Sink removal from digital elevation model – a necessary evil for hydrological analysis

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The present study involves a comparative appraisal of three different sink removal algorithms. The publicly available shuttle radar topographic mission (SRTM) digital elevation model (DEM) version 3.0 of 90 m resolution was used as input DEM. Three sink filling algorithms proposed by Jennson and Domingue (JD), Planchon and Darboux (PD), and impact reduction approach by Lindsay were evaluated for their efficiency in removing the sink from SRTM DEM with minimum alteration of original DEM quality. Various primary and secondary parameters were used for comparative assessment. It was found that all the three algorithms altered the originality of the DEM significantly, but to a different extent. It was found that the PD method of sink removal was better than the other two methods studied here. However, the results also substantiated that the hydrologist must take due care to minimize any uncertainty that might arise due to DEM preprocessing.

Keywords: Digital elevation model, hydrological preprocessing, sink filling algorithms, terrain analysis system.

DIGITAL elevation model (DEM) is a two-dimensional array of pixels, with each pixel corresponding to elevation values, representing points of the earth's topography. This raster DEM is considered as one of the most valuable data for GIS-based hydrological analysis and allied application at catchment scale[1]. Automated hydrological feature extraction using DEM is increasingly gaining popularity because of the availability of high-resolution DEM in public domain[2]. The extraction of hydrological features from DEM is not only accurate, but also less time-consuming.

However, automated extraction of hydrological features using DEM needs the removal of depression (sink) from the DEM surface. Sink, an inherent artefact, is a spurious pixel which has elevation value lower than its surrounding pixels (i.e. no outlet facilitating the movement of water down slope). It is thus a spatially structured error of a systematic nature and is often associated with the production of DEMs. However, in high resolution, DEM, sink may also arise due to man-made features such as bridges, weirs, culverts, dams, roadways and so on. Thus, removal of surface depression (sink) is an important preprocessing task in hydrological application of DEM[3,4]. A number of depression removal methods have been developed which generally differ with respect to depression treatments (artefact or true landscape feature), origin (elevation overestimation or underestimation), the size of scan window and the scan direction used. Some of the sink removal algorithms are purely based on depression filling[5–7] and breaching of elevated pixels[3] or combined filling and breaching operation[8]. However, none of these methods are perfect and they alter the original elevation values in DEM to a different magnitudes depending on the nature/complexity of the catchment topography[9,10]. In recent times, although few researchers have attempted to evaluate the effects of various sink removal algorithms[11–14], the results were not that promising to derive any universally accepted conclusion thereof, and this necessitates further investigation on the stated problem.

Keeping in view the above facts, the present study aimed at a comparative assessment of three most commonly used algorithms namely Jenson and Domingue (JD) method[5], Planchon and Darboux (PD) method[7], and Lindsay and Creed method[8] regarding their effectiveness in removing sink on the DEM surface.

The study site for the present research work was Maithon reservoir catchment (85.41°–86.90°E long. and 23.75°–24.56°N lat.), which is situated in Jharkhand state, India. The watershed covers an area of about 5553 sq. km. The elevation ranges from 120 to 1360 m above mean sea level. It is predominantly an agricultural watershed with a scattered area of active mines and sparsely distributed forest patches.

The source DEM used for this study was shuttle radar topographic mission (SRTM) DEM. SRTM DEM of 3 arc second version 3 (http://srtm.csi.cgiar.org) was downloaded from Consultative Group on International Agricultural Research-Consortium for Spatial Information (CGIAR-CSI)[15] and clipped for the Maithon reservoir catchment.

The sink can be removed either by filling methods or breaching methods or by the combination of both. In the present study, the depression or sink in DEM were removed using following three sink removal algorithms implemented in terrain analysis system (TAS) which is now available as open-source software in the name of Whitebox Geospatial Analysis Tools[16].

Jenson and Domingue (JD) method[5] is a sink removal algorithm which typically identifies local minima and then attempts to fill them in an iterative fashion bottom-to-top by exploring each cell's neighbourhood to find outlets. It follows a two-step process for removing the sink. The first step fills all single-cell sinks by keeping their elevation to the lowest elevation of their neighbours (i.e. pour points). The second step fills complex sinks of

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more than one cell by identifying and labelling the interior catchments of sink depressions through a calculation of flow directions for every cell in the DEM. A table of pour points is built for interior catchments adjacent to depressions. The path of the pour points for the adjacent depressions is traced until it reaches the border of the DEM. The threshold is considered as that pour point for which the elevation is highest. Then, all the cells in interior catchments of depressions, with an elevation lower than the highest pour point, are raised to the threshold value. After the depressions are filled, an iterative process is used to identify the drainage directions of flat surfaces. Although JD method copes with nested depressions, depressions with flat areas, truncated depressions, etc. it has high time complexity of $O(N^2)$.

Planchon and Darboux[7] (PD) method allows surface filling with the strictly flat or slightly sloped surface. This algorithm also involves two stages. First, it inundates the surface by assigning a maximal water surface elevation W to all DEM cells. Then, it iteratively drains excess water from every cell. A seed cell is used as the root and an upstream tree is progressively searched by following the dependence links. The excess water is removed for all the cells on the tree. During the second (final) stage, the water in depressions is drained to the level of the highest pour point on the flow path to an outlet on the border of DEM, resulting in flat depression surfaces. Water on the cells outside the interior catchments of depressions is completely drained out, and their final elevation values remain the same as before inundation. The DEM handled by PD algorithm has neither depressions nor flat surfaces. Therefore, it is easy to extract flow directions from the DEM. Depending on the terrain, the time complexity of PD algorithm ranges from $O(N^{1.2})$ to $O(N^{1.5})$.

Lindsay and Creed[8] algorithm uses a hybrid approach based on the constrained filling as well as breaching operation called impact reduction approach (IRA). The constraint is the minimum alteration of original elevation values. In this algorithm, sinks are filled up to a certain level followed by breaching to minimize the cost. The cost for transforming an input DEM into an output sink less DEM is obtained as the sum of the altitude differences between the input and output DEMs, as shown in the following equation in which input DEM is denoted as DEMi (before processing) and the output DEM as DEMo (after processing).

$$C = \sum[\text{DEMi}(x) - \text{DEMo}(x)],$$

where $1 < x < n$.

The sink removal algorithms were applied to the original SRTM DEM to obtain three separate sink-filled DEMs. In the next step, flow direction grids were determined by D8 method based on the steepest slope among the eight cardinal directions using each of the sink-filled DEMs. Flow direction grids were used to determine flow accumulation grids showing the accumulated weight of each pixel in the downslope direction. By applying a threshold value (500 pixels), beyond which all the flow accumulation grid pixels were considered being stream pixels. Similarly, flow accumulation grids were used for catchment boundary by using up-slope contributing area method. Next, the stream grid and watershed grids were converted to vector form. The catchment features obtained from three sink-filled DEMs were then compared with those catchment features derived from topographic maps. Similarly, the DEM surfaces of original and sink-filled DEMs were also compared to explore the degree of alteration caused by the individual sink filling algorithms. For comparison of DEM surfaces various parameters such as elevation, number of sinks, number of altered pixels, derived slope values, were used.

The drainage networks derived from either of these methods have a certain amount of error. For comparative assessment accuracy of the derived drainage networks, we digitized the drainage networks and catchment boundary from Survey of India (SOI) topographic maps of scale 1 : 50000 as reference stream and basin boundary respectively.

The accuracy of the three sink removal algorithms studied was evaluated using topographic attributes, impact on original/raw DEM, and by means of comparison of derived drainage network and basin boundary with the referred drainage networks obtained from SOI topographic maps.

The different topographic attributes were compared. These attributes, considered among the raw DEM and various processed DEMs were elevation, slope, slope length factor (one of the important parameters for Universal Soil Loss Equation (USLE) model of soil erosion estimation), and topographic wetness index (TWI – an indirect indicator of saturation excess runoff generation). Sinks are localized errors caused due to sampling imperfection and rounding effect during interpolation. Sink removal is a process that removes small imperfections in the raster data (Mark 1988). Hence, the maximum effect of sink removal algorithm on the DEM surface takes place where the DEM surface has a sink and/or flat area which impose difficulty in drainage delineation. The regions of DEM surface outside sink are generally less affected. The descriptive statistics of elevations for different DEMs are presented in Table 1.

Table 1 shows that the minimum and maximum elevations did not change during the sink filling process. There is no difference in minimum and maximum values of original DEM and other processed DEMs which was quite obvious. It was because the minimum and maximum elevations in DEMs corresponded to the outlet and peak points of the catchment. However, there were reasonable differences in mean elevation and standard deviation (SD) of the studied DEMs. The order of departure in the mean values was found to be DEM_JD < DEM_PD < DEM_IRA. The minor difference in mean elevations among the different DEMs is due to the fact that the portions of the DEM surfaces where substantial changes take place are relatively small as compared to the total area of the DEMs. The SD values of all the sink-filled DEMs changed considerably. In all the cases, SD values were found to be less than the SD of raw DEM. This revealed that the spatial variability (information content) of elevation decreased in each of the sink-filled DEMs. The decrease in SD values were found to be in the order of DEM_IRA < DEM_JD < DEM_PD.

Similarly, the maximum and minimum slope values in all the DEMs remained unchanged as compared to their original values in raw DEM (Table 2). The mean slope remained unchanged in case of DEM_IRA and decreased for DEM_JD and DEM_PD by an equal magnitude. In contrast, the SD of the derived slope was found to decrease in all the three DEMs in equal magnitude, demonstrating the loss of slope information in the processed DEMs than in raw DEM.

In order to explore the alteration in the DEM surface caused by various sink removal algorithms, the mean and absolute difference of elevation values (original DEM and processed DEM) were determined which is presented in Table 3. Accordingly, the alteration would certainly be more along the drainage pathway and as we move upward from the drainage pixels, the degree of alteration was supposed to decrease. Hence the alterations of DEM surfaces were determined for the entire DEM, and at a buffer distance of 1000, 2000 and 3000 m from the drainage path.

It is observed that JD and PD methods caused same degree of alteration for the entire DEM surface and at a buffer distance of 1000 m, while the IRA method brought more alteration to original DEM. But at a buffer distance of 2000 and 3000 m, the degree of alteration caused by these sink removal algorithms was found to be in the order of PD < IRA < JD.

Alteration in the original elevation values in DEM surface and efficiency of removal of flat land along with depression, are the important criteria for determining the suitability of the sink removal algorithm. The number of flat pixels in the different DEM surfaces are presented in Figure 1.

From Figure 1, it is clear that the number of flat pixels is highest in raw (original) DEM surface, whereas, they substantially decreased in all the processed DEMs. However, the number of flat pixels is least for DEM processed using PD algorithm followed by DEMs processed using IRA and JD algorithms.

The total stream length and stream frequency (total number of streams) and the total length of streams were determined for each DEM as shown in Table 4.

The stream frequency and stream length derived using sink-filled DEMs were found in the order of DEM_JD > DEM_IRA > DEM_PD which indicate that the sink filling algorithms have a significant effect on the derived stream network quality which will ultimately affect the subsequent hydrologic analysis at the catchment level. Besides these, the location of stream/drainage network and catchment boundary is also affected by the selection of the sink filling algorithm. Figure 2 shows the mean

Table 1. Descriptive statistics for the elevation of different DEMs

	DEM	DEM_JD	DEM_PD	DEM_IRA
Mean	314.157	314.158	314.160	314.103
Min	121.730	121.730	121.730	121.730
Max	1211.91	1211.910	1211.910	1211.910
SD	78.0768	78.013	78.0113	78.0368

Table 2. Descriptive statistics for slope (%) of different DEMs

	DEM	DEM_JD	DEM_PD	DEM_IRA
Mean	1.12	1.10	1.10	1.12
Min	0.00	0.00	0.00	0.00
Max	28.53	28.53	28.53	28.53
SD	2.23	2.21	2.21	2.21

Table 3. Spatial variation in DEM alteration (in m) for different sink removal algorithms

Methods	JD		PD		IRA	
DEM	Mean	Abs mean	Mean	Abs mean	Mean	Abs mean
Entire DEM	2.57	3.33	2.57	3.33	2.67	3.39
Buf1K	3.05	3.81	3.04	3.81	3.16	3.88
Buf2K	0.25	1.11	0.28	1.05	0.29	1.08
Buf3K	0.03	1.08	–0.019	1.06	0.03	1.09

Table 4. Stream frequency and length derived using different sink removal algorithms

Stream order	DEM_JD	DEM_PD	DEM_IRA
Stream frequency	738	695	731
Stream length	1809.43	1722.962	1784.182

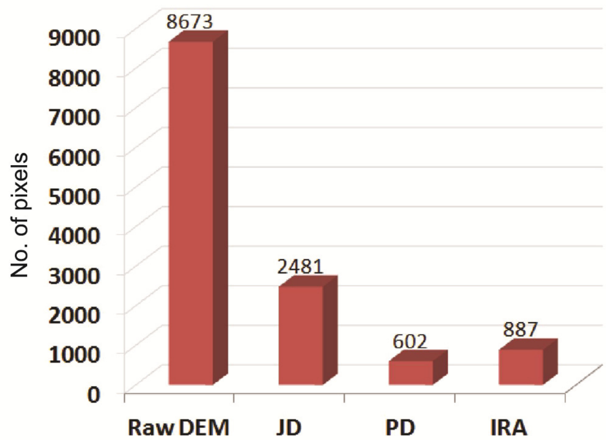

Figure 1. Number of flat pixels on the surface of different DEMs.

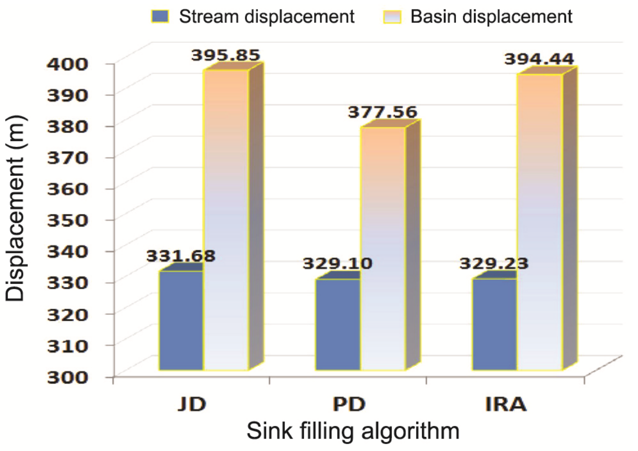

Figure 2. Average stream and basin displacement for different DEMs.

displacement of the stream network and the catchment boundary obtained using different preprocessed DEMs.

Figure 2 demonstrates that none of the drainage networks and basin boundaries are perfect and rather deviate from the original to a different degree. Basin displacement was found to be in the order of DEM_PD < DEM_IRA < DEM_JD, while the average displacement of the stream network was found to be in the order of DEM_IRA < DEM_PD < DEM_JD. Thus, it can be inferred that sink-filled DEM obtained using JD method produced the least quality drainage network and basin boundary in terms of average displacement.

In the above sections, several methods are presented to reveal the changes in original DEM made by the different algorithms. However, it is worth mentioning that there is no single universal criterion to derive a conclusion on the robustness of any algorithm. This is because, the magnitude of error imposed by sink removal algorithm is a complex function of DEM data source, sampling techniques, cell size, interpolation methods and terrain complexity. However, a brief analysis proposed in this study will enable users to get a certain clue on the magnitude of DEM alterations by different sink algorithms implemented in the hydrological model/software, which will help then to reduce a significant amount of uncertainty in the final outcome of any hydrological modelling.

The DEM preprocessing in terms of sink removal is one of the unavoidable exercises in GIS-based hydrological analysis. Literature offers numerous sink removal algorithms and all of them alter the quality of original raw DEM in one way or the other. The present comparative assessment in terms of change in elevation and slope values, spatial variability, degree of DEM alteration in the processed DEMs, showed that the Planchon and Darboux method outperformed the other methods of sink removal. Basin boundary and drainage characteristics derived using DEM_PD also showed good agreement (minimum displacement) with those derived using SOI topographic maps. However, these observations can be site-specific as performances of sink removal algorithms very often depend on the catchment's topographic characteristics. Since such alteration of DEM is inevitable, a robust assessment of DEM preprocessing techniques is recommended for any hydrological application.

1. Sharma, A., Tiwari, K. and Bhadoria, P., Quality assessment of contour interpolated digital elevation models in a diverse topography. *Int. J. Ecol. Dev.*, 2010, **15**, 26–42.
2. Sharma, A., Tiwari, K. and Bhadoria, P., Vertical accuracy of digital elevation model from Shuttle Radar Topographic Mission– a case study. *Geocarto Int.*, 2010, **25**(4), 257–267.
3. Garbrecht, J. and Martz, L. W., The assignment of drainage direction over flat surfaces in raster digital elevation models. *J. Hydrol.*, 1997, **193**(1–4), 204–213.
4. Babu, G. P., Sreenivas, B., Rafique, F. and Edida, R., Importance of breaching and filling for river network extraction using High Resolution DTM. In Second Space for Hydrology Workshop – Surface Water Storage and Runoff: Modeling, *In-Situ* data and Remote Sensing, Geneva, Switzerland, 12–14 November 2007; earth.esa.int/hydrospace07/participants/09_08/09_08_PrasadBabu.pdf (accessed on 11 December 2018).
5. Jenson, S. K. and Domingue, J. O., Extracting topographic structure from digital elevation data for geographic information system analysis. *Photogramm. Eng. Remote Sens.*, 1988, **54**(11), 1593–1600.
6. Wang, L. and Liu, H., An efficient method for identifying and filling surface depressions in digital elevation models for hydrologic analysis and modeling. *Int. J. Geogr. Inf. Sci.*, 2006, **20**(2), 193–213.
7. Planchon, O. and Darboux, F., A fast, simple and versatile algorithm to fill the depressions of digital elevation models. *Catena*, 2002, **46**(2–3), 159–176.
8. Lindsay, J. B. and Creed, I. F., Removal of artifact depressions from digital elevation models: Towards a minimum impact approach. *Hydrol. Process.*, 2005, **19**(16), 3113–3126.
9. Poggio, L. and Soille, P., Influence of pit removal methods on river network position. *Hydrol. Process.*, 2012, **26**(13), 1984–1990.
10. Woodrow, K., Evaluating the effects of DEM properties on the spatial and statistical distribution of hydrological surface attributes. M Sc thesis, University of Guelph, Guelph, 2014.
11. Barnes, R., Lehman, C. and Mulla, D., Priority-flood: An optimal depression-filling and watershed-labeling algorithm for digital elevation models. *Comput. Geosci.*, 2014, **62**(1), 117–127.
12. Pathak, K. and Kaushik, P., Analysis of time complexities and accuracy of depression filling algorithms in DEM IOSR. *J. Comput. Eng.*, 2015, **17**(3), 26–34.
13. Lidberg, W., Nilsson, M., Lundmark, T. and Ågren, A. M., Evaluating preprocessing methods of digital elevation models for hydrological modeling. *Hydrol. Process*., 2017, **31**, 4660–4668.
14. Wei, H., Zhou, G. and Fu, S., Efficient priority-flood depression filling in raster digital elevation models. *Int. J. Digit. Earth*, 2019, **12**(4), 415–427; doi:10.1080/17538947.2018.1429503.
15. Jarvis, A., Reuter, H. I., Nelson, A. and Guevara, E., Hole-filled seamless SRTM data V3. International Centre for Tropical Agriculture (CIAT), Cali, Colombia, 2006.
16. Lindsay, J. B., The terrain analysis system: a tool for hydro-geomorphic applications. *Hydrol. Process.*, 2005, **19**(5), 1123–1130.

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