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A New Algorithm to Automatically Extract the Drainage Networks and Catchments Based on Triangulation Irregular Network Digital Elevation Model

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Abstract: A new algorithm to automatically extract drainage networks and catchments based on triangulation irregular networks (TINs) digital elevation model (DEM) was developed. The flow direction in this approach is determined by computing the spatial gradient of triangle and triangle edges. Outflow edge was defined by comparing the contribution area that is separated by the steepest descent of the triangle. Local channels were then tracked to build drainage networks. Both triangle edges and facets were considered to construct flow path. The algorithm has been tested in the site for Hawaiian Island of Kaho'olawe, and the results were compared with those calculated by ARCGIS as well as terrain map. The reported algorithm has been proved to be a reliable approach with high efficiency to generate well-connected and coherent drainage networks.

Key words: drainage networks, catchment extraction, flow direction, triangulation irregular network (TIN), digital elevation model (DEM), hydrological model
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0 Introduction

Automatic drainage networks and catchments extraction from digital elevation model (DEM) has now been an area of growing interest of researchers in various fields. The method is especially important to physics-based distributed hydrological model because it not only make it more feasible but also help model development, i.e., from empirical models to physics-based models[1-2]. There are three main forms of digital terrain models (DTMs): digital elevation model storing elevations at points of a regular grid (Grid DEM), digital contours, and triangulated irregular networks (TINs).

As the Grid DEM is the prevail data structure for Geographic Information System (GIS) at present and most of the digital terrain model is designed based on it, it has received considerable attention for the extraction of drainage networks and catchment based on Grid DEM[3-7]. The typical approach to extract drainage network from Grid DEM can be categorized as single flow direction algorithm such as D8 algorithm[8-9] and multi-flow direction algorithm[7,10] such as Dinf algorithm. However, most of the algorithms for Grid DEM share the common shortcomings such as parallel watercourse, which affect both drainage system extraction and geographic feature extraction[7-13]. Drainage networks extracted directly from contour, associating the valley branches and the bending groups of contour lines were also reported[14-15], but the generated network may be in the direction other than the steepest descent[16]. Comparing to digital contour and Grid DEM, TINs are more suitable for representing complex drainage network and topography with adaptive, multiple resolution because the terrain defined by them are continuous and they can easily cover a wide range of element sizes with less data storage. As the development of physics-based hydrological models[2,17-20], it is essential to study drainage networks/catchments extraction from a TINs DEM.

The effort reported herein presents an efficient and appropriate algorithm developed with FORTRAN 90/95 language for drainage networks and catchments automatic extraction based on TINs. The major parts of the paper include: ① definition and assumption for drainage network based on TINs; ② flow path determination for depressions and flat regions; ③ site application for Hawaiian Island of Kaho'olawe and discussion.

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1 Methods

1.1 Assumptions

The major assumptions for the reported algorithm include: ① in channel, hydrological flow follows the direction of the steepest slope, crossing over the triangle facets or through triangle edges; ② hydrological flow continues until it gets into a depression or until it leaves the boundary of DEM; ③ at any node, there is a unique direction of steepest descent; ④ for any triangle, there is only one outflow edge; ⑤ cross-triangle flows are considered to make drainage networks.

1.2 Flow Direction

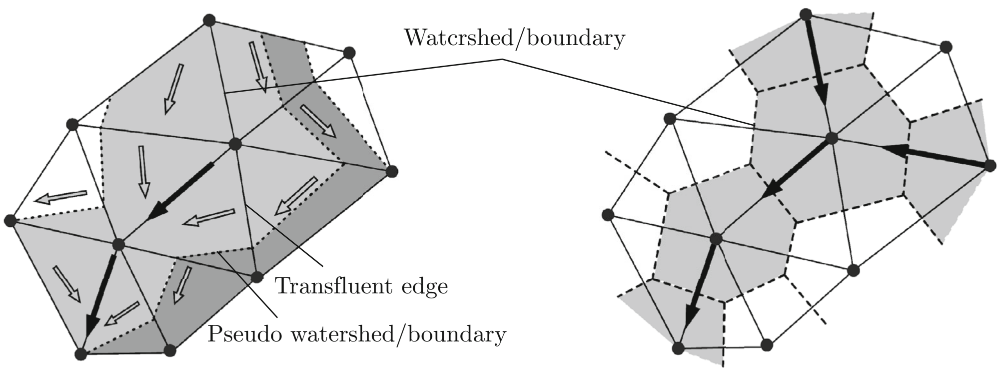
A TINs is a continuous terrain that consists of triangles, edges and nodes. Drainage extraction from TINs is based upon water flow direction. Depending on the flow direction definition, drainage network extraction from TINs can be classified into two types:

(1) Flow direction is decided by triangle's gradient (Fig. 1(a)). In this approach, water flow through the steepest descent in a triangle and an edge becomes a channel if flow comes from both adjacent triangles[21-24].

(2) Flow direction is decided by edge's gradient (Fig. 1(b)). In this approach, flow originating from a node's Voronoi polygon is routed downslope along the steepest of the spokes connected to that node[20,25].

For the first type, drainage basin boundaries consist of triangle edges and pseudo lines. For the second type, drainage basin boundaries consist of Voronoi polygons rather than triangle edges.

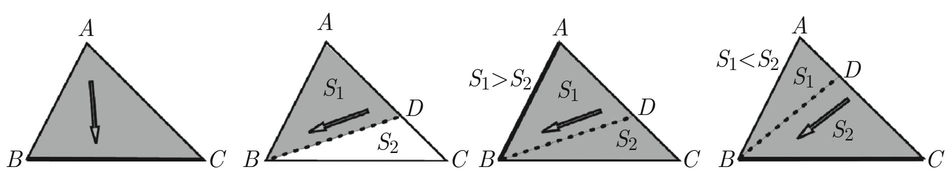
Both flow-direction definitions will introduce new nodes/edges in the extracted catchments (splitted meshes) and therefore the extracted drainage networks need to be reconstructed. However, a straight forward recombination of splitted meshes is impossible because additional information associated to the new nodes/edges is needed. Thus, a new definition of flow direction for TINs is developed: for surface runoff, water flow over triangle through the edge with larger contribution area; for channel runoff, water flow through the channel edge with the steepest gradient. Figures 2 and 3 show different cases of flow over a triangle. Figure 2(a) shows flow over a triangle through one edge; and Fig. 2(b) shows flow over a triangle through two edges. S_1 and S_2 are the contribution areas separated by the steepest descent, respectively. If $S_1 > S_2$, AB is determined as the outflow edge, else if $S_1 < S_2$, BC is the outflow edge, as shown in Figs. 2(c) and 2(d); if $S_1 = S_2$, elevation of node A or B needs minor modification to make water flow through edge AB or BC (the detailed judgment rules are explained in the next section). Figure 3(a) shows the result of local drainage extraction: triangles with the same gray belong to the same drainage.



(a) Flow direction is decided by triangle's gradient (b) Flow direction is decided by edge's gradient

• Node, — Triangle edge, ⇨ Steepest descent in a triangle
- - - Voronoi line, ······· Pseudo line, ➡ Flow line or local channel

Fig. 1 Illustration of steepest-descent flow routing in TINs framework by different definitions



(a) (b) (c) (d)

• Node, — Triangle edge, ⇨ Steepest descent in a triangle
- - - Voronoi line, ······· Pseudo line, ➡ Flow line or local channel

Fig. 2 The flow direction over a triangle surface

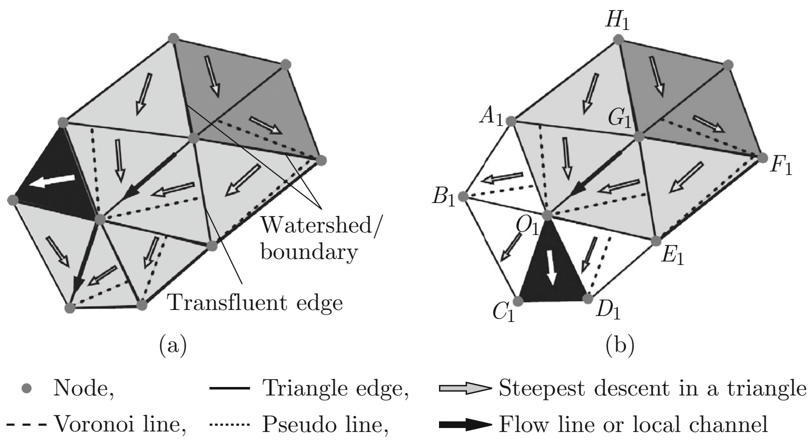


Fig. 3 The flow routing in TINS framework

1.3 Calculation of Flow Direction

A non-vertical spatial triangle ABC with vertexes $A(x_A, y_A, z_A)$, $B(x_B, y_B, z_B)$, $C(x_C, y_C, z_C)$ can be represented as following function:

$$z = f(x, y) = ax + by + c, \tag{1}$$

where $Oxyz$ is the cartesian coordinate system,

$$\left.\begin{aligned} a &= \frac{(y_A - y_B)(z_A - z_C) - (y_A - y_C)(z_A - z_B)}{(x_A - x_B)(y_A - y_C) - (x_A - x_C)(y_A - y_B)} \\ b &= \frac{(x_A - x_B)(z_A - z_C) - (x_A - x_C)(z_A - z_B)}{(x_A - x_B)(y_A - y_C) - (x_A - x_C)(y_A - y_B)} \\ c &= z_A - ax_A - by_A \end{aligned}\right\}. \tag{2}$$

The plane xOy projection of the steepest descent for triangle ABC is determined as following function:

$$\boldsymbol{s} = -a\boldsymbol{i} - b\boldsymbol{j}, \tag{3}$$

where $\boldsymbol{i}$ and $\boldsymbol{j}$ are unit vectors along x and y directions respectively.

The flow flag f of triangle edge AB, which defines the relationship between the steepest descent (vector $\boldsymbol{s}$) and triangle edge (AB), can be determined as

$$f_{AB} = -b(x_B - x_A) - a(y_B - y_A). \tag{4}$$

If $f_{AB} > 0$, edge AB is an inflow edge; if $f_{AB} < 0$, it is an outflow edge; if $f_{AB} = 0$, flow direction is parallel with edge AB. Note that the triangle vertexes ABC are counter-clockwise, or else, f_{BA} is calculated instead of f_{AB}. For each non-boundary side AB in the mesh, it has two value f_{AB}^{L} and f_{AB}^{R} which correspond to edge AB's left and right triangles, respectively; for each boundary side AB, it has only one value f_{AB}^{L} or f_{AB}^{R}. In this study, flow over triangle is considered as single direction flow. Therefore, if a triangle has two outflow edges, take the edge with larger outflow area as the outflow edge and change the flow flag of the edge with smaller outflow area to be zero, which means this edge is neither an inflow edge nor outflow edge, e.g., for triangle ABC shown in Fig. 2(b), $f_{AB} < 0$ and $f_{BC} < 0$, if $S_1 > S_2$, set $f_{BC} = 0$, else if $S_1 < S_2$, set $f_{AB} = 0$. For edges that with two inflow triangle (or one inflow triangle for boundary edges) are determined as flow line or local channel; for edges that with an inflow triangle and an outflow triangle are determined as translucent edge; the rest edges are determined as local watersheds or catchment (basin) boundaries.

If the triangle has two initial outflow edges, as shown in Fig. 2(b), comparison of S_1 and S_2 can be treated as comparison of distance from point A to line BD and from point C to line BD. Taking point B as the origin of coordinate, then equation for line BD is $ax + by = 0$, and points A and C are $A'(x_A - x_B, y_A - y_B)$, $C'(x_C - x_B, y_C - y_B)$, respectively. Then distance from a point to a line can be calculated by

$$\mathrm{dist} = \frac{|ax_0 + by_0 + c|}{\sqrt{a^2 + b^2}}, \tag{5}$$

where $c = 0$ and coordinate (x_0, y_0) represents point A or point C. For the current example, if

$$|a(x_A - x_B) + b(y_A - y_B) + c| > \\ |a(x_C - x_B) + b(y_C - y_B) + c|,$$

then $S_1 > S_2$, and the reverse is also true. As mentioned before, if $S_1 = S_2$, triangle ABC needs minor modification. In such cases, different small random values (e.g., 10^{-8}) will be added to z_A, z_B, and z_C. This small error is acceptable as this random value is much less than the DEM precision.

1.4 Drainage Networks Components

During the process of drainage network tracking, usually only edges were considered as flow path and cross-triangle flows (flow through triangle facet) were therefore ignored[22-24]. Furthermore, cross-triangle flow also introduced the situation of pseudo drainages (i.e., local drainage with a flow line connecting to outflow triangle facet instead of next flow line) in which flow lines are not continuous. Therefore, most network tracking algorithms include a pre-processing module to ensure water flow through triangle edges only, in other words, to avoid cross-triangles flows.

However, in the present method, not only edge flows but also cross-triangle flows were considered. By taking the cross-triangle flows into account, the method is able to not only secure continuous flow naturally, but also eliminate the extra computing time associated with pre-processing. Therefore, the present method, compared with other algorithms, fits better in the long-term research frame described before.

In the reported algorithm, when a flow line is connected to triangle facets, the triangle with the steepest gradient is taken as the next outflow path. As shown in Fig. 3(b), point O_1 is the flow line O_1G_1's outlet point for pseudo drainage $A_1O_1E_1F_1G_1H_1$, while neither of the edges O_1B_1, O_1C_1 and O_1D_1 are local channels. Triangle $O_1C_1D_1$ is the triangle with the steepest gradient among triangle $O_1A_1B_1$, $O_1B_1C_1$, $O_1C_1D_1$ and $O_1D_1E_1$, so the cross-triangle flow $O_1C_1D_1$ is determined as the next outflow path for pseudo drainage $A_1O_1E_1F_1G_1H_1$.

1.5 Flow over Depressions

An often-discussed problem in automatic drainage network extraction is the presence of depressions which introduces difficulty into flow routing. Several methods for removing spurious depressions of a DEM have been proposed. The first method is to fill the depression to the lowest elevation value on the rim[26-28]. This method may result in excessive number of parallel channels across flat regions, which in turn pose a problem for the determination of accurate flow directions. The second method is to change the interpolated elevation values or the flow direction grid[29-32], which may lead to straightening and shortening channels. Soille et al.[33] proposed an alternative approach, namely “carving”, to suppress each single pit by creating a descending path from it to the nearest lower point. Later, another optimal method combining both pit filling and carving was proposed to minimize the pit-elimination pre-processing cost[34]. Although the shape distortion in the form of potentially steep valley sides created by carving method present more of a problem than flat valley floors created by pit filling, Soille's method avoids to create large flat regions and excessive parallel channels.

In the present algorithm, an area-threshold of the basin area was used to determine if an individual depression should be merged into adjacent drainage larger than the area-threshold or not. Depressions smaller than the area-threshold are treated as error of interpolation: the algorithm takes the lowest elevation node on the rim as the outflow node. As Fig. 3(b) shows, suppose local drainage $A_1O_1E_1F_1G_1H_1$ is a depression and node O_1 is the outflow node, we take cross-triangle flow $O_1C_1D_1$ as the outflow path of depression $A_1O_1E_1F_1G_1H_1$. Depressions larger than the area-threshold are considered as realistic geographic feature and kept as individual depression, such as lakes and reservoirs.

1.6 Flow over Flat Region

Processing of flat region is another often-discussed problem in automatic drainage network extraction. One typical approach is to enforce a positive gradient to the flat surface[35] by computing the geodesic distance function from the descending border of the flat region and within the flat region itself[36]. Another approach, which is employed by the ARCINFO software, is to estimate the flow direction over flat region utilizing the DEM information without any further modification: first, a most probable outflow point for the flat area is identified, and then an iterative procedure is employed to assign a flow direction to every unassigned element of the horizontal spot and then iteratively back track until each element has been assigned. However, this method often generates unrealistic banded effects of flow lines following straight, parallel directions[37].

In this study, flat regions were removed by slightly modifying the elevation of the flat triangle's nodes. Similar to interpolation, this processing method may generate artificial depressions, but they could be processed by the proposed method that determines flow over depressions.

1.7 Drainage Networks Tracking

For catchments with outflow point at the boundary of TINs terrain, drainage networks extraction algorithm contains two steps.

(1) Track local channels: start from the outflow point (boundary nodes with the local lowest elevation) to all the local channels that flow to this point, then to any channels that flow to any of the tracked channels. The backward tracking will be repeated until there are no inflow channels.

(2) Track cross-triangle flows: from each local channel to any triangle that flows to it, and then to any triangle that flows to the tracked triangles.

The backward tracking will be repeated until there is no inflow triangle. Pseudo drainages are merged into the drainages which contain their outflow triangles.

For each depression, track from its bottom point and then use the drainage networks extraction algorithm to fulfill tracking. If the depression's area is smaller than area-threshold of drainage basin, the depression will be merged into adjacent drainage, or else, the depression is kept individual.

The detailed process of drainage network extraction is illustrated in Fig. 4.

2 Application

The application site of this study is the Hawaiian Island of Kaho'olawe which locates approximately 10 km southwest of Maui Island. Kaho'olawe is

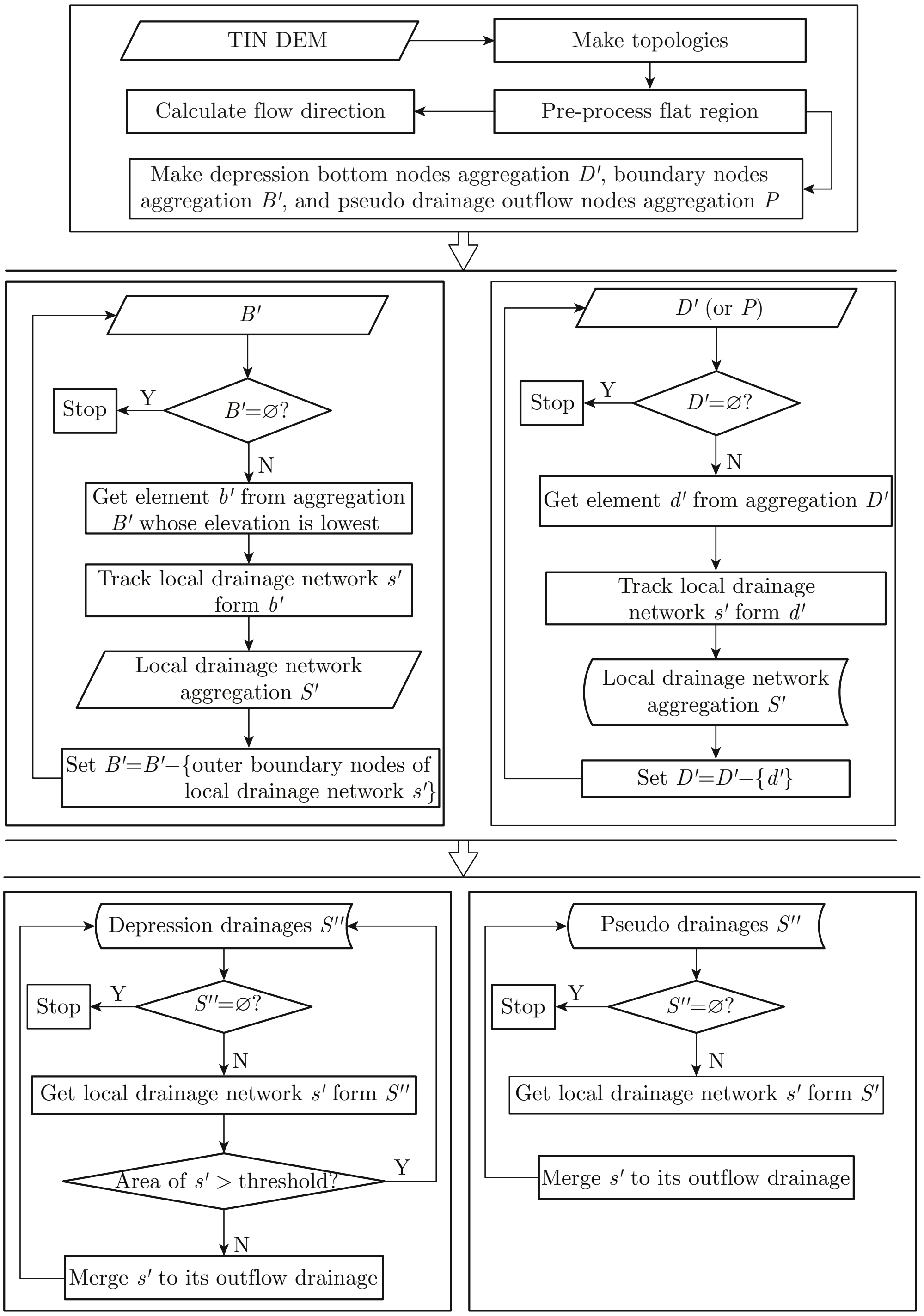


Fig. 4 Process of drainage networks extraction

selected because it has been the application site of the long term research mentioned before. Kaho'olawe is the 8th largest island of Hawaii with an area of 117 km^2 and a highest elevation of 450.2 m. A contour map of Kaho'olawe (United States Geological Survey, 1926) is shown in Fig. 5 and the manually extracted catchments based on the contour map is shown in Fig. 6.

In this study, the input data for the reported algorithm include TINs mesh elements and nodes with elevation information. The TINs mesh for Kaho'olawe is first created. Then the elevation data were extracted from the contour map and interpolated to the TINs mesh with inverse distance weighted method[38-39]. The resolution of the TINs DEM ranges from 10 to 80 m, and the total numbers of triangles and nodes is 438 670 and 220 639, respectively.

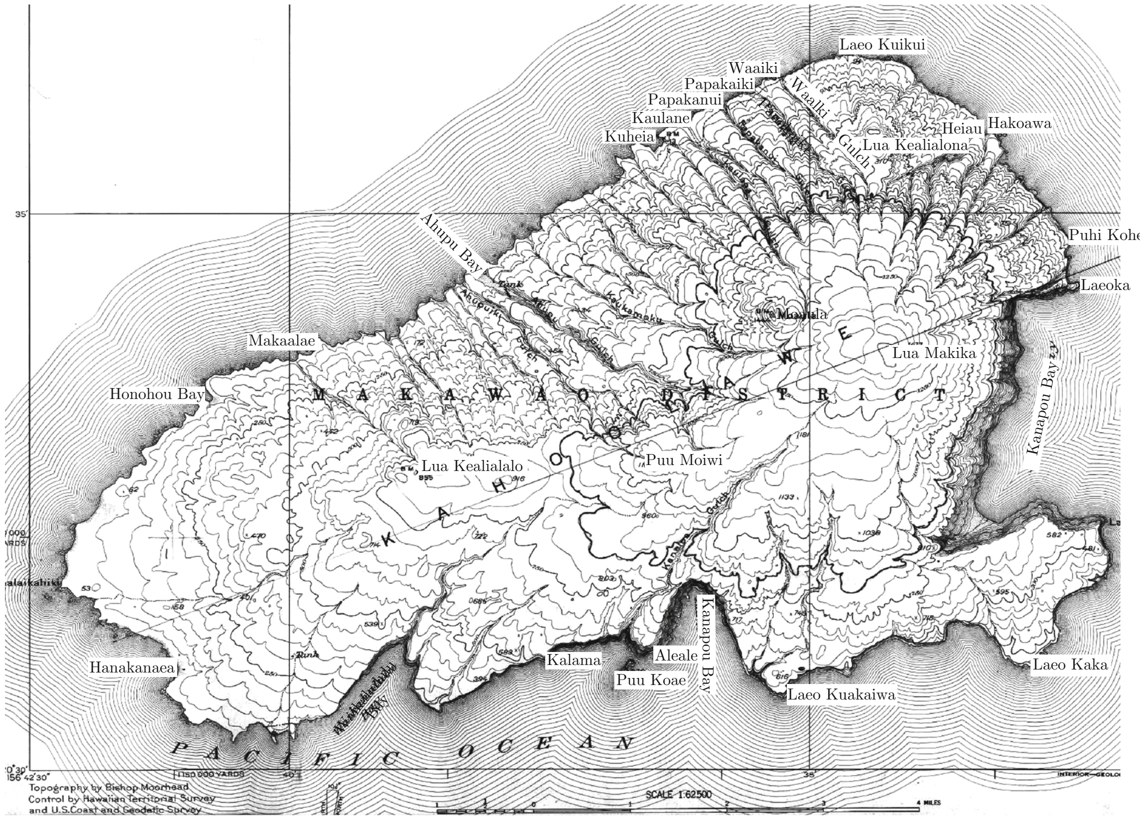


Fig. 5 Contour map of Kaho'olawe Island (Geological survey of USA, 1926)

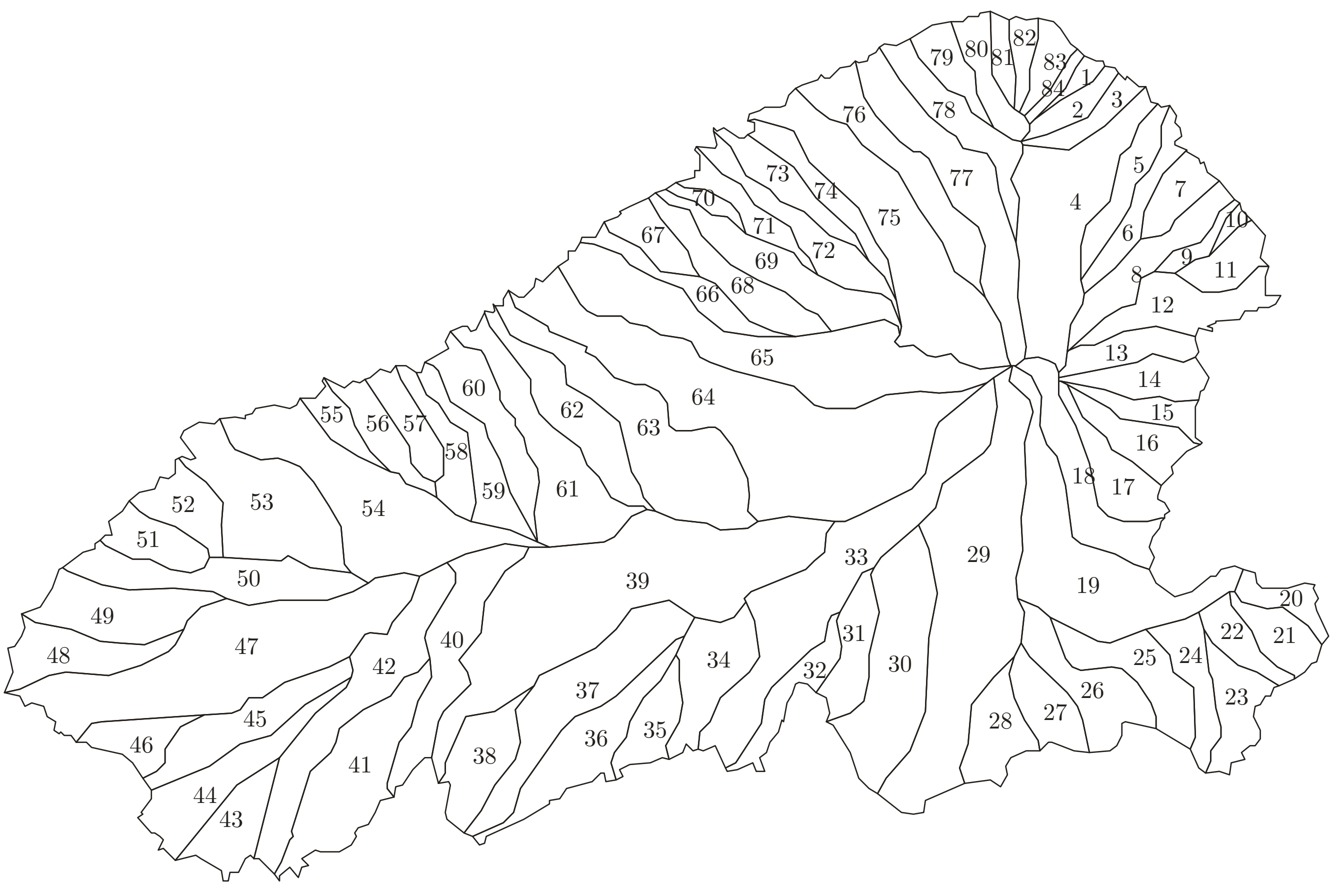


Fig. 6 The 84 manually extracted catchments of Kaho'olawe Island

3 Results

3.1 Extracted Drainage Networks and Catchments

The reported algorithm has been applied to the entire island of Kaho'olawe, with generated drainage networks and the boundaries of catchments showing in Fig. 7. The gray lines are catchment boundaries and the black lines are channel networks. All depressions have been merged into its outflow drainages. Any local channel with a cumulative area larger than $0.125\,\mathrm{km}^2$ has been displayed in Fig. 7 (0.125 is selected because it is the area threshold used by ARCGIS). Comparing with the original map, the reported algorithm gives reasonable drainages networks. It should be pointed out that there exist many extremely small catchments on the boundary. In practical application they will be merged into adjacent catchment.

The resolution of the TINs DEM ranges from 10 to 80 m, and the total numbers of triangles and nodes is 438 670 and 220 639, respectively. The gray lines are catchment boundaries and the black lines are channel networks.

For the purpose of comparison, the present algorithm takes the minimum drainage area of manually extracted catchments (see Fig. 6) as the area threshold, which means any catchment smaller than the threshold is merged into adjacent catchment. The comparison of automatic extracted catchments, both by ARCGIS and the present algorithm, with manually extracted ones (Wahlstrom et al., 1998) is listed in Table 1, showing good statistical agreement among them.

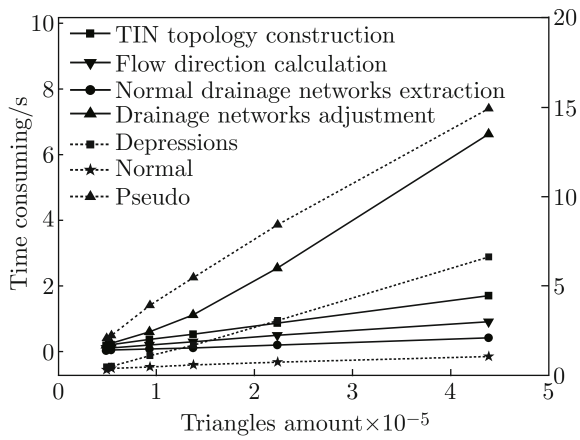


Fig. 7 Relation ship between efficiency and triangles amount

Table 1 Comparison of automatic extracted and manually extracted catchments

Catchments	Total catchments number	Drainages area/km^2			
		Minimum	Maximum	Average	Total
Manually	84	0.10	6.36	1.37	115
By ARCGIS	113	0.13	7.14	9.40	116
By the presented algorithm	98	0.10	8.87	1.18	116

3.2 Efficiency Test

The execution efficiency (in terms of running time) of the present algorithm has been tested on an IBM T40 laptop (Pentium M 1.3 GB, DDR333 Ram 1.0 GB) for Kaho'olawe Island. Different scenarios with triangles amounts ranging from 48 985 to 438 670 were considered. The test result is shown in Fig. 7, It is shown that the efficiency of TIN construction, flow direction calculation, normal drainage networks (drainage basins with outflow point on the boundary) extraction is of linear correlation with triangles amount. The efficiency of drainage adjustment, including merging depressions and extremely small drainages, is approximate linear correlation with triangles amount. As the depressions and pseudo drainages' amount increases, execution time for drainage adjustment also increases quickly. It can be seen that the present algorithm is of high efficiency and drainage adjustment process is the main time consumer. For ideal situation without depressions, time complexity of drainage extraction for the present algorithm is $O(n)$, where n represents triangles amount of TINs mesh.

4 Discussion

There is not yet an established method for precise evaluation of the accuracy of drainage network extraction. Various criteria such as drainage area, stream order, stream length, bifurcation ratio, length ratio etc., have been selected to be criteria, showing that no algorithm can always give best result[40-42]. Since the application site of this study is a hilly island without perennial stream, the mentioned parameters are inappropriate and an alternative approach is needed.

Theoretically, the extracted drainages should be validated by comparing with absolutely standard drainage networks of the same area[11,43]. However, a practical alternative approach is employed since no standard drainage networks have been established for Kaho'olawe. Drainage networks generated by the present algorithm (Fig. 8) are compared with those by ARCGIS (Fig. 9). The input data for ARCGIS which employs D8 routing algorithm based on Grid DEM is the same as the one used by the present algorithm. It is shown in Fig. 9 that the ARCGIS-extracted drainage networks feature in many straight, parallel catchment boundaries and drainage channels.

To further illustrate the detail of the extracted drainage network by the presented algorithm, the result for one single catchment is compared with that by ARCGIS, as shown in Fig. 9. It can be seen that one common problem of the present algorithm and ARCGIS is that the extracted channels are poor connected without processing of depressions and pseudo drainages, as shown in Figs. 10(a) and 10(c). Both results fit well with the real terrain except minor difference.

It is worth pointing out that the present algorithm does not pre-process depressions as most of the other approaches would do. This is important because some of the depressions are the reality topographic features, and elimination of them could introduce new uncertainty. Other than the accurate representation of the real terrain, the advantages of the present algorithm lies in its efficiency.

Although the reported algorithm is based on single flow direction assumption, comparing with D8 algorithm applied for Grid DEM, it is more reliable and suitable to depict flow routing. Calculating flow routing based on TINs DEM can avoid, or significantly reduce the occurrence of parallel flow routing. The worst scenario of parallel flow routing occurs when the TINs is converted from Grid DEM which means neither resolution is changed nor new elevation points are interpolated, and subsequently, TINs is composed of isosceles right triangles only. The situation could be improved by adding new random elevation point by interpolation, or using multi-flow direction algorithm, which will be the future work.

It should be pointed out that the reported algorithm is far from perfect. Flat regions are treated by minor modifying elevation of triangle node, may lead to random local flow direction. Another limitation should be taken into consideration is that single flow direction may be insufficient to describe the flow over triangles, especially in flat region or when water can flow through two edges of a triangle. This limitation affects catchment boundary, local channels and their cumulative area. Therefore, further work is needed to improve the present algorithm.

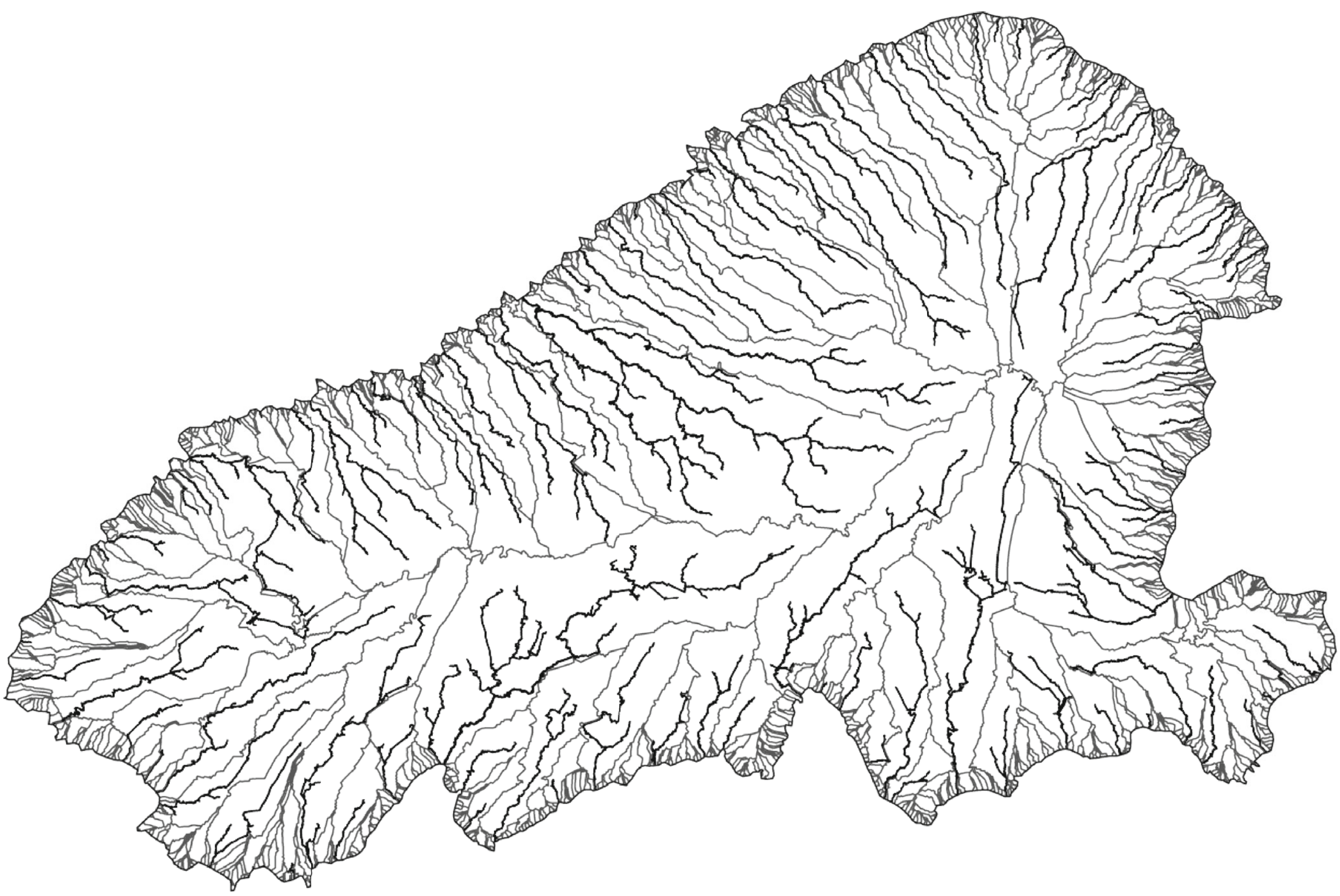


Fig. 8 Drainage networks and catchments extracted by the presented algorithm

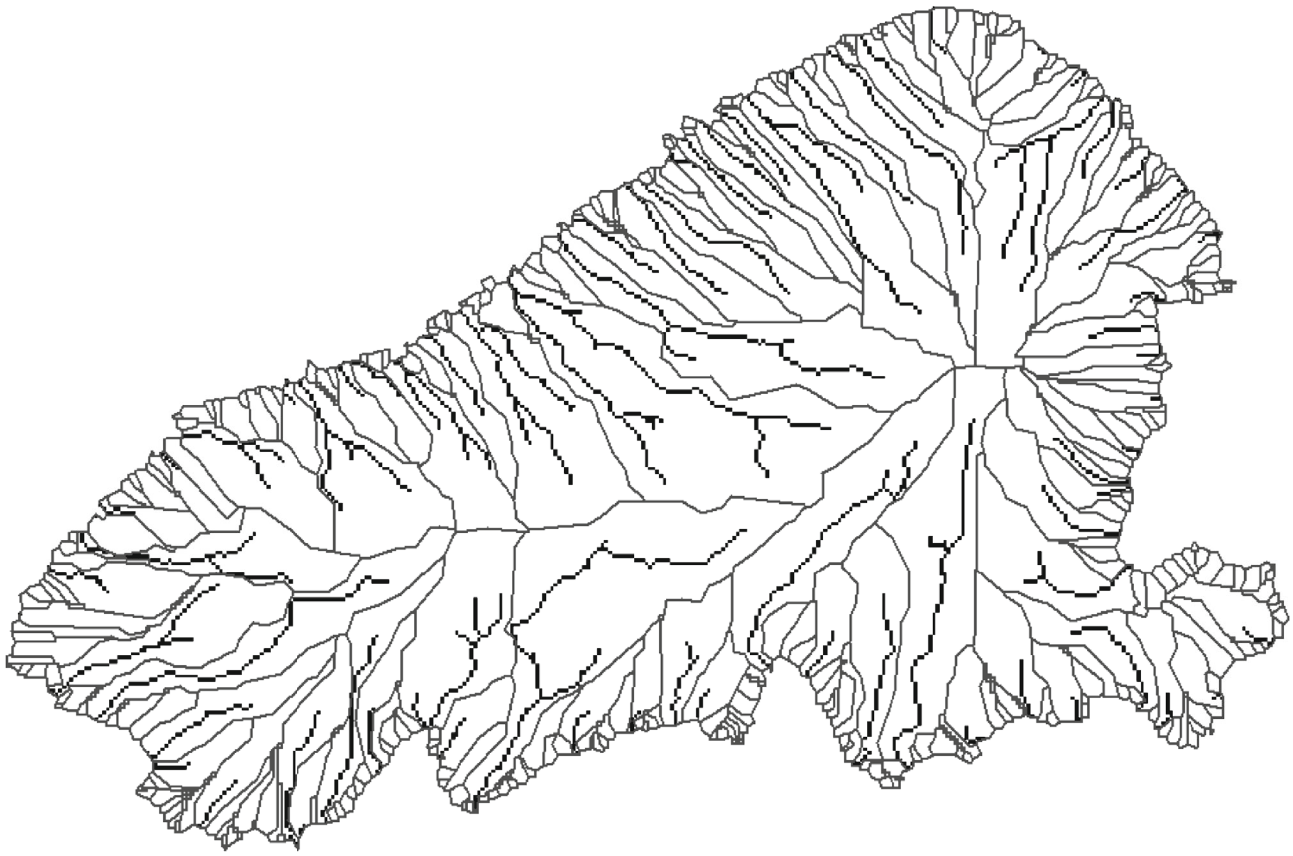
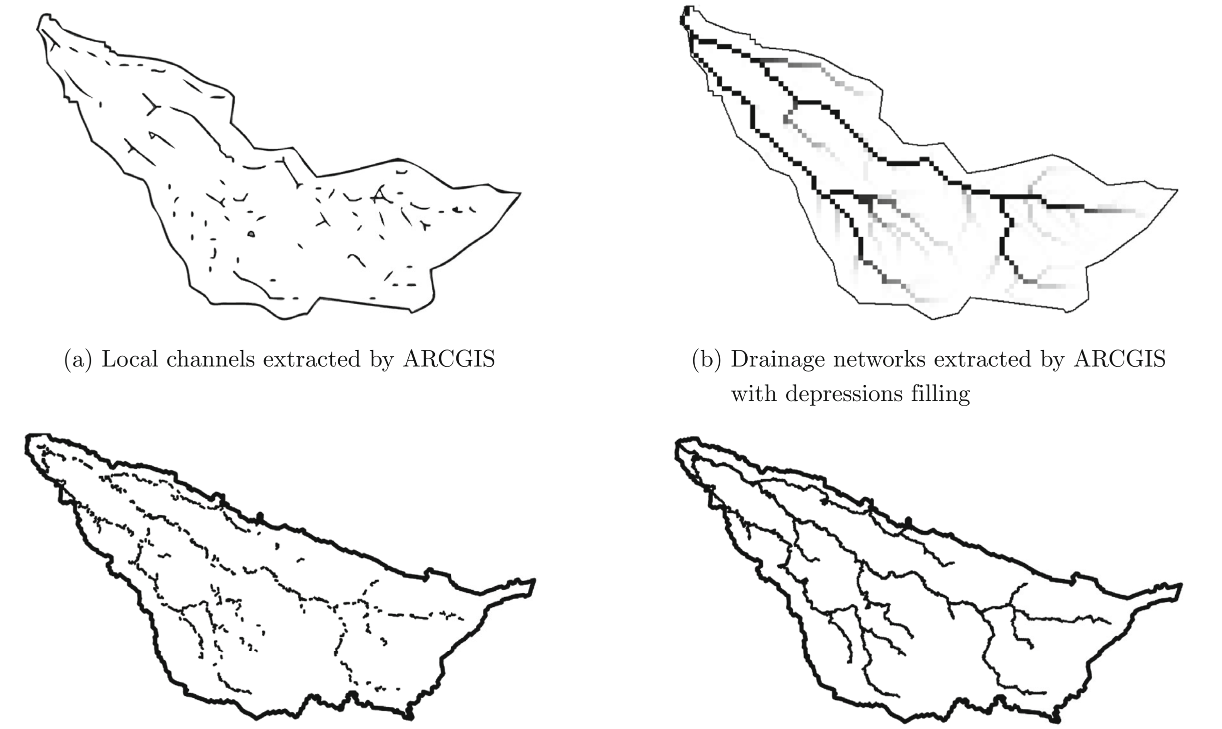


Fig. 9 Drainage networks and catchments extracted by ARCGIS



(a) Local channels extracted by ARCGIS

(b) Drainage networks extracted by ARCGIS with depressions filling

(c) Local channels extracted by presented algorithm without consideration of cross-triangle flows and local depressions' outflows

(d) Drainage networks extracted by presented algorithm with consideration of cross-triangle flows and local depressions' outflows

Fig. 10 Channels with cumulative area larger than $0.125\,\mathrm{km}^2$

5 Conclusion

This paper presents a single flow direction algorithm to extract drainage networks and catchments automatically from TINs DEM without pre-processing depressions and pseudo drainages. The drainage networks extracted by the reported algorithm are compared with terrain map and results generated by ARCGIS. The reported algorithm has been proved to be a reliable tool with high efficiency to generate well-connected and coherent drainage networks.

Acknowledgements The program is a free software under the term of the GNU's Not Unix General Public License. The source code and example can be downloaded via http://code.google.com/p/tin-drainage-extraction-fortran/.

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