

A NEW METHOD TO DEFINE FLOW DIRECTION USING GRID DIGITAL ELEVATION MODELS

Roshan SHRESTHA¹, Yasuto TACHIKAWA² and Kaoru TAKARA³

¹Graduate Student, Dept. of Civil Engineering, Kyoto University, (Gokasho, Uji, 611-0011, Japan)

²Member of JSCE, Dr. Eng., Associate Professor, DPRI, Kyoto University, (Gokasho, Uji, 611-0011, Japan)

³Fellow of JSCE, Dr. Eng., Professor, DPRI, Kyoto University, (Gokasho, Uji, 611-0011, Japan)

Digital elevation models (DEM) are extensively used in hydrological analysis to obtain distributed hydrological attributes and the flow direction. Demerits are consistently hindering hydrologists despite the ease of using DEM with several existing methods. A new method of assigning flow directions based on flow tendency is proposed in this paper. Iterative search of continuous pits and flats are embedded inside. This method is named as Ranked Flow Tendency (RAFT) method. A storage function method is used to simulate the water movement taking the DEM of Kamishiiba Reservoir Site (210 km²) as the case. The results are compared against the conventional D8 method and modified D8 method for flow networks. The proposed RAFT method yields better flow path and is able to trace the reservoir sites. This method shows its better ability to involve more cells at off-peak wet region in flow routing.

Key Words : DEM, flow direction, flow tendency, RAFT method

1. INTRODUCTION

Digital elevation models (DEM) are widely used in hydrological analysis to determine the flow paths. A window of continuous iterative flow path defining algorithm is usually run from beginning grid cells to the end, which, in the mean time, calculates and assigns the flow direction for each cell. The obtained flow direction information are not only used to trace hydrological attributes such as river networks, channel positions, hydrological flow routing, sediment and contaminant movements but also to measure distributed quantities like upslope area and specific catchment area. Several researchers ^{1),2),3),4),5),6)} have used the upslope area and specific catchment's value as an important distributed quantity in grid-based distributed modeling of hydrological processes. It is therefore understandable the significant importance of flow direction to a hydrologist that represents the natural flow process accurately as much as possible.

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 method⁷⁾ and modified D8 method.

2. BACKGROUND

The earliest and simplest method for specifying flow directions using grid DEM is to assign flow in the direction with steepest downward slope from each cell to one of its eight neighbors. Designating this method as D8 method⁷⁾, it 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^{2),8),9)}. 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 method¹⁰⁾ (usually termed as MS method) recognizes Multiple Slopes (MS) to allocate fraction of flow proportional to slope downstream. Another similar method¹¹⁾ 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 method¹²⁾ is suggested to obtain the flow direction, which is criticized on its disability to reproduce the result and random wiggles. Improved Rho8 method¹³⁾, called Lea's method, has routed the flow as a rolling ball released on a plane from the center of each grid cell. DEMON²⁾ 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.

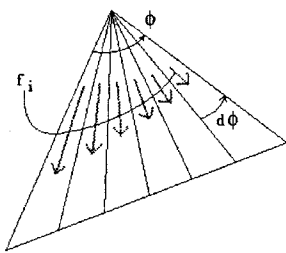


Fig. 1 Strip VFT representing flow potential

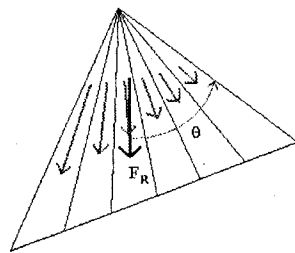


Fig. 2 Resultant VFT of entire area

A triangular facet based D_∞ method⁹⁾ calculates steepest descent for the triangular facets same as that of triangular irregular network (TIN) surface slope¹⁴⁾ by constructing facet from DEM¹⁵⁾. 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 method¹⁶⁾ 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 approach¹¹⁾ and pure stream lines¹⁵⁾.

MS methods^{10),11)} 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. Then the flow direction information is utilized to calculate 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 of prime concern.

Demerits, those the hydrologists want to remove, are still appearing even after 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.

3. RANKED FLOW TENDENCY METHOD

(1) Basic concept

While conceptualizing the slope as a driving agent to cause flow; the non-linear relation between flow and slope should not be neglected. To assume the surface slope as a measure to define the flow direction, one should recall that any slope just represents the tendency to occur flow along that direction by the magnitude of its non-linearly dependent component. 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 can be divided into multiple infinite strips of uniform sloped surfaces. VFT exists for each of these strips (see Fig.1). A resultant vector shown in Equation (1) of the multiple strip VFT vectors should represent the resultant VFT vector for that area (see Fig.2).

$$F_R = \frac{\int f_i d\phi}{\sum_i} \quad (1)$$

Here, f_i is i^{th} strip VFT, which is a function of surface characteristic and slope. ϕ is spread angle of the surface and F_R is a resultant VFT. The orientation θ 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., sometime may suit to some specific topographies.

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) Flow direction within triangular facet

Using a DEM, infinite numbers of strips can not be involved in calculation. Inside a 9 grid cells' window, one can easily form 8 planar triangular

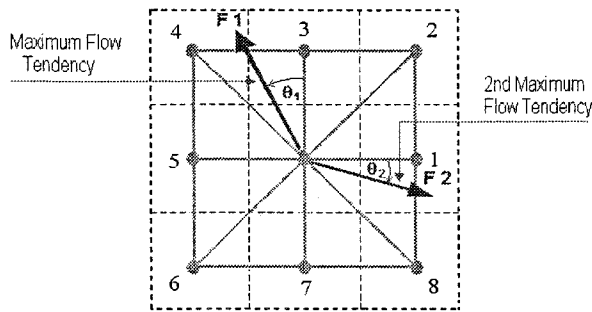


Fig. 3 Ranked Flow Tendency search

facets by connecting the center point of all 8 neighbor grid cells to the center of central grid cell (see Fig.3). To obtain finer strips by interpolation may not be practical alternate because of discrete DEM surface and huge computational burdens. Adopting the triangular facets as primary regions of flow surface, their edge strip VFTs are evaluated from the edge slopes. A cross product of the two readily available edge VFTs then gives the resultant VFT vector F_R for the triangular surface, which is an effective strategy to reduce the computational load. The orientation of resultant slope S_R may differ from that of F_R (see Fig.4 and 5) 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° range at center point. If the VFT angle θ is within the facet angle, it represents the resultant flow direction on that facet. If the VFT angle θ is outside the facet, the direction associated with that facet is taken along the steepest edge.

(3) Magnitude of flow tendency

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

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

Here, F is the flow tendency (see Fig.3), s_1 and s_2 are adjacent and diagonal slopes respectively (see Fig.4), 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 flow direction from the central cell of the window.

(4) Multiple flow potentials

To choose the maximum F as the flow direction is, in fact, selecting one triangular facet for down-pouring from the central cell of the window. It means only two downstream cells, at maximum, may receive the flow from upstream. Moreover, better results can be obtained by including additional downstream cells, if exists, as receiver.

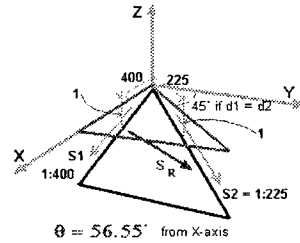


Fig. 4 Resultant slope vector

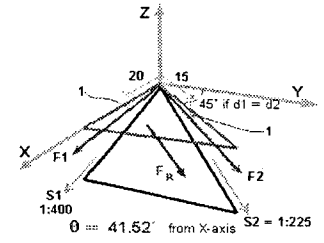


Fig. 5 Resultant VFT vector

The significances of including more downstream receiver cells to represent diverge flow and to prevent grid bias 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 has not produced significant change in result than the D8 method. From an investigation using arbitrary DEM data, it is revealed that multiple flow directions often appear at local peak regions by their method, which mostly remains dry on flow routing. Ascending and descending lines mostly overlap at off-peak wet regions and premises of major channel, which may have produced negligible improvement on entire hydrological simulation.

The proposed VFT approach attempts to fulfill the need of multidirectional divergence at off-peak region. A strategy of involving multiple higher F_s improves the ability to trace most of the lower cells. The multiple F_s are chosen on the basis of their rank from the maximum (see Fig.3) 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, maximum four lower cells, those connected with two triangular facets, are traced by choosing the highest and second highest F_s . Similarly, maximum six lower cells may be traced if third highest F is also accommodated. In this way, the Ranked Flow Tendency becomes able to incorporate much larger wet zones.

(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° 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.

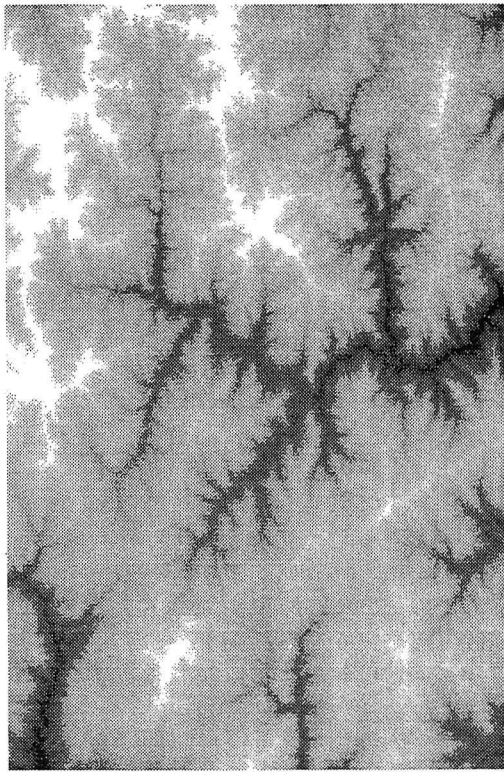


Fig. 6 Elevation map of DEM

- 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.

(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.

Generally, the highest and second highest values $F1$ and $F2$ (see Fig.3) are found almost enough to trace most of the significant divergences at wet flow region including pits and flats in a test simulation using arbitrary DEM data. The concept of Ranked Flow Tendency (RAFT) based on the presented description is proposed to define the flow direction in a DEM based analysis and hydrological simulation.

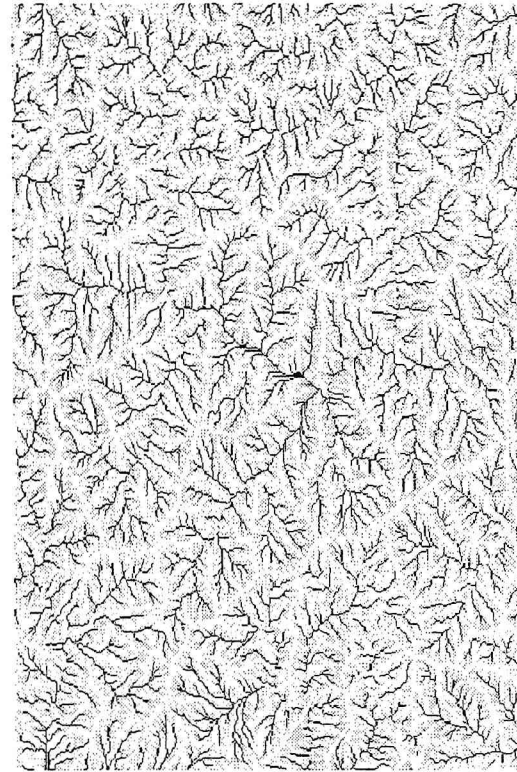


Fig. 7 Density map of flow accumulation using D8 method

4. APPLICATION AND RESULT

The proposed method is applied to Kamishijiba reservoir site using a DEM of 50-m grid resolution. This data is referred from Digital Map of Geological Survey Institute, Japan (shown in Fig.6). 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 $F1$ and $F2$. The distribution weights are determined on the basis of flow direction and chosen $F1$ and $F2$ to allocate fractions of flow to the connected cells.

To create a density map of flow accumulation, unit depth of effective rain water is fed to all grid cells in the beginning, which gradually disappear from the peak regions and accumulate along the off-peaks in both D8 and RAFT method. The density map plots darker segment for higher accumulation of water and vice versa resulting a flow path map (see Fig.7). The D8 method's flow accumulation technique can not simply be used in any multidirectional methods, including RAFT as it may produce cyclic accumulation. Instead, a new algorithm to catch higher flow during the flow routing is used in RAFT method. By plotting a density map of the caught flows, it produces the flow path map.

The pits are treated in RAFT method by iterative search of connected pits, but D8 method generates parallel lines (discussed in section 5). To

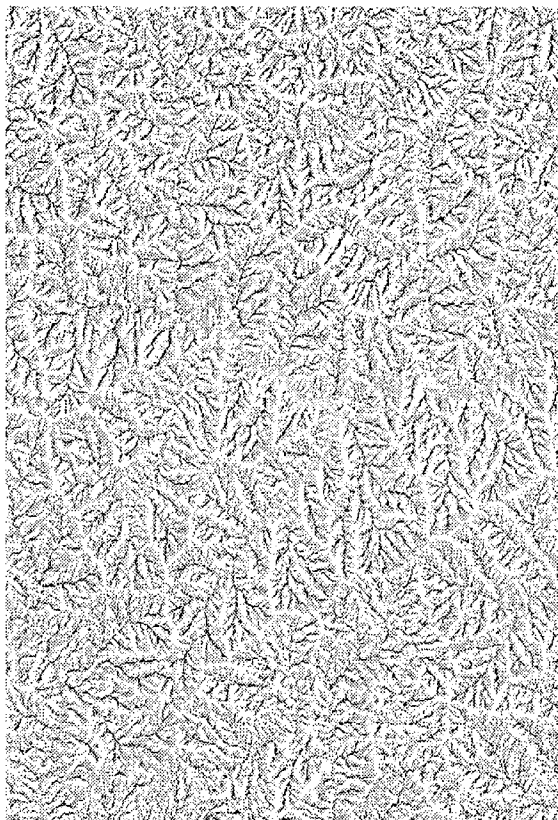


Fig. 8 Density map of flow using modified D8 method

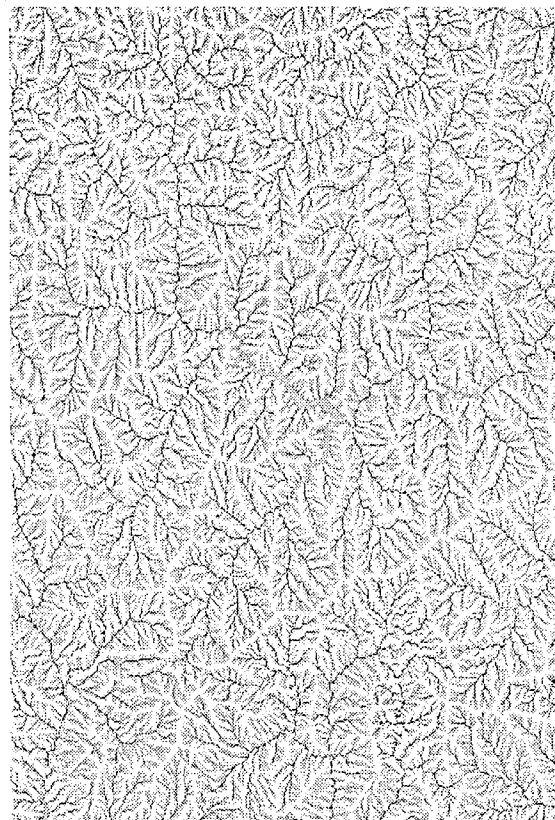


Fig. 9 Density map of flow using RAFT method

make the results comparable from the two methods, the pit removal technique of D8 method is replaced by iterative search technique and keeping other processes same, which is termed as a modified D8 method hereafter. Modified D8 method effectively avoids the parallel flow line representation of lakes and flats. It is created mainly to compare the results by unidirectional D8 and multidirectional RAFT method with hydrological model.

A storage function method is used to represent the cell hydrological behavior, whose parameter is determined by the kinematic wave formulation. Each grid cell is treated as a single reservoir. The cell discharge is calculated by

$$\frac{dh}{dt} = r - q \quad (3)$$

$$q = \left(\frac{1}{k} \right)^{5/3} h^{5/3} \quad (4)$$

$$k = \frac{5}{8} \left(\frac{n}{\sqrt{s} L} \right)^{3/5} L^{8/5} \quad (5)$$

Here, r is inflow depth, q is outflow depth, h is storage depth, n is Manning's coefficient, s is slope determined by h along flow path, L is flow length.

Uniform depth of effective rainfall, which is applied as input at the beginning, generates runoff at the outlet of reservoir. The runoff from the reservoir is treated as discharge from the cell to transfer to downstream cell. Discharge from upstream

reservoir is fed to downstream reservoir directed by the direction obtained using the presently proposed approach. The amount of transferred discharge along each path is the multiplication of total reservoir discharge and the distribution fraction given by the flow directions and magnitude of flow tendencies. The storage of water is updated at every calculation step. The flow model parameters are updated at every calculation step depending on the available water depth inside the reservoir. Corresponding density maps of flow movement are plotted in Figs. 8 and 9 for comparison.

5. WHAT ARE THE DIFFERENCES?

Figures 7, 8 and 9 presented here for comparison, clearly show the difference between the D8, modified D8 and the new RAFT methods. The RAFT method (Fig. 9) has performed better to represent the topographic characteristics and flow map that are clearly visible comparing it against elevation density map (Fig. 6) and other results.

Many disconnected river segments that appeared in D8 method (Fig. 7) are improved by the RAFT method (Fig. 9). RAFT method has displayed improved modeling of the flow along the multiple sets of adjacent off-peak cells (Figs. 10-c and 10-d) unlike that in D8 method (Figs. 10-a and 10-b), which may be useful to imagine the channel width.

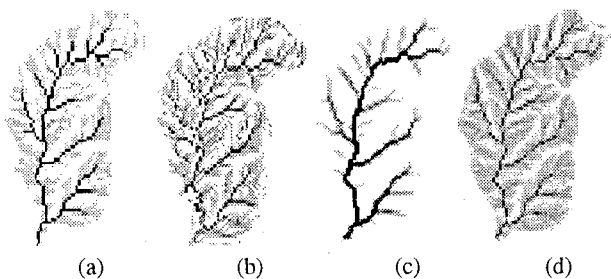


Fig. 10 Typical comparison of flow paths : (a) Channel network by D8 method , (b) Flow density map by modified D8 method (c) Channel network by RAFT method (d) Flow density map by RAFT method

The parallel lines, which are generated on reservoir site by D8 method (Fig. 11-a), are not repeated in RAFT method (Fig. 11-c), but instead, it displayed uniform water level representing the reservoir area. D8 method with modified pit removal algorithm has not produced parallel lines, and it still fails to give well result (Fig. 11-b) as that of RAFT method (Fig. 11-c). 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 be 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.

6. 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.

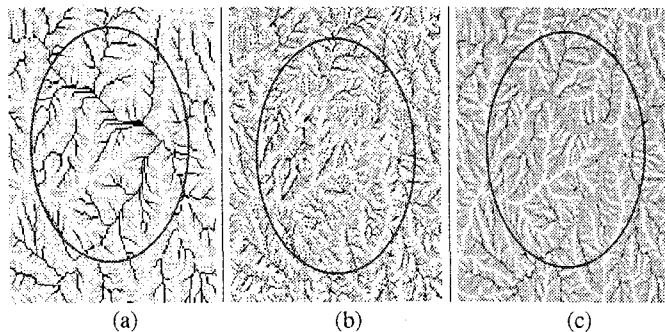


Fig. 11 Comparison of reservoir area flow paths obtained from (a) D8 method, (b) modified D8 method and (c) RAFT method

REFERENCE

- 1) Moore, I. D., R. B. Grayson, and A. R. Ladson, Digital terrain modeling: A review of hydrological, geomorphological, and biological applications, *Hydrol. Process.*, 5(1), 3-30, 1991.
- 2) Costa-Cabral, M., and S. J. Burges, Digital elevation model networks (DEMOM): A model of flow over hillslopes for computation of contributing and dispersal areas, *Water Resour. Res.*, 30(6), 1681-1692, 1994.
- 3) Beven, K. J., and M. J. Kirkby, A physically based variable contributing area model of basin hydrology, *Hydrol. Sci. Bull.*, 24(1), 43-69, 1979.
- 4) Beven, K., M. J. Kirkby, N. Schofield, and A. F. Tagg, Testing a physically based flood forecasting model (TOPMODEL) for three UK catchments, *J. Hydrol.*, 69, 119-143, 1984.
- 5) Wood, E., F. M. Sivapalan, and K. Beven, Similarity and scale in catchment storm response, *Rev. Geophys.*, 28(1), 1-18, 1990.
- 6) Tarboton, D. G., R. L. Bras, and I. Rodriguez-Iturbe, On the extraction of channel networks from digital elevation data, *Hydrol. Process.*, 5(1), 81-100, 1991.
- 7) O'Callaghan, J. F., and D. M. Mark, The extraction of drainage networks from digital elevation data, *Comput. Vision Graphics Image Process.*, 28, 328-344, 1984.
- 8) Moore, I. D., R. B. Grayson, and A. R. Ladson, Digital terrain modelling: A review of hydrological, geomorphological, and biological applications, *Hydrol. Process.*, 5(1), 3-30, 1991.
- 9) Tarboton, D. G., A new method for the determination of flow directions and upslope areas in grid digital elevation models, *Water Resour. Res.*, 33(2), 309-319, 1997.
- 10) Quinn, P., K. Beven, P. Chevallier, and O. Planchon, The prediction of hillslope flow paths for distributed hydrological modeling using digital terrain models, *Hydrol. Proc.*, 5, 59-80, 1991.
- 11) Freeman, T. G., Calculating catchment area with divergent flow based on a regular grid, *Comput. Geosci.*, 17(3), 413-422, 1991.
- 12) Fairfield, J., and P. Leymarie, Drainage networks from grid digital elevation models, *Water Resour. Res.*, 27(5), 709-717, 1991.
- 13) Lea, N. L., An aspect driven kinematic routing algorithm, in *Overland Flow: Hydraulics and Erosion Mechanics*, edited by A. J. Parsons and A. D. Abrahams, Chapman & Hall, New York, 1992.
- 14) Tachikawa, Y., Shiiba, M. and Takasao, T., Development of a basin geomorphic information system using a TIN-DEM data structure, *Water Res. Bulletin, American Water Res. Assoc.* 30(1), 9-17, 1994.
- 15) Douglas, D. H., Experiments to locate ridges and channels to create a new type of digital elevation model, *Cartographica*, 23, 29-61, 1986.
- 16) Shiiba, M., Ichikawa, Y., Sakakibara, T. and Tachikawa, Y., A new numerical representation form of basin topography, *Journal of Hydraulic, Coastal and Environmental Engineering*, 621(II-47), 1-9, 1999.

(Received September 30, 2002)