

## **Ordering Disconnected Watershed Digital Stream Networks with Developing an Object Oriented Model in GIS Environment**

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### **Abstract**

The Watershed stream network is a collection of stream and water courses that is responsible to conduct and to drain surface water flows in a watershed. These spatial data have very important roles in a watershed and are used for estimation and calculation of physical parameters of watersheds as well as soil erosion and runoff. One of the watershed physical parameters is bifurcation ratio, which shows the amount of elongation and roundness of watersheds. In general, the bifurcation rate is one of the criteria used to evaluate watershed flood hydrograph pattern which is calculated based on an ordered stream network. Disconnected stream networks are a serious obstacle in ordering watersheds stream network. These digital spatial data layers, prepared in different formats and scales, often have deficiencies in their topology structures (disconnection of stream networks and inaccurate coincidence with watershed flow direction pattern). These deficiencies make problems in calculation of watershed parameters e.g. stream length, stream ordering, stream density, bifurcation ratio and so on. On the other hand, current built-in GIS functions are not able to correct them accurately. In the present research, in the GIS environment, using ESRI ArcObjects, a new model has been designed and developed which is capable of solving the problems of watersheds stream network. In Summary, a new stream network is produced with the model in which no additional stream is constructed but original disconnected streams and their wrong flow directions are precisely corrected and this new stream network later can be used to the watershed stream ordering.

**Key words:** Bifurcation Ratio, Stream and River Network, ArcObjects, DE

### **Introduction**

In physiographic studies, hydrology and water resources, watershed stream network parameters have an important role in calculation of run-off, sediment, soil erosion and etc. The parameters of watershed stream networks such as length, slope, ordering, density, time of concentration are all a small part of required parameters for these studies. On the other hand, the accurate calculation and precise analysis of these parameters are based on the existence of a continuous stream network which must be precisely coincided with watershed flow direction pattern. Physiographic and hydrology studies often show that in most of the times in pixel scale, watershed stream networks do not follow of the watershed flow direction. Also, they have many disconnections especially in low land

areas. The existence of such conditions namely disconnections and wrong flow direction make big problems to calculate stream network parameters such as stream ordering, stream length, stream density and etc (fig. 1, 2).

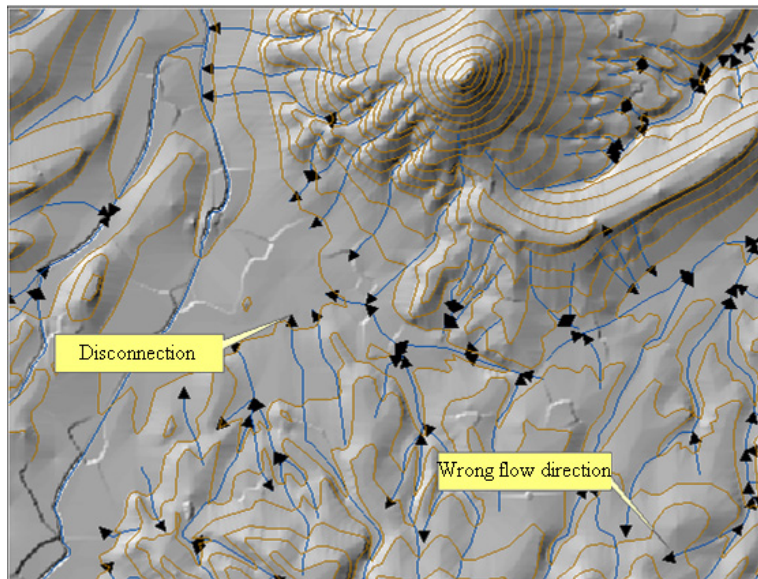


Fig. 1. Disconnection and wrong flow direction in the stream Network of The study watershed

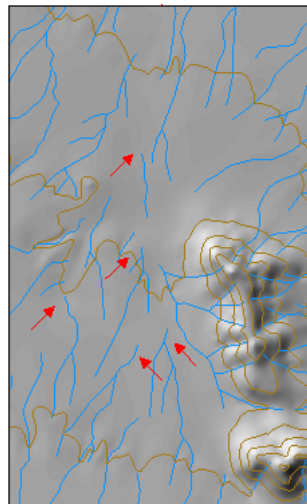


Fig. 2. Disconnection in the stream Network of the study watershed

In fig. 1 and fig. 2, as they show, the stream networks of the study watershed have some disconnections and wrong flow directions. These problems are increased in low lands of the watershed where the slope of the surface is very low.

One of the physical parameters of watersheds which is an index to evaluate run-off hydrograph shape is bifurcation ratio (BR). This parameter shows the amount of elongation or roundness of a watershed and can be calculated based on eq. 1:

$$BR = \left( \frac{n_1}{n_2} + \frac{n_2}{n_3} + \frac{n_3}{n_4} + \dots + \frac{n_{i-1}}{n_i} \right) \frac{1}{i-1} \quad \text{Eq. 1}$$

Where:

BR, bifurcation ratio;  $n_i$ , the number of streams in each order;  $i$ , latest stream number or main stream number.

The range of the BR is between 3 and 5 and whatever this ratio be smaller the watershed shape to be closed to a circle and run-off hydrograph shape of the watershed will have more kurtosis. Inversely, with increasing BR, the watershed shape is elongated and the shape of run-off hydrograph will be flat and wide (Fig. 3).

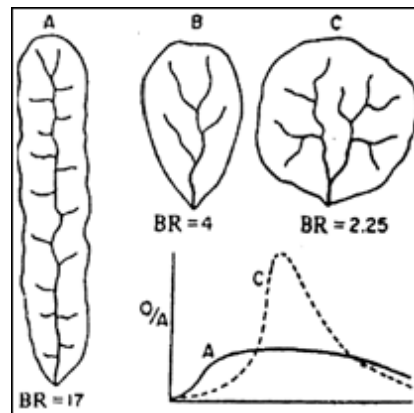


Fig. 3. The effect of bifurcation ratio amount on run-off hydrograph shape

Stream bifurcation ratio is a physical parameter of the watersheds and can be calculated only when the watershed has an ordered stream networks. As it was showed before, one of the main problems in watersheds is the lack of accurate and continuous stream networks especially in low land areas. In these conditions, most of the users usually edit these spatial features manually (according to aerial photograph or satellite images of their interest area) that do not have enough accuracy and in the areas in which the density of streams are too much this manual method is not feasible.

Another way to overwhelm this problem is the use of GIS built-in functions which are very popular among users. Anyway, as we will discuss latter, these solutions are mainly based on a parameter called threshold. This parameter is a criterion which is used with watershed flow accumulation map to specify and to extract a set of cells as watershed stream network.

With having flow direction and flow accumulation maps of a watershed, users can define this parameter and extract a artificial stream network for a watershed. Anyhow, because of that this parameter is variable, so a watershed can have different stream networks by different users and also in low land areas where the variation of slope is very low this method acts very poor (Tabatabaei, 2008).

In continue, an overview of some of the researches results which are related to the present research are explained.

To automatic extraction of watershed artificial stream network Jenson and Domingue (1988); Tarboton and Bras (1991) defined a threshold on watershed flow accumulation map (a raster layer) and those cells which meet the defined condition were extracted as stream cells. In this method, those cells with having higher value are considered as main stream. Saunders (2000), with decreasing DEM<sup>1</sup> cells along the watershed stream network could improve watershed flow direction map in which the flow direction pattern is coincidence with streams path.

Guy and Kienzle (2003), in a similar way with Saunders (2000) and under name REA<sup>2</sup>, imposed road and bridge features on a DEM and improved the surface flow.

<sup>1</sup>Digital Elevation Model

<sup>2</sup>Road Enforcement Algorithm

In ArcSWAT<sup>3</sup> model, Winchell and Srinivasan (2005), developed a method by which along the watershed streams path the cells value of a watershed DEM (elevation) are noticeably reduced so that if this DEM is used to make watershed flow direction, the path of streams on it is very sharp and by defining a threshold on the watershed flow accumulation map there is a possibility to extract watershed artificial stream network. This method, called DEM burning, has very important value in areas of watershed in where the variations of elevation are very low. At the result of using the method, the path of streams on the watershed flow direction map is identified very clearly. In ArcGIS software, Hellweger (1997) presented a program, under name ArcHydro, which is capable of DEM burning. By using a threshold on watershed flow accumulation map, users are able to extract watershed stream networks.

Daniels and Maxwell (2011) provide an algorithm that can help to make precise watershed water flow pattern especially in the flat areas where because of the lack of elevation data DEM values usually are not very accurate.

Shen and Sheng (2011) believe that the study area should first divide as flat and non flat areas and then in the flat sections, using existing possibilities in remote sensing, continuous streams can be made. They also state that in the steep slope areas, lonely DEM model is adequate to use in extracting watershed drainage network.

Jaroslaw and MarkusMet (2011) developed GRASS software by embedding a set of tools that are capable of using different algorithms (D8, MFD) to make watershed flow pattern. This flow pattern then can be used to extract watershed stream network.

In continue the concept of stream ordering and the ordering method used in the research are explained.

Streams ordering mean that dividing streams from their junction as separated longitudinal sections and giving consecutive numbers to them according to their rank of importance (Hoseini 2010). Another good definition for it is the relative position, or rank, of a stream channel segment in a drainage network [12].

For ordering streams of a watershed there are some different methods such as Strahler, Horton, Shreve, Scheidegger and etc. Because of that Strahler method has been used in the research, this method is briefly explained.

Strahler's (1952) stream order system is a simple method of classifying stream segments based on the number of tributaries upstream. A stream with no tributaries (headwater stream) is considered a first order stream. A segment downstream of the confluence of two first order streams is a second order stream. Thus, a n<sup>th</sup> order stream is always located downstream of the confluence of two (n-1)<sup>th</sup> order streams (Fig. 4)[8, 16].

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<sup>3</sup>Soil and Water Assessment Tools

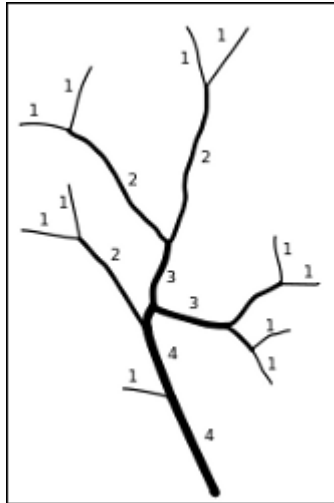


Fig. 4. Stream ordering by Strahler method

In general, the aim of this research is the development of geographical information system (ArcGIS software) to repair discontinues stream networks of a watershed and also to correct their digital directions according to their watershed flow pattern. Afterwards, corrected stream network is ordered by Strahler method. By using this developed method no additional stream features add to preliminary watershed stream network.

### Materials and method

#### Description of study area

The research has been done in Shahriari watershed in Yazd province in Iran. The Shahriari watershed has 15000 ha area and is located between  $54^{\circ} 13' \sim 54^{\circ} 22' E$  and  $29^{\circ} 32' \sim 29^{\circ} 42' N$  (Fig. 5).

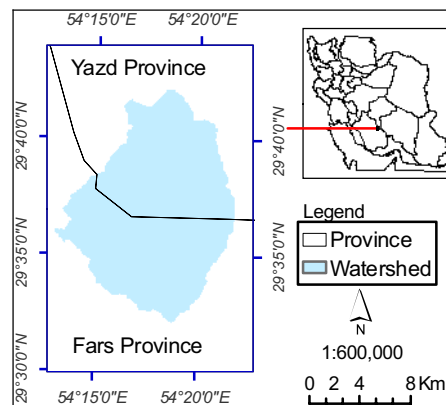


Fig. 5. Location map of Shahriari Watershed

### Materials

The data used in the research are topographic contour lines along with elevation points in scale of 1:25000, watershed stream network and ArcObjects which are structural components of ArcGIS software.

### ArcObjects

ArcObjects is the development platform for ArcGIS Desktop, ArcGIS Engine and ArcGIS Server. ArcObjects consists of objects and classes. An *object* represents a spatial feature such as a road or a vegetation stand. In a Geodatabase, an object corresponds to a row in a table and the object's attributes appear in columns. A *class* is a set of objects with similar attributes. An ArcObjects class can have built-in interfaces, properties, and methods (Chang 2008).

## Methods

To do the research, following stages have been done respectively which is briefly explained in the following:

Stage 1, developing ArcGIS environment using ESRI ArcObject components. Because of that many of required operations are not as built- in functions in ArcGIS and on the other hand it is necessary to call different functions during running program, so a separate graphical user interface is designed and programmed.

Stage2, preparing the watershed digital elevation model. In order to construct required DEM, the topographic contour lines (in scale of 1:25000) of interest area along with their elevation points are interpolated and cell size of the surface model is defined based on the required spatial resolution and contour line congestion.

Stage 3, enforcing the watershed drainage network to the watershed DEM.

To improve and to repair the disconnected watershed stream network, the existence of an accurate and precise watershed flow direction pattern is very essential. The values of this flow pattern will show the path of watershed streams while the running developed program needs to know the streams path. To do this, along the path of watershed streams, cells values of the watershed DEM are decreased and as a result of this, the watershed flow direction (which is further constructed by DEM) will show the path of watershed streams very sharply (Fig. 6).

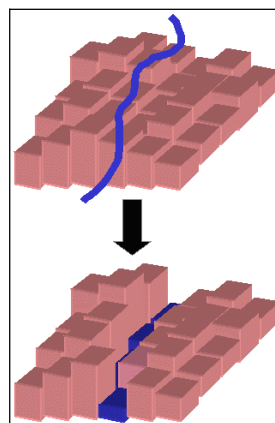


Fig. 6. Decreasing DEM cells values along the path of a stream

Hudgens (1999) states that the decreasing DEM cells values along a stream path digs deep channels in it as it is possible to trace the path of streams in the flat areas.

Stage 4, filling digital sinks.

Digital elevation model has an important role to construct watershed flow direction and flow accumulation maps and also those spatial layers that need to use watershed surface

elevation data. So, it is necessary to remove errors of DEM. One of the famous DEM errors is digital sink.

A sink is a cell or set of spatially connected cells whose flow direction cannot be assigned one of the eight valid values in a flow direction raster. This can occur when all neighboring cells are higher than the processing cell or when two cells flow into each other, creating a two-cell loop (Mark 1988). To remove digital sinks from the Watershed DEM, Fill function of ESRI ArcGIS software is used. Fig. 7 shows profile a sink and its neighbor cells before and after running Fill function.

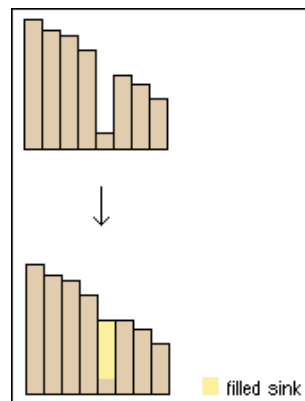


Fig. 7. Presentation of a sink profile before and after running Fill function

Stage 5, preparing the watershed flow direction and flow accumulation maps.

After filling the watershed DEM, the flow direction map of the watershed is created by D8 algorithm. According to the algorithm the direction of flow is determined by the direction of steepest descent from each cell (Jenson and Domingue 1989). In Fig. 8, the position of a cell of a hypothetical flow direction map (showed with ×) and its 8 neighbor cells has been showed. According to the pattern the water in the central cell can flow into its 8 different neighbors which are labeled with 8 numbers (1, 2, 4 ... 128). For example, the number 2 means that the water in central cell flows toward the south east cell.

32	64	128
16	×	1
8	4	2

Fig. 8. Labeling the flow directions around a central cell (×)

After creating the watershed flow direction map, the watershed flow accumulation map can be respectively produced. The flow accumulation map like the flow direction map is a raster map where each cell has a numerical value representing the number of cells is drained to it. In the accumulation map, cells with higher value are considered as main flows of the watershed. So, by defining a threshold on the watershed flow accumulation map, it is possible to create an artificial stream network for the watershed. In the Fig. 9 (left side), a hypothetical flow direction map has been showed to create a flow accumulation map (right side). In the research, both of these maps are produced by built-in GIS functions.

Stage 6, producing a new corrected stream network for the watershed.

To create a new stream network for the watershed it is necessary that tracing operations



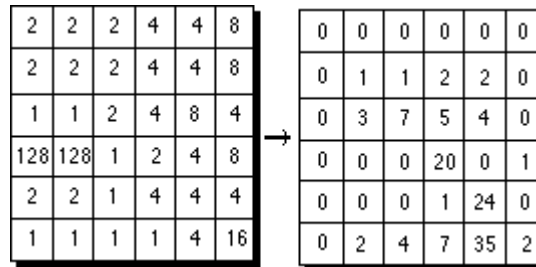


Fig. 9. Hypothetical flow direction (left) and flow accumulation maps (right)

are done on all watershed streams. Also, to trace the watershed streams to the outlet, the starting points of streams are needed. The starting points are the highest points of streams where each stream starts. To find these points, all points which comprise each stream are firstly calculated and then among them by regarding to the watershed DEM the highest point is selected as starting point of each stream. Afterwards, according to the watershed flow direction and flow accumulation maps, from each starting point, a new stream is created. To do this task, from each starting point to the watershed outlet, the trace operations are done cell by cell and traced cells are finally converted to the vector format (Fig. 10).

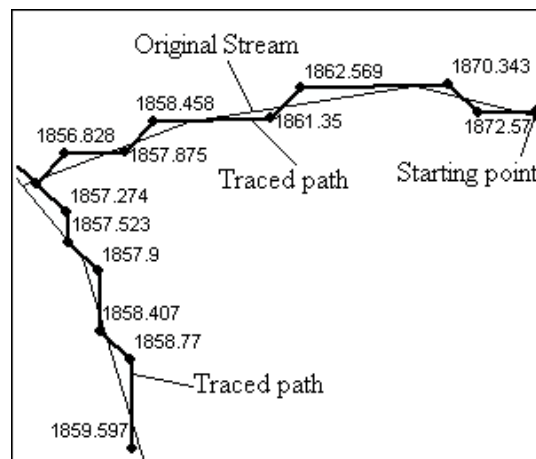


Fig. 10. Calculating the starting points of a stream and tracing its flow to the outlet

Stage 7, ordering watershed streams and calculating streams bifurcation ratio (BR)  
 Ordering of the watershed stream network is done by Strahler method which is a popular method in hydrology studies. After creating a corrected stream network, the ordering of watershed streams can be performed based on the watershed flow direction and built-in GIS function (Stream Order Function). Also, in order to smooth the produced watershed streams and to improve the quality of them, Smooth built-in function is used. Afterwards, based on equation 1, the bifurcation ratio (BR) of the watershed streams is calculated.

#### Stage 8, Evaluation method of model results

In order to evaluate the model results, some comparisons are done between watershed original stream network and the stream network constructed by the model. The comparisons are based on position, length and the number of streams in watershed original streams network and their match streams in the derived streams of the model. The evaluation method for comparing the streams length is based on the Paired-Samples T Test. This test compares the means of two variables for a single group. The procedure



computes the differences between values of the two variables for each case and tests whether the average differs from 0 (Eq. 2 and 3).

$$t = \frac{\bar{d} - d_0}{\overline{sd}} \quad \text{Eq. 2}$$

$$\overline{sd} = \frac{sd}{\sqrt{n}} \quad \text{Eq. 3}$$

Where:

$\bar{d}$ , average of differences between the original streams length and the length of derived streams of the model (in each order);  $d_0$ , difference between average of the original streams length and the average of model derived streams length ( $\mu_1 - \mu_2$ );  $\overline{sd}$ , standard deviation of differences between original streams length and the length of derived streams of the model;  $n$ , the number of compared streams

In a specific  $df$  (degree of freedom) and  $\alpha$  (significance level) amount of  $t$ , resulted from the eq. 2, is compared with critical  $t$  value (extracted from statistical  $t$  table) and then the null hypothesis ( $H_0$ ) is evaluated. In the research, the null hypothesis states that there is no meaningful difference between average of the watershed original streams length and average of the model derived streams length. In other words  $d_0$  or ( $\mu_1 - \mu_2$ ) is zero.

Using built-in GIS functions, the number of streams both original and simulated are evaluated. Also, the position of simulated streams is considered by eye.

## Results

1. Fig. 11 shows Hillshade map of the study area (Shahriary watershed). As can be seen, a large area of the watershed is very flat and as it will be discussed a bit later in these areas there are the most problems in relation to the discontinuous streams.

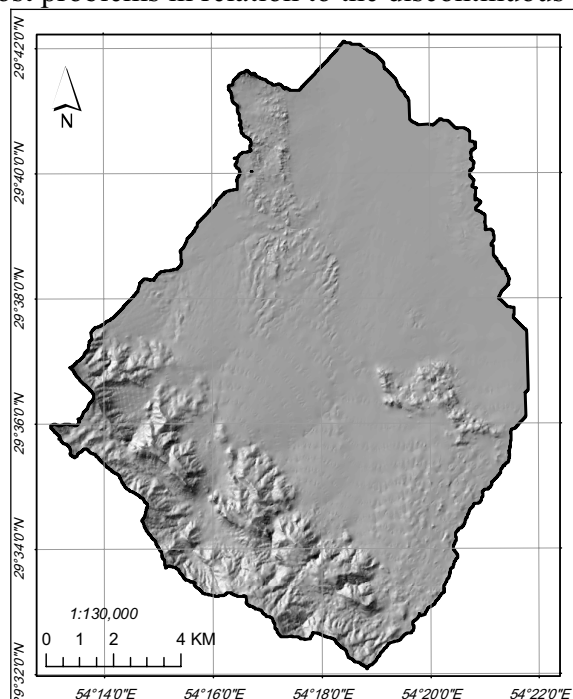


Fig. 11. Hillshade map of the study area

2. The model has been designed and developed by ESRI ArcObjects components. In fig. 12, some lines of program are presented. Fig. 13 shows the main graphical user interface (GUI) of the model. Also, fig. 14 shows the model GUI to input data layer.

```

Dim stream_order As IGeoDataset
Dim stream_order As IGeoDataset
Set stream_order = pHydrologyOp.StreamOrder (stream_pOutputRaster, flow_dir,
esriGeoAnalysisStreamOrderStrahler)
Dim x As IRasterLayer
Set x = New RasterLayer

```

Fig 12. A part of program written by ESRI ArcObjects

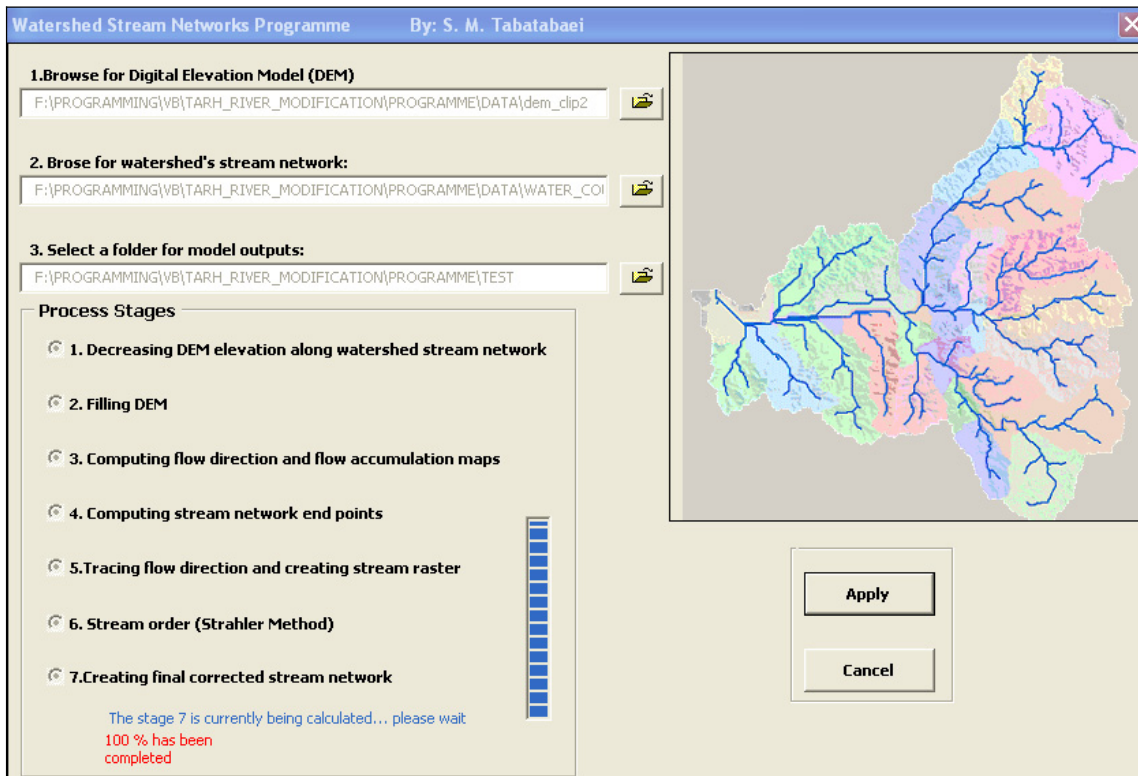
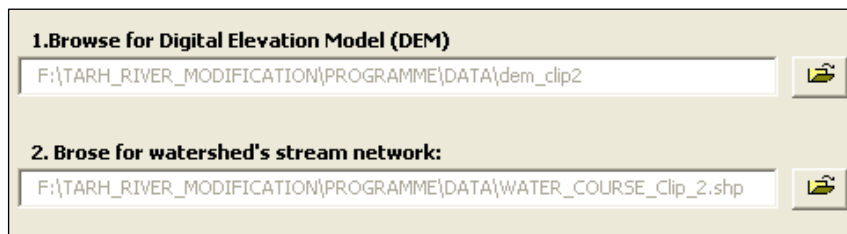


Fig. 13. The main graphical user interface of the model



3. The model results show that the number of simulated streams and their positions are coincidence with the watershed original streams. Also, disconnections and wrong directions of original streams have been corrected (fig. 15 and fig. 16).

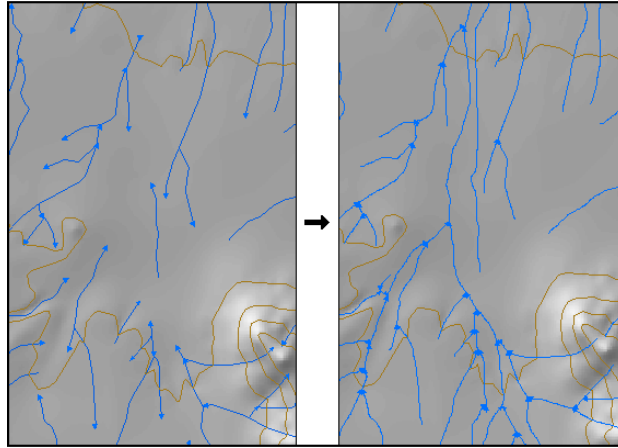


Fig. 15. Apart of watershed stream network before (left) and after (right) running the model

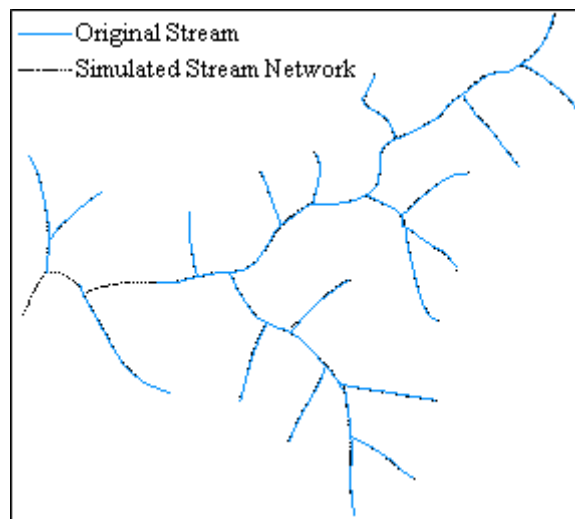


Fig. 16. Comparison between the watershed original and simulated stream network

One of the valuable and important results of the developed model is that except for original streams there are no additional streams in the model output.

4. In fig. 17 (a), the original and discontinuous stream network of a sub watershed of the study area has been showed. As can be seen, because of the existence of discontinues streams there is no automatic way for stream ordering. In fig. 17 (b), there is a corrected stream network, resulted by the developed model, in which disconnections and wrong water flow direction have been corrected. Also, according to the Strahler method, stream ordering has been done on them. Table 1 summaries some characteristics of the corrected stream network presented in fig 17(b).

5. The derived statistical results from the Paired-Samples T Test show that there is no meaningful difference between average of the watershed original streams length and average of the model derived streams length. The comparisons were done in two different sub watersheds and on 180 streams in different order. In Tables 1 and 2, the statistical results for one of the sub watershed have been showed.

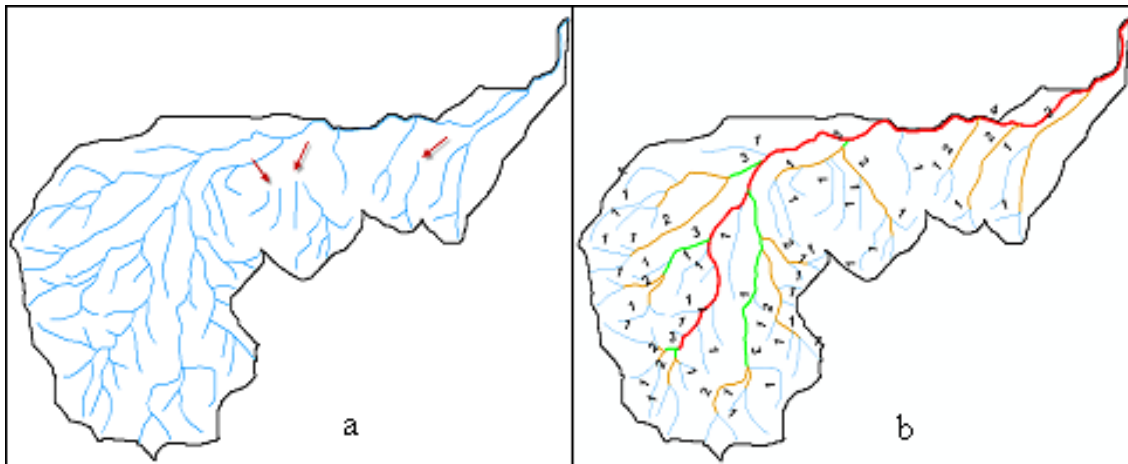


Fig. 17. (a) The original and discontinuous stream network of a sub watershed of the study area. (b) The model results in which corrections for discontinuous streams and stream ordering has been done.

Table1, summary information of the corrected stream network presented in fig. 17 (b)

The biggest order	Bifurcation Ratio	Order 4		Order 3		Order 2		Order 1		Working unit / Stream Order and stream length (Km)
		Length(Km)	Number	Length(Km)	Number	Length(Km)	Number	Length(Km)	Number	
4	4.1	3.2	1	1.4	6	5.1	17	11.6	71	Sub watershed(k_6)

Table 2, derived statistical results of Paired-Samples T Test for one of the study sub watershed

Statistical Parameters	Stream with Order 1	Stream with Order 2	Stream with Order 3
$\bar{d}$	1.62	-1.92	-.25
$sd$	11.9	14.2	3.46
$\overline{sd}$	2.04	3.8	.96
Calculated t	.79	-.5	-.26
n	34	14	13
df	33	13	12
$t(\alpha=5\%, df)$	$\pm 1.96$	$\pm 2.16$	$\pm 2.179$
$H_0: (\mu_1 - \mu_2) = d_0 = 0;$ $H_1: (\mu_1 - \mu_2) \neq d_0 \neq 0;$			
Test Results	fails to reject the null hypothesis	fails to reject the null hypothesis	fails to reject the null hypothesis

## Discussion

In general, to produce the watersheds artificial stream network, the most GIS built-in hydrological functions use a threshold value on the watershed accumulation map. With defining a threshold value, those cells which have a cell value equal or more than threshold value are extracted as stream cells. This variability in defining the threshold value makes different stream networks for one watershed. So, for a specific watershed, different users make different stream networks. In such conditions, sometimes, the additional streams, which are not existence in reality, are produced. On the contrary, with defining a small value of the threshold, more streams are produced (fig. 18 a, b and c).

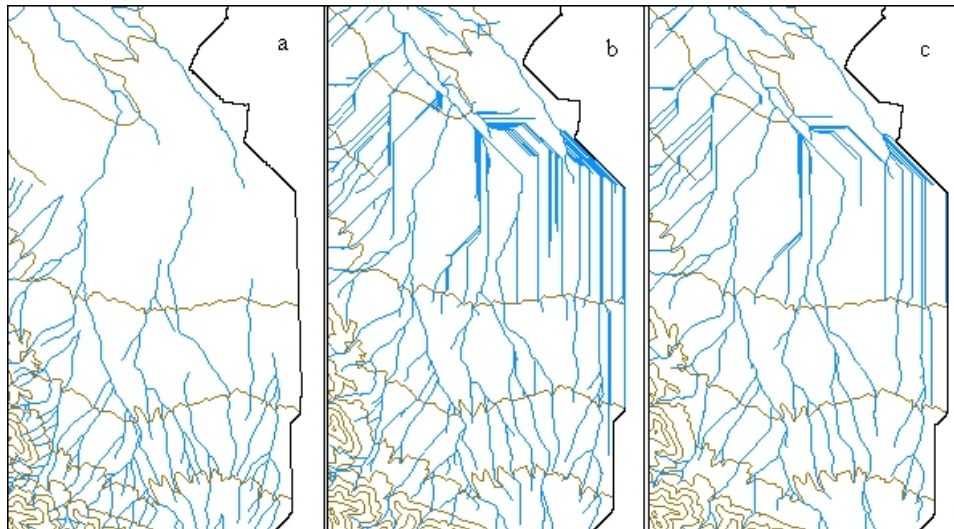


Fig. 18. (a) Original stream network. (b) And (c) are the produced artificial stream networks with threshold of 500 and 1000 respectively.

### Conclusions

The derived results of the research show that in the flat areas of topographic maps where the variations of the earth surface slope are very low, the streams are mostly discontinuous. So, stream ordering operations cannot be automatically done. On the other hands, as it was described before, GIS built-in functions use a threshold parameter to produce artificial stream networks. Using this parameter causes that the produced stream network has less or more streams when it is compared with original streams in topographic maps.

It seems that using the developed model especially in flat areas can be a good solution to correct and to repair discontinuous watershed stream networks.

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