Watershed delineation from grid DEMs in GIS: effects of drainage lines and resolution

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Abstract Watershed delineation is essential process in hydrological modelling and analysis since it allows evaluating the quality and quantity of water resources geographically. Most common approach that commercial GIS software offer is based on grid Digital Elevation Models (DEMs). Water flow direction and flow accumulation grids are required to extract drainage lines in this approach. Therefore, selected threshold value for flow accumulation is a distinctive input for watershed delineation. However, there is not a reliable method to define this value at different DEM resolutions. In this paper, an approach is proposed which is used to determine appropriate flow accumulation threshold value to extract drainage lines and their effect to the watershed delineation by comparing different approaches on this subject. Additionally, effects of the DEM resolution on watershed delineation are studied by using 10-metre and 30-metre DEMs in ArcGIS-ArcHydro and GeoMedia Grid software.
Keywords: watershed delineation, drainage lines, DEM resolution, flow accumulation, GIS

INTRODUCTION

A watershed is a region in which all the rainfall coming from the land drains to a particular body of water or common point. If you look up hill from any given point, the watershed would encompass all the land above that point (Risse and Tanner, 2004). In other words, the term watershed or catchments basin refers to the entire physical area or basin drained by a distinct drainage or riverine system, physically separated from other watersheds by ridgetop boundaries (http://files.dnr.state.mn.us).

Delineation and parameterization of landscape drainage features is an important study area in geomorphology and hydrology. Delineation of drainage networks involves their representation by a set of measurable physical properties. These properties are then used in various models to extract other characteristics, and also to ascertain the response of the drainage system to other variables (Naveen, 2005).

Watershed delineation from grid Digital Elevation Models (DEMs) consists of six main stages. First of all a filled DEM of the study area should be obtained and flow direction and flow accumulation values should be determined based on this DEM data. Drainage network is extracted from the DEM based on flow direction and accumulation values. Finally sub catchments and watershed are extracted after the drainage network is segmented (Olivera et al., 2002; Chang, 2006).

Various approaches are used in different stages of the watershed delineation process from the grid DEMs. Derivation of drainage network and DEM quality and resolution should be considered as

vital processes since the changes occurring in these parameters directly influence the outcome of the process.

Many scientists have studied on extracting drainage networks using DEMs produced based on triangulated irregular network (TIN) or grid DEMs (Mark, 1984; Yoeli, 1984; Seemuller, 1989; Aumann et al., 1991; Tang, 1992; Meisels et al., 1995; Chang et al., 1998; Gulgen and Gokgoz, 2004). However, most of geographic information system (GIS) software supports grid approach. Drainage network is derived based on flow accumulation grid which is obtained from flow routing/direction grid. In other words, these values of the grids are fundamental parameters of this process. There are various flow routing algorithms; however, they can mainly be categorized as single flow direction (SFD) algorithms where the total amount of flow should be received by a single neighbouring cell which has the maximum downhill slope with the current cell and multiple flow direction (MFD) algorithms where the flow from the current cell should be distributed to all lower neighbouring cells according to a predetermined rule (Zhou and Liu, 2002).

Deterministic eight-node (D8) algorithm was proposed by O'Callaghan and Mark in 1984. On a 3×3 local window of a DEM, the slopes between the centre cell and its eight neighbouring cells are computed. The flow direction of the centre cell points to the centre of the neighbouring cell with the maximum downhill slope, and that single neighbour will receive all flow accumulated in the centre cell. The algorithm is the most popular one, particularly in commercial GIS software, because of its simple and efficient computation, and strong capability in dealing with local depressions and flat areas. Random eight-node (Rho8) algorithm recognizes that the flow over a grid DEM can be arbitrary thus introduced randomness into D8. It is a stochastic version of D8 that aims to break up parallel flow paths that may be resulted from D8, and produces a mean flow direction equal to the aspect. However, it still cannot model flow dispersion. Multiple flow direction (MFD) algorithms recognize flow divergence over a natural landscape (Zhou and Liu, 2002).

DEMs play a crucial role in watershed analysis as the primary data source of the process. DEMs can vary in both resolution and quality and these characteristics of the DEMs influence watershed delineation (Liu et al., 2005, Chang, 2006). A 30-metre DEM is likely to be too coarse to provide detailed topographic features for geomorphic and hydrologic modelling. Besides, 10-metre DEM can better define the topographic features than the 30-metre DEM. Barber and Shortridge (2005) states that cell size is more significant factor than production method of DEM. It is proved that for studies of small watersheds, researchers have advocated DEMs with a 10-metre resolution and even higher (Chang, 2006).

Automated watershed delineation typically uses the drainage network derived from a flow accumulation grid. The derivation is based on a threshold accumulation value. Its choice can be arbitrary. Ideally, resulting drainage network from a threshold value should correspond to a network obtained from traditional methods such as high-resolution topographic maps or field mapping (Chang, 2006). Experiences prove that the results would be ideal if the threshold is set to the mean value of accumulation of all the cells according to Tang (Li et al., 2005, Tang, 2000).

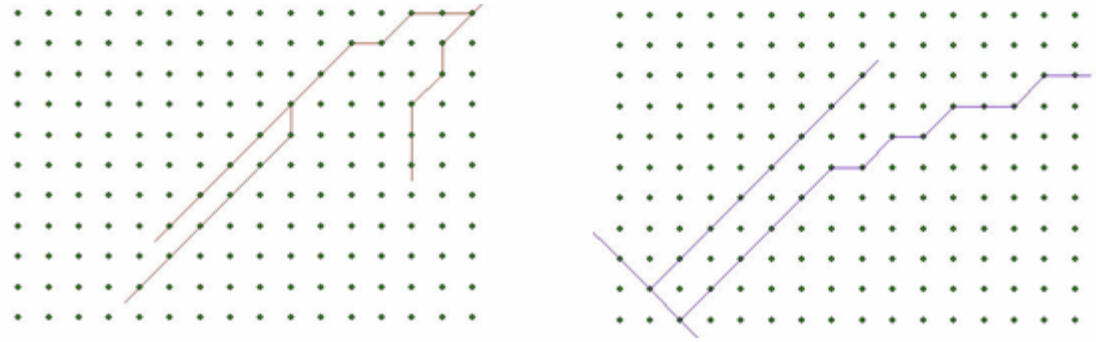
A method that can integrate a vector-based drainage layer into the process of watershed delineation is commonly referred to as "stream burning". Hutchinson (1989) proposes modifying DEM by adding raster digital river and lake network (DRLN) to improve D8 approach (Turcotte et al., 2001). However, this approach can also have some limitations: They are unable to cope with lakes and they will produce parallel flow paths when the raster DRLN differs for more than one cell with the modelled network. Saunders (1999) determines flow directions of DEM cells overlapped by DRLN using DRLN connections only and obtained better results (Turcotte et al., 2001). But "stream

burning" requires extensive data pre-processing, and the hydrography-enhanced DEM may produce distorted watershed boundaries (Chang, 2006).

PROBLEM AND PROPOSAL

A drainage line is a channel down which surface water naturally concentrates and flows, conveying water only during or immediately after (hours or days) periods of heavy rainfall. In other words, drainage lines are the common paths formed by combination of the steepest slope lines. Drainage lines are obtained by defining flow accumulation threshold value and there are two practical methods that may be used in this concept. The first one is using the threshold value set as the mean accumulation value of all cells (Tang, 2000; Li et al., 2005). In the second approach, %1 of maximum accumulation value is given as default value while extracting the drainage networks (Olivera et al., 2002).

In a real valley, all steepest slope lines coming from hillsides proceed by joining along the deepest points of the valley. Therefore, a single drainage line appears on the terrain. However, steepest slope lines do not join in plain or shallow valleys and multiple, parallel drainage lines can occur in these exceptional situations. A single drainage line is exactly more realistic representation of the ground truth. In this study, this characteristic of drainage lines is used as criterion while determining flow accumulation threshold value and a new approach is proposed to select it appropriately: "the first value at which parallel steepest slope lines disappear and a single drainage line is obtained" Our proposal is compared with existing methods in the case study to introduce the effects of the flow accumulation threshold value selection to the drainage line extraction and watershed delineation.



(a) **(b)**

Figure 1. Examples of parallel drainage lines: a) Incorrect, b) Correct

Figure 1a and 1b illustrates the problem for a better understanding. In some cases, when a value is chosen as flow accumulation threshold, not only single drainage lines are derived but also multiple steepest slope lines appear on the hillsides of the valley as can be seen in Figure 1a. This parallel structure does not coincide with geomorphological reality. Although the steepest slope lines shown in Figure 1b are in parallel forms, they can be accepted as drainage lines due to the DEM points between them. As mentioned above, it is understood that terrain is shallow in this part. On the other hand, since the characteristic of the terrain (whether it is shallow or not) can not be decided in Figure 1a, so it can not be accepted as the drainage line.

Different flow accumulation threshold values are resulted in the drainage lines with different lengths and different quantity. As the accumulation value increases less and shorter drainage lines are extracted. Therefore, it can particularly cause errors in the delineation of sub-watershed

boundaries. In other words, it creates more or less number of sub-watersheds than in reality and also affects their boundaries.

CASE STUDY

Case study is performed using 10-metre and 30-metre DEM datasets of a hilly area in the Mid-Anatolia region of Turkey, collected with photogrammetric methods (See Figure 2). ArcGIS-ArcHydro and GeoMedia Grid software are used for this purpose. Watershed delineation process mentioned above is applied successively in the process.

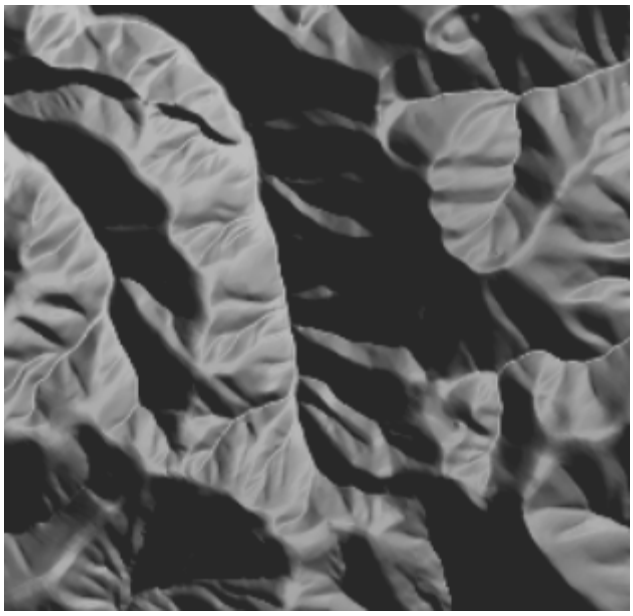


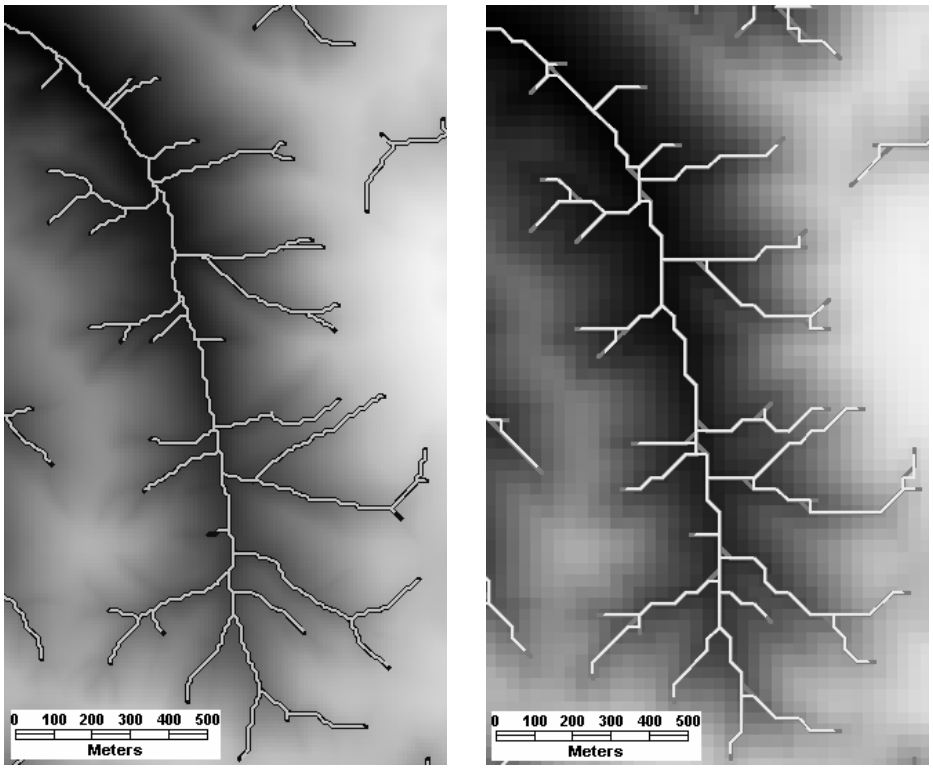
Figure 2. 3D Shaded Relief Image of Study Area.

After determining flow directions, flow accumulation value was calculated based on proposed criteria. For this purpose, flow accumulation threshold value is increased until valid drainage lines are obtained in the valley. While this value increases, the number of parallel steepest slope lines decreases. The smallest value with which parallel drainage network structures disappear was selected as the threshold value by considering proposed approach. In addition to this value, results of the existing methods were used as threshold for both 10 and 30 metre DEMs. Mentioned flow accumulation values calculated for both 10 and 30 metre DEMs are presented in Table 1.

Table 1. Different Flow Accumulation Threshold Values for 10-metre and 30-metre DEMs

Flow Accumulation Threshold Value					
Proposed values		**Tang, 2000**		**ArcHydro default**	
10-metre DEM	**30-metre DEM**	**10-metre DEM**	**30-metre DEM**	**10-metre DEM**	**30-metre DEM**
117	16	81	26	193	22

Figure 3 shows the resulting drainage lines extracted by using ArcGIS-ArcHydro and GeoMedia Grid software. Proposed accumulation values for 10 and 30 metres DEMs were used in this manner. As it is seen in the figure, GIS software gives the similar results for drainage network derivation for both 10 and 30-metre DEMs since they use similar algorithms. Some small differences occur due to raster-to-vector conversion.



(a) **(b)**

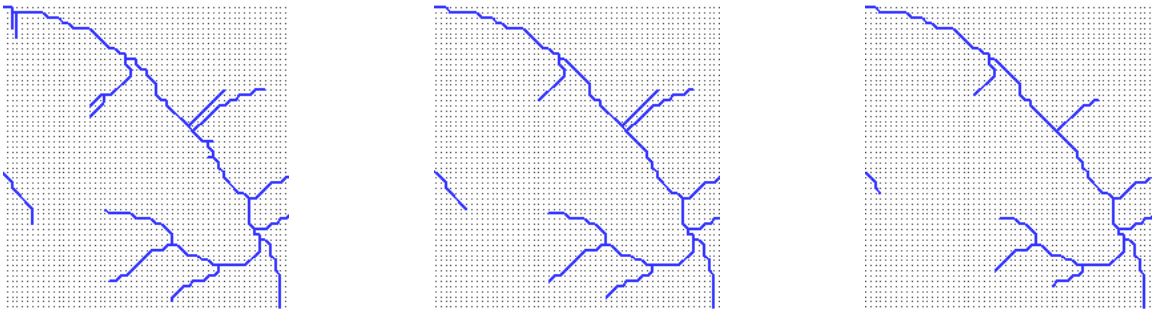
Figure 3. Drainage lines produced with; a. 10-metre DEM in ArcGIS-ArcHydro (darker lines) and GeoMedia Grid. b. 30-metre DEM in ArcGIS-ArcHydro (darker lines) and GeoMedia Grid.

However, significant differences occur when different flow accumulation threshold values are used for drainage network extraction. Figure 4 (a,b,c) shows the differences between the drainage networks extracted from 10-metre DEM by using three different accumulation values which are proposed approach, Tang (2000) and ArcHydro default respectively while Figure 4 (d,e,f) represent the results of 30-metre DEM for the same values. As can be seen in this figure, as the accumulation value increases, drainage network becomes more and more simple. Number of the lines decreases just as their lengths. On the other hand, as the value decreases, more complicated network structures and parallel structures appear, which do not coincide with the ground truth? Therefore, an optimum method and criteria should be determined to extract geomorphologically valid drainage networks. Otherwise, all of these drainage networks will result in a different watershed structure; especially small catchments (sub-watersheds) are affected from these differences.

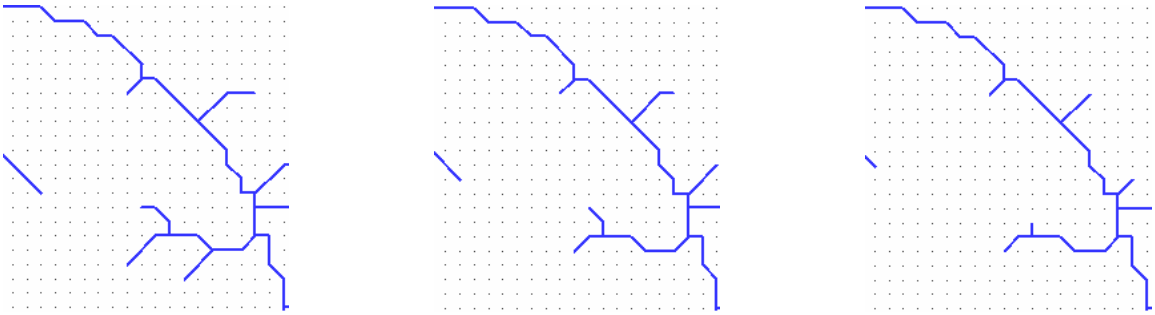
RESULTS AND DISCUSSION

Results of the study applied in this paper are presented in Table 2 and Figure 5. Table 2 gives a comparison of the statistical results of the whole study area obtained by using different accumulation values. As it is seen in the table, the varying final statistics of the drainage lines for different threshold values prove the effect of the accumulation value on the drainage line extraction. Since the drainage line number changes, number of the sub watersheds change too. Because, each drainage line represents the main skeleton of the sub watersheds. Therefore, number of the drainage lines is equal with number of the sub watersheds.

Resolution of the DEM mainly affects the number and the length of the drainage lines as it is proved by the statistics. 30-metre DEM gave shorter, geometrically more simplified and less number of drainage lines than 10-metre DEM. Therefore, slopes of drainage lines and areas of



(a) 81 – DEM 10 (b) 117 – DEM 10 (c) 193 – DEM 10



(d) 16 – DEM 30 (e) 22 – DEM 30 (f) 26 – DEM 30

Figure 4. The differences between the drainage networks extracted by using 10 and 30 metre DEMs with three different values which are proposed at Table 1

sub-watersheds are obtained with less precision. On the other hand, it is possible to see the small difference in main watershed area (total area of sub watersheds). However, this difference is not as important as the changes in number of the sub watersheds and number of drainage lines.

Figure 5 shows the graphic results of the watershed delineation by using DEMs with different resolution and the areas of these watersheds are stated in Table 2. The main problem in this position is to determine the threshold value for the flow accumulation. Proposed approach gives best results in case that each (main) watershed is handled separately. So, valid results in terms of our proposal can be obtained with different threshold values; however, it will not meaningfully affect main watersheds as can be seen from the statistical results in Table 2.

Table 2: Statistical results

	Proposed Approach		**Tang (2000)**		**ArcHydro Default**	
	10 metre DEM 117	**30 metre DEM 16**	**10 metre DEM 81**	**30 metre DEM 26**	**10 metre DEM 193**	**30 metre DEM 22**
Number of Drainage Lines	72	65	113	45	47	47
Total Length of the Drainage Lines	10364.04	9869.42	12208.95	7940.75	8333.95	8600.68
Number of Sub-Watersheds	72	65	113	45	47	47
Total Area of Sub-Watersheds	1981776.81	1981977.28	1981878.81	1981975.31	1981878.81	1981975.31

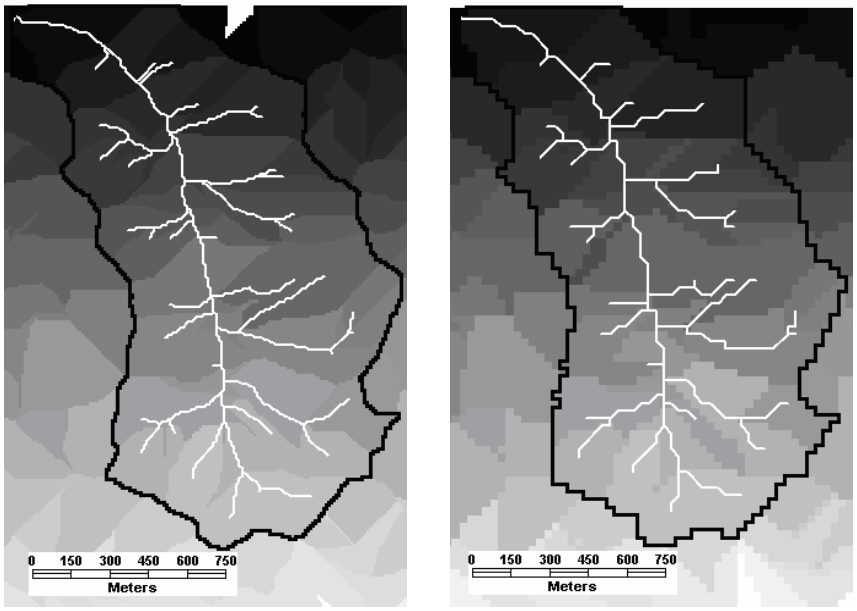


Figure 5. Sub and main watersheds obtained from 10 and 30 metres DEMs using proposal values.

CONCLUSIONS AND FUTUREWORKS

In this paper, effects of drainage lines and resolution to the watershed delineation from grid DEM are studied. A proposal is especially made for determining flow accumulation threshold value to extract valid drainage lines, which have critical role in subsequent processes of watershed delineation. From geomorphologic and hydrologic aspects, previous proposals mentioned above are unsatisfactory, particularly with respect to sub-watershed delineation, but the approach proposed in this study can be considered as more valid since it is appropriate to natural characteristics of drainage lines in real world.

As a result of the study, it is observed that GIS software give similar results for the same data set while extracting drainage lines and delineating watersheds. However, the distinctive effects of DEM resolution and flow accumulation threshold value over sub-watershed delineation proved again in this study since they influence the number and the length of drainage lines, and consequently the number and area of sub watersheds. On the other hand, effects on main watersheds are quite small with these DEM data sets. Next study is to find an automated approach using various geomorphologic and hydrologic characteristics of terrain.

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