

A DATA-INDEPENDENT METHOD FOR QUANTITATIVE ACCURACY ASSESSMENT OF MORPHOLOGICAL PARAMETERS EXTRACTED FROM GRID-BASED DTM

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ABSTRACT

This paper reports a research project on the methodology for quantitative and objective assessment on errors generated from grid-based hydrological modelling algorithms. Surfaces were defined using selected mathematical functions with different spatial resolutions. Because the theoretical values of surface morphological parameters on these mathematical surfaces are known through inference, they can be used as benchmarks that are independent from data structure and computer application algorithms. These mathematical surfaces were used to test selected terrain modelling algorithms, which can be found and implemented from literature. The actual output values from different algorithms were compared with the theoretical expectations so that the standard errors can be computed and their spatial distribution can be mapped. A preliminary test have shown that some existing algorithms that extract geomorphological and hydrological features from grid-based DTM failed to produce a reasonable result, indicating that these algorithms have some significant weakness and limitations due to their assumptions and data processing methods. While tested against the 'real world' DTM, these weakness were masked by the uncertainty of the accuracy of the source data and the fact that errors may be subtracted in the 'real world' DTM. While tested against the mathematical surfaces, on the other hand, the errors generated by the algorithms would be accumulated and propagated. Thus, the test has proven to be sensitive to algorithm errors and it can provide a quantitative and objective assessment on the correctness and accuracy of the computer algorithms for surface morphological parameter extraction.

1 INTRODUCTION

GIS-based hydrological modelling techniques are well developed and have been widely applied in various research and application fields, such as geomorphology, soil sciences, hydrology and land use studies (Moore, *et al.*, 1994). In past years, methods and mathematical models have been developed and implemented using computer technology to simulate surface run-on and runoff. This was further extended to the investigations where the nature of the surface water flow plays a critical role, such as soil erosion and geomorphological processes (e.g. landslide), and land capability and suitability evaluation.

The most critical spatial data required for computer-based hydrological models is the surface elevation, often represented in the form of a grid-based Digital Terrain Model (DTM). Numerous methods have been developed to interpret the DTM into some critical parameters in hydrological process of surface water, such as flow direction (Jenson and Domingue, 1988; Holmgren, 1994), flow accumulation and catchment area (Freeman, 1991), topographic index, (also known as $\ln(a/\tan P)$ index, Quinn, *et al.*, 1991, 1995) and drainage networks (Mark, 1984; Band, 1986; Meisels, *et al.*, 1995). This DTM inevitably creates significant "grid bias" which forces the samples on the terrain surface be regulated into a constant intervals with a fixed orientation. For the visualisation of the terrain, the grid-based model would not present a critical problem if the resolution (determined by the grid cell size) were high enough. For the quantitative measurements of surface morphological parameters, however, this bias may largely influence the interpretation results. It has thus been recognised that hydrological modelling algorithms employed in many today's GIS software may produce poor results which lead to some significant artificial facts (known as "artifacts") in the output of the interpretation. One of the main reasons is that the assumptions on the runoff pattern of surface water implied by these algorithms are often over-simplified and the influence of the grid-bias inherent in the DTM is not adequately considered (Wolock and McCabe Jr., 1995, Pilesjö and Zhou, 1996).

To further investigate the issues of accuracy and correctness of hydrological models, it is fundamental to establish a methodology for quantitative and objective measurements of errors generated by the DTM algorithms. In the past, the most commonly used method was to apply proposed algorithms on 'real-world' digital elevation data sets. The results from the simulation were then visually or statistically examined against 'common knowledge' on what should be expected or digital data derived from cartographic resources (maps or aerial photographs) (Band, 1986; Wolock and McCabe, 1995). Some attempts were also made to compare the results against the ground measurements (Skidmore,

1989). This approach, however, is challenged by the fact that the DTM itself is the sample of the reality and inevitably contains errors, so that the 'true value' of the terrain elevation and the morphological parameters largely remains unknown. Therefore the conclusion of the assessment can always be questioned from two aspects, namely, the quality of the DTM data itself and uncertainty of the reference data against the 'true value'.

Freeman (1991) presented an alternative method that used an artificial surface, a cone, to assess divergent flow simulation algorithms. The results were assessed using the pattern of catchment area which theoretically should follow a given pattern. This method has eliminated the uncertainty of the data so that it made more convincing testing result. However, a methodology with authority to the test of hydrological models requires that a set of benchmarks be established so that different algorithms and models can be quantitatively compared.

This paper reports a research project on the methodology for quantitative and objective assessment on errors generated from grid-based hydrological modelling algorithms. Surfaces were defined using selected mathematical functions (e.g. plane surface with different slope and aspect in the 3-dimensional space, spherical and other 2nd-order polynomial surfaces) with different spatial resolutions. Because the theoretical values of surface morphological parameters on these mathematical surfaces are known through inference, they can be used as benchmarks that are independent from data structure and computer application algorithms. These mathematical surfaces were used to test selected terrain modelling algorithms, which can be found and implemented from literature. The actual output values from different algorithms were compared with the theoretical expectations so that the standard errors can be computed and their spatial distribution can be mapped.

2 SURFACE FLOW ALGORITHMS

The hydrological models with the concern of this paper include those addressing surface flow and drainage network simulation. Common algorithms reported to date generally fall into one of the two categories, namely, *profile scan* and *hydrological flow modelling* methods (Chorowicz, *et al.*, 1992).

Profile scan algorithms are generally used to detect drainage networks and identify catchment basins as reported by many investigators (Martz and de Jong, 1988; Qian, *et al.*, 1990; Skidmore, 1990; Meisels, *et al.*, 1995). The generic approach of this method is to extract, for example, local concave upward surfaces, and then post-process the result to produce a reasonable overall result. The principles of differential geometry, commonly involve using elevation, slope and its curvature at a given point, are usually employed (Chorowicz, *et al.*, 1992).

The more common approach is the hydrological flow modelling methods that are widely applied to geomorphological and hydrological problems (Moore, *et al.*, 1994). This method is based on the following basic principles:

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

One 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 gridded DEM, implementation of this over-simplified single flow direction method resulted in that hydrological flow at a point only follows one of the eight possible directions (Mark, 1984; O'Callaghan and Mark, 1984; Band, 1986). This would obviously create significant artifacts in the results, as stated by Freeman (1991), Holmgren (1994); Wolock and McCabe, 1995; and Zhou, *et al.* (1997). Attempts have been made to overcome the problem by implementing a multiple flow direction algorithms, which assumes that flow from a given point can be divergent so that it may flow into more than one neighbouring pixels (Freeman, 1991; Holmgren, 1994; Quinn, *et al.*, 1995; Pilesjö, *et al.*, 1998).

3 EXPERIMENT DESIGN AND IMPLEMENTATION

The experiment of this study is to develop a methodology which can assess the results from different hydrological modelling algorithms independently from DEM. The generic approach is to use artificial surfaces which can be described by a mathematical model. The results of the test can therefore easily assessed against mathematical expectation of the surface model. To illustrate the methodology, a preliminary test and its results are demonstrated in this paper.

3.1 Artificial Mathematically-defined Surfaces

This study employs artificial mathematically-defined surfaces as the basis of test. These surfaces include plane surface with different slope and aspect in the 3-dimensional space, spherical and other 2nd-order polynomial surfaces. The influences of varying spatial resolution (i.e. grid cell size) was also tested. In this paper, two such mathematical surfaces are selected to test the accuracy and correctness of selected algorithms. The two surfaces are convex and concave surfaces which were generated from a spherical model. To ensure the data values of the scenario within a reasonable range close to the real world situation, the surfaces (as shown in Figure 1) were produced using the following criteria:

- a) The surface should provide enough details and smoothness. For this purpose, a grid of 511 x 511 pixels (i.e. 511 x 511 distance units) was used.
- a) The surface was generated as perfect spherical surfaces with the resolution of the grid.
- b) At the edge of the convex surface, the slope is equal to 45° and elevation is assigned to 0.
- c) The concave surface is the reverse of the convex surface, and elevation at the centre is 0.

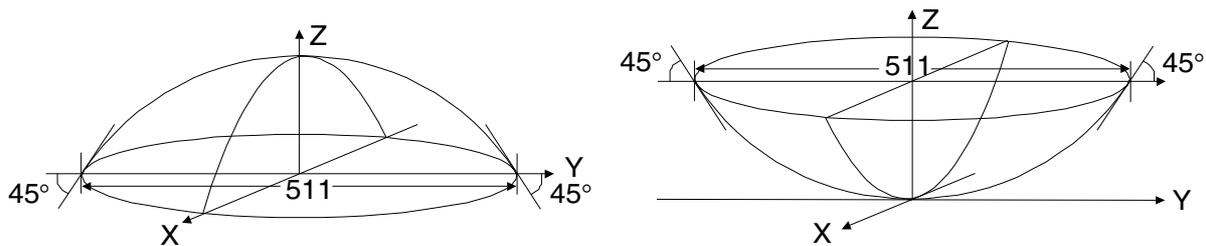


Figure 1. The decision of the convex (left) and concave (right) surfaces for the experiment.

The surface functions can be derived as (refer to Figure 2):

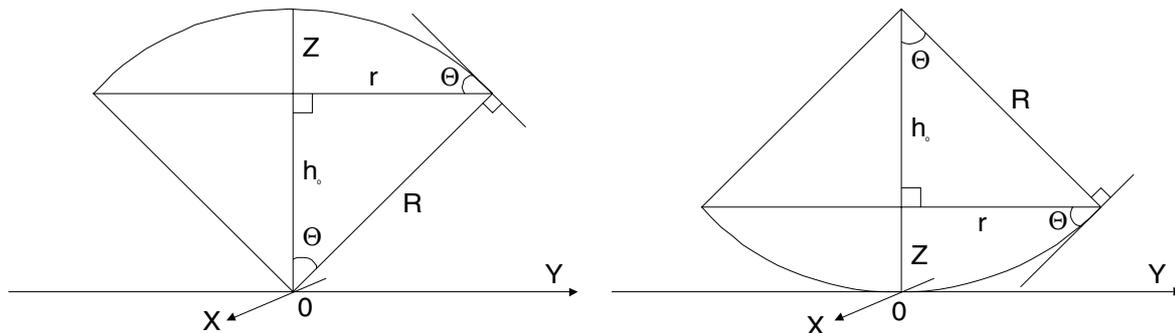


Figure 2. Spherical model for calculating elevation on the convex and concave surfaces.

For a given r and Θ there are $R = \frac{r}{\sin \Theta}$ and $h_0 = \frac{r}{\tan \Theta}$.

Therefore, for a spherical convex surface, there is:

$$Z = \begin{cases} \text{no - data - value} & (\text{for } (x - x_0)^2 + (y - y_0)^2 > r^2) \\ \sqrt{R^2 - (x - x_0)^2 - (y - y_0)^2} - h_0 & (\text{for } (x - x_0)^2 + (y - y_0)^2 \leq r^2) \end{cases} \quad (1)$$

For a spherical concave surface, there is:

$$Z = \begin{cases} \text{no - data - value} & (\text{for } (x - x_0)^2 + (y - y_0)^2 > r^2) \\ R - \sqrt{R^2 - (x - x_0)^2 - (y - y_0)^2} & (\text{for } (x - x_0)^2 + (y - y_0)^2 \leq r^2) \end{cases} \quad (2)$$

3.2 Experiment Design

We selected two representative algorithms for the test, namely:

- **Algorithm 1:** the skeletonization algorithm proposed by Meisels, *et al.* (1995), and
- **Algorithm 2:** the single flow direction algorithm described by O'Callaghan and Mark (1984).

The Algorithm 1 was selected as the one implementing the profile scan method described above which is fundamentally based on the curvature of the slope. The Algorithm 2 is the most commonly used for today's GIS.

The application of Algorithm 1 is to generate drainage network, while the output of Algorithm 2 generally specifies the catchment area at each pixel (or flow accumulation). Therefore, for the purpose of this study, only the patterns of the results from the algorithms were analysed.

3.3 Implementation

Two spherical surfaces were generated and shown as in Figure 3, using an in-house program that implements the function described above.

To avoid controversy that may occur due to the implementation of the algorithms tested, the software codes or executables were inquired directly from the authors of proposed algorithms, except that the commonly used single flow direction algorithm that is tested using ARC/INFO software.

For the purpose of comparison, the results from Algorithm 1 is presented by generated drainage network. The 'flowaccumulation' function of ARC/INFO was used to derive the results of Algorithm 2. The values of the result of Algorithms 2 were then normalised for the comparison.

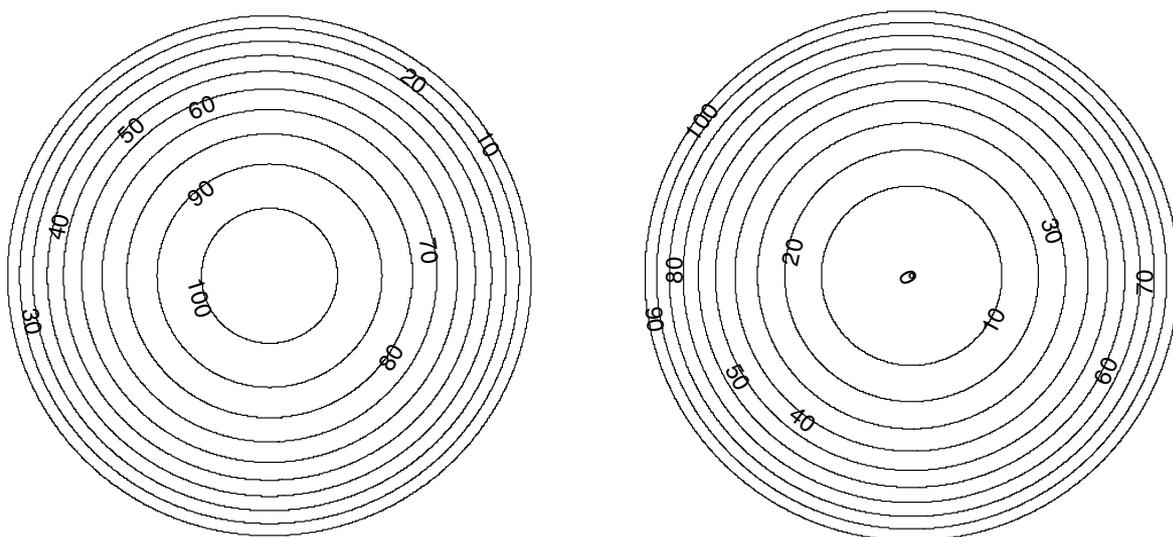


Figure 3. The convex (left) and concave (right) surface used for the test.

4 RESULTS AND DISCUSSION

For the given surfaces, the theoretical pattern on the hydrological flow can be predicted. On the convex surface, the flow is divergent at any point with the outlets at the edge of the surface. Therefore, the drainage network on this surface

should follow the direction from the centre towards the edge, while the catchment area should show a perfect circular pattern with the highest value (therefore the largest catchment area) at the edge. On the concave surface, the flow is cumulative at any point with only one depression at the centre. Therefore, the drainage network on this surface should follow the direction from the edge towards the centre, while the catchment area should also show a perfect circular pattern but with the highest value at the centre.

4.1 Algorithm 1 Results

The results from Algorithm 1 are shown in Figure 4. It is clear that the skeletonization algorithm has produced a reasonable result with the resolution of the grid. However, significant error is also visible, of which the most obvious one is the bias on the pattern along the octant directions. The very gentle slope at the centre also created problems to the algorithm because the curvature of the slope is less than the inherent threshold of the software.

The result of this test has clearly shown the effect of "grid bias" inherent in the grid-based DTM. However, since the algorithm is based on the cross-slope profile analysis to determine the drainage lines, the analysis seems to be quite independent at each assessment location, thus the results do not show significant cumulative (propagated) errors.

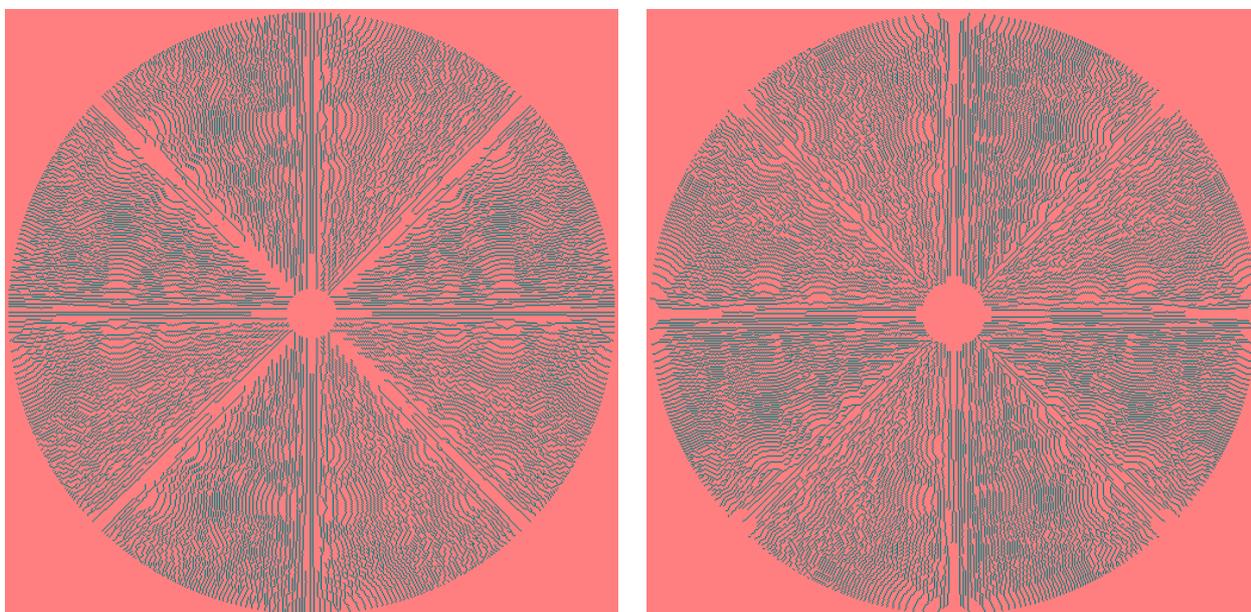


Figure 4. Drainage networks on the convex (left) and concave (right) surfaces, generated from the skeletonization algorithm (Meisels, *et al.*, 1995) with $K_T = 3$.

4.2 Algorithm 2 Results

The flow accumulation produced by ARC/INFO is shown in Figure 5. The results have shown a very significantly high level of errors on both convex and concave surfaces, with the worst on the convex surface. This is obviously due to the problematic assumption of the single flow direction that may only follow one of the eight possible directions. With this assumption the divergent flow understandably created the most significant errors. This result also confirms the observation from Freeman's test on a cone surface (1991).

It is also noted that the flow accumulation algorithm is largely influenced by the cumulative errors, i.e. the locally less-significant errors are propagated through the process. Since the artificial mathematical surfaces do not have the supplementary aspects that may subtract algorithm errors, which are often the case of 'real-world' DTM, the processing error created in each location is always propagated and accumulated into the lower reach of the drainage area. This gives a high sensitivity of the test method.

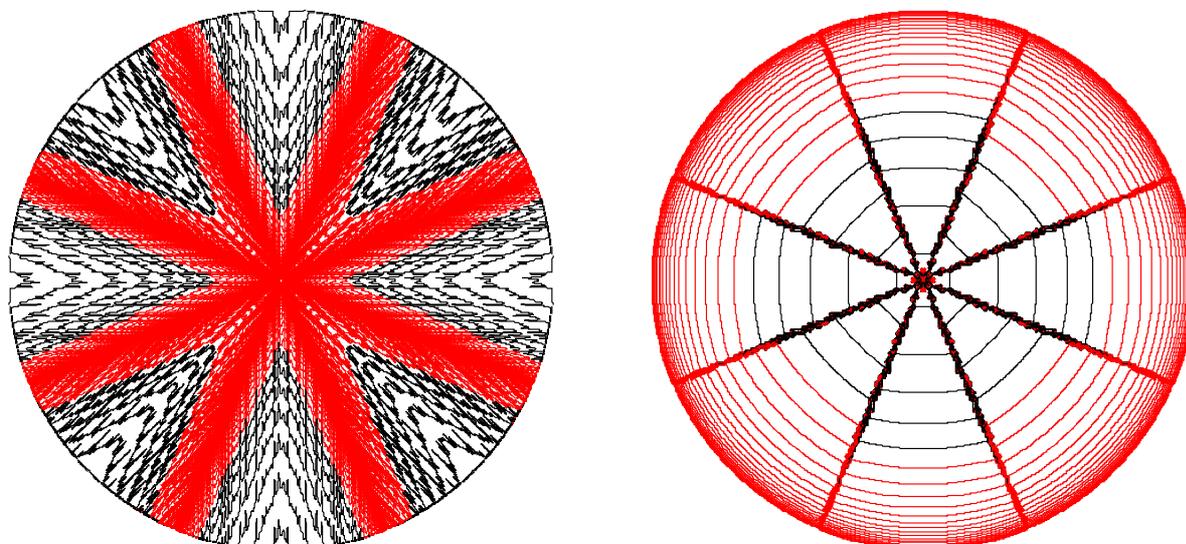


Figure 5. Normalised flow accumulation on the convex (left) and concave (right) surfaces generated from ARC/INFO flowaccumulation function.

4.3 Comparison between algorithms

It seems that skeletonization algorithm has produced the better results than the single flow direction algorithm, though itself still generated significant errors. The single flow direction algorithm expectably created obvious bias, or artifacts, patterned by the octant directions, although such bias also exist in the profile-based skeletonization algorithm. The most significant difference between the results from the two algorithms is that the single flow direction algorithm is very significantly influenced by the error propagation during the process, producing ridiculously large errors in the final results.

5 CONCLUSION

To assess and test hydrological modelling algorithms, it is necessary to develop a methodology that is based on a number of DEM independent benchmark tests. This study has attempted to use artificial mathematically 'perfect' surfaces for the benchmarking and has shown the potential of the methodology as an objective approach to assess the flow algorithms used in hydrological modelling. It is revealed here that tested algorithms have produced significant errors, therefore, the care must be taken by applying these algorithms to the real-world applications.

Although accuracy tests were normally included in the literature for proposed hydrological modelling algorithms, the test against the 'real world' DTM may mask the weakness of the algorithms because of the uncertainty of the accuracy of the source data and the fact that errors may be subtracted in the 'real world' DTM. While tested against the mathematical surfaces, on the other hand, the errors generated by the algorithms would be accumulated and propagated. Thus, the test has proven to be sensitive to algorithm errors and it can provide a quantitative and objective assessment on the correctness and accuracy of the computer algorithms for surface morphological parameter extraction.

Further research is needed to create a set of 'standard' surfaces that emulate the most typical scenarios of the real landscape. It is also necessary to calculate theoretical values of the catchment area for any locations on a given surface, purely based on the mathematical function that defines that surface. The quantitative comparison, therefore, can be made between the simulated results and the theoretical expectation.

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