A simple depression-filling method for raster and irregular elevation datasets

PIN-CHUN HUANG¹ and KWAN TUN LEE^{1,2,*}

¹*Department of River and Harbor Engineering, National Taiwan Ocean Univ., Keelung 202, Taiwan, Republic of China.*

²*Taiwan Typhoon and Flood Research Institute, National Applied Research Lab., Taipei 100, Taiwan, Republic of China.*

**Corresponding author. e-mail: ktleee@ntou.edu.tw*

A variety of methods have been developed to process digital elevation models (DEMs) in order to extract morphological properties of land surfaces. Almost all rely on depression filling to facilitate drainage analysis. This study proposes an intuitive and relatively simple depression-filling algorithm, which is readily applicable to raster and irregular datasets. In this study, topographic data of two watershed areas were provided to test the capability of this new algorithm. The results show that the proposed algorithm can accurately identify the locations of depressions and efficiently assign pseudo flow directions across the filled depressions.

1. Introduction

Douglas (1986) provides one of the earliest series of complete computer algorithms to extract watershed ridges, channel networks, and other topographic features from raster-based digital elevation models. The difference in elevation between adjacent cells is the primary basis used to conduct calculations and make decisions in this and subsequent algorithms (Jenson and Domingue 1988; Lee 1998). Although topographic relief dominates the flow drainage patterns, the assumption of pseudo flow paths for deep potholes, lakes or large flat areas is required and it is the preliminary issue in processing DEM datasets. Earlier studies have proposed methods to detect and remove surface depressions to successfully extract topographic properties from DEMs (Marks *et al.* 1984; Jenson and Domingue 1988; Martz and Garbrecht 1998).

The earliest literature applies an elevation-smoothing method (Marks *et al.* 1984; O'Callaghan and Mark 1984). The algorithm is started by

removing all the single-cell depressions found from a DEM; subsequently, the large closed depressions with flat bottoms are stepwise identified and filled. However, several studies (Freeman 1991; Wang and Liu 2006) have pointed out that the fundamental concept of this method would lead to overestimated areas of depressions and inappropriate locations of pour points in certain situations. To solve this problem, modifications to this approach were provided by adding rules to cope with complex depressions (Martz and Jong 1988; Martz and Garbrecht 1999), although with additional consumption of computer memory and higher cost of computation time.

To accommodate all kinds of spatial distributions of depressions, a more rigorous depression-filling technique was developed (Jenson and Domingue 1988). The fundamental procedure for depression filling can be summarized as follows:

- identify the single-cell depressions;
- mark the depression cells;
- merge the local pits into a large depression;

Keywords. Digital elevation model; depression filling; pseudo flow direction; irregular terrain dataset.

- search the boundary cells of each depression and determine the corresponding pour point;
- uplift the depression cells; and
- assign the pseudo flow directions for depression areas.

Although, their algorithm can directly fill all the cells in a large closed depression, it requires additional running time and complex processing steps to repeatedly seek pour points.

Considering recent developments in light detection and ranging (LiDAR) technology, high-resolution DEMs with cell sizes finer than 5 m are readily

available for applications. Consequently, the efficiency of identifying depressions for high-resolution topographic data and the capability to handle various formats of datasets are the two essential issues. An innovative idea to treat the depressions in raster DEMs was subsequently proposed by Wang and Liu (2006), who established a simplified approach to seek the locations of pour points before identifying the depression cells. Their algorithm enhanced the computational efficiency in comparison with the aforementioned methods.

This study developed an intuitive and simple concept to fill depressions in order to easily accommodate both

Figure 1. Different types of depression in DEM datasets.

Figure 2. Schematic diagrams for depression-filling process.

raster and irregular (TIN) datasets. Moreover, the process to cope with the flow directions for depression cells is simplified by creating the pseudo elevation descents in depression areas. In subsequent sections of this paper, step-by-step procedure for depression filling is illustrated with a series of diagrams. Two watersheds were selected to test the

efficiency and applicability of the proposed method. Computational costs of depression-filling treatment by employing other algorithms as well as the RiverTools commercial software are provided for comparison. The distribution of depression areas and drainage network obtained by implementing the Arc Hydro Tools are also presented.

	C1	C2	C3	C4	C5	C6	C7	C8
R1	28	23	24	22	20	22	25	27
R2	25	21	20	18	18	21	17	26
R3	25	22	17	18	18	19	23	25
R4	24	20	18	18	18	18	21	24
R5	23	18	18	17	18	21	22	23
R6	25	22	18	18	18	18	20	22
R7	26	23	20	23	20	21	18	22
R8	28	29	27	25	24	22	21	18

(a) Original dataset

	C1	C2	C3	C4	C5	C6	C7	C8
R1	28	23	24	22	20	22	25	27
R2	25	21	20	18	18.1	21	19.1	26
R3	25	22	18.1	18.1	18.1	19	23	25
R4	24	20	18	18	18	18.1	21	24
R5	23	18.1	18	18.1	18.1	21	22	23
R6	25	22	18.1	18.1	18.1	18.1	20	22
R7	26	23	20	23	20	21	18.1	22
R8	28	29	27	25	24	22	21	18

(b) 1st round

	C1	C2	C3	C4	C5	C6	C7	C8
R1	28	23	24	22	20	22	25	27
R2	25	21	20	18.2	18.2	21	19.1	26
R3	25	22	18.1	18.1	18.1	19	23	25
R4	24	20	18.1	18.1	18.2	18.2	21	24
R5	23	18.1	18.2	18.2	18.2	21	22	23
R6	25	22	18.2	18.2	18.2	18.2	20	22
R7	26	23	20	23	20	21	18.1	22
R8	28	29	27	25	24	22	21	18

(c) 2nd round

	C1	C2	C3	C4	C5	C6	C7	C8
R1	28	23	24	22	20	22	25	27
R2	25	21	20	18.2	18.2	21	19.1	26
R3	25	22	18.2	18.2	18.2	19	23	25
R4	24	20	18.2	18.3	18.3	18.3	21	24
R5	23	18.3	18.3	18.3	18.3	21	22	23
R6	25	22	18.3	18.3	18.3	18.2	20	22
R7	26	23	20	23	20	21	18.1	22
R8	28	29	27	25	24	22	21	18

(d) 3rd round

	C1	C2	C3	C4	C5	C6	C7	C8
R1	28	23	24	22	20	22	25	27
R2	25	21	20	18.3	18.3	21	19.1	26
R3	25	22	18.3	18.3	18.4	19	23	25
R4	24	20	18.4	18.4	18.4	18.4	21	24
R5	23	18.4	18.4	18.4	18.4	21	22	23
R6	25	22	18.4	18.4	18.3	18.2	20	22
R7	26	23	20	23	20	21	18.1	22
R8	28	29	27	25	24	22	21	18

(e) 4th round

	C1	C2	C3	C4	C5	C6	C7	C8
R1	28	23	24	22	20	22	25	27
R2	25	21	20	18.4	18.4	21	19.1	26
R3	25	22	18.4	18.5	18.5	19	23	25
R4	24	20	18.5	18.5	18.5	18.5	21	24
R5	23	18.5	18.5	18.4	18.4	21	22	23
R6	25	22	18.5	18.4	18.3	18.2	20	22
R7	26	23	20	23	20	21	18.1	22
R8	28	29	27	25	24	22	21	18

(f) 5th round

	C1	C2	C3	C4	C5	C6	C7	C8
R1	28	23	24	22	20	22	25	27
R2	25	21	20	18.5	18.6	21	19.1	26
R3	25	22	18.6	18.6	18.6	19	23	25
R4	24	20	18.5	18.5	18.5	18.5	21	24
R5	23	18.6	18.5	18.4	18.4	21	22	23
R6	25	22	18.5	18.4	18.3	18.2	20	22
R7	26	23	20	23	20	21	18.1	22
R8	28	29	27	25	24	22	21	18

(g) 6th round

	C1	C2	C3	C4	C5	C6	C7	C8
R1	28	23	24	22	20	22	25	27
R2	25	21	20	18.7	18.7	21	19.1	26
R3	25	22	18.6	18.6	18.6	19	23	25
R4	24	20	18.5	18.5	18.5	18.5	21	24
R5	23	18.6	18.5	18.4	18.4	21	22	23
R6	25	22	18.5	18.4	18.3	18.2	20	22
R7	26	23	20	23	20	21	18.1	22
R8	28	29	27	25	24	22	21	18

(h) 7th round

Figure 3. Depression filling for the example raster DEM dataset.

2. Proposed method

2.1 Fundamental concept

As shown in figure 1, depressions can be categorized as:

- single-cell pit,
- flat area,
- closed depression containing several local pits, and
- closed depression containing a flat area.

In handling closed depressions, the assignation of pseudo flow directions is required to construct a complete drainage network. Although the treatment of closed depressions as well as the pseudo flow directions has been widely discussed (Marks *et al.* 1984; O'Callaghan and Mark 1984; Jenson and Domingue 1988; Martz and Jong 1988; Martz and Garbrecht 1999; Liang and Mackay 2000), all repeatedly seeking the locations of pour points require a process that reduces computational efficiency.

This study exploits a simple concept for the depression-filling algorithm. Figure 2 shows a series of schematic diagrams to illustrate the proposed method. Figure 2(a) is an original terrain represented

by six connected cells, where the outlet is located at C6 and two local pits (C2 and C4) are found. In the first round of filling (figure 2b), each local pit is individually raised to a new elevation equal to the lowest elevation among the eight adjacent cells, and is then raised by an additional small value. Although, the two original pits are removed during the first round of filling, the small increment of elevation produces a new local pit at C3. The new generated local pit (C3) is filled and raised by an additional small increment in the second round (figure 2c). The same procedure is repeatedly conducted until no local pit is found. Figure 2(f) shows the final state of the depression filling. Although, an iterative filling process is required to handle depressions, the descent path shown in figure 2(f) is imposed with no additional processing. There is no need to specifically seek the locations of pour points and cope with the flow directions of depression cells.

2.2 Algorithm for raster datasets

An 8×8 raster DEM shown in figure 3(a) is used in this section to clarify the proposed depression-filling method. The algorithm is implemented

Figure 4. Variation of local pits in the depression-filling process for the example raster DEM dataset.

	C1	C2	C3	C4	C5	C6	C7	C8
R1	28	23	24	22	20	22	25	27
R2	25	21	20	18.7	18.7	21	19.1	26
R3	25	22	18.6	18.6	18.6	19	23	25
R4	24	20	18.5	18.5	18.5	18.5	21	24
R5	23	18.6	18.5	18.4	18.4	21	22	23
R6	25	22	18.5	18.4	18.3	18.2	20	22
R7	26	23	20	23	20	21	18.1	22
R8	28	29	27	25	24	22	21	18

(a) Depression filled dataset

	C1	C2	C3	C4	C5	C6	C7	C8
R1	-	-	-	-	-	-	-	-
R2	-	↖	↓	↓	↓	←	↖	-
R3	-	→	↓	↓	↓	↓	←	-
R4	-	↓	↘	↘	↓	↘	←	-
R5	-	→	→	→	→	↓	↓	-
R6	-	→	→	→	→	↘	↓	-
R7	-	↖	↑	↑	↑	→	↘	-
R8	-	-	-	-	-	-	-	○

(b) Flow direction assignation

Figure 5. Updated elevation values and pseudo flow directions in the example raster DEM dataset.

starting at R2-C2 and the sequence followed from the upper left corner to the lower right corner. The first cell required to be uplifted is located at R2-C5 with an original elevation of 18. A small elevation increment (in this case 0.1) is added to obtain a new elevation of 18.1 ($18+0.1$). Subsequently, the elevation at R2-C7 is uplifted to 19.1, according

to the lowest elevation at R3-C6 among the eight adjacent cells. Although only nine pits (i.e., R2-C5, R2-C7, R3-C3, R3-C5, R4-C6, R5-C2, R5-C4, R6-C6, and R7-C7) are found in the original elevation data (figure 3a), new pits are successively produced while conducting this algorithm. For example, after the local pit at R3-C3 is raised to 18.1, a new pit

Figure 6. Original dataset and routing sequence of the example TIN dataset.

Figure 7. Variation of local pits in the depression-filling process for the example TIN dataset.

Figure 8. Updated elevation values and pseudo flow directions in the example TIN dataset.

at R3-C4 is generated and it should be uplifted in the same way. Figure 3(b) shows the result after the first round of filling. The cells shaded gray denote

that their elevations are changed during the current round. The subsequent filling rounds can be seen from figure 3(c–h), in which the elevation values are

Figure 9. Comparison of different algorithms for depression filling.

Figure 10. Depression-filling treatment by using Jenson and Domingue's method.

marked blue if they have been altered before the current round. The filling treatment is iteratively conducted until all the pits are uplifted. Figure 4 shows the variation in the number of pits during each round of filling. It is shown that the number of pits is eventually decreased to zero. Figure 5(a) shows the elevation data after completing all depression-filling rounds. The pseudo elevations in depression areas can be directly used to assign flow directions as shown in figure 5(b), which indicates

that the pseudo flow paths can successfully be assigned to the right pour point at R8-C8.

2.3 Algorithm for irregular datasets

One of the merits of the proposed algorithm is the capability to treat depressions for irregular DEM datasets. The triangular irregular network (TIN) is the most efficient approach to represent the land

Figure 11. Depression-filling treatment by using the proposed method.

Figure 12. Flow chart of the proposed method for depression filling.

surface. This method has been widely employed to develop distributed models for watershed hydrological simulations (Goodrich *et al.* 1991; Ivanov *et al.* 2004; Qu and Duffy 2007). Figure 6(a) shows a TIN dataset, consisting of a set of non-overlapping contiguous triangular facets. To cope with the irregular datasets, arranging the routing sequence of each facet is necessary before conducting the depression-filling algorithm. As shown in figure 6(b), following the predetermined routing sequence, the analysis approach illustrated in the previous section can be implemented until all the pits have been removed. Figure 7 shows a decline in the number of pits during the filling rounds. No pit is found after the ninth round. Figure 8(a) shows the TIN dataset

after the depression-filling treatment. The depressionless dataset can be directly used to determine the flow directions according to the steepest descent as shown in figure 8(b).

2.4 Execution of proposed method

The proposed method is capable of improving the efficiency for depression filling. As shown in figure 9, the proposed analysis procedure is simpler than that provided by Jensen and Domingue (1988), which has been widely implemented in commercial packages. The depression treatment following the procedure proposed by Jensen and Domingue

(a) Geographical location of the Tou-Chien River Basin

(b) Different sizes of DEM datasets used for depression filling

Figure 13. Location and topography of the Tou-Chien River Basin.

(1988) is shown in figure 10. Complicated processes such as marking the depression cells, merging the contiguous depressions, and searching for the pour point, are required to handle each depression. The checking procedures (figure 10a–e) are repeatedly conducted until all the depression areas have been uplifted. The final result of the filling treatment is shown in figure 10(f). However, as shown in

figure 11, the proposed algorithm can cope with all the single-cell pits in the DEM at each round of identification to avoid the tedious processes as illustrated in figure 10. The difference of computation time between the proposed algorithm and the Jensen and Domingue's method would be substantial if the elevation data contains an abundance of depressions.

(a) Geographical location of the Walnut Gulch Watershed

(b) DEM datasets used for depression filling

Figure 14. Location and topography of the Walnut Gulch Watershed.

Table 1. Computational efficiency of the proposed method for depression filling and flow direction determining.

Row	Column	DEM datasets	CPU time (s)			
		Ratio of depression areas (%)	Proposed method	RiverTools	Wang and Liu	Jensen and Domingue
200	200	28.6	1	1	5	32
500	500	22.1	2	17	41	268
1000	1000	16.5	6	94	127	1968
2000	2000	13.4	59	235	309	35,062
4000	4000	5.7	273	872	1191	–
6000	6000	3.0	425	1637	2143	–

A flow chart (figure 12) is provided to show the execution of the proposed algorithm. In this flow chart, the number of single-cell pits N is counted at each round. The algorithm is iteratively implemented until the N value declines to zero. It should be noted that the small increment adopted in this algorithm for depression filling mainly depends on the vertical resolution of the DEM dataset. If the maximum length of the depression in the DEM dataset is about m cells, the small increment should be set about $1/m$ of the vertical resolution for depression filling.

3. Results and discussion

To investigate the performance of the proposed algorithm in real watersheds, DEM datasets from two watersheds, a steep one and a mild one, were collected for the tests. As shown in figure 13, the Tou-Chien River Basin is located in the northwest

of Taiwan. The drainage area is 431 km^2 and the average slope of the watershed is 0.717. Figure 14 shows the location and topography of the Walnut Gulch Watershed. Walnut Gulch is a major tributary of the upper San Pedro River in south-eastern Arizona, United States of America. The drainage area is 149 km^2 and the average slope is 0.113. In the following sections, the DEM dataset from the Tou-Chien River Basin is adopted to test the efficiency of the proposed algorithm, and the dataset from the Walnut Gulch Watershed is used to demonstrate the accuracy of depression identification and stream network extraction of the proposed algorithm.

3.1 Tou-Chien River Basin

As shown in figure 13, six sizes of DEM datasets (200×200 , 500×500 , 1000×1000 , 2000×2000 , 4000×4000 , and 6000×6000 cells) in 5 m resolution were selected for the tests. Table 1 shows the results

Figure 15. Depression areas in the Tou-Chien River Basin identified by different algorithms.

of the CPU tests obtained by using the proposed method, the algorithm developed by Jensen and Domingue (1988), the widely discussed method proposed by Wang and Liu (2006), and the RiverTools software in version 2.4. In order to highlight the difference in CPU time, all the tests were performed on a personal computer with a 2.67 GHz Intel Core i3 processor and 2.99 GB of RAM instead of being implemented on a high speed computer. As shown in table 1, the difference of running time was apparent when a massive dataset was adopted. For the 2000×2000 -cell DEM dataset, the method proposed by Jensen and Domingue (1988) required

35,062 s (9.7 hr) to identify the depressions and determine the flow directions, whereas the proposed algorithm only required 59 s (0.016 hr). In considering that the CPU time would be extremely long by Jensen and Domingue's method, the more massive DEM datasets larger than 2000×2000 -cell were not performed. It is shown that the proposed algorithm outperformed the Jensen and Domingue's method by a factor of 30–590. In this case, the efficiency of the proposed algorithm was also better than that of Wang and Liu's algorithm and the RiverTools software. The spatial distribution of depressions identified by the proposed

Figure 16. Distribution of depressions in the Walnut Gulch Watershed.

method was compared with that generated from the RiverTools. As shown in figure 15, the locations of depressions obtained from the RiverTools (figure 15a) are identical to those identified by the proposed algorithm (figure 15b).

3.2 Walnut Gulch Watershed

The proposed algorithm was further tested in the Walnut Gulch Watershed which is a lower relief

relative to the Tou-Chien River Basin. The DEM dataset of the Walnut Gulch Watershed, having a horizontal resolution of 10 m and vertical resolution of 0.1 m, was provided by the United States Department of Agriculture (USDA). The commercial package Arc Hydro Tools was adopted to establish the validity of the proposed method. Figure 16(a) shows the spatial distribution of depressions identified by the Arc Hydro Tools, in which a total of 37,743 cells were recognized as depressions in Walnut Gulch Watershed. The depressions

(a) Arc Hydro Tools

(b) Proposed method

Figure 17. Extraction of drainage networks from the Walnut Gulch Watershed (the threshold area is set as 50,000 m²).

identified by using the proposed algorithm are shown in figure 16(b) for comparison. In performing the proposed algorithm, the small increment for the depression filling process was set as 0.0001 m. It can be shown that the two figures have identical spatial distribution for the depressions generated using different algorithms; moreover, the depression area detected by the proposed algorithm also covers 37,743 cells.

Based on the flow direction of the cells, the flow accumulation value of each cell can be used to extract stream network of the watershed. Figure 17 shows the stream networks extracted by using the Arc Hydro Tools and proposed algorithm, in which the threshold area was set as 50,000 m². Although the pseudo flow directions assigned in the depression areas depend on the assumption of the algorithm, similar spatial distributions of the stream networks are found as manifested in figure 17(a and b).

4. Conclusions

Depression-filling treatment is conducted to ensure that each cell in depressions can be assigned a flow direction to drain water to the watershed outlet. This study proposed a simple and intuitive way of depression filling. There are two main advantages of the proposed method. First, the concise concept makes the algorithm readily applicable to irregular dataset. Second, the pseudo elevation descent can be generated as long as the depression-filling treatment is complete; hence, tedious processes to merge the depressions and search for the pour point can be omitted. In this study, a raster DEM dataset of the Tou-Chien River Basin in Taiwan was used to demonstrate the efficiency of the proposed method. The results indicated that the proposed method outperformed Jenson and Domingue's method by a factor of 30–6000, and the proposed method was about 3–15 times faster than RiverTools software. Although the efficiency of the proposed method is not guaranteed to surpass all existing commercial packages, the cost of CPU time using a personal computer was satisfactory. Another DEM dataset from the Walnut Gulch Watershed in U.S. was used to show that the spatial distribution of depressions and drainage network determined by the proposed method were identical to those obtained from the Arc Hydro Tools.

Acknowledgements

This research was supported by the Ministry of Science and Technology, Taiwan, ROC, under grant NSC 103-2923-E-019-001-MY3. Digital elevation datasets provided by Taiwan Aerial Survey Office, Forestry Bureau, and Agricultural Research Service, United States Department of Agriculture are gratefully acknowledged.

References

- Douglas D H 1986 Experiments to locate ridges and channels to create a new type of digital elevation model; *Cartographica* **23**(4) 29–61.
- Freeman T G 1991 Calculating catchment area with divergent flow based on a regular grid; *Comput. Geosci.* **17** 413–422.
- Goodrich D C, Woolhiser D A and Keefer T O 1991 Kinematic routing using finite elements on a triangular irregular network; *Water Res. Res.* **27**(6) 995–1003.
- Ivanov V Y, Vivoni E R, Bras R L and Entekhabi D 2004 Catchment hydrologic response with a fully distributed triangulated irregular network model; *Water Resour. Res.* **40** 11, doi: 10.1029/2004WR003218.
- Jenson S K and Domingue J O 1988 Extraction topographic structure from digital elevation data for geographic information system analysis; *Photogramm. Eng. Remote Sens.* **54**(11) 1593–1600.
- Lee K T 1998 Generating design hydrographs by DEM assisted geomorphic runoff simulation: A case study; *J. Am. Water Resour. Assoc.* **34**(2) 375–384.
- Liang C J and Mackay D S 2000 A general model of watershed extraction and representation using globally optimal flow paths and up-slope contribution areas; *Int. J. Geogr. Infor. Sci.* **14**(4) 337–358.
- Marks D, Dozier J and Frew J 1984 Automated basin delineation from digital elevation data; *Geo-Processing* **2** 299–311.
- Martz L W and Jong E D 1988 CATCH: A Fortran program for measuring catchment area from digital elevation models; *Comput. Geosci.* **14** 627–640.
- Martz L W and Garbrecht J 1998 The treatment of flat areas and closed depressions in automated drainage analysis of raster digital elevation models; *Hydrol. Process.* **12** 843–855.
- Martz L W and Garbrecht J 1999 An outlet breaching algorithm for the treatment of closed depressions in a raster DEM; *Comput. Geosci.* **25** 835–844.
- O'Callaghan J and Mark D M 1984 The extraction of drainage networks from digital elevation data; *Comput. Vision Graphics Image Process* **28** 323–344.
- Qu Y and Duffy C J 2007 A semi-discrete finite volume formulation for multiprocess watershed simulation; *Water Resour. Res.* **43** 8, doi: 10.1029/2006WR005752.
- Wang L and Liu H 2006 An efficient method for identifying and filling surface depressions in digital elevation models for hydrologic analysis and modeling; *Int. J. Geogr. Infor. Sci.* **20**(2) 193–213.