علـوم محـیطی سال چهارم، شماره سوم ، بـهار ۱۳۸٦
ENVIRONMENTAL SCIENCES Vol.4, No.3 , Spring 2007
49-60

An Evaluation of Hydrological Pit Filling Methods in the Ekbatan Watersheds

Ali Akbar Matkan*, Alireza Shakiba, Davoud Ashorlo
Faculty of Earth Science, Department of Remote Sensing and GIS, Shahid Beheshti University

Abstract
Distributed hydrological models of sediment and runoff estimation for simulating the sediment-runoff-precipitation processes in watershed surfaces require digital maps and some other information of the basin's elevation. For example, the correct execution of erosion models which, according to the RULSE method, work in a distributed environment greatly depends on the quality of such information. The Digital Elevation Model (DEM), slop, flow direction and accumulative flow are considered as topographical derivations, a number of which can be extracted by standard Geographical Information Systems (GIS). According to the kind of interpolation method and DEM cell size, errors like digital holes and flat zones occur in the DEM. These errors usually cause some problems in the representation of the basin runoff and sediment delivery by hydrological and erosion models. In order to examine different methods of eliminating DEM errors, three algorithms are compared in this paper, namely: D8, DE and combination D8 and DE. The parameters used in these algorithms are: length profiles of the main river, the basin's accumulative flow, basin slope and comparison of built DEMs. The result shows that the algorithm in which the DE (Drainage Enforcement) takes place primarily and then the elimination of ditches in the conventional way executed by some GIS software systems is the most appropriate method. Conformity of the drainage with paper maps and also the removal of digital ditches is a way that the drainage directions in the DEM point correctly to the water channel, is the main adventage of this research.

Keywords: hydrology, models, DEM error, filling methods, DE, D8.

* Corresponding author. *E-mail Address:* A_matkan@sbu.ac.ir

مقایسه تطبیقی روش‌های حذف خطاهای مدل ارتفاعی رقومی (DEM) حوضه‌های آبخیز

علی اکبر متکان*، علیرضا شکیبا، داود عاشورلو
دانشکده علوم زمین، گروه سنجش از دور و GIS، دانشگاه شهید بهشتی

چکیده
مدل‌های توزیعی هیدرولوژیکی برآورد رواناب و رسوب جهت شبیه سازی فرآیندهای بارش - رواناب-رسوب در سطح حوضه‌های آبخیز نیاز به نقشه‌های رقومی ارتفاع و مشتقات آن حوضه دارند . به عنوان مثال صحت اجرای مدل‌های فرسایش که بر اساس روش RUSLE دریک محیط توزیعی عمل می‌نمایند، به شدت تابع کیفیت نقشه‌های رقومی ارتفاع حوضه می‌باشد. مدل ارتفاعی رقومی (DEM) ، شیب ، جهت جریان و جریان تجمعی از جمله مشتقات توپوگرافی محسوب می‌گردند که برخی از آنها توسط سیستم‌های اطلاعات جغرافیایی استاندارد قابل استخراج می‌باشند . بسته به نوع روش درون‌یابی (Interpolation) و اندازه سلول شبکه DEM ، خطاهایی مانند گودال‌های رقومی و مناطق مسطح در DEM ایجاد می‌گردد. این خطاها غالباً موجب بروز اختلال در شبیه سازی رواناب و رسوب حوضه‌ها توسط مدل‌های هیدرولوژیکی و فرسایشی می‌شوند. به منظور بررسی روش‌های مختلف حذف خطاهای DEM، سه الگوریتم در این مقاله مورد مقایسه قرار گرفتند. این سه الگو شامل D8، DE و ترکیب D8 و DE می‌باشند. شاخص‌های مقایسه‌ای عبارتند از : پروفیل طولی رودخانه اصلی ، جریان تجمعی حوضه ،شیب حوضه و مقایسه DEMهای ساخته شده. نتایج تحقیق نشان می‌دهد که الگوریتمی که در آن ابتدا عملیات DE (Drainage Enforcement) و سپس حذف گودال‌ها به شیوه مرسوم در برخی از نرم افزارهای GIS اجرا می‌گردد ، مناسب‌ترین روش می‌باشد . در این الگوریتم تطابق شبکه زهکشی با نقشه‌های کاغذی و نیز رفع گودال‌های رقومی، بنحوی که جهات زهکشی در DEM به نحو صحیح به سمت شبکه آبراهه‌ها باشد ، از مزایای عمده این تحقیق می‌باشد.

کلیدواژه‌ها : هیدرولوژی ، مدل ،خطای مدل رقومی ارتفاع، پر کردن چاله، D8، DE.

Introduction

Hydrological models of sediment and runoff of the event-based type are the main mathematical instruments for converting rainfall to runoff and estimating sediments in aquiferous basin surfaces. Floodwater estimation is considered to be one of the model's uses in hydrological engineering. While traditional hydrological models have usually considered the watershed as a monotone unit, new models have a distributed nature.

The application of GIS for the preparation of the distributed models data has greatly expanded in the last few years.

The elevation, slope and flow direction which are some of the data needed for these models are included as maps with a suitable scale. Considering that digital methods in most distributed models are of the limited subtraction kind, the basin is ruptured as a cellular net. The preparation of a DEM with a cellular net structure is of great importance in the effective application of distributed models.

Preparing a DEM also for hydrological purposes is especially important because of the element known as an effective factor in spatial rainfall changes and some other elevation factors. Furthermore, many hydrological processes including water penetration in the soil, runoff flow direction and speed are dependents of the watershed elevation and its gradient. Hence, maps showing topographical derivations including the slope the dominant slope direction or the flow direction are needed for the simulation of the basin's runoff quantity using hydrological distributed models. The extraction of these maps is considered to be a dependent of the method of production and the quality of the DEM. Moreover, some models use the changes in the length profile and also the flow accumulation quantity, which is derived from the DEM with a specific operation.

In fact, the main method of DEM preparation is based on the interpolation function existing in the GIS on the maps which themselves are the result of the digitalization of the contour lines maps. However, the production DEM has local errors in comparison with topographical paper maps considering the basin's topographical complexity, the distance between contour lines, the degree of the basin's highs and lows, the size of the chosen cell, the primary precision in the digitalization of topographical maps and also the method type.

One of the most significant errors is the creation of digital pits, areas without sloping or flat areas. These kinds of errors produced in the DEM are considered to be some of the main obstacles for the usage of hydrological models, because areas with artificial pits or flat surfaces prevent the runoff from running in the correct direction. Furthermore, by not including the share of these areas in the basin's existing runoff they usually cause some disturbances in the stages of simulation by the models. One of the basic elements of reform and comparison of models is a digitalized map of the watershed drainage and thus making the best match between the DEM and the topographical paper maps (as the main accessible source of the topographical data) is desired.

In this paper, DEM errors are dealt with and then the method for correcting these errors for the preparation of a DEM with a hydrological basis is examined. To achieve this, the software Arc/Info GRID (ESRT, 1997) watershed with all known methods of hydrological DEM production were used. It should be mentioned that the problem errors in the paper maps are not examined and the field work is not included.

Study Area

The study area comprises one of the sub-basins of the Ekbatan dam; the city of Hamadan is located on the northwestern part of the basin (Figure 1). The highest point of the basin has an elevation of 3,560 m and the outlet height of the basin, the lowest point, is 1,960 m. The area of the basin is around 45.28 km^2.

The base map of this research is the topographical map of the geographical department of the army with a scale of 1 / 50,000, which is used, in most hydrological and physiographical studies.

Figure 1- Location of study area (Ekbatan dam)

Flow Direction Determining Algorithm in the GIS

The flow direction determines the direction of the runoff movement and the speed of the movement of the runoff. Flow accumulation or the drainage area's TCA (Total Contributing Areas) are made available depending on the flow direction. On the basis of the DEM many algorithms have been designed in the GIS that usually use the dominant slope or the direction of slope for determining the flow direction. The D8 algorithm was first suggested by O'Callaghan and Mark (1984). In this method, the flow is only emptied and spilled over from one cell into one of its adjacent cells, and the chosen cell is the one which has the highest slope or difference of elevation with that specific cell. This algorithm is used in some standard GIS's like GRID or STAND. The simplicity of this method and its harmony in declined areas has expanded its use. But two of its main limitations, which are the one-dimensional flow in the vertical or diametrical directions, will not meet the analysis of the flow in the divergent and convergent areas in which the width of the flow cut changes towards the downside.

Other algorithms such as Rho 8, Lea (1992), DEMON (Costa Cabral and Burges, 1994) and Doo (Tarboton, 1997) that have not yet been used in standard GIS have also been designed. The comparison of these algorithms is not the subject of this paper. In this research the most commonly used algorithm which is the D8 that is supported by GRID ARC/INFO is employed.

Digital Pits and the Algorithm of their Elimination

In the D8 algorithm, cells without flow direction are considered as artificial pits. In other words, artificial pits are cells that have no flow towards any of their neighboring cells, and their elevation is lower than the cells around them. With a reduction in the cell sizes, the number of the pit cells in the DEM increases. The first examination shows that roughly less than 5 percent of the DEM cells depending on the kind of method and cell size can be considered pits. The production of digital pits in the DEM can be caused by errors of elevation data entering the method or the bilferal effect of the cell size with the distance of contour lines in areas with a low slope. Researches have shown that, even with the elevation data taken as completely correct, because of the nature and the kind of methods which enter mathematical estimations into the calculations the existence of pits in the DEM is inevitable.

Many algorithms for the elimination of artificial pits have been presented; the first of them operates by the increase of the pit elevation to the lowest elevation of the eight neighboring cells (the Filling Method). This method was later on completed more precisely by O'Callaghan and Mark (1984) and then Band (1986); Jonson and Dominique (1989) also elevated it. The main problem of the primary method (Filling) is that it changes the pit cells into flat areas, and its advantage is that it does not interfere with the rest of the cells. Unfortunately, changing the pits into flat areas can cause the displacement of the location of the drainages from their main situation. In the method which was suggested by O'Callaghan and Mark (1984) for the elimination of flat areas the elevation of every cell in the DEM is replaced with the according to weight mean of the elevation of its eight surrounding cells. This method which is a kind of smoothing filter, gains some suitable results through a small number of repetitions in small flat areas where more repetition is needed it results in the increase of error and an over smoothing takes place. Nelson and Jones (1995) with a similar method, used the N by N filter which has a great application in satellite image processing, but when it came to execution, many cells were inferred with.

One of the algorithms suitable for eliminating the errors is the DE method which was presented by Hutchinson (1988) and Hutchinson and Dowling (1991) based on the ANUDEM program. The basis of this algorithm is the utilization of drainage digital maps so that the DEM in the location of drainage is reformed in the direction of the basin slope and the ultimate effort is also taken to eliminate pits in the whole basin. But there is no insurance for the complete elimination of all pits. Furthermore, in this algorithm the elimination operation of pits in the drainage cells is a dependent of a maximum limit. This maximum limit is suggested to be half the quantity of the distance of the level lines. This method is very effective in the elimination of pits and the preservation of the model and the situation of the drainage (Hutchinson and Dowling, 1991)

Methods and Materials

The following algorithm has been chosen for the comparison of different methods of eliminating digital pits in this research. Before executing the algorithms, first the 100 m and drainage lines were digitalized. Then, using the ANUDEM method with the 60-meter cell size, the primary DEM was extracted. The end result and the expanse of the primary model pits are shown in Figure 1. Also, in order to examine the three different algorithms, three independent parameters were used. These three algorithm parameters are: the main river length profile, flow accumulation and basin slope.

Algorithm I

In this algorithm, a method called fill (Jenson and Dominique, 1998) which is one of the existing dependents in the software ARC/INFO was used. The main result of this method showed that the elevation of the outlet is 1,960 m and the drainage area in the outlet is equal to 46.24 km^2. After executing the extraction dependent, the flow direction and the flow accumulation (Figure 2), a digital drainage map was also obtained in which the displacement in comparison with drainage was seen.

Algorithm II

In this algorithm the DE method was used. The elevation of the outlet was 1,960 m and the drainage area was calculated to be 43.5 km^2. Although all the pits are not necessarily eliminated by this method, if a pit is situated in the path of a river, the accumulative flow continues to increase along the drainage (through the execution of the DE method). The situation of the remaining pits after the execution of this algorithm is shown in Figure 1 and the flow model in Figure 3.

Algorithm III

In algorithm IIIa, algorithms I and II were used such that the out put of was regarded as the Input for algorithm I. In this method the outlet elevation was equal to 1,960 meters and the drainage area in this area was calculated to be 45.9 km^2 (Figure 4). In algorithm IIIb, algorithm II is executed in another way because this algorithm changed all the elevations of the DEM cells, while the DE is performed in algorithm IIIb by determining a distance from the river. This region is equal to three cells. The outlet of this algorithm is then placed as the entry point of algorithm I; the elevation of outlet is equal to 1,960 m and the drainage area in this algorithm is 45.5 kilometers square (Figure 5)

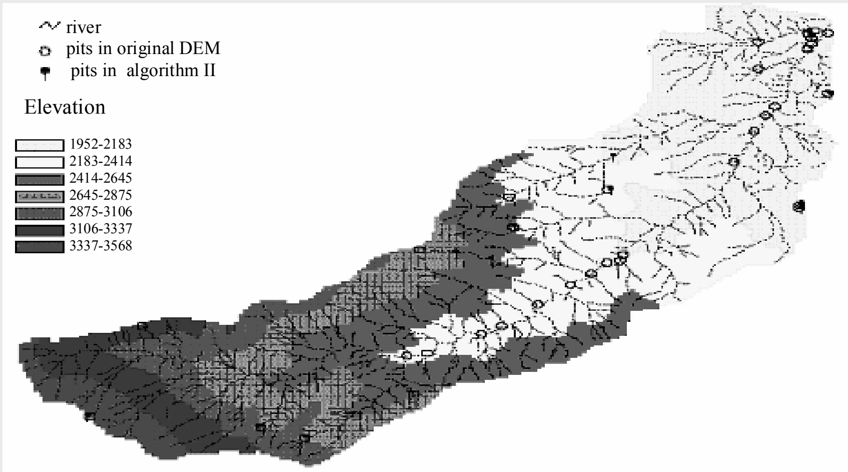

Figure 2- DEM and drainage with spatial distribution of pits.

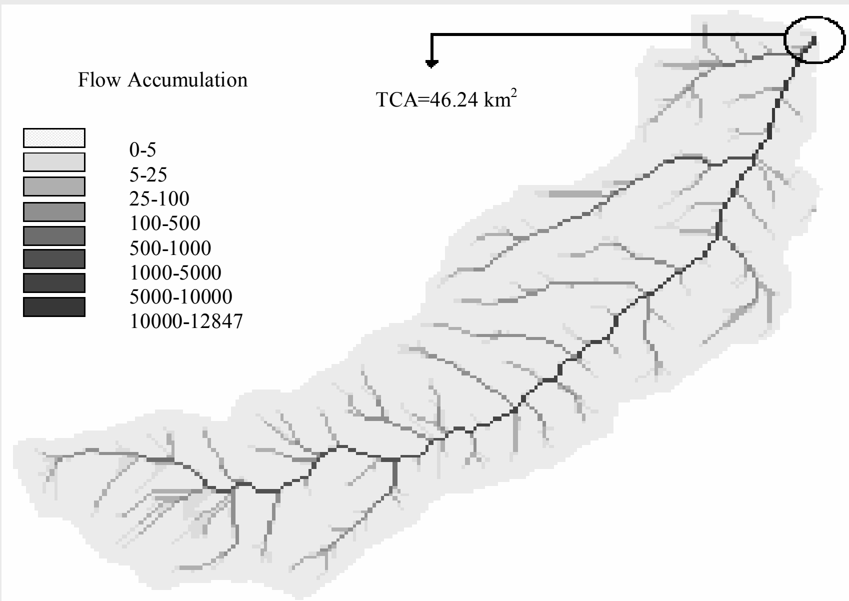

Figure 3- Flow accumulation map for algorithm I.

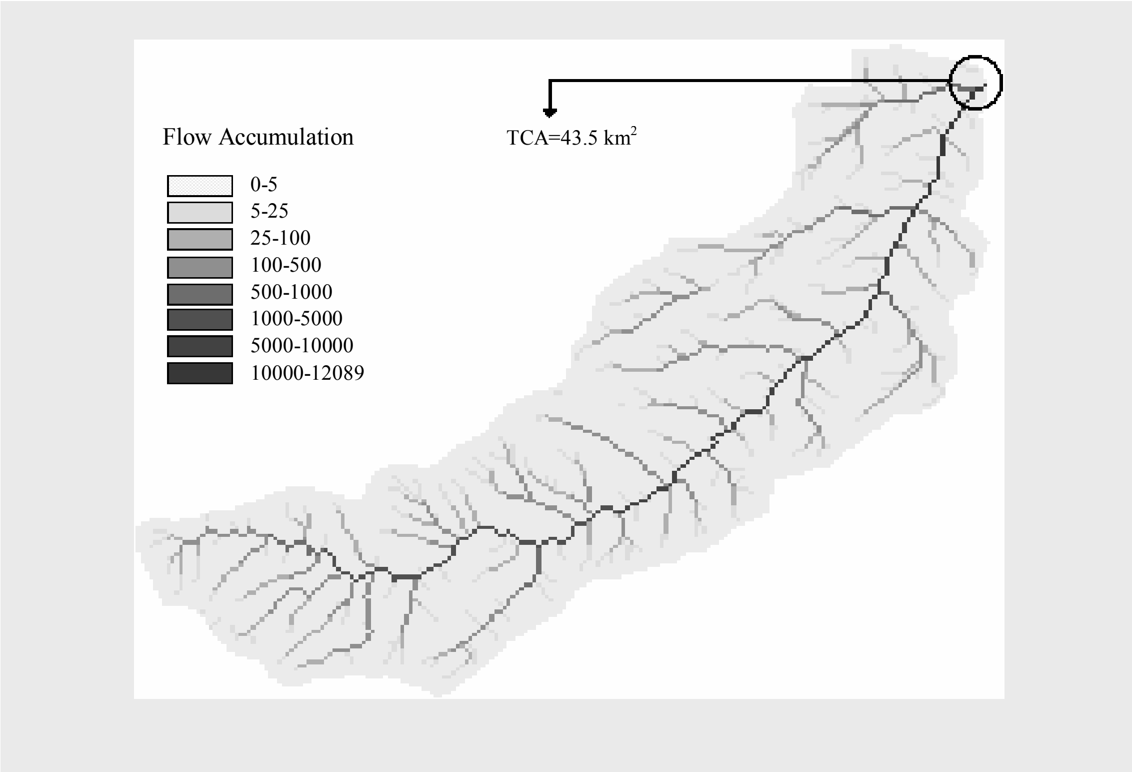

Figure 4- Flow accumulation map for algorithm II.

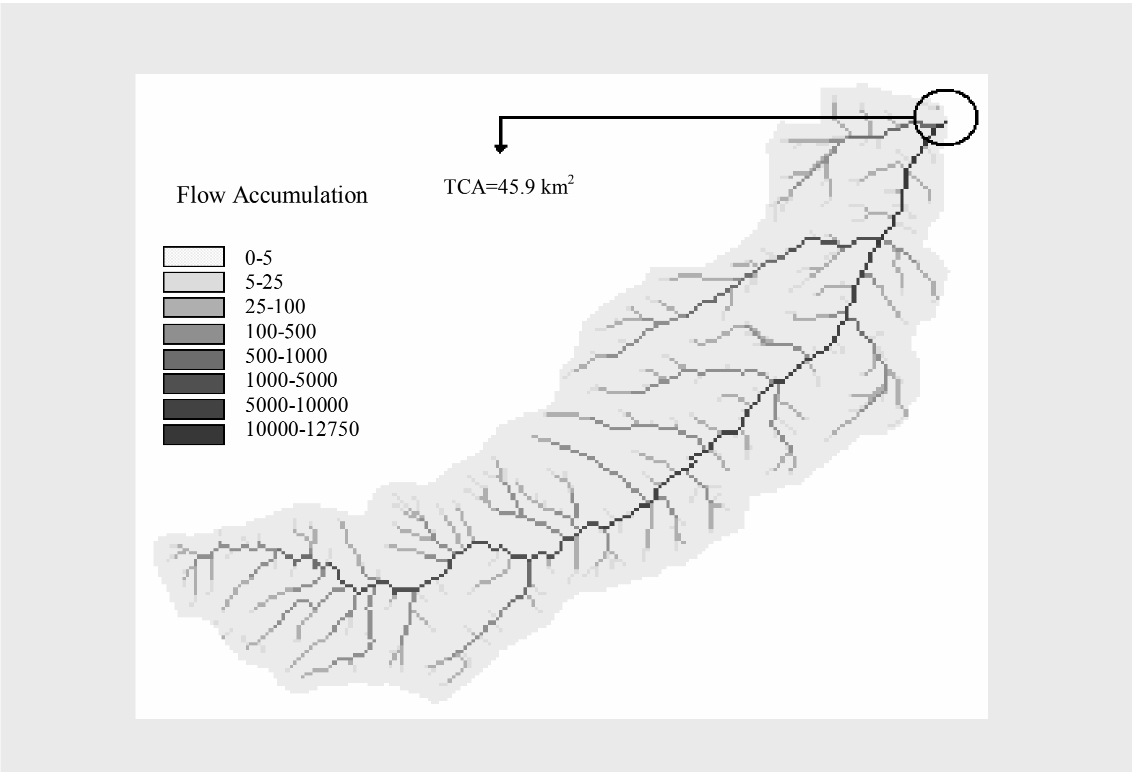

Figure 5- Flow accumulation map for algorithm IIIa.

sudden falls. In algorithms 2 and 3, this phenomenon

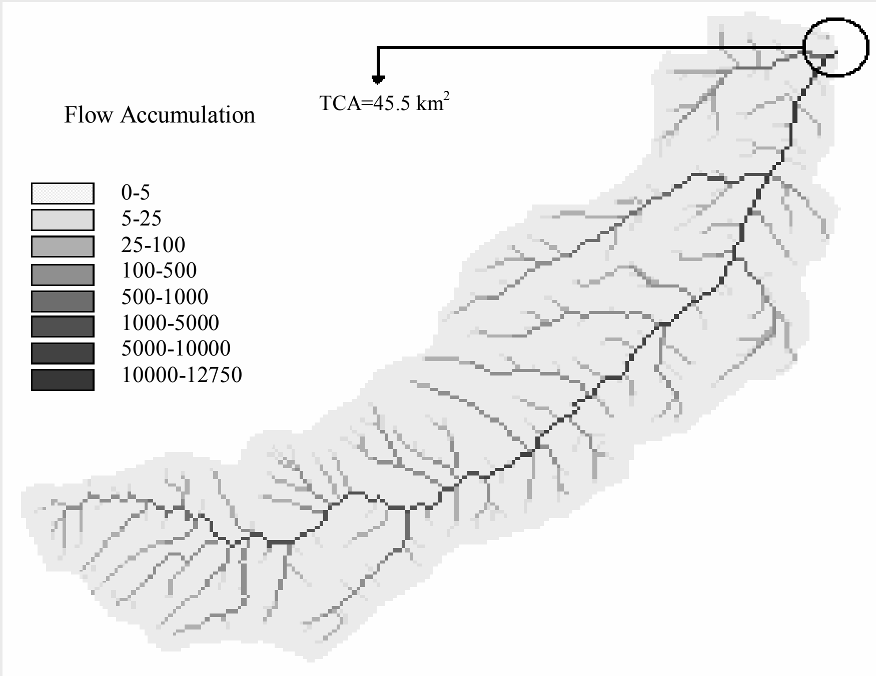

Figure 6- Flow accumulation map of algorithm IIIb.

is not seen because of the nature of these algorithms which is the entrance to a drainage net for the optimization of the DEM in order to match the built Dem with the existing drainage model, and also no pits are seen in the path of the drainage in algorithms II and III. As was expected, the match of the profiles of algorithms II and III with the existing profile is better. Table 1 also shows the displacement of the main drainage extracted from the three algorithms with the main drainage (extracted from the digital map) according to cell number.

Table 1- Statistical results of the drainage moving index between algorithms I and III and a major river of the basin.

	Algorithm I	Algorithm III
Difference =1pixel	66	0
Difference =2 pixel	2	0

Results

By executing algorithms I, II and III the reformed DEM were created. Then, according to the DEM, the flow direction and flow accumulation were also calculated. Using the accumulative flow map and dividing it into groups, the new drainage map was produced and compared with the existing map (extracted from the digitalization of a topographical paper map). The results of examination parameter are as follows:

Main River Length Profile

In Figure 7 the main river length profile in all three algorithms is shown along with the primary profile of the paper map. The length profile drawn is a part of the main drainage path from the basin outlet to the elevation of 2,655 m. As it can be seen in the profile resulting from algorithm I, parts of the path are systematically low sloping and as a result they have

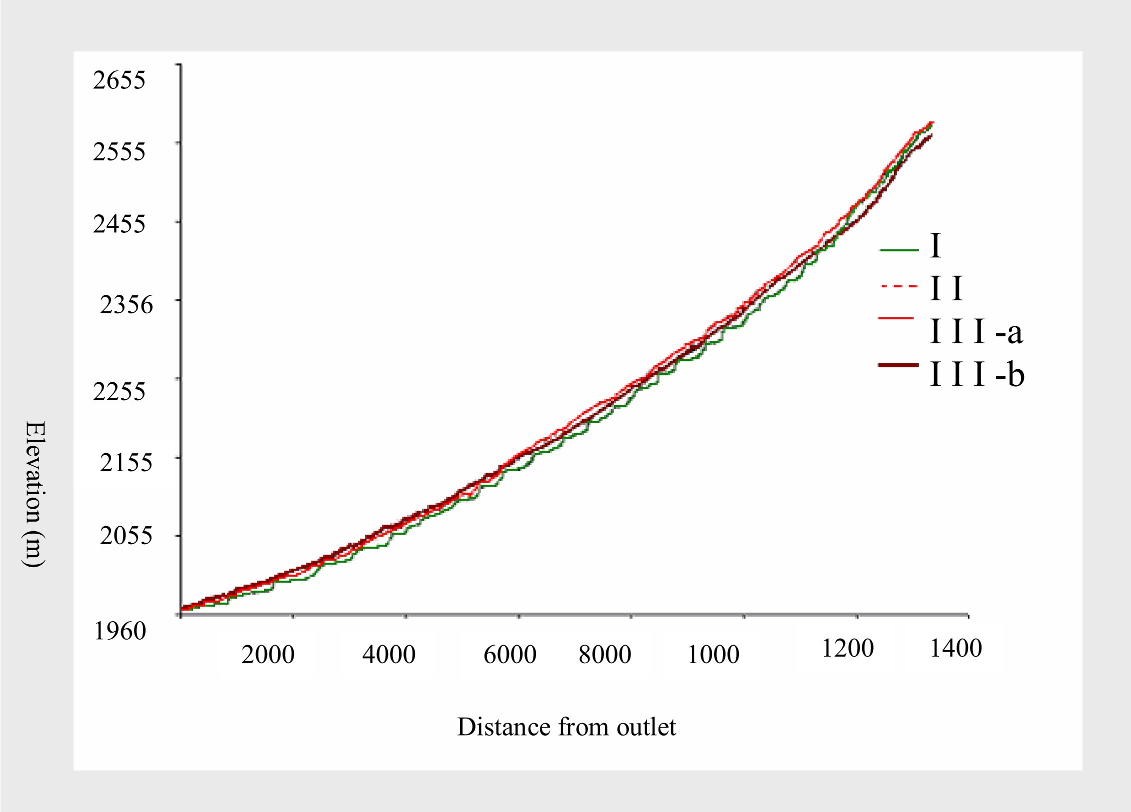

Figure 7- Main River Length Profile in three algorithms

Flow Accumulation

Bearing in mind the importance of the element of flow accumulation, maps of this element were also obtained based on all three algorithms. Frequency changes in flow accumulation were compared in Figure 8. As can be seen, the distribution of the quantity of flow accumulation in algorithms II, III and IIIb compared to algorithm I, cells with low flow accumulation are a greater percentage and the distribution of the quantity of the flow accumulation in algorithms II and III is close to one another. The reason for this is the similar drainage structure in algorithms II, IIIa and IIIb for the use of drainages. This drainage structure, as is clear in Figure 8 showing the flow accumulation of these algorithms, it has a paw form which causes low flow accumulation cells to reach a greater percentage. Moreover, the whole basin drainage area in the three algorithms is different from one another and this is because of the existence of a pit in algorithm II, on the one hand, and the entrance of a number of outside basin cells in the drainage area in algorithms I, IIIa and IIIb. In the primary DEM 35 cells and in the DEM of algorithm II, 13 cells were recognized as pits.

Basin Slope

One of the most important elements needed for hydrological models is the basin slope. The final results of building a slope map in all three algorithms are compared in Figure 9. While the results of algorithms II and IIIa are almost the same, the similar distribution of slope resulting from algorithm I and the primary DEM slope also show the limited number of pits as a result minor changes in the primary DEM. Moreover the distribution of the slope in algorithm IIIb, solely because it changes the elevation of the cells close to drainage, is closer to the slope resulted from algorithm I and the primary DEM slope.

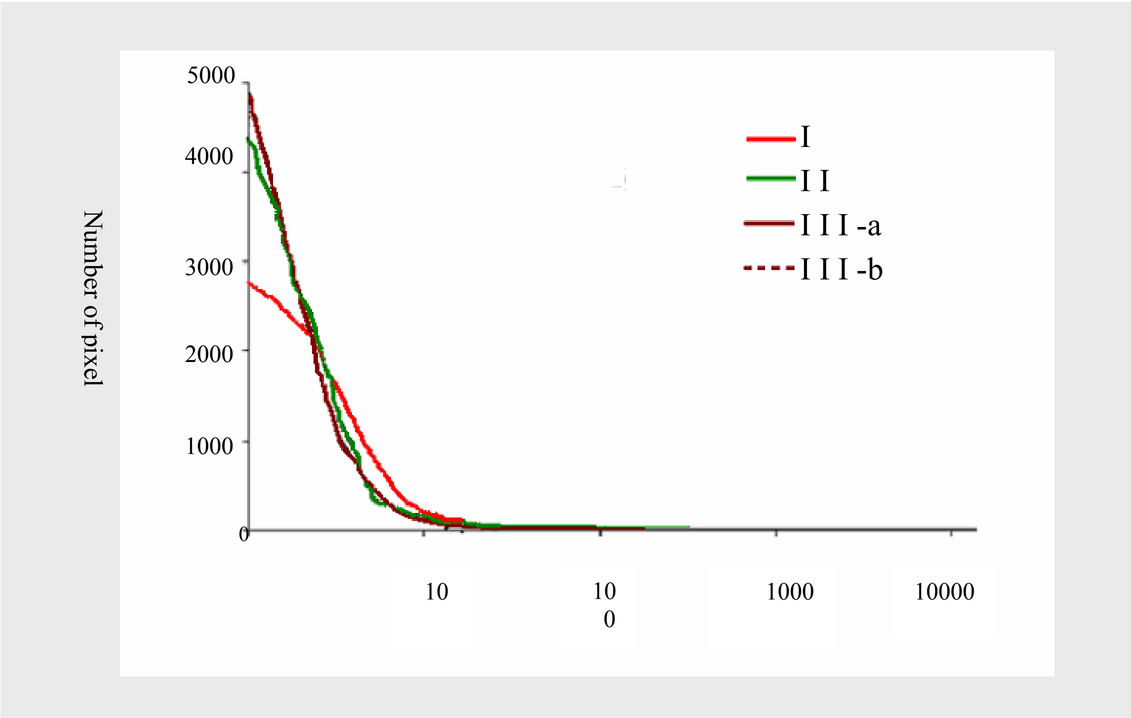

Figure 8- Flow accumulation frequency distribution.

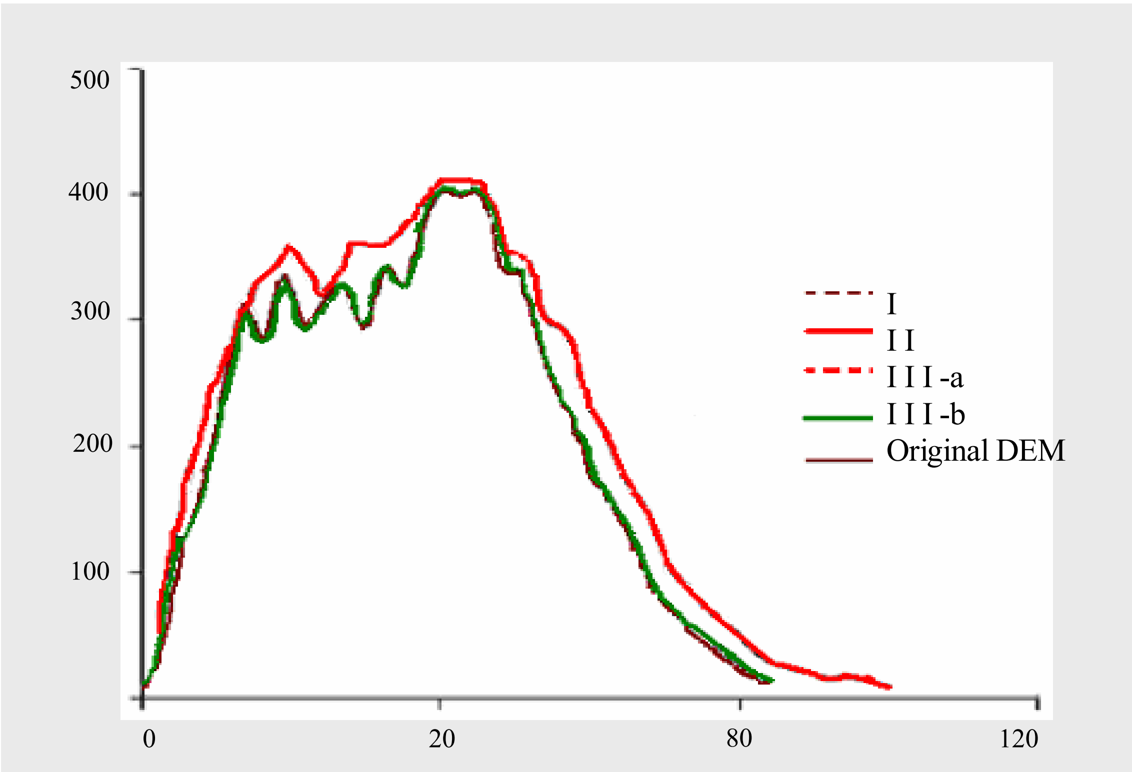

Figure 9- Slop frequency distribution.

Comparison of the Built DEM's

Subtraction of the main DEM from the used algorithms' DEM showed that algorithm I is slightly different from the main DEM (Table 2), which is due to the elimination of a number of 35 pits in this algorithm. But algorithm II and IIIa have a great difference because of entering the river into building the DEM. The amount of this difference is the same in both algorithms (Table 2), and the reason for this similarity is that algorithm IIIa only fills pits present in algorithm II and algorithm IIIb by determining a region of drainages that interferes with the DEM. This region is equal to three cells. In this algorithm, the percentage of cells in the main DEM has changed.

Summary and Conclusion

In this paper, three algorithms were examined in order to eliminate DEM digital errors and their effect on some basin elevation elements. To achieve this goal, first the primary DEM was produced on the basis of contour lines digital maps with the ANUDEM method. Algorithm I only attempts to eliminate digital pits by increasing their elevation. Furthermore, the drainage resulting from it does not necessarily match the digital drainages. Algorithm II deals with the execution of the DE method channel network combination and maintains the main drainage directions in drainage. Algorithm III is a mixture of the execution stages of algorithm II and then III. The comparison of results was carried out on the main drainage length profile, the flow accumulation distribution or the basin's area of drainage and slope. The comparison of the length profiles showed that algorithms II and III successfully simulated the profiles extracted from paper maps. Algorithm I only tries to eliminate the pits without considering the situation of the drainage nets and caused major errors in the length profile. For the flow accumulation and basin slope, algorithms II and III reached similar results.

In sum, it can be said that for the basin under study algorithm IIIb, as a combination of the other two algorithms, (on the condition that DEM changes only take place in one section of the drainages), can preserve the general drainage model and may be regarded as the most suitable method for the correction of DEM errors. Algorithms I and II cannot by themselves present suitable results for the elimination of the DEM errors and the sustenance of the drainage model at the same time even in such a relatively sloping basin. A basin with a moderate slope needs a special examination of their own because the probability of having DEM errors is many times higher than basins with a high slope.

Table 2- Differences between the original DEM and three algorithms.

	Min	Max	Mean	Standard Deviation	Cells have changed
Algorithm I- original DEM	-1	0	-0.0025	0.018	35
Algorithm III(a)- original DEM	-197	755	15	60	12656
Algorithm III(b)- original DEM	-4	11	1.32	2.8	2135

References

Band, L. E. (1986). Topographic partition of watershed with digital elevation models, *Water Resources Research*, 22(1), 15-24.

Costa-Cabral, M. C. and S. T. Burges (1994). Digital elevation model network (DEMON): A model of flow over hillslopes for computation of contributing and dispersal areas, *Water Resources Research*, 30(6), 1681-1692.

Environmental System Research Institute, Inc. (1997). Using GRID with ARC/INFO, Redland, CA.

Hutchinson, M. F. (1988). Calculation of hydrologically sound digital elevation models, Third International Symposium on Spatial Data Handling, Columbus, Ohio.

Hutchinson, M. F. and T. I. Dowling (1991). A continental hydrological assessment of a new grid-based digital elevation model of Australia, *Hydrological Processes*, 5, 45-58.

Jenson, S. K. and J. O. Dominique (1988). Extracting topographic structure from digital elevation data for geographic information system analysis, *Photogrammetric Engineering and Remote Sensing*, 54(11), 1593-1600.

Lea, N. L. (1992). An aspect driven kinematic routing algorithm in overland flow, In Hydraulics and Erosion Mechanics, edited by A. J. Parsons and A. D. Abrahams, Chapman and Hall, New York.

Nelson, E. J., and N. L. Jones (1995). Reducing elevation roundoff errors in digital elevation models, *J. of Hydrology*, 169, 37-49.

O'Callaghan, J. F. and D. M. Mark (1984). The extraction of drainage networks from digital elevation data, Computer Vision Graphics Image Process., 28, 323-344.

Tarboton, D. G. (1997). A new method for the determination of flow directions and upslope areas in grid digital elevation models, *Water Resources Research*, 33(2), 309-319