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COMPARISON OF DEPRESSION REMOVAL METHODS IMPLEMENTED IN OPEN-SOURCE SOFTWARE

Abstract: Modern tools for hydrological analysis are based on data derived from DEM. Hydrological methods that create a stream network by overland flow simulation require to remove depression (pit or sink) on DEM first. Depression occurs when a cell or group of cells is surrounded by adjacent cells at higher altitudes. Even though their removal creates an incorrect DEM, it is common practice to remove all topographic depressions (real, artificial, or combined) not to interrupt the creation of stream networks. There are two basic methods of depression removal: the filling method and the carving or breaching. Combined methods contain good characteristics of both procedures. GIS software includes a depression removal algorithm within its hydrological analysis module. The paper investigates which methods are implemented within individual open-source software SAGA and GRASS. A comparison of DEM before and after depression removal for each method is given. The methods were tested on a DEM, resolution 5x5 meter for a hilly area intersected by a significant number of watercourses.

Keywords: DEM, depression removal, open-source software, stream network, filling method, carving method

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Introduction

The concept of the Digital Terrain Model (DTM) in Croatia (DMR) includes original and derived DTM (URL1). Since the data for the paper were collected by interpolation from the original DTM, the paper uses the term the Digital Elevation Model (DEM). DEM was created from the original DTM with the regular raster elevation data structures stored in the derived DEM. The digital elevation model is the base of all the geomorphometric and hydrologic analyses and is the basis for spatial analysis and data modeling. For the needs of hydrological analysis, such as Catchment area, Drainage area, Stream network and Flow direction a digital model with depressions (pit, sink) removed is necessary.

In geomorphometry, a depression is a landform sunken or depressed below the surrounding area. Surface depressions on the landscape vary greatly in size, ranging from relatively small, unmanaged water storage systems to large, regularly managed water bodies such as lakes and reservoirs. Small surface depressions include wetlands embedded within uplands or those along river corridors, ponds, and other similar small waterbodies (Biggs et al., 2017).

For hydrological analysis to be carried out, GIS software contain modules for depression removal within their hydrological modules. Depression removal alters the geomorphometry of the DEM. Depression removal affects the relief related parameters, so the choice of depression removal method is an important step in hydrological analyses to obtain a morphometrically minimally altered model after depression removal.

GIS technology has improved and accelerated the possibilities of manipulation, analysis, and visualization of local and global spatial data, but the prerequisite for quality and resilient results are correct input data, created by methods optimal for geomorphometry of the area. Geodesy and geomatics, as interdisciplinary professions, can provide guidelines for the application of certain methods within this phase of data preparation (Šamanović, 2014).

Research area and methodology

In this paper we used data obtained by collecting a raster of height points by interpolation at a resolution of 5x5 meters for the area of Papuk (Fig. 1).

The Papuk mountain, located on the northern and northwestern border of the Požega valley in the eastern part of Croatia, was chosen for the research area. The general characteristics of the basin channels are the water torrents channels that form on the steep slopes of the mountains. Stream channels are unstable. Stream channels are unstable. Due to heavy rains, water overflow and frequent changes in watercourses occur.

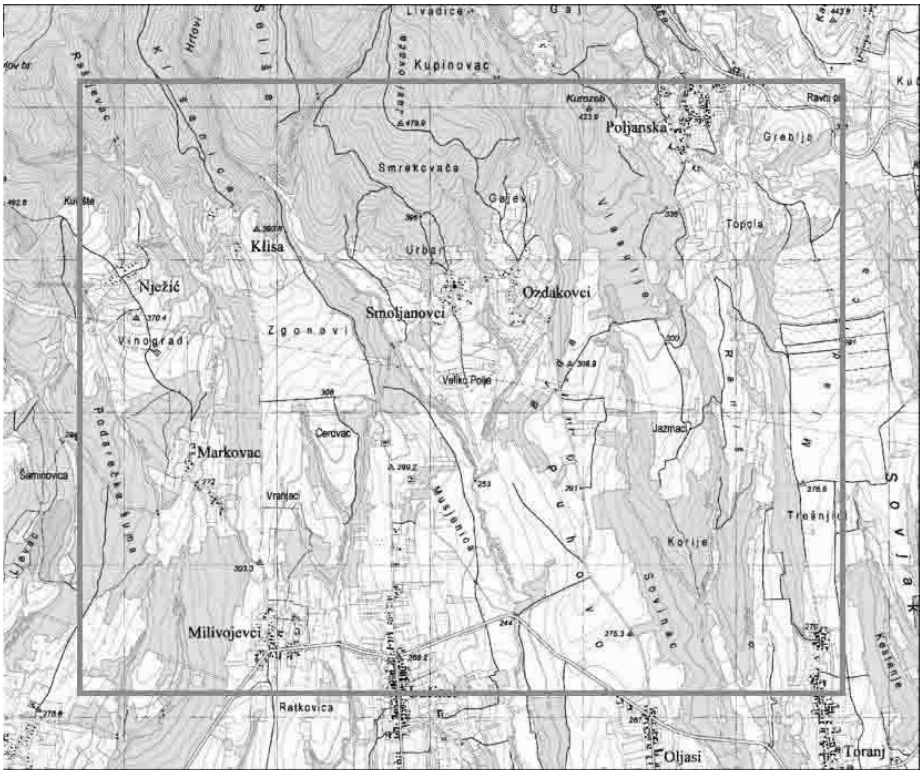

Fig. 1. Research area Papuk
Source: Šamanović, 2013

Altitude points grids (digital elevation models) that were used in subsequent analyses were obtained by interpolation. The data obtained with the parameters listed in Table 1 were loaded into the GIS software and the results are DEM shown in Figure 2. Interpolation is a procedure in the scope of which the value of a function is determined based on two known values (Frančula & Lapaine, 2008). The data are gathered by combining three interpolation methods: linear method, least-squares method, and finite element method. The basic idea behind the linear interpolation method is to use several first-degree polynomials instead of a single higher degree polynomial (Bosner, 2013).

Table 1. Area borders in meters and resolution in cells for test area

max x	6 468 540.00	max y	5 033 360.00
min x	6 463 740.00	min y	5 030 160.00
Δx	4 800.00	Δy	3 200.00
columns	960	rows	640

Source: own elaboration

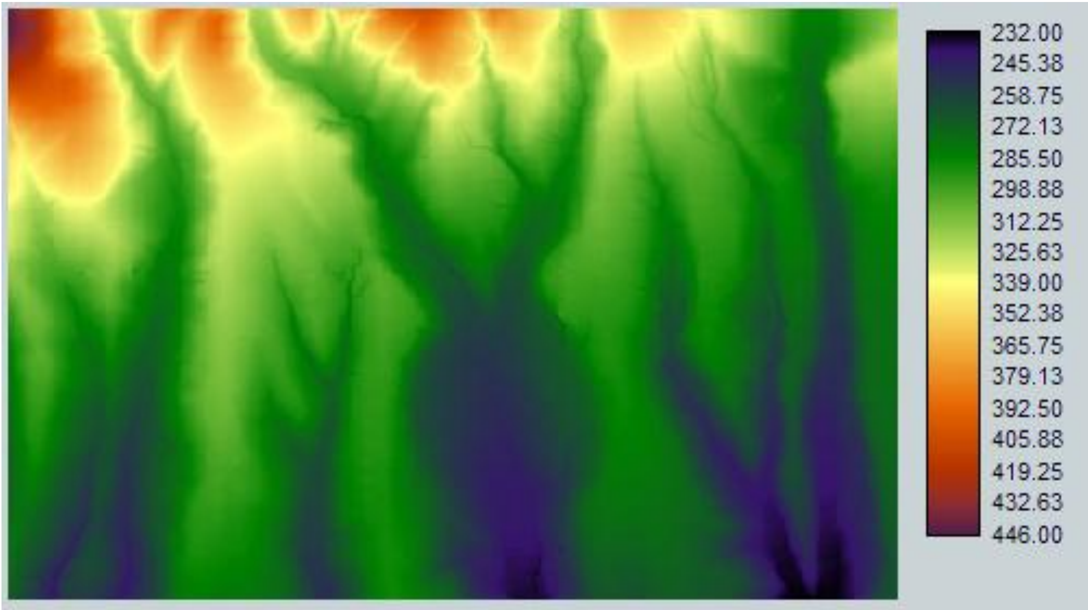

Fig. 2. DEM of Papuk area (elevation are in meters)
Source: Šamanović, 2013

Hydrological methods that create stream networks and drainage areas based on overland flow simulation require removal of depression first. Pits in the DEM are depressions or local minimum (Planchona & Darboux, 2001) and occur when a cell or group of cells is surrounded by adjacent cells of higher elevation. Depressions may consist of flat surfaces and smaller nested depressions within pre-existing ones. Regardless of the way DEM is created, depressions occupy 5% of the total DEM area (Tarboton et al., 1991). The existence of depressions in the DEM will interrupt the creation of a stream network as well as the modeling of other spatial hydrological processes.

Topographic depressions can be real, artificial, or combined. Natural depressions are areas of natural accumulation or natural soil change. Artificial depressions are often the result of errors during sampling (misclassified input data) or interpolation, generalization, rounding of the interpolated value to lower accuracy, smoothing of cells within the area, or smoothing because of resampling. Observing DEM makes it difficult to determine whether depression is natural or artificial. Although techniques are being developed today to distinguish between natural and artificial depressions, the only safe method is field research (Lindsay & Creed, 2005).

As no technique aimed at differentiating natural from artificial depressions (except on-site surveys) can provide fully reliable results, and as the procedures are also quite complex, the depression removal algorithms operate in an unselective manner in all GIS software. Most natural depressions finally overflow into the downstream discretization cell, and, despite unselective removal of depressions, such a corrected model can in fact be accurate (Šamanović et al., 2015).

There are two basic methods of depression removal (Fig. 3.): the filling method and the carving or breaching method. A simpler and more commonly used method is the method of filling depressions (DEM). The method raises the DEM cell to the altitude of the lowest neighboring cell and continues with the process until the cell is filled.

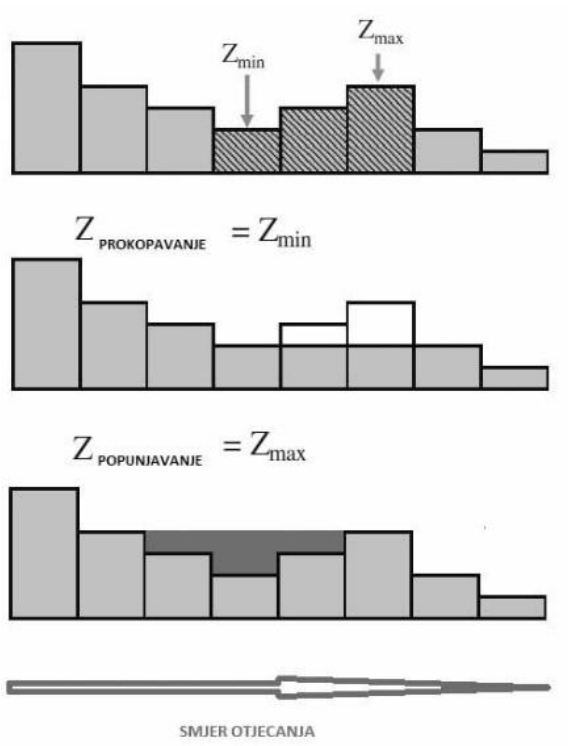

Fig. 3. Examples of depression removal method
Source: Šamanović et al., 2017

The filling method is the most widespread method, primarily due to its simplicity, and to date, several algorithms have been developed to fill the depression. Most GIS software within the hydrological analysis module contains a procedure-based depression removal module which raises the height of the depression until the level reaches the height of the points from which competition is possible (Grimaldi et al., 2007). The fill grows to the overflow point, and the result are cells whose value is always the same or higher than the DEM. The procedure is repeated until all the depressions are overfilled or more correctly until all the cells are associated with the runoff path.

The carving method solves the problem of depression by creating lines of water runoff and lowers the elevated cells in the DEM by carving channels. Algorithms create a way from depression by finding the lowest adjacent cell, and in the case of multiple cells of the same height, the shortest path is considered. Cells that are in depression are brought to the nearest cell of the lowest height or to the edge of the model.

This paper compares five depression removal methods implemented in open-source GIS software SAGA and GRASS. Methods developed by Planchon and Darboux, Conrad and two algorithms developed by Wang and Lie implemented in SAGA GIS and methods developed by Jenson and Domingue implemented in Grass are discussed. The methods developed by Planchon and Darboux and Jenson and Domingue remove depressions by the filling method, the method developed by Conrad fills depression by the carving method, while Wang and Liu developed two methods that combine the two basic methods.

Overview of depression removal methods

The following case is a theoretical overview of the five depression removal methods used in this paper.

The Planchon and Darboux algorithm replace depression with a strictly horizontal surface but is also used to create a drainage network where the depression is replaced by a slightly sloping surface. The Planchon and Darboux process can be divided into two phases (Planchona & Darboux, 2001): flooding the entire DEM with water and draining water surplus. The algorithm first floods the surface by increasing of the water level at all cells and then iteratively drains water surplus from each cell. In the final phase, the water from the depression is drained at the level of the highest overflow points and creates a flow path to the DEM boundary resulting in a model with depressions removed.

Olaf Conrad developed a method that, based on a DEM uses a runoff pathway to form a modified digital model. Depression removal is based on the cell value lowering to find an exit from the depression, and it consists of two steps (Brenning, 2017). In the first step, the algorithm recognizes the route of the concentrated runoff line and, at that, the area without depression is marked with zero, and then the values ranging from 0 and 8 are attributed to the depression, depending on the route by which evacuation from the depression will be operated. The second step involves depression removal using the concentrated runoff calculation line (Šamanović, 2014). The direction of water runoff is determined starting from the depression, over the minimum cell elevation that is lower than the depression point, considering eight adjacent cells (O'Callaghan & Mark, 1984).

The Jenson and Domingue algorithm gives satisfactory results for fewer data sets. The problem occurs with a large data set, where smaller depressions are nested in larger ones (Fig. 4), so the search of the entire data set must be performed multiple times to find a nested depression. The algorithm is quite complex and difficult to implement.

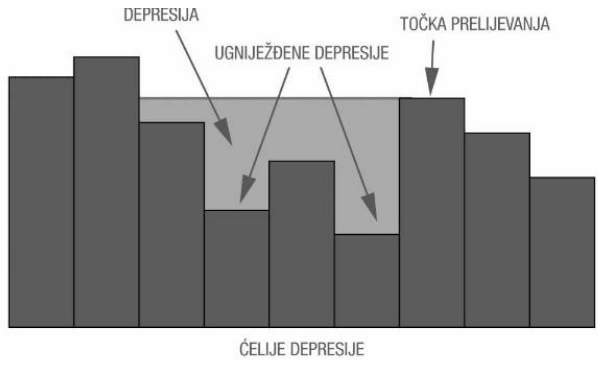

Fig. 4. Nested depressions
Source: Šamanović, 2013

Wang and Liu introduced a new concept of overflow from depressions and a progressive method of optimal overflow pathway, based on the structure of priority order data and analysis of the optimal outflow pathway. They have proposed a new efficient depression filling method that can simultaneously determine runoff direction and spatial distribution of drainage areas, all this in a single step (Wang, 2006). If the elevation is sufficient to establish the downstream direction of the flow to the second basin, the cell does not need to be elevated, and its overflow elevation is the same as its elevation on the original DEM. If the cell is not high enough to establish runoff, we need to raise it to its runoff elevation. In one step, the method creates a depression-free DEM and identifies places and depths of depression, using a priority data structure, avoiding the eight-way search used by Planchon and Darboux.

Modul XXL Wang Liu uses an algorithm proposed to identify and fill surface depressions in digital elevation models. The method was enhanced not only to fill the depressions but also to preserve a downward slope along the flow path. This is accomplished by preserving a minimum slope gradient between cells. This version of the module is designed to work on large data sets e.g., LIDAR data (URL2).

As already mentioned, these algorithms are embedded in Grass GIS and SAGA GIS and are the subject of this paper. There are many different algorithms implemented in open-source software. Below are descriptions of some of them.

The open-source GIS Whitebox GAT use breaching method develop on Lindsay and Dhun (Lindsay, 2016). Lindsay and Dhun proposed a method based on identifying depression cells, and after that algorithm create breaching channel. GIS Whitebox GAT also have implemented fill depression developed by Wang and Liu. Fill depression algorithm base on the computationally efficient approach of examining each cell based on its spill elevation, starting from the edge cells, and visiting cells from lowest order using a priority queue (UTL3).

Integrated Land and Water Information System (ILWIS) offers a range of simple procedures to reduce spurious sink that might not perform equal successful in all areas (Hengl, 2009). Process depends on number of pixels in depression. When a depression of a single pixel is encountered the height value of this pixel will be increased to the smallest value of its 8 neighbor's pixels. When a depression of multiple pixels is encountered the height values of this depression will be increased to the smallest value of a pixel that is both adjacent to the outlet for the depression, and that would discharge into the initial depression.

MATLAB-based software for topographic analysis TopoToolbox has implemented process of filling pit using replacing negative values and zeros with 'NaN' values. Then algorithm computed flow direction on the filled DEM (Pastor, 2017).

Result and discussion

Input data for analysis is DEM of Papuk area where depressions were not removed. Table 2 provides a statistical analysis of each method to see a comparison to the model without depressions removed. From the table that the three methods do not change the height range of the DEM, while the method developed by Conrad and Jonson and Domingue lowers the terrain elevation.

Table 2. Statistical parameters DEM with depression and DEM on which depressions were removed

METHOD	CELLS NUMBER	CELL SIZE	MEAN	MIN	MAX	VAR	ST DEV	STD DEVLO	STD DEVHI
DEM with depression	614400	5	289.7005	0	445.06	1595.4649	39.9433	249.7572	329.6437
Planchon_and Darboux	614400	5	289.7014	0	445.06	1595.4280	39.7585	249.7585	329.6442
Conrad (QM)	614400	5	290.2473	-0.96	445.06	1472.3950	38.3718	251.8755	328.6191
Wang and Liu	614400	5	289,7014	0	445.06	1595.4264	39.9428	249.7586	329.6441
XXL and Wang_Liu	614400	5	289,7014	0	445.06	1595.4264	39.9428	249.7586	329.6441
Jenson and Domingue	614400	5	290.2497	-0,10	444,96	1471.8475	38.3647	251.8850	328.6144

Source: own elaboration

Since the removal of depressions affects the creation of the surface runoff line, surface runoff networks have been created. Figure 5 shows the model in which the depressions were not removed. The stream network was interrupted.

To compare five methods of depression removal, on the DEM Papuk, depressions were removed in two software (SAGA and GRASS) with five described methods. Figures 5, 6 and 7 show the same areas after the depression was removed. In selected circles shown the areas where differences between individual methods of depression removal are visible. From figure 6 and 7 can see that by applying four methods of depression removing obtained results deviate lesser extent from each other. The method developed by Jenson and Domingue (Figure 8) gives a significantly different stream network created. Apart from the complexity of the algorithm, the reason lies in the large range of data for which the module is not suitable.

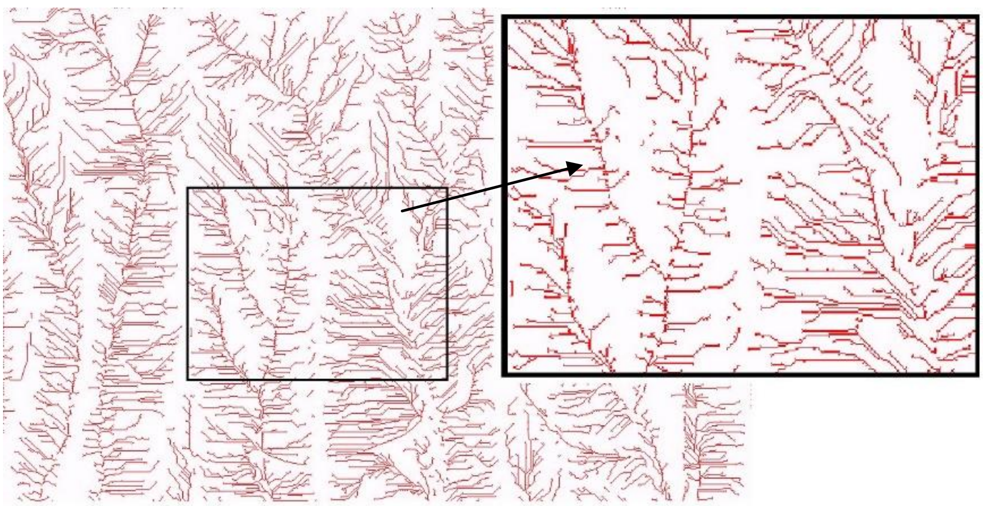

Fig. 5. A network of runoff network without depressions removed
Source: own elaboration

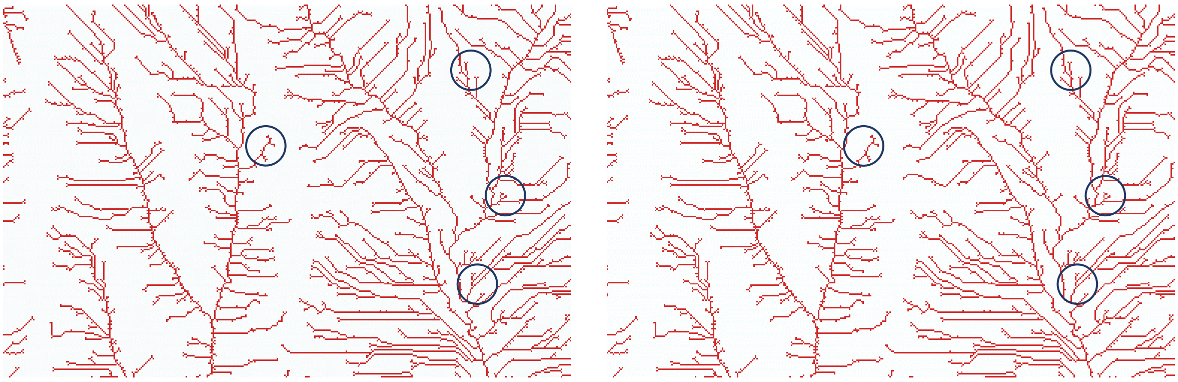

Fig. 6. Enlarged view of part of the area with depressions removed with Planchon and Darboux method (left) and Conrad method (right)
Source: own elaboration

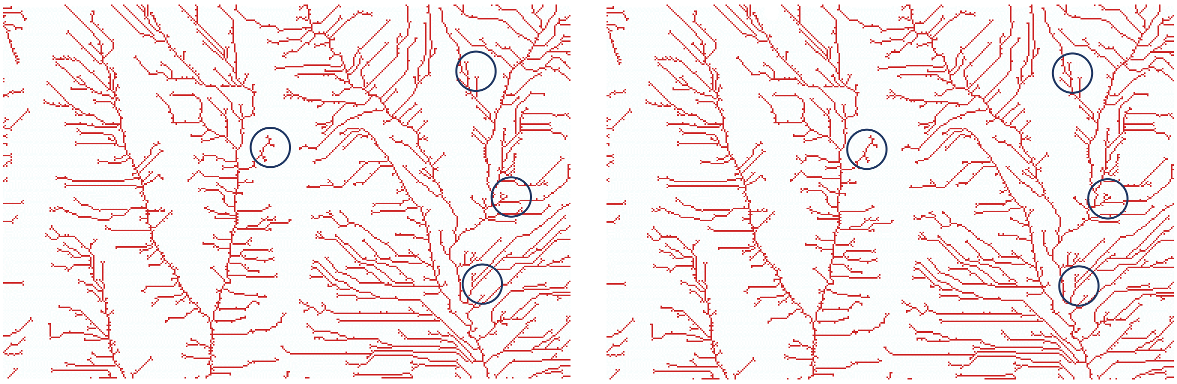

Fig. 7. Enlarged view of part of the area with depressions removed with Wang and Liu method (left) and XXL Wang and Liu (right)
Source: own elaboration

Fig. 8. Enlarged view of part of the area with depressions removed with Jenson and Domingue
Source: own elaboration

To notice the differences in the connection of broken stream network, representations were created in which blue lines represent connected stream network and red existing networks created from DEM data without depressions removed (Figures 9, 10 and 11).

Table 3 shows the number of changed cells for all applied methods. The three methods implemented in SAGA which remove depressions by the method of filling change the creation of a stream network in almost equal influences. The method developed by Conrad washes the stream network to a slightly greater extent, while the method developed by Jenson and Domingue significantly affects the change in the stream network. As the XXL module was adapted to Lidar data that we did not use, two modules developed by Wang and Lie behaved the same.

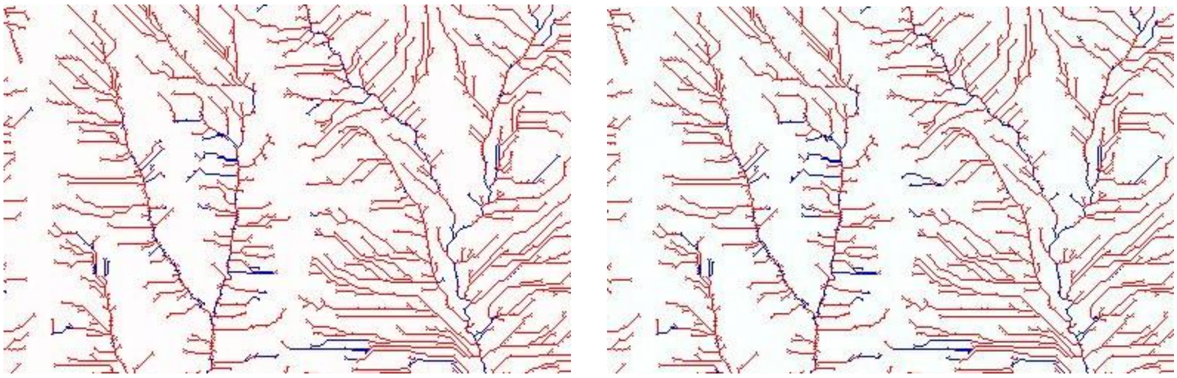

Fig. 9. Stream network after filling the depression with the Planchon and Darboux method (left) and Conrad method (right)
Source: own elaboration

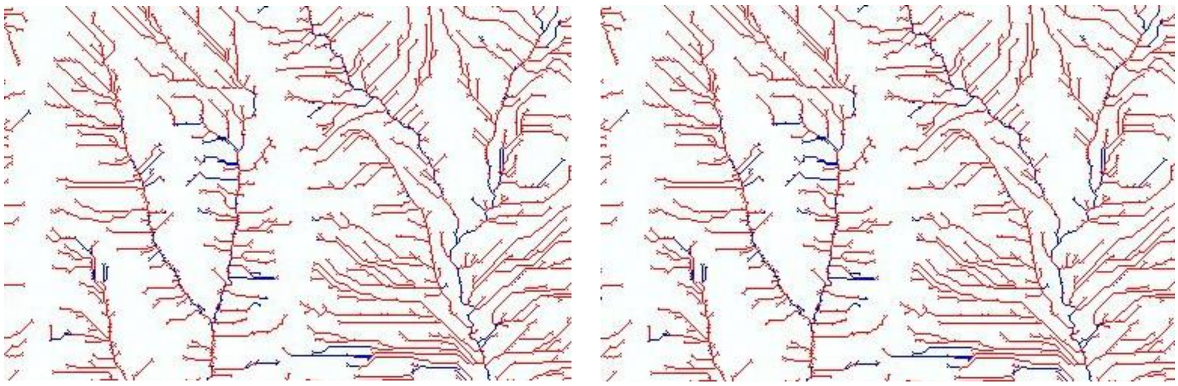

Fig. 10. Stream network after filling the depression with the Wan and Liu method (left) and XXL Wang and Liu method (right)
Source: own elaboration

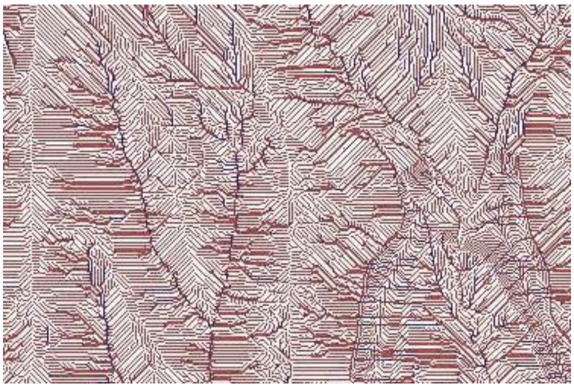

Fig. 11. Stream network after filling the depression with
the Jenson and Dominique method
Source: own elaboration

Table 3. Amount of changed and unchanged cells after the depression filling

Method	**Number of no data cells**	**Number of changed cells**	**Number of unchanged calls**
Planchon and Darboux	556170	7318	50912
Conrad (QM)	556084	7508	50808
Wang and Lie	556152	7354	50894
XXL Wang and Lie	556152	7354	50894
Jenson and Domingue	348028	251917	14455

Source: own elaboration

Conclusion

Automatic surface runoff calculation from DEM has become increasingly popular over the last 20 years, due to the availability and bigger DEM resolutions. Algorithms for determining the direction of stream network are used to check cells watercourses on the DEM as well as the movement of water to lower points in the field. Basically, runoff algorithms define the path by which surface runoff will move from a given cell to one or more adjacent lower cells (Šamanović, 2014). Such provides a quality base for modeling the movement of the surface water flows. To create the surface runoff, it's necessary to identify and remove depression on the DEM, whether it's the real depression or depression created as an artifact during the DEM creation. The depression removal process' disadvantage is the DEM's cell elevation change.

Depression removal creates new altitude areas, leading to inaccurate calculations of runoff directions and basins. The five methods compared in this paper are used within open-source software. Although the two methods (Planchon and Darboux and Jenson and Dominigue) remove depression by the filling method, the number of cells with altered heights is significantly different due to the inadequacy of the Jenson and

Domingue algorithm to a large range of data and geomorphometric relief characteristics. The carving method in the area intersected by numerous watercourses and all terrain slope to the south, gives results slightly better compared to the two mentioned methods, but also the combined methods developed by Wang and Liu.

New methods for the choice depression removal algorithms need to adapt to the terrain's geomorphometric characteristics, the area's size and the number of watercourses. The recognition of depressions should be semi-automatic to distinguish real depressions from errors during the DEM creation. In addition to the above, the partial application of certain methods to the DEM would enable the creation of a more accurate DEM as a basis for calculating stream network and catchment areas.

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