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Ordering Discontinuous Digital Stream Networks in a Watershed by Developing an Object-oriented Model in the GIS Environment

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Abstract

A watershed stream network consists of a collection of rivers and streams that drain surface water flows within a watershed. These spatial data are key in calculating various aspects of a watershed, such as physiography, hydrology, soil erosion, sediment, etc. One of physical parameters in a watershed is the "bifurcation ratio", which shows the level of roundness or elongation of a watershed related to a stream network. The bifurcation ratio is calculated on the basis of an ordered stream network and it is one of the main criteria used to evaluate watershed flood hydrograph patterns. The main problems in ordering watershed stream networks are the discontinuity in stream networks of topography maps and differences with water flow model maps. These deficiencies create problems in calculating other watershed parameters such as length, ordering, and density of streams. As current GIS software is not able to compensate for these shortcomings, the present research used a previously designed GIS model (ArcGIS environment, using ESRI ArcObjects), applying a new approach for ordering watershed stream networks. The results of this study showed that this methodology could be applied to conduct a more accurate ordering of stream network (based on Strahler's Algorithm) where there is no discontinuity between streams in a network, and to gain better harmony with water flow model of a watershed.

*Keywords***:** ArcObjects, Bifurcation ratio, DEM, Ordering, Stream network.

رتبه‌بندی شبکه‌های آبراهه‌ای رقومی ناپیوسته حوزه‌های آبخیز با توسعه یک مدل شیءگرا در محیط GIS

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چکیده

شبکه آبراهه‌ای حوزه آبخیز مجموعه‌ای از آبراهه‌ها و رودخانه‌ها بوده که وظیفه هدایت و زهکشی جریان های آب سطحی را در یک حوزه آبخیز بعهده دارند. این داده‌های مکانی، نقش مهمی را در مطالعات فیزیوگرافی، هیدرولوژی، فرسایش و رسوب یک حوزه آبخیز به عهده دارند. یکی از پارامترهای فیزیکی حوزه آبخیز نسبت انشعاب بوده که مقدار کشیدگی یا گردی حوزه آبخیز را نشان می‌دهد. بطور کلی، نسبت انشعاب حوزه آبخیز که بر اساس شبکه آبراهه‌ای رتبه‌بندی شده محاسبه می گردد، یکی از معیارهای ارزیابی الگوی آبنمود سیل حوزه آبخیز می‌باشد. در این رابطه، شبکه‌های آبراهه‌ای ناپیوسته، یک مانع جدی در برابر رتبه‌بندی آبراهه‌ها می‌باشند. این لایه‌های مکانی رقومی که در قالب و مقیاس‌های مختلف آماده می‌شوند غالبا" دارای نقایصی در ساختار توپولوژی خود می‌باشند (ناپیوستگی و عدم انطباق صحیح با الگوی جهت جریان آب در حوزه آبخیز). این نقایص، مشکلات دیگری درمحاسبه سایر پارامترهای فیزیکی حوزه آبخیز نظیر طول آبراهه‌ها، تراکم آبراهه‌ها، رتبه‌بندی آبراهه‌ها و نظایر آن بوجود می‌آورد. از سوی دیگر، توابع درونی ساخته شده در نرم افزارهای سامانه اطلاعات جغرافیائی قادر به تصحیح این گونه آبراهه‌ها نیستند. در تحقیق حاضر، در محیط نرم افزار ArcGIS با استفاده از اجزاء ArcObjects یک مدل جدید طراحی و ساخته شده است که قادر به حل مشکلات شبکه آبراهه‌ای حوزه آبخیز می‌باشد. بطور خلاصه، بوسیله مدل ساخته شده، یک شبکه آبراهه‌ای ساخته می‌شود که در آن، هیچ‌گونه آبراهه اضافی تولید نشده بلکه آبراهه‌های اصلی ناپیوسته و جهت‌های جریان نادرست آن‌ها اصلاح می‌گردد. این شبکه آبراهه‌ای سپس بوسیله مدل رتبه‌بندی شده و می‌تواند در محاسبه نسبت انشعاب و سایر محاسبات که در آن‌ها شبکه آبراهه‌ای پیوسته و منطبق با الگوی جریان نیاز است مورد استفاده قرار گیرد.

کلمات کلیدی: اشیاء ArcObjects، رتبه بندی، شبکه آبراهه، مدل ارتفاعی رقومی زمین، نسبت انشعاب.

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Introduction

A stream network in a watershed (drainage network) consists of all the streams in a watershed that drain the surface water flows. Some of these streams are in the form of permanent or seasonal rivers, or run-offs that are present only during and after rainfall. When all these streams are mapped they form a tree, called the "stream network" of a watershed (Alizadeh, 2007).

In physiography, hydrology and water resource studies, the "bifurcation ratio" (BR) is used to show stream divisions and its impacts on flood hydrographs. BR is an index that varies between 3 and 5 in normal watersheds. However, the smaller this value, the rounder the shape of the watershed, with a run-off hydrograph that has a taller peak. With an increasing BR value, the watershed shape will be more elongated, with the shape of run-off hydrograph flatter and wider (Fig. 1) (Alizadeh, 2008).

The bifurcation ratio may be calculated based on the following equation (Eq. 1):

$$BR = (\frac{n1}{n2} + \frac{n2}{n3} + \frac{n3}{n4} + ... + \frac{ni-1}{ni})\frac{1}{i-1} \quad \text{Eq. 1}$$

Where:

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

As shown in the above equation, the first step in calculating the bifurcation ratio, is to order the stream network of a watershed. However, accurate calculation and precise analysis of these parameters as well as ordering can only be pursued if the stream network is continuous. Tabatabaie *et al.*, (2008) showed that, in pixel scale, the stream network often has shortcomings, such as discontinuity, especially in lowlands (Figs. 1 and 2). This contributes to inaccuracies in calculation of ordering, density, length of a stream and other stream network parameters (Fig.2).In

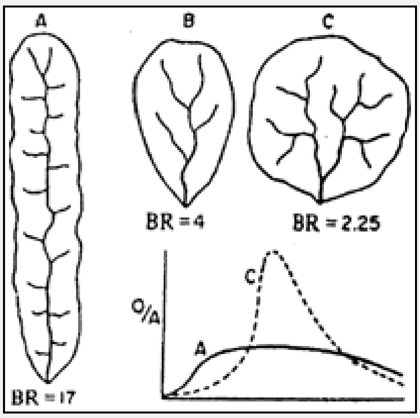

Figure1. The effect of bifurcation ratio amount on run-off hydrograph shape.

physiography, hydrology and water resource studies, the stream network parameters of a watershed have an important role in calculation of run-off, sediment, soil erosion, etc. The parameters of watershed stream networks such as length, slope, ordering, density, time of concentration all represent a small part of the required parameters for these studies.

As shown in Figures 2 and 3, the stream network of the study watershed shows some discontinuity with opposite flow directions. These problems are increased in flat areas of the watershed where the slope of the surface is very low.

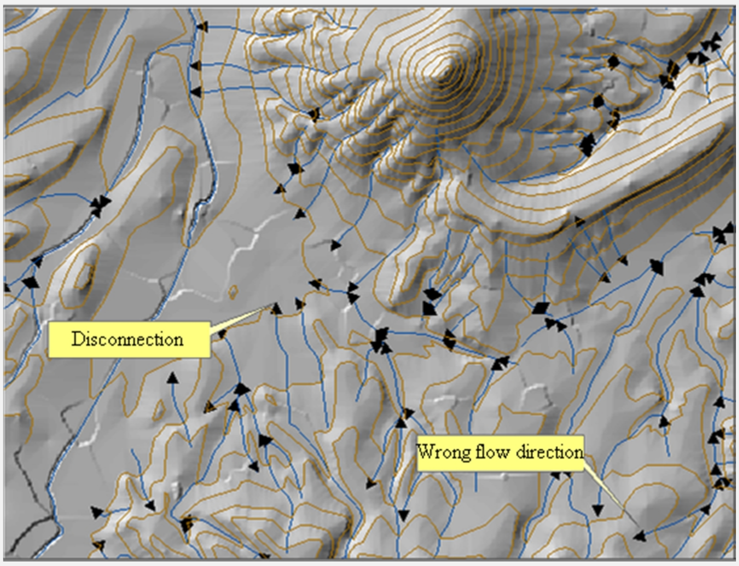

Figure 2. Discontinuous and wrong flow direction in the stream network of the study watershed.

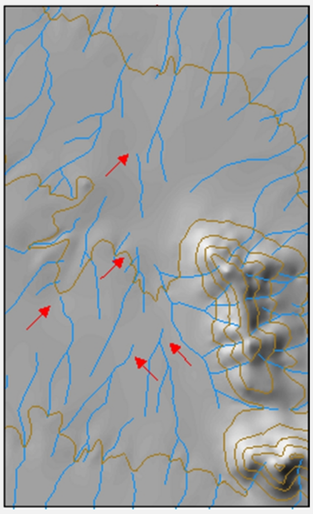

Figure 3. Discontinuous stream network of the study watershed.

As mentioned before, the stream bifurcation ratio is a physical parameter of watersheds that can be calculated only when the watershed has an ordered stream network. As shown in the above figures, one of the main problems in watersheds is the lack of accurate and continuous stream networks especially in flat areas. On the other hand, due to differences between the spatial data of a stream network with the water flow model (at pixel scale) in a watershed, the pattern of water flow in raster models may become difficult to identify. Therefore, it can be concluded that one of the main problems in ordering a stream network is discontinuity and lack of coincidence between the stream network and the water flow model. Under these conditions, most of the users usually edit spatial features manually (according to aerial photograph or satellite images of the study area). This methodology does not have enough accuracy and in the areas in which the density of the streams is too high, the manual method is not feasible.

Another way to overcome this problem is to use GIS built-in functions which are very popular among users. These applications which will be discussed later, are mainly based on a parameter called "threshold", which is a criterion used along with the watershed flow accumulation map to specify and to extract a set of cells as watershed stream network. By having flow direction and flow accumulation maps of a watershed, users can define threshold values through GIS. As this parameter may be variable, a watershed can have different stream networks by different users and also, in low-lying areas where the variation of slope is very low, this method acts very poorly (Tabatabaei, 2008).

In the following paragraphs, an overview of some of the research studies that have been conducted on this aspect (ordering a stream networks) are presented. For automatic extraction of an artificial stream network in a watershed (Jenson and Domingue, 1988); (Tarboton and Bras, 1991) defined a threshold on a watershed flow accumulation map (on a raster layer), and those cells which met the defined conditions were extracted as "stream cells". In this method, those cells with higher values were considered as main streams. (Saunders, 2000), with decreasing DEM[1] cells along a watershed stream network could improve watershed flow direction map, in which flow direction pattern overlapped with streams path. (Guy and Kienzle, 2003), in a similar study with (Saunders, 2000) and called REA,[2] imposed road and bridge features on a DEM and improved the surface flow.

In the ArcSWAT[3] model, (Winchell and Srinivasan, 2005) developed a method by which along the watershed streams path, the cell values of a watershed DEM (elevation) were noticeably reduced so that, if this DEM was used to create a watershed flow direction, the path of streams on it was very sharp, and by defining a threshold on the watershed flow accumulation map, there was a possibility to extract a an artificial stream network. This method, called "DEM burning", was very important and valuable in areas of watershed where variations of elevation were very low. By using this method, the paths of streams on the watershed flow direction map were identified very clearly.

In ArcGIS software, (Hellweger, 1997) presented a programme, under the name of "ArcHydro", which was capable of DEM burning.

By using a threshold on watershed flow accumulation map, users were able to extract watershed stream networks. Daniels and Maxwell (2011) provided an algorithm that could help to make precise water flow patterns especially in the flat areas of a watershed. Shen and Sheng (2011) believed that the study area should first be divided into flat and uneven areas and, then, in flat sections, using remote sensing, continuous streams could be produced. The same authors also stated that in the steep slope areas, DEM model was adequate to use in identifying watershed drainage networks. Jaroslaw and MarkusMet (2011) developed a method in GRASS software which, by embedding a set of tools that were capable of using different algorithms (D8, MFD), could make a watershed flow pattern. This flow pattern then could be used to form a watershed stream network.

Stream ordering means dividing streams from their junction into separate longitudinal sections and giving consecutive numbers to them, according to their rank of importance (Hosseini, 2010). Another good definition for it is the relative position, or rank, of a stream channel segment in a drainage network (Mark, 1988). For ordering streams of a watershed there are some different methods such as Strahler, Horton, Shreve, Scheidegger and others (Hosseini, 2009). As the Strahler method was used in this 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 downstream segment of the confluence of two first order streams is a second order stream. Thus, a n^{th} order stream is always located downstream of the confluence of two $(n-1)^{th}$ order streams (Fig. 4) (Strahler, 1952).

Figure 4. Stream ordering by Strahler method.

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

Materials and Methods

The study Area

The research was conducted in Shahriari watershed in Yazd province of Iran. The Shahriari watershed has an area of 15000 ha and is located between 54° 13′~ 54° 22′E and 29° 32′~29° 42′N (Fig. 5).

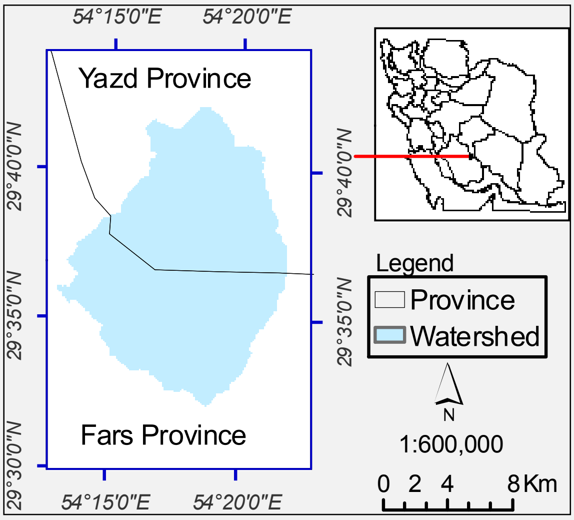

Figure 5. Location map of Shahriari Watershed.

The data used in the research were topographic contour lines along with elevation points in scale of 1:25000, watershed stream network and ArcObjects which were 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).

To conduct this research, the following stages were followed respectively:

Stage 1 - Developing ArcGIS environment using ESRI ArcObject components.

Because many of the required operations were not built-in functions in ArcGIS, and since it was necessary to call different functions while running the programme, a separate graphical user interface was designed and programmed.

Stage2 - Preparing the watershed digital elevation model.

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

Stage 3 - Imposing the watershed drainage network to the watershed DEM.

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

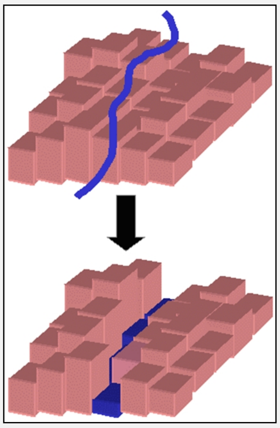

Figure 6. Decreasing DEM cell values along the path of a stream.

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

Stage 4 - Filling digital sinks.

The digital elevation model plays an important role in forming watershed flow direction and flow accumulation maps, as well as those spatial layers that need to use watershed surface elevation data. So, it was necessary to remove any errors of DEM. One of the famous DEM errors is the digital sink. A sink is a cell or set of spatially connected cells to whose flow direction cannot be assigned one of the eight valid values in a flow direction raster. This can occur when all neighbouring 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, the Fill function of ESRI ArcGIS software was used. Figure 7 shows the profile of a sink and its neighbor cells before and after running the Fill function.

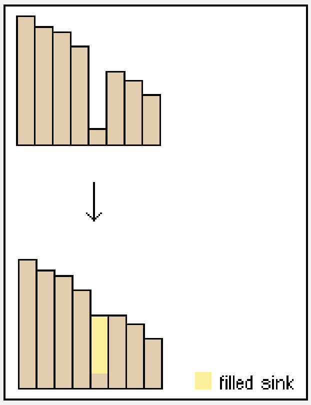

Figure 7. Presentation of a sink profile before and after running Fill function.

Stage 5 - Preparing the watershed flow direction and flow accumulation maps.

After filling the watershed DEM, the flow direction map of the watershed was created by a D8 algorithm. According to the algorithm, the direction of flow was determined by the direction of the steepest descent from each cell (Jenson and Domingue, 1989). In Figure 8, the position of a cell of a hypothetical flow direction map (showed with an ×) and its 8 neighbouring cells are shown. According to this 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, number 2 means that the water in central cell flows toward the southeastern cell.

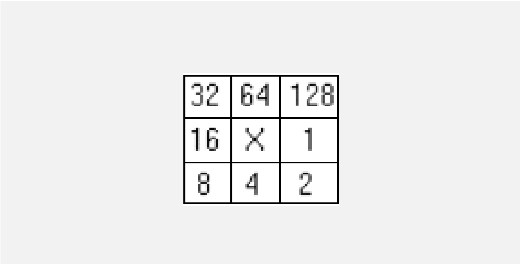

Figure 8. Labelling the flow directions around a central cell (×).

After creating the watershed flow direction map, the watershed flow accumulation map was accordingly 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 Figure 9 (left side), a hypothetical flow direction map is shown to create a flow accumulation map (right side). In this research, both maps are produced by built-in GIS functions.

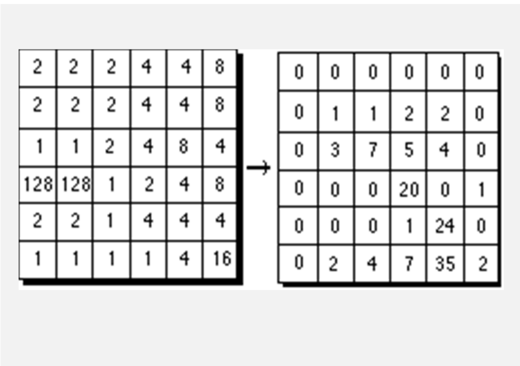

Figure 9. Hhypothetical flow direction (left) and flow accumulation maps (right).

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

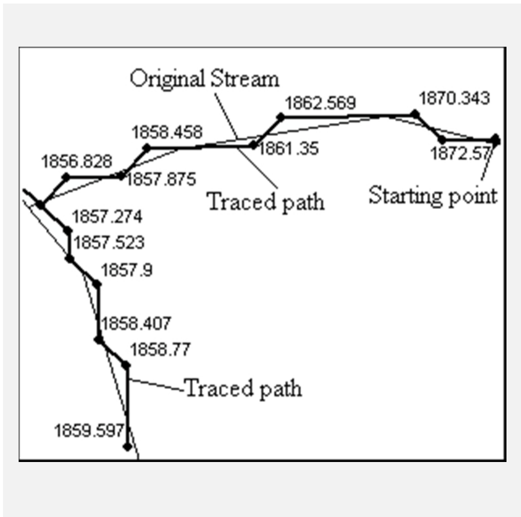

Figure 10. Calculating the starting points of a stream and tracing its flow to the outlet.

Stage 7 - Ordering watershed streams and calculating their bifurcation ratio (BR).

Ordering of the watershed stream network was conducted by applying the Strahler method which is a popular method in hydrology studies. After creating a corrected stream network, the ordering of watershed streams was 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, a smooth built-in function was used. Finally, based on equation 1, the bifurcation ratio (BR) of the watershed streams was calculated.

Stage 8 - Evaluation method of model results.

In order to evaluate the model results, some comparisons were performed between the original stream network and the stream network that was created by the model. The comparisons were based on position, length and the number of streams in the original stream network and their matching streams in the derived model. The evaluation method for comparing the streams length was based on the Paired-Samples T Test. This test compared the means of two variables for a single group. The procedure computed the differences between values of the two variables for each case and tested whether the average differed from 0 (Eq. 2 and 3).

$$t = \overline{d} - d0 / \overline{sd} \qquad \text{Eq. 2}$$

$$\overline{sd} = sd / \sqrt{n} \qquad \text{Eq. 3}$$

Where:

$\overline{d}$, average of differences between the original stream length and the length of derived stream of the model (in each order); $d0$, difference between average of the original stream length and the average of model derived stream length ($\mu_1 - \mu_2$); $\overline{sd}$, standard deviation of differences between original stream length and the length of derived stream of the model; n, the number of compared streams

In a specific df (degree of freedom) and α (significance level) amount of t, resulted from the eq. 2, was compared with critical t value (extracted from statistical t table) and then the null hypothesis (H_0) was evaluated. In this research, the null hypothesis stated that there was no meaningful difference between average of the original streams length and average of the model derived streams length. In other words $d0$ or ($\mu_1 - \mu_2$) was zero.

Using built-in GIS functions, the numbers of streams, both in the original and simulated were evaluated. Also, the positions of simulated streams were examined by eye.

Results

1. A model was designed and developed by ESRI ArcObjects components. In Figure 11, some lines of program are presented. Figure 12 shows the main graphical user interface (GUI) of the model. Also, Figure 13 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, esri GeoAnalysisStream OrderStrahler)
Dim x As IRasterLayer
Set x = New RasterLayer
```

Figure 11. A part of programme written by ESRI ArcObjects.

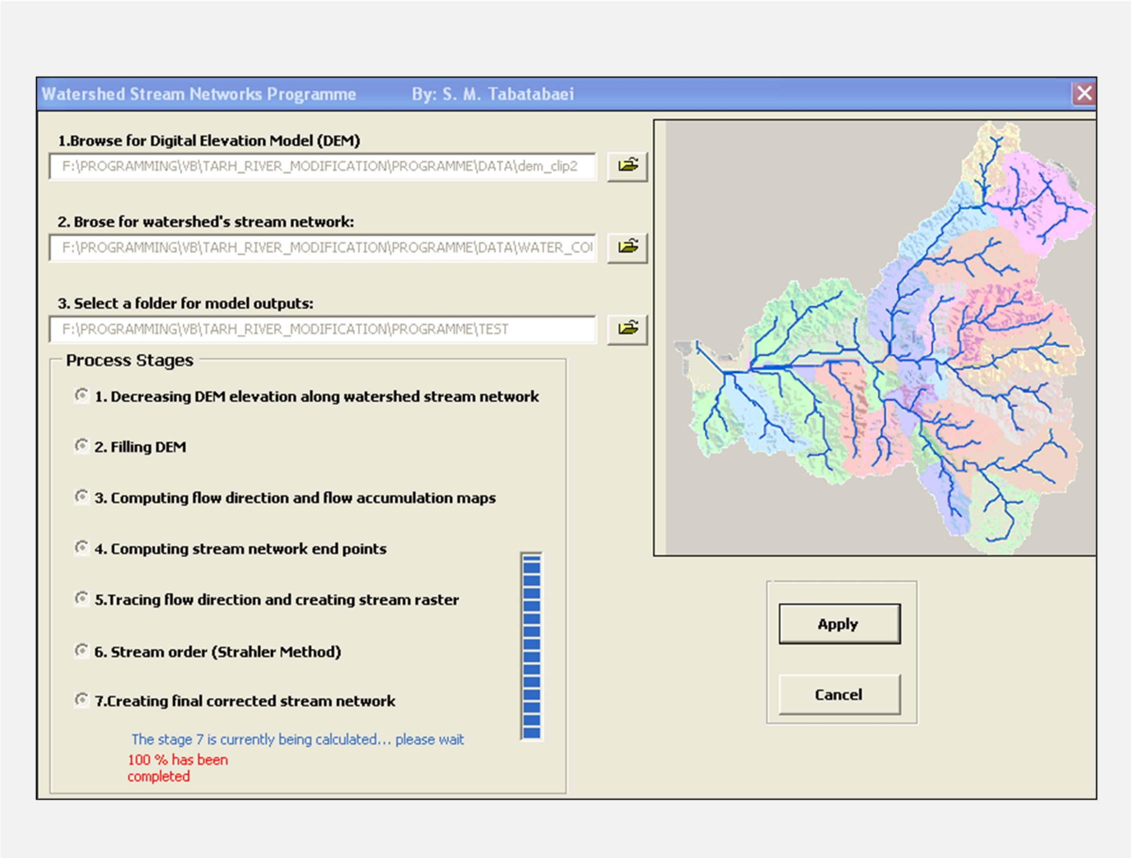

Figure 12. The main graphical user interface of the model.

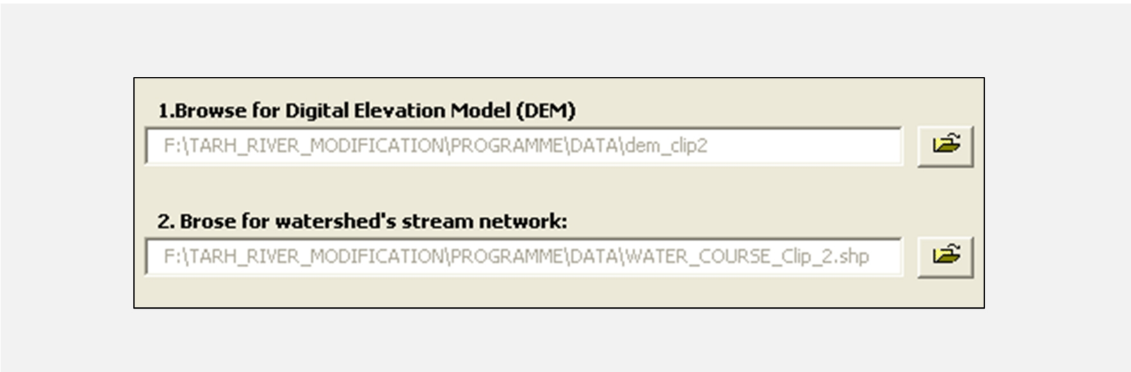

Figure 13. The model GUI to input data layer

2. Figure 14 shows Hillshade map of the study area (Shahriary watershed). As can be seen, a large area of the watershed is very flat, and as stream network will be discussed in these areas, there are most problems in relation to the discontinuity of streams.

The model results show that the number of simulated streams and their positions were coincided with the watershed's original streams. Also, discontinuity and opposite directions of original streams were corrected (Figs. 15 and 16).

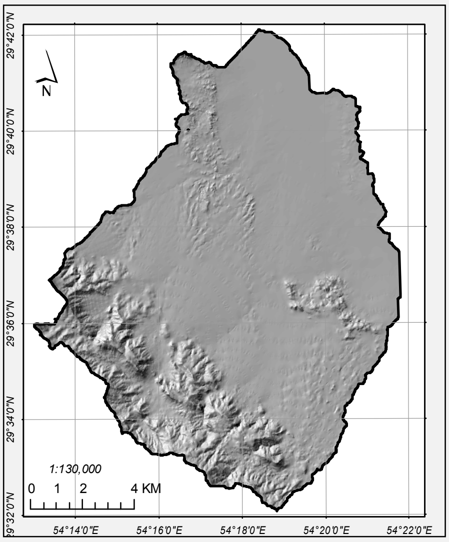

Figure14. Hillshade map of the study area.

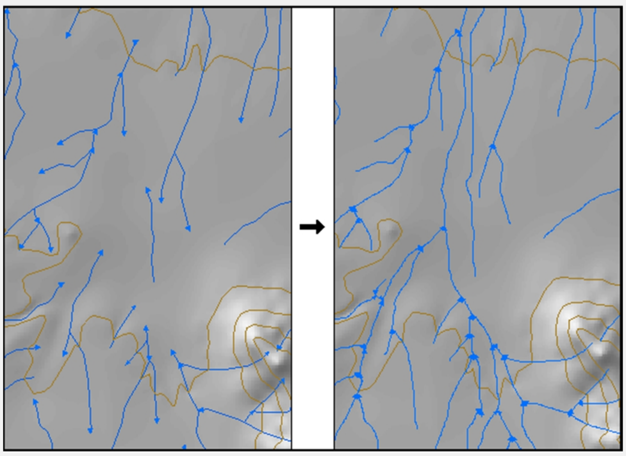

Figure 15. A part of watershed stream network before (left) and after (right) running the model.

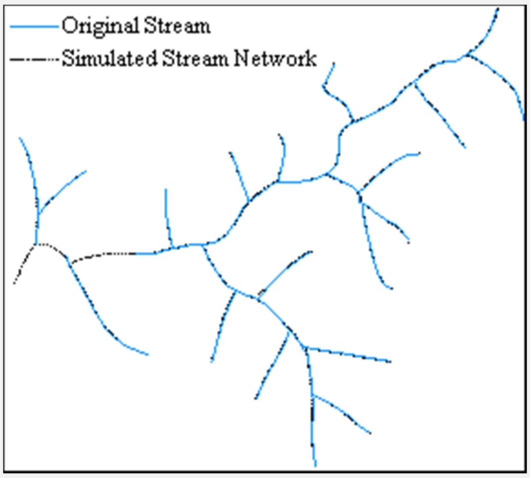

Figure 16. Comparison between the watershed's original and simulated stream network.

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

3. In Figure 17 (a), the original and discontinuous stream network of a sub watershed within the study area is shown. As can be seen, because of the existence of discontinuity in streams, there is no automatic way for stream ordering. In Figure 17 (b), there is a corrected stream network, resulting from the developed model, in which discontinuity and opposite water flow directions have been corrected. Also, according to the Strahler method, stream ordering was applied to them. Table 1 summaries some characteristics of the corrected stream network presented in Figure 17(b).

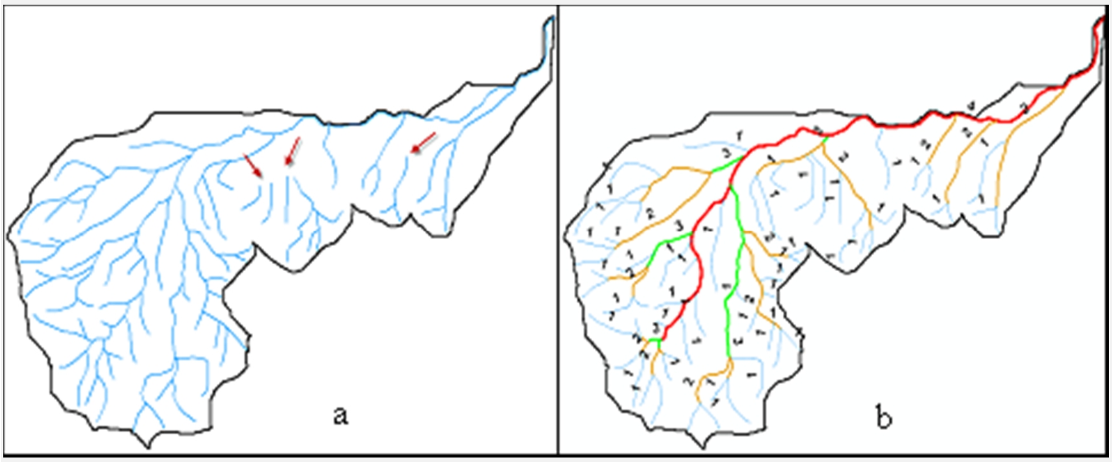

Figure 17. (a) The original and discontinuous stream network of a sub watershed in the study area. (b) The model results in which corrections for discontinuous streams and stream ordering were conducted

4. The derived statistical results from the Paired-Samples T Test showed that there was no meaningful difference between average length of the original stream and the average length of the derived model. Comparisons were conducted between two different sub-watersheds and on 180 streams in different order. In Table 2, the statistical result for one of the sub watersheds is shown.

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. Statistical results of the Paired-Samples T Test for one sub-watershed in the study area.

Statistical Parameters	Stream with Order 1	Stream with Order 2	Stream with Order 3
$\overline{d}$	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(α=٪5, df)	±1.96	±2.16	±2.179
$H_{0:}\ (\mu_1 - \mu_2) = d_0 = 0$; $H_{1:}\ (\mu_1 \neq \mu_2) \neq d_0 \neq 0$;			
Test Results	fails to reject the null hypothesis	fails to reject the null hypothesis	fails to reject the null hypothesis

Discussion

In general, mainly GIS built-in hydrological functions are used to calculate a threshold value on the watershed accumulation map in order to produce an artificial stream network of a watershed. By defining a threshold value, those cells which have a cell value equal or more than the threshold value are extracted as stream cells. This variability in defining the threshold value forms different stream networks for one watershed. So, for a specific watershed, different users may produce different stream networks. In such conditions, sometimes, the additional streams, which do not exist in reality, are produced. On the contrary, by defining a big value as threshold, fewer streams may be created (Fig. 18).

The results derived from this research showed that, in flat areas of topographic maps where the surface slope is very low, the streams are mostly discontinuous and, so, stream ordering operations cannot be automatically done. On the other hand, as it was described, GIS built-in functions use a threshold parameter to produce artificial stream networks. Using this parameter, the resulting stream network may have fewer or more streams, compared to the original streams on a topographic map.

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

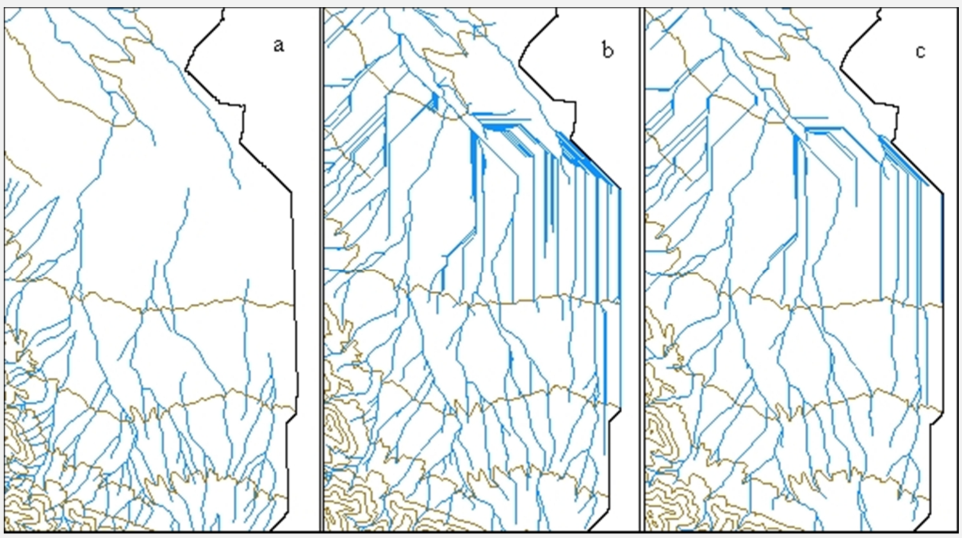

Figure 18. (a) Original stream network. (b) and (c) Artificial stream network produced with thresholds of 500 and 1000, respectively.

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پی‌نوشت‌ها

1. Digital Elevation Model
2. Road Enforcement Algorithm
3. Soil and Water Assessment Tools

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