The Derivation of Skeleton Lines for Terrain Features

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1 Introduction

A terrain skeleton indicates the presence of significant terrain features like ridges and valleys. Skeleton lines are used widely in cartography, geoscience engineering, and digital photogrammetry\(^1\)\(^4\)\(^8\). Skeleton lines exist implicitly in digitized contour and DEM data. Many researchers have devoted themselves for years to devising methods for the automatic derivation of skeleton lines from digital terrain data\(^9\)\(^13\). The algorithmic methods fall into two broad categories: physical and geometric. The physical analysis methods define drainage areas or watersheds through the simulation of water movement across the terrain surface. The geometric analysis methods identify terrain features through an examination of their morphologic features and properties (such as slope, aspect, and curvature) in two- or three-dimensional space. Both physical and geometric analysis methods have their strengths and weaknesses and neither seems to generate satisfactory results discussed below.

2 Means of extracting terrain skeleton

2.1 Physical analysis

The physical analysis method rests upon the fact that ridges form the dividing lines that separate the movement of water, viz, water on both sides of a ridge flows in opposite directions. It follows that drainage points are reception areas of falling water from higher grounds. In principle, an algorithm for the physical analysis method contains five steps:
1) Computing the slope and direction of falling water;
2) Estimating accumulation rates of drainage points;
3) Determining the terminal drainage points or roots of each drainage system;
4) Tracing of the drainage network;
5) Defining ridges or boundaries of watersheds and sub-watersheds.

The algorithm for physical analysis is deficient in several aspects below.
1) A prior analysis of the terrain surface to locate high and low points is an essential step.
2) The procedure to fill and trim minor indentations and protrusions to obtain leveled grounds is needed to ensure that waterflow would not be interrupted by insignificant pits and bumps in the modelling of water movement [11].
3) The algorithm is computationally intensive and the amount of computation increases with an increase in the resolution of the DEM data.

Another undesirable consequence with better data resolution is the simultaneous increase in data noise. The corollary is that DEM data with a coarse resolution would yield valleys and ridges of reduced reliability. It is, therefore, imminent to strike a balance between resolution and noise to maximize the creditability of the results.

There are noticeable discrepancies among watershed boundaries and drainage points derived from the physical analysis method and the actual ridges and valleys. These differences exist because drainage points are established on the sole condition of flow accumulation. A low-altitude drainage point with a large accumulation rate has a greater probability to be classified a valley than similar points situated in higher altitudes. There is a need to reexamine these points in various altitudes to determine if they are indeed valleys. Furthermore, the physical analysis method tend to yield ridges as boundaries of watersheds in the form of a closed curve, which is not necessarily valid. This inherent trait of the physical analysis method signalizes the need for remedial measures.

2.2 Geometric analysis

The geometric analysis method for the extraction of skeleton lines comprises three approaches: feature point extraction and ordering, medial axes, and aspect tracing.

The approach of feature point extraction and ordering first selects feature or candidate points for the skeleton lines and then order these feature points to constitute the skeleton lines following a few guidelines [12]. Feature points are selected either from digitized contour points whose curvature is greater than a given threshold, or from DEM data whose height is a local maximum or minimum. Feature points derived from digitized contour points are less satisfactory for two reasons:
- The use of a single threshold throughout the selection process undermines the complexity of the terrain;
- The fact that contours are analyzed in isolation precludes the total effects of the terrain.

While the use of changeable thresholds [14] is a possible option for improvement, there is no simple solution to the line by line approach in the handling of contour data in a serial-processing environment. This deficiency means that feature points thus derived will contain noise which invariably clouds the issue of establishing guidelines to the structure of the terrain skeleton. The same deficiency exists for feature points extracted from DEM data because the maximum and minimum heights are locally derived. Furthermore, DEM data of a higher resolution would inherit much noise while those of a lower resolution would fail to detect relevant feature points.

The medial axes approach considers concave and convex corners along digitized contours [1]. The method of equidistant line is used for computing points on the bisectors or medial axes for a short interval from these concave or convex corners [15]. These points on the medial axes are then chained with those of the neighboring contours to form skeleton lines. It is apparent that the medial axes approach can only account for one contour line at a time but gives no consideration to the totality of the terrain. The formation of skeleton lines by
chaining together neighboring axes points produces a high incidence of undesirable feature lines of little resemblance to the reality.

The approach of aspect tracing is comparable to the physical analysis method\[16]. But unlike the physical analysis method which relies on the rate of flow accumulation, the aspect tracing method attempts to extract valleys and ridges by simulating only the direction (and excluding the rate) of flow. The procedure begins with computing an aspect matrix from digitized contour data. The aspect value for each cell is compared with those of the neighboring cells and water channels can be upwardly or downwardly traced. This aspect tracing method is straightforward but computationally intensive since every cell in the matrix must be traced at least once.

3 Proposed stepwise approach for the extraction of terrain skeleton

3.1 Conceptual argument

We have seen that the physical analysis method assume the global approach but suffer from imprecision at the local level. On the contrary, the geometric analysis procedures focus on the local variation without recourse for the totality of the landscape. Henceforth, the former produces terrain features that maintain the overall characteristics of the landscape but lose the details; the latter is able to detect the presence of morphologic features but their association and interrelationships within the larger context are less satisfactory.

In the cartographic discipline, the geometric analysis method is preferred because they are more effective in the detection of topographic features like crests or ridges and pits or valleys. The two long-standing difficulties in these methods are none other than noise in the feature data points thus extracted and the structuring of the skeleton lines. Noise exists in the data because of the non-global approach in the ordering of feature points which, in turn, affects how the feature points are chained to become terrain skeletons. It is also of interest to note that the geometric analysis methods are quite effective in the identification of morphologic features over a small area. It follows that if a studied area of a large spatial extent could be partitioned into smaller units, then geometric analysis methods would be applied favorably to the feature extraction.

As indicated above, the physical analysis method seems to capture the overall characteristics of the landscape. They are quite effective in inferring the general trends of waterflow within individual sub-watersheds. It can be thus argued that results of physical analysis method can be used to guide the ordering of feature points derived from the geometric analysis method, thereby producing more acceptable skeleton lines of terrain highlights.

The combination of the two methods seems a sensible alternative. First, geometric analysis methods are not only computationally intensive but also weak in the ordering of feature points. Geometric analysis method can perform better if data can be partitioned into smaller subsets for processing and the ordering of feature points made more rational. Second, the physical analysis method can maintain the dominant characteristics of the terrain through its global perspective. The results of physical analysis method can help redress the problems of geometric analysis method. Third, the insensitivity of the physical analysis method in recognizing finer details of the terrain can be overcome by the use of geometric analysis method of a greater penetrating power. Conversely, the dominant characteristics of the terrain by the physical analysis method can provide useful guidance towards the ordering of feature points from the geometric analysis.

3.2 Combining physical and geometric analysis methods

The proposed stepwise approach for the extraction of skeleton lines has three distinct phases:

1) deriving feature points
2) establishing trends of waterflow
3) ordering of feature points

In the first phase, feature points along digitized contours that bear a significant directional change are extracted by means of the split algorithm\[17]. The split algorithm is a geometric analysis ap-
proach that involves the recursive partition of a curve at points whose distances from a given chord connecting two terminal vertices are the farthest and greater than a given threshold. The end result is a collection of feature points that are candidate points for either valleys or ridges. However, not all of the feature points will become a part of the terrain skeleton, Phases 2) and 3) will help determine how and which of the feature points will be linked to reveal the presence of depressions and peaks.

In the second phase, a coarse DEM (about two to three times the width of the contour interval) is built from the digitized contour data to help define the trend of waterflow by the physical analysis method. Watersheds are delineated by considering the 8 directions of waterflow and the accumulation rate in subsequent cells. A coarse DEM requires less computation and yields a crude representation of the terrain and subwatersheds with fewer adverse effects of terrain noise. Though not very accurate, the partitioning of subwatersheds and the general trend of waterflow provide sufficient structure toward the formation of skeleton lines described below.

In the final phase, feature points abstracted from Phase 1) are examined against trends of waterflow from Phase 2) in the derivation of skeleton lines that represent ridges or valleys. Unlike the conventional geometric analysis method that links up neighboring feature points without decree, this method proposes to connect feature points with specific reference to the information content of each point. The method involves the detection of valleys and ridges. In the case of valleys, each of the trench lines from Phase 2) is traced from the highest elevation to the lowest. The tracing procedure aims at retrieving feature points within a zone of width no larger than two DEM grids from both sides of the trench lines. Only one feature point per contour line is selected and, in the case of multiple feature points, the one closest to the trench line and whose curvature is the largest is used. The tracing procedure excludes consecutive feature points (i.e. 3 or more in a downward trend) of diminishing curvature that are situated in the lower elevations and within cells of increasing rates of flow accumulation. The foregoing conditions would signal the flattening of the terrain or the end of a valley. The tracing procedure also extends its search in the upper elevations to include additional feature points of a larger curvature that are situated in the higher altitudes as points on the skeleton line for the beginning of a valley.

It should be noted that ridges identified from Phase 2) are closed curves or boundaries of subwatersheds. Using the same reasoning as that for the detection of valleys but varying some conditions, points along the skeleton line for a ridge can be derived. The tracing begins to search for points in the upper elevations of the watershed boundaries and progresses downward. Unless the curvature for consecutive feature points remains small, the points are retained as part of the skeleton lines.

4 An empirical example

The stepwise approach is applied to an empirical data set as follows. Fig. 1 (a) shows the contour representation at 20 meters contour interval of the study area. Fig. 1 (b) is the surface representation in three dimensions. Fig. 2 shows the results in each phase of the derivation of skeleton lines. A total of 259 features points was identified through the split algorithm from a set of 1803 contour points in Phase 1) (Fig. 2(a)). This set of feature points, if properly linked, should reveal the presence of valleys and ridges of the terrain. To aid the ordering process, a crude analysis of the trends of waterflow was obtained in Phase 2) using a coarse DEM (Fig. 2(b)). The results show a series of trench lines (representing valleys) and watershed boundaries (representing ridges). These feature lines initiated a series of tracing procedures whereby feature points in proximity to the lines are selected for evaluation. Upon consideration of other criteria set forth in earlier discussions, a refined set of valleys and ridges are established (Fig. 2(c)). The total number of feature points is 75, of which 32 are valley points and 43 ridge points.

A visual comparison between Fig. 2 (c) and
Fig. 1(b) indicates an extremely good match among valleys and ridges from the two figures. The result also indicates that the use of a coarse DEM is effective in removing noises as minor bumps and dens have been excluded. Likewise, the chaining of feature points in Fig. 2(a) would be chaotic without some rational guidance.

5 Conclusion

Though successful in its first implementation, the stepwise approach still has a number of loose ends to patch. There is the question of the coarseness of the DEM data. While a coarse DEM would avoid the problem of noise, an excessively coarse DEM would forego some essential attributes. Next is the question of a suitable width for the tracing procedure. The width is subject to coarseness of the DEM in Phase 2) as well as the threshold value for the splitting algorithm in the selection of feature points in Phase 1). Even though the selection of these parameters for the empirical test was purely arbitrary, the results do indicate that the approach is feasible and superior in the extraction of skeleton lines.

It is generally recognized that both feature points and feature lines are high in information content. The subwatershed boundaries and trenchlines, though crude and somewhat grainy, do provide suf-
ficient guidance for the chaining of feature points to form skeleton lines. We believe, first of all, that these feature lines provide a means of classifying feature points and focusing our attention on piecemeal analysis. Second, these feature lines contain significant information on slopes which help determine if closeby feature points are collection or spillage points. Third, this stepwise and structured approach toward defining valleys and ridges may be a low-cost substitute and the next best thing to the artificial intelligence approach.

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