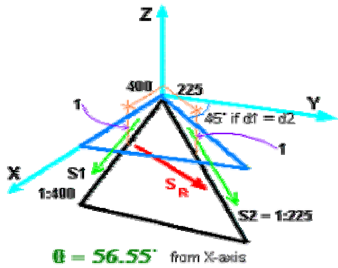

Figure 2. Resultant slope vector

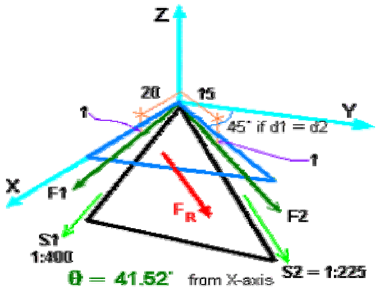

Figure 3. Resultant VFT vector

2.3 Magnitude of flow tendency

To quantify the magnitude of flow tendency along the direction q of F_R on that plane, the following equation is used.

$$F = s_1 \cos 2\theta + s_2 \sin 2\theta \qquad (2)$$

Here, F is the flow tendency (see Fig.1), s_1 and s_2 are adjacent and diagonal slopes respectively (see Fig.2), which are assigned zero if negative. The maximum F is then found by comparing the F of all 8 triangular facets. The direction corresponding to the maximum F determines the direction of flow from the central cell of the window.

2.4 Multiple flow potentials

By choosing the maximum *F* as the flow direction acknowledges only two downstream cells, at maximum, as the receiver cells. To include additional downstream cells, if the receiver cells exist, should yield a better result. The significances of including more receiver cells in a diverged flow mechanism have already been displayed by Quinn et al. (1991), Freeman (1991), Tarboton (1997) and Shiiba et al. (1999).

Shiiba et al. (1999) reported that their proposed method produced insignificant change in result. From an investigation using arbitrary DEM data, it was revealed that the method designated multiple flow directions often at local peak, which mostly remains dry on flow routing. Ascending and descending lines mostly overlap at off-peak wet regions and premises of major channel, which might have caused insignificant change in results.

The proposed VFT approach attempts to fulfill the need of multidirectional divergence at off-peak region. It involves multiple higher *F*s to enable tracing almost of the off-peak cells. The multiple *F*s are chosen on the basis of their rank from the maximum (see Fig.1) that designates this method as Ranked Flow Tendency (RAFT) method. The RAFT method provides facility to limit the maximum number of receiver cells. For example, the maximum four lower cells, those connected with two triangular facets, are traced by choosing the highest and second highest *F*s to incorporate much larger wet zones.

2.5 Fraction of flow

The flow direction information in multidirectional mode is generally referred to calculate the fraction of flow to distribute among the receiver cells along either grid axes or diagonal. For a triangular facet, the fractions of flow represent the flow along edges 45^{o} apart. When a resultant VFT overlaps triangular facet's one edge, the other edge should have no flow and vice versa. To evaluate fraction reflecting these behavior, the following techniques are applied.

- For the ease, the angle is always measured from axes, not from diagonals.
- $\cos 2\theta$ represents weight (w_1) to axis line and $\sin 2\theta$ represents weight (w_2) to diagonal line.
- Multiply the weights by respective magnitude of *F* to accommodate multiple flow tendencies.
- The individual weights are divided by sum of weights to get fraction to corresponding lines.

2.6 Pit removal

DEM data contains pits and flats either representing the naturally existed pits or due to some error within itself. The VFT remains negative (that represents no down slope) in such cells. The pits need preprocessing to fill up such that a leveled surface is formed by referring the lowest neighbor cell. The adjacent flat surface grid cells are linked together to behave as a flat region. An iterative checking is performed whether the flat regions are again behaving as a pit or not. If, entire flat region is behaving as a pit, then the region is broadened, until it detects a cell that drains to a neighbor cell, which ultimately drains to a lower elevation. The water level inside pits and flats are maintained uniform every time allowing them to flow any direction.

3 APPLICATION AND RESULT

The proposed method is applied to Kamishiiba reservoir site using a DEM of 50-m grid resolution. This data is referred from Digital Map of Geological Survey Institute, Japan. After necessary preprocessing of pit removals, the flow directions and corresponding *F* values are evaluated. Then the connection relations among the grid cells are defined by choosing F_1 and F_2. The distribution weights are determined on the basis of flow direction and chosen F_1 and F_2 to allocate fractions of flow to the connected cells.

In order to visualize the flow network, the flow is accumulated from upstream to downstream side. This gives a flow accumulation map and a density map of flow accumulation. The density map plots darker segment for higher accumulation of water and vice versa resulting a flow path map. This method works for any unidirectional method, such as the D8 method. However, this method cannot simply be used in any multidirectional methods, including the RAFT as it produces cyclic accumulation through the diverged flow path. Instead, by employing a hydrological model, it is possible to obtain a flow density map without cyclic conflict. The method is described in detail by (Shrestha *et al.* 2003). Corresponding density maps of flow movement are plotted in Figs. 4 and 5 for comparison.

4 WHAT ARE THE DIFFERENCES?

Figures 4 and 5 presented here for comparison, clearly show the difference between the D8, modified D8 and the new RAFT methods. The RAFT method (Fig. 5) has performed better to represent the topographic characteristics and flow map that are clearly visible. Many disconnected river segments that appeared in D8 method (Fig. 4) are improved by the RAFT method (Fig. 5). RAFT method has displayed improved modeling of the flow network along the multiple sets of adjacent off-peak cells unlike that in D8 method.

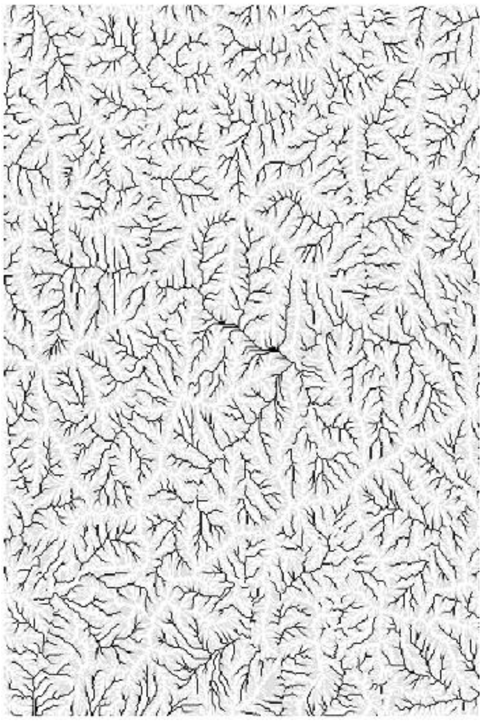

Figure 4. Density map of flow accumulation using D8 method

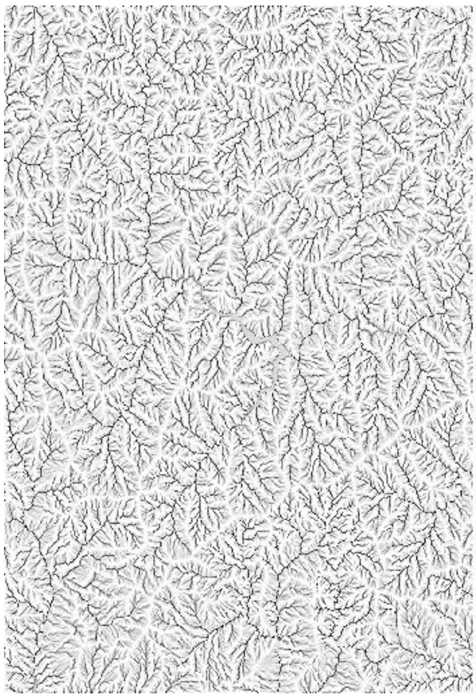

Figure 5. Density map of flow using RAFT method

The parallel lines, which are generated on reservoir site by D8 method, are disappeared in RAFT method, but instead, a uniform water level encircled the reservoir area properly. The D8 method with modified pit removal algorithm has not produced parallel lines, and it still fails to give well result as that of the RAFT method. Thus, the proposed method displays promising ability to handle the lake/reservoir. Parallel flow line representation of lake often is matter of headache to hydrologists as they produce erroneous interpretations in hydrological simulation.

Only the flow direction issues, of course, not necessarily are enough to define the correct hydrological process because the hydrological model's algorithm and parameters do matter a lot. Nevertheless, to analyze DEM based hydrological process without correct representation of flow direction may be analogous to a blind man's walking without his white stick.

5 CONCLUSION

There is a remarkably great attraction of using DEM in hydrological analysis. To represent the correct flow condition in DEM based analysis is, therefore, an important work for a hydrologist. A new RAFT-method is proposed and tested in Kamishiiba reservoir site, Kyushu, Japan.

The RAFT method has displayed better representation of channel networks. The RAFT method is able to represent the diverge distribution of flow and converge distribution as well. It has displayed promising ability of displaying and modeling the lake/reservoir site. The RAFT method is found able to trace most of wet regions in the tested area.

Modified D8 method gives significant indication of rapid flow down unlike the RAFT method. Multidirectional consideration of RAFT method should represent the real water movement more correct than the modified D8 method.

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