

Analysis of Digital Elevation Models by using a GIS

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One of the important capabilities of GIS is the description of the topography of a region. Techniques used in the computer description of topography are called as Digital Elevation Model (DEM). DEM's are arrays of numbers that represent the spatial distribution of terrain altitudes. Main data sources for DEM's are ground surveys, existing topographic maps, photogrammetric stereomodels and surveys done by radar or laser altimeters carried in aircrafts and spacecrafts.

DEM Data Sources

At present, there are five main sources of the elevation data:

1. Ground surveys;
2. Airborne photogrammetric data capture;
3. Existing cartographic surveys (e.g. topo-maps);
4. Airborne laser scanning and
5. Stereoscopic or radar-based satellite imagery.

Traditionally, the elevation data has been collected by land-surveyors from ground surveys or by semi-automated digitising using stereoplotters. This is the most accurate but also the most expensive data collection method. The most recent developments consider automated stereo-image matching, use of laser scanning and remote sensing imagery, either with stereo-scope overlap (IRS, SPOT, ASTER) or interferometric imagery. Note that in the case of elevation Data derived from the remote sensing sources, the sampling density is closely related to the ground resolution.

SOI Derived DEM

The most common method of acquiring elevation data in a digital raster format is to digitize the contours from a topographic map (e.g., by the Survey of India, SOI) and apply an interpolation method to transform the contour data into a DEM. If the elevation data is sampled at point locations or digitised from the contour lines, a primary DEM generation concern is the interpolation method. These range from nearest point, triangulation, inverse distance, minimum curvature and splines up to different kriging techniques. Although the quality of DEM essentially depends on the topographic map used, the interpolation algorithm used for DEM resampling has also a significant influence. The interpolation algorithm used for DEM resampling may be designed according to different requirements. Many technique aim at minimising the RMS error; this criterion is the one most commonly applied in DEM quality assessment. On the contrary, some other techniques tend to preserve the terrain texture.

CARTOSAT DEM

The CARTOSAT-1 spacecraft launched by the Indian Space Research Organisation in May 2005 is dedicated to stereo viewing for large-scale mapping and terrain modeling applications. It is configured with two panchromatic cameras, AFT (Afterward looking) and FORE (Foreword looking) with a spatial resolution of 2.5 m, which facilitates along-track stereo vision of the imaging scene. It covers a swath of ≈ 30 km with a base-to-height ratio of 0.62. The time difference between the acquisitions of the same scene by two cameras is about 52 sec. The principle of binocular vision is used to produce a 3-D view of the imaging scene. The two cameras are mounted on the satellite in such a way that near simultaneous imaging of the same scene from two different angles $+26^\circ$ (FORE) and -5° (AFT) along the track with respect to nadir is possible. This provides stereoscopic image pairs in the same pass and facilitates the generation of accurate 3-D maps.

SRTM DEM

The Shuttle Radar Topography Mission (SRTM) is an international project led by the U.S. National Geospatial-Intelligence Agency (NGA), U.S. National Aeronautics and Space Administration (NASA), the Italian Space Agency (ASI) and the German Aerospace Center (DLR). SRTM obtained elevation data on a near-global scale to generate the most complete high resolution digital topographic database of Earth, including three resolution products of 1 km and 90 m resolutions for the world, and a 30 m resolution for the US (USGS, 2004). The elevation data used in this study is the 90 m resolution (3-arc SRTM), which consists of a specially modified radar system that flew onboard the Space Shuttle Endeavour during an 11-day mission in February of 2000. All SRTM data are freely available at: <http://seamless.usgs.gov/Website/Seamless/>. The SRTM-DEM was downloaded from the USGS ftp site. These data are presently supplied free of cost for scientific study. The data were supplied in GeoTIFF format. These DEMs were exported to the format as unsigned 32-bit data in ERDAS Imagine platform. Sometimes variation in pixel intensity (digital numbers) may be caused by differing sensitivities or malfunctioning of the detectors, topographic effects, or/and atmospheric effects. To correct such variations, radiometric calibration were carried out. The SRTM-DEM was already projected in Geographic lat/long and WGS84 datum.

ASTER DEM

On 29 June 2009, the Global Digital Elevation Model (GDEM) was released to the public. A joint operation between NASA and Japan's Ministry of Economy, Trade and Industry (METI), the Global Digital Elevation Model is the most complete mapping of the earth ever made, covering 99% of its surface. The previous most comprehensive map, NASA's Shuttle Radar Topography Mission, covered approximately 80% of the Earth's surface, with a global resolution of 90 meters, and a resolution of 30 meters over the USA. The GDEM covers the planet from 83 degrees North to 83 degrees South (surpassing SRTM's coverage of 56°S to 60°N), becoming the first earth mapping system that provides comprehensive coverage of the Polar Regions. It was created by compiling 1.3 million VNIR images taken by ASTER using single-pass stereoscopic correlation techniques, with terrain elevation measurements taken globally at 30 meter (98 ft) intervals. The GDEM is produced

with 30 meter postings, and is formatted in 1 x 1 degree tiles as GeoTIFF files. The GDEM is referenced to the WGS84/EGM96 geoid.

ASTER DEM data are freely available at: <http://gdem.ersdac.jspacesystems.or.jp>. These data are presently supplied free of cost for scientific study. The data supplied in GeoTIFF format. Anyone can easily use the ASTER GDEM to display a bird's-eye-view map or run a flight simulation, and this should realize visually sophisticated maps. By utilizing the ASTER GDEM as a platform, institutions specialized in disaster monitoring, hydrology, energy, environmental monitoring etc. can perform more advanced analysis.

ASTER GDEM tiles can be downloaded electronically from ERSDAC by clicking on the above link.

DEM DATA STRUCTURES

Various data structures are in use for DEMs, each with their own merits and shortcomings. There is no structure which satisfies all requirements; much will depend on the purpose and also on the computer facilities available. The basic structures are the line model, the triangulated irregular network and the grid network. The classical form of representing topography is the contour line mapping. The contours can be represented digitally as a set of point to point paths (vectors) of a common elevation. The line model describes the elevation of terrain by contours (stored as Digital Line Graphs i.e. the x,y coordinate pairs along each contour of specified elevation). Typical GIS operations based on the line model are carried out by overlaying the contours on to thematic maps or remotely sensed classifications.

An alternative approach to producing DEM's relies upon determination of significant peaks and valley points in the terrain, which is then represented by a collection of irregularly spaced points connected by lines. The TIN model splits up the true surface into triangular elementary planes. The terrain surface is sampled by points (nodes) that are located at positions which capture the terrain characteristics. The grid based methods may involve the use of a regularly spaced triangular, square or regular angular grid. The element area is the cell bounded by three or four adjacent grid points, depending upon the method. The raster based GISs use the square grid networks. The advantage of the regular grid method is the simplicity of the data storage usually as sequential z coordinate along the x (or y) direction, with a specified starting point and grid spacing.

DEM RESOLUTION AND SCALE FOR REPRESENTING TOPOGRAPHY

There are three principal ways of structuring a network of elevation data for its acquisition and analysis:

1. Contour
2. Raster
3. Triangular irregular network

Contour-based methods of representing the land surface elevations or other attributes have important advantages for hydrologic modeling because the structure of their elemental areas is based on the way in which water flows over the land surface. The raster data structure is perhaps one of the more familiar data structures in hydrology. Many types of data are often measured and stored in raster format. Raster of pixels is also a useful format for representing geographical data, particularly remotely sensed data, which in its native format is a raster of

pixels. Raster data is also referred to as grids. Raster DEMs are one of the most widely used data structures because of the ease with which computer algorithms are implemented.

The raster GIS grid cell data structure makes it possible to represent locations as highly defined discrete areas. The size of a grid cell is commonly referred to as the grid cell's resolution, with a smaller grid cell indicating a higher resolution. The grid cell size imposes a scale on raster GIS analyses. DEM accuracy has been shown to decrease with coarser resolutions that average elevation within the support. Smaller grid cell sizes allow better representation of complex topography and these high resolution DEMs are better able to faithfully represent the characteristics of undulating topography. This has led many DEM users to seek the highest DEM resolutions possible, increasing the costs associated with both data acquisition and processing. The hydrologic literature has established that the grid cell size of a raster DEM significantly affects derived terrain attributes.

A map of topography can be shown at any scale within a GIS. Once data is digitized and represented electronically in a GIS, resolution finer than that at which it was compiled is lost. Subsequent resampling to a coarser or finer resolution obscures the inherent information content captured in the original map. A small-scale map is one in which features appear small, have few details, and cover large areas. An example of a small-scale map is one with a scale of 1:1000000. Conversely, large-scale maps have features that appear large and cover small areas. An example of a large-scale map is one with a scale of 1:2000. A map compiled at 1:1000000 can easily be displayed in a GIS at a 1:2000 scale, giving the false impression that the map contains more information than it really does. Because GIS provides the ability to easily display data at any scale, we must distinguish between the compilation or native scale and the user-selected scale. The scale and resolution at which the data is collected or measured is termed the native scale or resolution. If the spot or point elevations are surveyed in the field on a grid of 100 m, this is its native resolution. Once contours are interpolated between the points and plotted on a paper map at a scale of, for example, 1:25000, we have introduced a scale to the data. Once the paper map is digitized, there will be little more information contained at a scale larger than 1:25000; enlarging to 1:1000 would make little sense. The importance to hydrology is that variations in landform, slope or topography may not be adequately captured at resolutions that are too coarse. Further, to claim that we have a 1:1000 scale map simply because we can set the scale in the GIS is misleading, because the small variations that may have been present were lost when the contours were compiled at 1:25000. The hydrologist must decide what scale will best represent hydrologic processes controlled by the topography.

A variety of algorithms have been used to compute topographic slope from grid-DEMs using various grid cell resolutions. In general as the DEM resolution becomes finer, the calculated maximum slope becomes larger. This effect is related to the topography's complexity. If the topography is complex, greater discrepancies can be expected between grid cells.

The choice of resolution has an important impact on the hydrologic simulation. Choosing a coarse resolution DEM, deriving slope, and using this in a surface runoff model has two principal effects. One is to shorten the drainage length, because many of the natural meanders or *crookedness* of the drainage network is short-circuited by connecting raster grid cells together by way of the principal slope. The other effect is a *flattening* of the slope due to

a sampling of the hills and valleys at too coarse resolution. These effects together may have compensating effects on the resulting hydrograph response. A *shortened* drainage length decreases the time taken by runoff from the point of generation to the outlet. A *flattened* slope will increase the time.

FOUR PRIMARY DEM PRODUCTS

The four data or products which, alone or in certain combinations, are the key instruments in deriving most of the important properties for hydrologic modelling are described below.

I. ELEVATION

The most common method of acquiring elevation data in digital raster format is often the least accurate one, namely digitizing contours from a topographic map and applying an interpolation method to transform the contour data into a DEM. A DEM using contour interpolation has been generated for the example basin. Contour interpolation first rasterizes contour lines in the segment map. This results in values for all pixels that are located on the segments. Then values have to be calculated for pixels that fall in between the segments. For each undefined pixel, the distance is calculated towards the two nearest contour lines. The DEM of the study basin has been prepared and shown in Figure 1.

II. SLOPE

After obtaining an interpolated raster DEM; other terrain properties can be extracted using filtering techniques. First, gradients in X and Y direction are derived, transforming the scalar into vector field. Each pixel becomes a vector with two components the partial derivatives in X and Y direction. After creating gradients say, GX and GY, the absolute gradients can be used as a slope map.

Slope is a widely used topographic measurement that describes the nature of the land surface and, more importantly, influences the flow rates of water. The slope of the example basin has been prepared and the slope varies from 0.28% to 150%.

Numerous algorithms exist for calculating topographic parameters. For example, slope is calculated for the center cell of a 3×3 matrix from values in the surrounding eight cells. Algorithms differ in the way the surrounding values are selected to compute change in elevation (Skidmore, 1989; Carter, 1990; Guth, 1995; Dunn and Hickey, 1998; Hickey, 2001). Different algorithms produce different results for the same derived parameter and their suitability in representing slope in varied terrain types may differ.

III. FLOW (DRAINAGE) DIRECTION

The routing of flow over a surface is an integral component to the derivation of subsequent topographic parameters such as watershed boundaries and channel networks. Many different algorithms have been developed to compute flow direction from gridded DEM data and are referred to as single or multiple flow path algorithms. The single flow path method computes flow direction based on the direction of steepest descent in one of the 8 directions from a center cell of a 3×3 window (Jenson and Domingue, 1988), a method referred to as D8. The D8 algorithm is the flow direction algorithm that is provided within mainstream GIS software packages (such as ESRI GIS). However, the users in the hydrologic community recognize that

the D8 approach oversimplifies the flow process and is insufficient in its characterization of flow from grid cells. In response, researchers have developed multiple flow path methods that distribute flow in all possible down-slope directions, rather than just one; see for example (Quinn et al., 1991; Costa-Cabral and Burgess, 1994; Wolock and McCabe, 1995; Tarboton, 1997; Zhou and Liu, 2002). Multiple flow path methods attempt to approximate flow on the sub-grid scale. Multiple flow path functions are currently not part of standard GIS packages and are, therefore, not readily available to DEM users. Desmet and Govers (1996) compared six flow routing algorithms and determined that single and multiple flow path algorithms produce significantly different results. Thus any analysis of contributing areas such as watersheds or stream networks will be greatly affected by the algorithm implemented. Other approaches to deriving channel networks and watershed boundaries have been developed such as those that incorporate additional environmental characteristics (Vogt et al., 2003). Unfortunately, GIS packages do not differentiate between rough and smooth surfaces when applying a slope or provide users with an option when it comes to derivation of terrain parameters. Users cannot choose a particular method; only one algorithm for derivation of parameters such as slope, aspect and flow direction is embedded in a particular GIS software package. This lack of flexibility in software capability introduces the likelihood of further error transferred to derived topographic parameters. Additional research on the appropriateness of certain algorithms for various terrain types is needed.

The flow direction derived for the example application is shown in Figure 3. The flow direction operation determines the neighbouring pixel into which any water in a central pixel will flow. To determine this, the steepest slope method has been applied as follows:

- For each block of 3x3 input pixels, this operation calculates the height difference between the central pixel (CP) and each of the 8 neighbour pixels.
- If, for a neighbour, the height difference is positive (i.e. central pixel has larger value than the specific neighbour), then:
 - for corner neighbours, height differences are divided by (distance) 1.4
 - for horizontal neighbours, height differences are divided by (distance) 1

This determines the steepness between the central pixel and its neighbours.

- Now the (position of the) neighbour with the largest 'steepness' value is the output flow direction for the current central pixel.

In addition to the above, the following rules are also applied:

- Pixels along the edges of the input map (margins and corners) will always return the undefined value in the output map.
- If all neighbouring pixels of a central pixel have a larger value than the central pixel itself (i.e. a sink or pit), the undefined value will be returned in the output map.
- When a central pixel has the undefined value, undefined will be returned in the output map.
- Neighbour pixels that have the undefined value are ignored during the calculation.
- If from eight neighbour pixels considered, three adjacent neighbour pixels in a single row or column are found to have the same steepest slope or the same smallest height value, then the position of the neighbour pixel that is in the middle of those three neighbours is used.

- If from eight neighbour pixels considered, two neighbour pixels are found to have the same steepest slope or smallest height value, then the position of one of these two neighbour pixels is used arbitrarily.

IV. FLOW ACCUMULATION

A flow accumulation function was defined by O'Callaghan and Mark (1984) as "an operator which, given the drainage direction matrix and a weight matrix, determines a resulting matrix such that each element represents the sum of the weights of all elements in the matrix which drain to the outlet".

If the weight matrix is set to one, the flow accumulation matrix will contain the contributing drainage area of every cell. For example, the value of the flow accumulation matrix at the catchment outlet will represent the catchment area. Cells having a flow accumulation value of one, which means no inflow, will correspond to ridges or hilltops.

A cell with a value higher than a certain threshold will form a connected drainage network provided that the DTM has no pits or depressions without outlet. The flow accumulation operation performs a cumulative count of the number of pixels that naturally drain into outlets. The operation can be used to find the drainage pattern of a terrain. The flow accumulation figure for example application is given in Figure 3. The accumulated flow value for each pixel is calculated using a recursive function.

When a pixel has neighboring pixels pointing to itself, the values of these neighbours are accumulated, including the value of the pixel itself.

- The calculation is initialized by calling the recursive function for the outlet pixel.
- The function then recursively calls itself for all pixels that flow to the outlet pixel.
- The recursion stops when a pixel is reached that has no more neighbour pixels that flow into it.

The distance to the outlet is calculated as the overall distance from each cell to the nearest channel it flows into, and the continuation down to the channel outlet network to the basin outlet.

APPLICATIONS

DEM can be put in use in variety of applications. The most common products derived from DEM relate elevation, slope, aspect, convexity/concavity of terrain etc. Considerable research has been carried out in the field of drainage network extraction and watershed boundary delineation by hydrologists and geologists. Both the slope and the aspect of land are important determinants for ecological site classification and natural resource management and use. For example soil classifications often use landscape categories such as 0-5% slope, 5 to 15% slope, and 15 to 45% slope because it influences the pattern of native vegetation. In a similar fashion land with northern aspects produces different plant communities than land with southern aspect.

Slope is a widely used topographic measurement that describes the nature of the land surface and, more importantly, influences the flow rates of water. A drainage network can be extracted from a DEM with an arbitrary drainage density or resolution. The characteristics of

the extracted network depend on the definition of channel sources on the digital land surface topography. Once the channel sources are defined, the essential topology and morphometric characteristics of the drainage network are implicitly defined because of their close dependence on channel source definition. Thus, the proper identification of channel sources is critical for extraction of a representative drainage network from DEMs.

CONCLUDING REMARKS

Topographic data are one of the key inputs required for natural resource management, and in the form of particularly larger scale DEMs, are currently set to assume an even more important place in GIS.

Grid-type Digital Elevation Models (DEM) is often used as a source of topographic data for distributed watershed models. However, as with most data, DEM have shortcomings and limitations that must be understood before using the data in water resources modeling applications. DEM quality and resolution are two important characteristics that can impact application results. DEM quality and resolution must be consistent with the scale of the application and of the processes that are modeled, the size of the land surface features that are to be resolved, the type of watershed model (physical process, empirical, lumped, etc), and the study objectives. DEM are often processed by GIS packages to define the configuration of the channel network, location of drainage divides, channel length and slope, and subcatchment properties. Basin areas, maximum length of flow and time-area graphs to produce instantaneous unit hydrographs are promising because their derivation is not as critical, and because of their direct application in hydrologic modelling.

The automated derivation of such information from DEM is faster, less subjective and provides more reproducible measurements than traditional manual evaluation of maps.

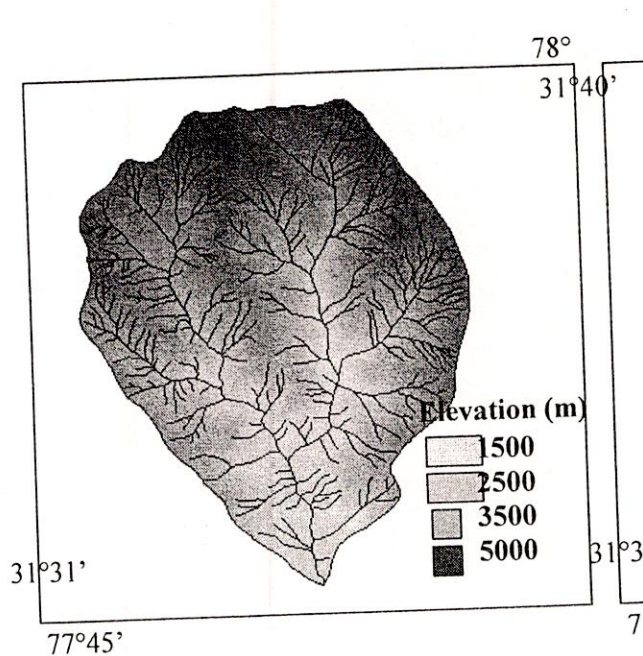


Fig. 1: Digital Elevation Model

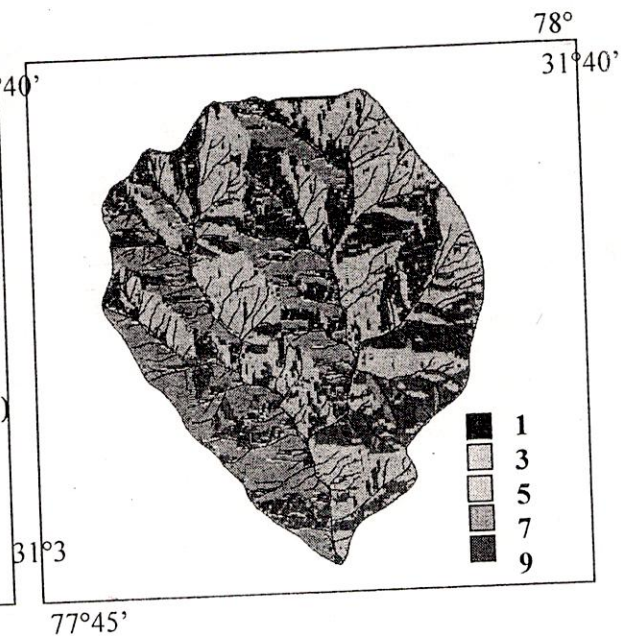


Fig. 2: Flow Direction Map

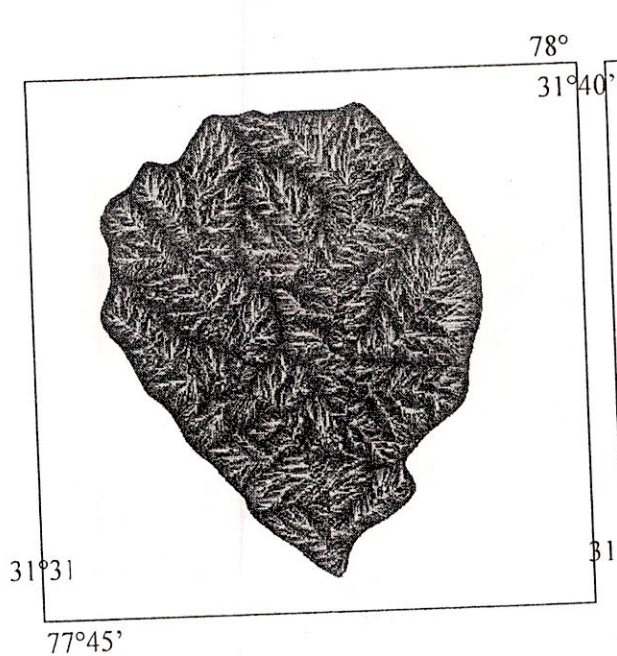


Fig. 3: Flow Accumulation Map

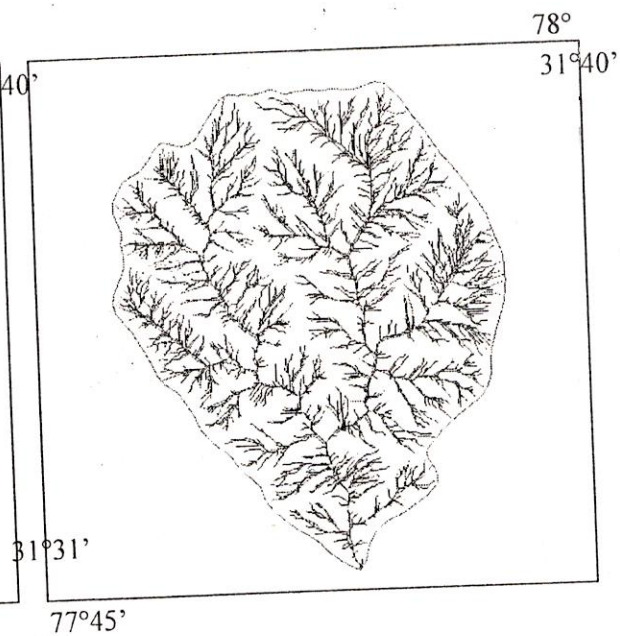


Fig. 4: Drainage Network Map
