IOSR Journal of Computer Engineering (IOSR-JCE)
e-ISSN: 2278-0661,p-ISSN: 2278-8727, Volume 17, Issue 3, Ver. V (May – Jun. 2015), PP 26-34
www.iosrjournals.org

Analysis of Time Complexities and Accuracy of Depression Filling Algorithms in DEM

Kritika Pathak[1] and Praveen Kaushik[2]
Department of Computer Science and Engineering Maulana Azad National Institute of Technology, Bhopal, M.P.,India

Abstract: *The recent development of digital representation has stimulated the development of automatic extraction of topographic and hydrologic information from Digital Elevation Model (DEM). A DEM is used to create hydrologic models which can be used for various purposes such as predicting stream discharges, river network definition, estimating flood extent and timing, locating areas contributing pollutants to a stream, and simulating the effects of landscape alterations on surface water runoff. DEM is processed to produce accurate stream delineation. The process includes filling of sinks and depressions, treating flat areas and determining flow direction at every pixel. Depressions (or pits) and flat surfaces (or flats) are general types of terrain in raster digital elevation models. Depressions are lower areas surrounded by terrain without outlets and flat surfaces are areas with no local gradient. The problem with these pits and depressions is that they interrupt continuous flow paths in DEMs. To avoid these problems, all pits have to be rectified and create a depressionless DEM before calculating flow directions or any related topographic parameters. Various algorithms like Jenson and Dominigue, Planchon and Darboux, Carving etc. have been developed to treat the sinks, depressions and flat areas. The conventional methods are computationally intensive and time consuming. Moreover they are inadequate for high resolution DEMs. The conventional algorithms for creating a depressionless DEM have time complexity of* $\boldsymbol{O(n^2)}$ *where n is the number of cells.*
Drainage networks obtained after processing the DEM should be accurate. At the same time it is desirable to simplify the automatic extracting procedure with minimum modification to retain its originality. Recent improvements are successful in reducing the complexity to ***O(nlogn)*** *with accuracy, minimum space and time requirement and less modifications to pixels. This survey analyses on various conventional approaches to fill depressions, their time complexities, advantages, limitations and evolution of modern methodologies with improved time requirements and accuracy.*

I. Introduction:

A DEM is a digital representation of a continuous terrain surface and consists of a two-dimensional array of elevation values at regularly spaced ground positions. To create a fully connected and fully labeled drainage network and watershed partition, water outflow at every grid cell of the DEM needs to be routed to an outlet on the border of the DEM[3][6][7][18]. Nevertheless, the frequent presence of surface depressions in the DEM prevents simulated water flow from draining into outlets, resulting in disconnected stream-flow patterns and spurious interior sub-watersheds pouring into these depressions. Due to the undesirable results, surface depressions in DEMs are treated as nuisance features in hydrologic modelling[11]. The common practice is to locate and remove surface depressions in the DEM at the very first step of hydrologic analysis. Only then the flow directions can be determined[1][2][8]. Marks et al. and O'Callaghan in 1984 were the first to give solution to this depression problem. They developed a method to fill surface depressions based on the identification of the pour point for each depression. The algorithm applies a smoothing filter to remove problematic feature which causes information loss in non problematic regions and hence interfere with the originality of DEM. Jenson and Domingue[16] in 1988 developed a method which is faster and more operationally viable. The J&D algorithm consists of two steps to handle depressions. The first step fills all depressions containing a single cell by raising each cell's elevation to the lowest elevation of its neighbors. The second step fills complex depressions containing more than one cell. Its time complexity is $O(n^2)$. Therefore it is inadequate for large data sets.

Planchon and Darboux(2001)[5] proposed an algorithm which is faster than Jenson and Dominigue. The P&D algorithm first inundates the surface by assigning a maximal water surface elevation to all DEM cells, and then, it iteratively drains excess water from every cell. Despite its simplicity and delicacy, this algorithm remains difficult to understand due to its three complex subroutines and its recursive execution.

An alternative approach Carving[10] was proposed by Soille (2004). It suppresses each single pit by creating a descending path from it to the nearest point having a lower elevation value. This method is easy to implement but it significantly reduces accuracy by interfering with the originality of DEM. Therefore, a new hybrid approach[23] was introduced which combines both approaches of pit filling and carving. It minimizes the cost necessary for transforming an input digital elevation model into a pitless digital elevation model.

While searching for outlet of pit or flat, the methods described above only check the eight adjacent cells of pit or flat and do not consider the general trend of the DEM. The actual drainage lines and the stream line network obtained by above methods are different. A heuristic approach was introduced later in which the direction of flow is determined by finding the direction of maximum drop from each cell to its eight adjacent neighbors. This algorithm is based on Dynamic programming and comparatively slow.

Wang and Liu presented a Priority-flood Algorithm[9][17][24]. All the edge cells of the DEM are pushed into a priority queue(which internally forms a min- heap) for processing. This algorithm processes depressions from the edge cells of the DEM to the interior cells. The worst case time complexity of this algorithm is **O(nlogn).** It is faster than all other filling algorithms.

A new approach, unlike all existing methods was introduced to reduce the processing time from **O(nlogn)** to **O(n).** This is called as Quantile Classification method[14]. The DEM is classified in eight groups and then the algorithm is applied. It is thousand times faster than Jenson and Dominigue's method and seven times faster than Planchon and Darboux's method.

A mathematical approach includes Linear Interpolation method[22] which treats flat areas and depressions. It provides a natural way to scale elevation adjustments with minimum modification which is an advantage over conventional approaches.

II. Creating a depressionless DEM and removing pits and Flats:

A depression is also known as a sink or pit. It is a local minimum that does not have a down slope flow path to any adjacent cells in a DEM. A surface depression may consist of one or a group of spatially connected cells of the same elevation that are completely surrounded by other cells at a higher elevation. Depressions in DEMs can be natural, real landscape features or spurious artefacts. Spurious depressions represent imperfections in DEMs. They may arise from input-data errors, interpolation defects during DEM generation, truncation or rounding of interpolated values to lower precision, or averaging of elevation values within grid cells.

In fact, depressions within DEMs are often a combination of actual topographic depressions and artificial depressions caused by various data collection and processing. Research has shown that depressions interrupt overland flow routing in a DEM and significantly alter defined flow directions used for hydrological parameter extraction.

The algorithm used for the former group applies a smoothing filter to remove problematic features. The smoothing operation is effective in removing artificial depressions, but it usually causes information loss in non problematic regions of the DEM. To preserve the original information of the DEM, over smoothing should be avoided; however, this has been proven difficult to control.

A number of algorithms are available to deal with pits in DEMs. They can be categorized into three main classes according to their approach of rectifying pits[4][19].

a. **Incremental methods**: fill pits by increasing their elevation value until their lowest pour point is reached.
b. **Decremental methods**: where values along a path starting from the bottom of the pit and reaching a pixel of lower elevation value are decremented by setting their elevation value to that of the bottom of the pit.
c. **Hybrid methods:** combining incremental and decremental methods.
d. **Heuristic Approach:** uses Dynamic Programming approach.

2.1 Incremental methods:

2.1.1 Jenson and Domingue algorithm (J&D):The J&D algorithm[16] consists of two steps to handle depressions. The first step fills all depressions containing a single cell by raising each cell's elevation to the lowest elevation of its neighbors (pour points).The second step fills complex depressions containing more than one Cell. This is achieved by identifying and labeling the interior catchments of depressions by calculating the flow directions for every cell in the DEM. Instead of filling depressions one by one, 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. Among all the pour points on the path, the one with the highest elevation is selected as the threshold. Then, all cells in the interior catchments of the depressions, which are 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 the J&D algorithm can accommodate complex depressions and flat surfaces, its **time complexity is $O(n^2)$,** thus clearly making it inadequate for large data sets.

2.1.2 Planchon and Darboux Method: Planchon and Darboux[5] introduced a pit filling algorithm which reduces the time complexity of the existing algorithm The new method involves two basic stages. The P&D

algorithm first inundates the surface by assigning a maximal water surface elevation to all DEM cells. i.e. the surface *W* is initialized with infinite altitudes except for the boundaries. It iteratively drains excess water from every cell i.e. Altitudes of the surface *W* are decreased iteratively. With a seed cell (a cell that is used to generate a dependence graph) as the root, an upstream tree is progressively searched by following the dependence links, and excess water is removed for all cells on the tree.During the 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 the 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 keep the same as before inundation.The DEM handled by the P&D algorithm has neither depressions nor flat surfaces (depressions have been filled and increments added to the flat surfaces); therefore, it is easy to extract flow directions from the DEM. The terrain makes the time complexity of the P&D algorithm unstable, ranging from **$O(n^{1.2})$**, on average, to **$O(n^{1.5})$,** for the worst case. In addition, the P&D algorithm adds increments directly to the DEM's elevation, which might entail a significant alteration of the DEM. Figure 1 shows how much time is reduced by using this algorithm over J&D.

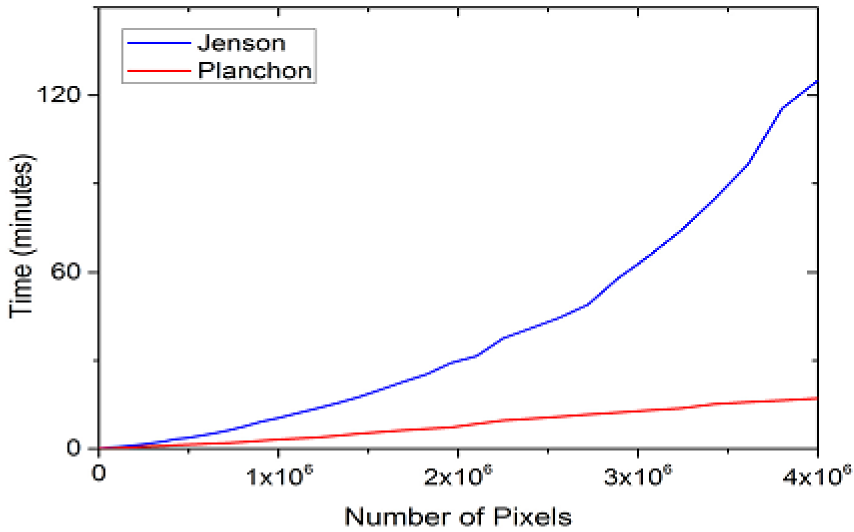


Figure 1

Analysis of Figure 1: The earliest approach J&D method is very time consuming and inefficient for large DEMs as compared to P&D algorithm. For small sized DEMs any one of the above two algorithms can be used. The performance difference varies by 0.581 deviation for small DEM s. But as the size of pixels increases from $0.5*10^6$ to $4*10^6$, the standard deviation shows steepest increase from 2.51 to 42.06 with a very large variance of 1769.04 in case of J&D algorithm. While in case of P&D algorithm, the deviation from 2 to 5.301 is acceptable for DEM growing large in size with upcoming technologies. A small variance of 28.1 serves the purpose. Hence it is more suitable to use this algorithm with large DEMs of high resolutions.

2.1.3 Priority-flood algorithm (Wang and Liu): A new Priority flood algorithm or W&L algorithm has been a stardom among all the algorithms which has been continuously improving and accepted in 2013[9][17][24].The W&L algorithm consists of two parts. The first part is to initialize the algorithm by pushing all of the edge cells of the DEM into a priority queue and marking these cells with a Boolean array. In the priority queue, a cell with lower elevation has greater priority, and the cell with the lowest elevation in the priority queue is always the cell popped first. The second part is an iterative process .In each iterative step, a cell is popped from the priority queue (this cell is called the center cell, and its elevation is the current lowest spill elevation), and its neighbors are traversed. When an adjacent cell is unprocessed and lower than the center cell (a depression), the adjacent cell's elevation is raised to that of the center cell, and it is pushed into the priority queue. When an adjacent cell is unprocessed and it is not lower than the center cell, the adjacent cell is pushed into the priority queue directly. The W&L algorithm finishes when the priority queue is empty. It reduces the time complexity to **O(nlogn)**.

The reduced time complexity is followed by some limitations. Each cell is sorted with its elevation in the priority queue to determine the priority, but the cells of depressions or flat surfaces have the same elevation (the depressions become flat surfaces after being filled); thus, there is no need to sort these cells. The W&L algorithm only fills depressions; it does not add increments to flat surfaces.

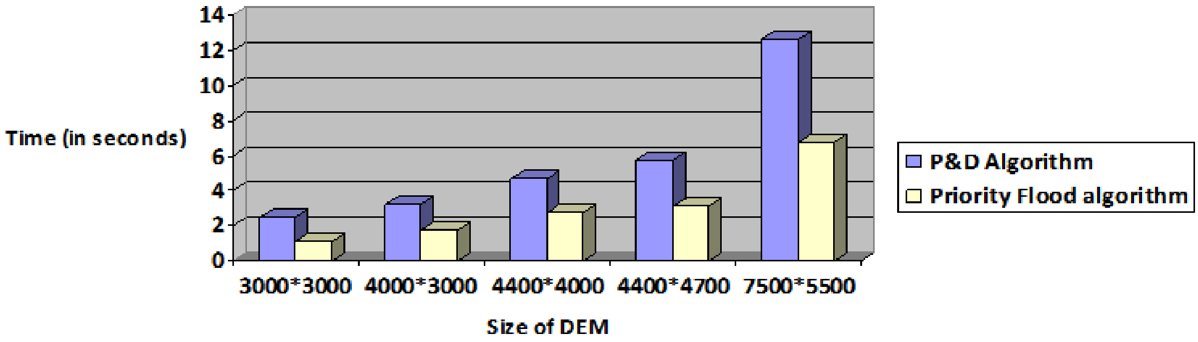


Figure 2

Analysis of Figure 2: It is clear from the figure that performance of Priority flood algorithm outperforms P&D method for small as well as large DEMs. For small DEMs within the range of 4000*4000 pixels, the time difference is between the two is quite less which lies between 1.38 to 1.91 seconds. As the size of DEM increases to 7000* 5500 pixels, the time required to execute P&D algorithm increases rapidly from 5.75 to 12.67 seconds while in Priority Flood, it is much less. i.e. 3.1 to 6.75. The deviation is much more higher in P&D method which is 4.0743. Therefore it is not suitable for large DEMs.

2.1.4 Quantile classification Method: A new innovative approach, unlike all existing methods that process DEM data straightforward without utilizing the topographic features implied in them, was proposed in this study to improve the DEM-processing efficiency. First, classify the initial DEM data into eight groups according to the elevation values using the quantile classification method, and set each category cell values to its quantile and store them in a transient matrix[14]. Second, scan the transient matrix from the minimum category to the maximum one, restore its initial value if its initial value is larger than or equal to its neighbor's, else set its value to the minimum of its neighbor's if its quantile is larger than its neighbor's and repeat this process until all the depressions are filled.

Furthermore, unlike the traditional method, which have to scan all the DEM cells in each loop, the new one only scan the data needed to be further processed by storing their location information into two stacks. As a result, the total cells and scanning times are dramatically decreased .It helps improving the accuracy and also does less modifications on DEM to retain the originality.

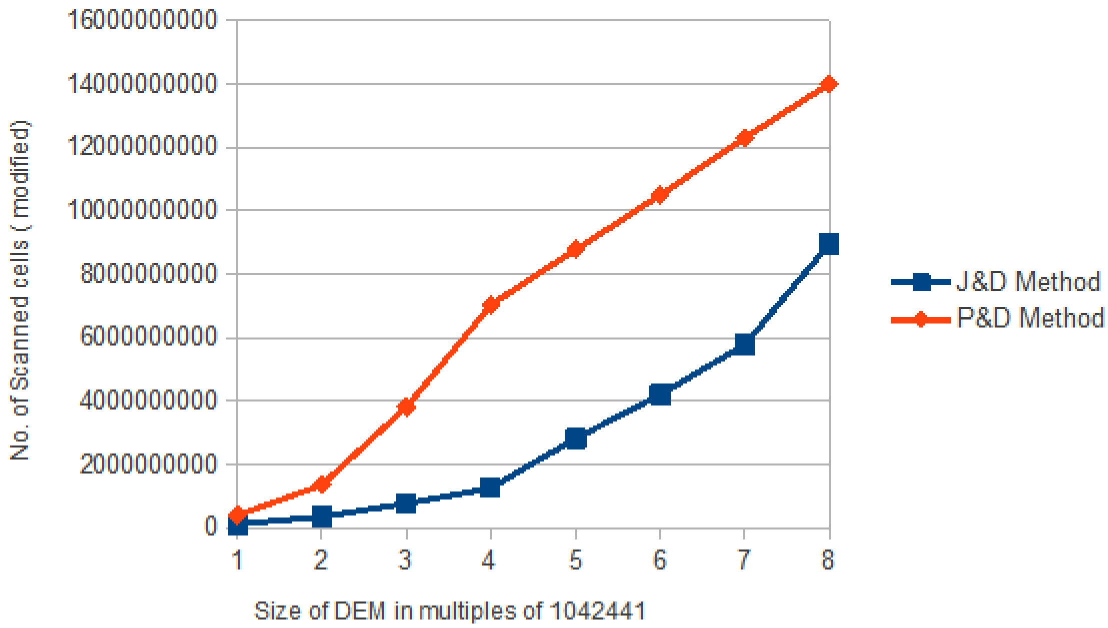


Figure 3

Analysis of Figure 3: We can conclude that more number of alterations are required to execute P&D algorithm for the DEM of the same size. For J&D method, the deviation for initial 2 points is 177528401.48. As the size of DEM increases to 8* 1042441, it shows a steeper increase in deviation up to 3095436120.77. However, P&D

algorithm performs ample of modifications. The deviation varies from 694088130.811 for small DEMs to 5298336085.73 for large DEMs, which is much higher than J&D algorithm.

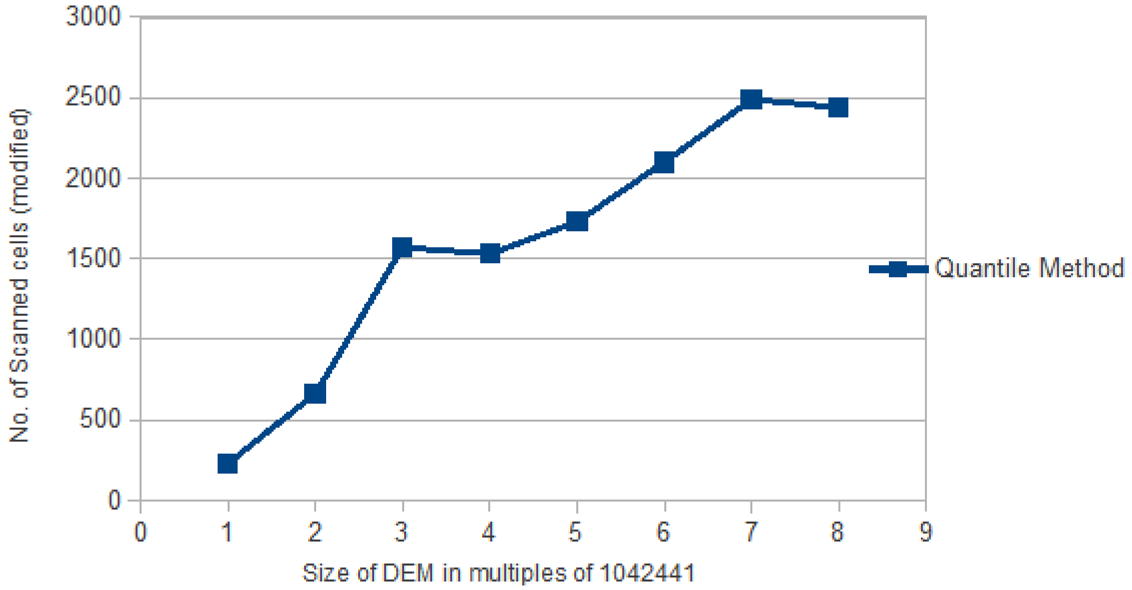


Figure 4

Analysis of figure 4: While executing quantile classification approach, the number of cells modified increases from 229 for small DEMs of size 1*1042441to 2440 for large DEMs of size 8*1042441. The curve shows a constant increase in variation up to 683.91 when the size of DEM reaches to 3*1042441. A slight decrease in number of modified cells reduces the overall deviation amount to 661.25 for DEM of size 4* 1042441. It shows a linear increase in number of modified cells with rise in deviation upto 785.8019 which is much less than conventional methods.

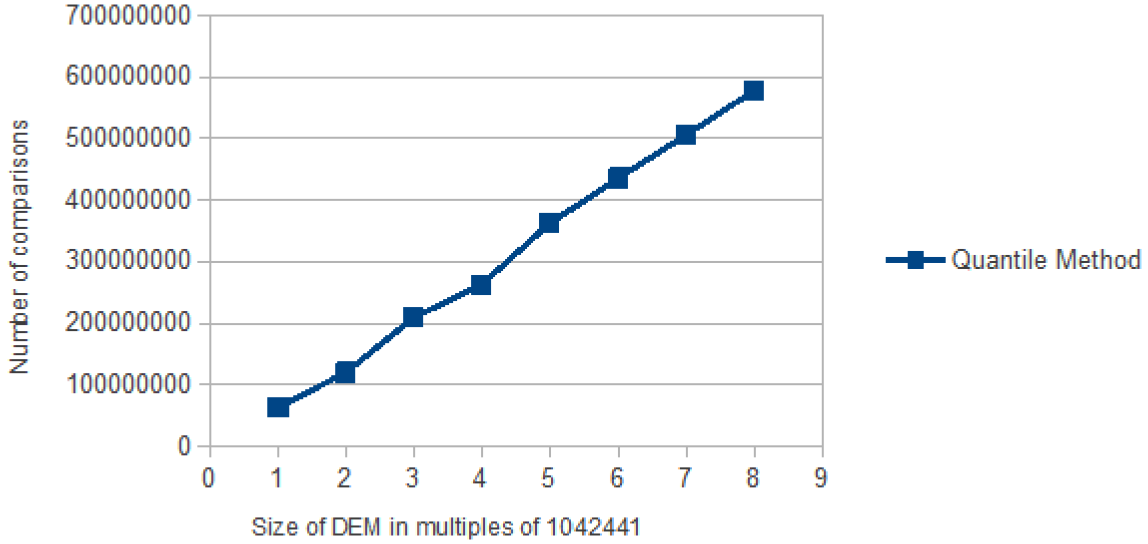


Figure 5

Analysis of Figure 5: No. of comparisons increase linearly with the size of DEM. A steep rise is seen in number of comparisons from 62800000 for small DEMs to 578000000 for large DEMs. The standard deviation also shows a linear increase from 40446507.88 to 184404276.4 as the size of DEM grows large.

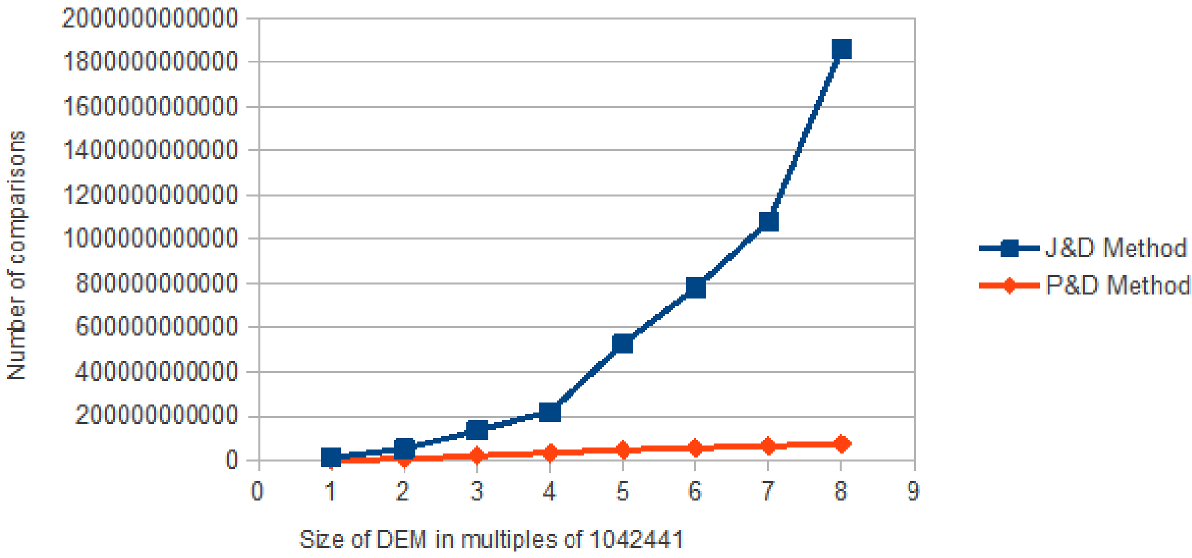


Figure 6

Analysis of Figure 6: From the above figure, it is clear that number of comparisons increase with increase in the size of DEM. While P&D method shows a linear increase from $1.8*10^9$ to $7.45*10^{10}$, it is much better than the conventional J&D method in terms of comparisons. The curve representing J&D method shows a drastic increase in number of comparisons when the size of DEM grows from 4*1042441 pixels. The deviation of J&D curve from $2.8*10^{10}$ (for small DEMs) to $6.39*10^{11}$(for large DEMs) is much higher than P&D method which shows a deviation increase from $2.7*10^9$ to $3.45*10^{10}$. More is the number of comparisons, more is the complexity.

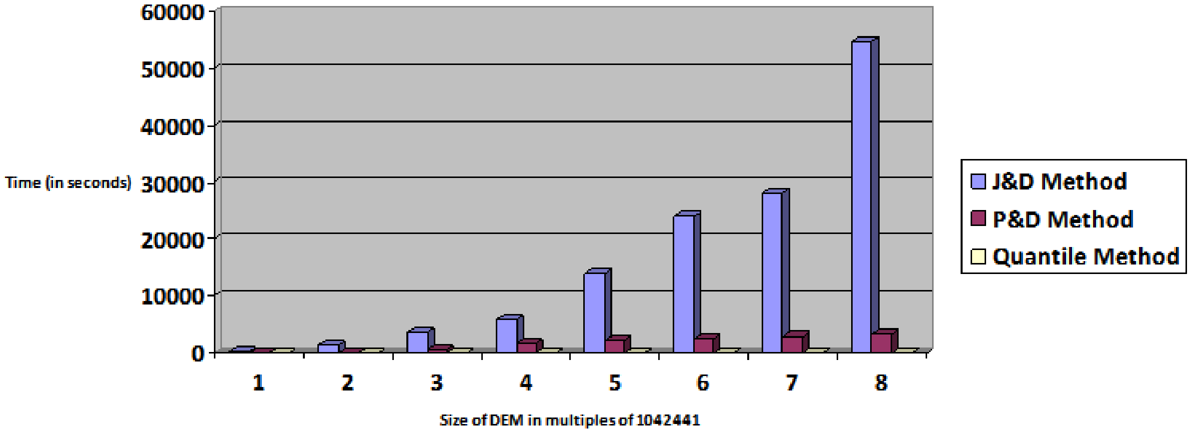


Figure 7

Analysis of Figure 7: Figure shows how much time is required for the execution of three algorithms. Time required for executing J&D method increases drastically from 4.7 minutes for small DEMs (1*1042441) to 15.2 hours for large DEMs (8*1042441) which is very inefficient. P&D method reduces the time complexity to some extent. For small DEMs it takes 17-100 seconds while for large DEMs it takes 55.71 minutes (1 hour approx).Quantile Classification magnificently improves efficiency by executing in 1-10 seconds for small as well as large DEMs. The deviation shows a drastic decrease from 18664.30 (J&D method) to 1303.66 (P&D method) and further to 5.89 (Quantile classification method).

Analysis of Incremental Methods: Incremental methods are widely used in Depression Filling and flat surface processing. Conventional incremental methods involve a lot of comparisons and modifications, thus resulting in a very high time complexity and alteration to non problematic regions. Figure 1 and 2 shows how Priority Flood algorithm improves efficiency and reduces the time complexity and surpasses the performance of old depression filling methods.

From Figure 3 and 4, it is clear that P&D Algorithm scans a lot more cells than J&D algorithm due to three complex subroutines and a recursive routine in its procedure. However there was an improvement in its direct implementation due to which the time complexity reduced to $O(n^{1.2})$. But No. of cells required to be scanned

could not be less than J&D Method despite of every improvement. The new approach called Quantile classification [14] has significant advantages. Furthermore, unlike the traditional method, which have to scan all the DEM cells in each loop, the new one only scan the data needed to be further processed by storing their location information into two stacks. As a result, the total cells and scanning times are dramatically decreased due to stack's nature of "first in last out", and the location information of depressions is all stored in one of the two stacks, which facilitate the subsequent hydrologic analysis.
From Figures 5 and 6, we can conclude that no. of comparisons required to execute is very large in J&D Algorithm which has a direct impact on time complexity. While it is slightly less in P&D Algorithm and much less in Quantile Classification approach. From Figure 7 it is clear that, new method (Quantile) is thousands of times faster than the famous Jenson and Domingue's (1988) method and is over seven times faster than Planchon and Darboux's on average.

2.2 Decremetal methods

2.2.1 Carving: Spurious pits in grid digital elevation models are often removed by filling them up to the level of their outflow point. [10] Recently, an alternative approach called carving has been proposed to suppress each single pit by creating a descending path from it to the nearest point having a lower elevation value. The cost of this transformation is defined by the sum of the altitude differences between the input and output pitless digital elevation models. In contrast to the pit filling procedure which acts along two-dimensional regions, carving acts along one dimensional path. Therefore carving usually leads to smaller transformation costs than pit filling. Although carving leads to smaller transformation costs than pit filling for any DEM of reasonable size, some specific pits may be removed at a lower cost by pit filling. The carving procedure, its application to adaptive drainage enforcement and an enhanced algorithm for determining flow directions on plateaus are detailed by Soille et al. in 2003.

Decremental methods are not very popular since they cause unnecessary modification in non problematic regions. They are either not used or used only with incremental approaches.

2.3 Hybrid Approach: A hybrid approach of carving and pit filling method is being used to alter the less DEM[23].It is done as an improvement to carving where the modification to original DEM can be minimized and accuracy can be achieved. Rather than suppressing a pit by either pit filling or carving depending on the cost of each individual procedure, we propose to go one step further by defining a hybrid approach allowing for combinations of both procedures. That is, pits are filled up to a certain level and carving proceeds from this level.We define the cost for transforming an input DEM into an output pitless DEM as the sum of the altitude differences between the input and output DEMs, denoting the input DEM by DEM_i (before processing) and the output DEM by DEM_o (after processing).

C= Sum [$DEM_i(x)$- $DEM_o(x)$] where $1<x<n$ and C= cost of transformation

Although carving leads to smaller transformation costs than pit filling for any DEM of reasonable size, some specific pits may be removed at a lower cost by pit filling. Pit filling method has a limitation of creating artificial flat areas and carving alters the originality of DEM. This new hybrid implementation of the combination of pit filling and carving can solve many problems. We can device new algorithms for the efficient and proper mixing of pit filling and carving in a better way. Table 1 gives information about cost of transformation and cells modification in a DEM of resolution of 250*250.

METHOD USED	COST OF TRANSFORMATION(m)	CELLS MODIFIED
Plain Pit Filling	$1.7*10^6$	$2.0*10^5$
Plain Carving	$4.4*10^5$	$7.3*10^4$
Hybrid Implementation	$3.4*10^5$	$7.9*10^4$
Filling Part	$2.1*10^5$	$5.2*10^4$
Carving Part	$1.3*10^5$	$2.6*10^4$

Table 1

Analysis of Table 1: It is clear from the above scenario that the cost of transformation and number of modified cells decreases when we use hybrid approach instead of using filling or carving alone. It improves accuracy.

2.4 Heuristic algorithm: While searching for outlet of pit or flat, the methods described above only check the eight adjacent cells of pit or flat and do not consider the general trend of the DEM. In other words, they have no additional information about states beyond that provides in the problem definition. All they can do is generate successors and distinguish a goal state from a non goal state. These methods can find the outlet, but they are incredible and inefficient in most cases. Unrealistic parallel drainage lines, unreal drainage patterns and spurious terrain features are most likely to be generated.

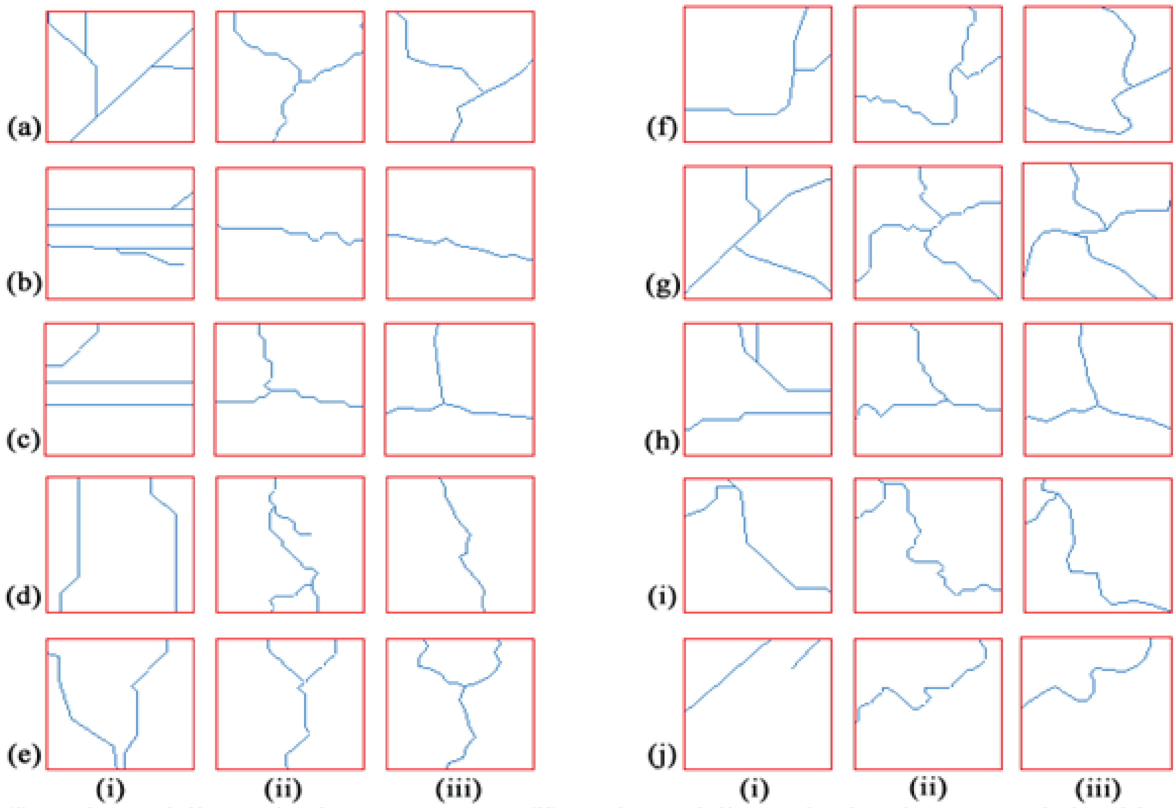
This heuristic method[12][20][21] contains two steps. First we calculate the incipient flow direction using the basic algorithm. The direction of flow is determined by finding the direction of maximum drop from each cell to its eight adjacent neighbors (D-8 Algorithm). The second stage is the master stage to find the optimal outlet of pits or flats**.** We scan the reconditioned DEM and put all the sinks and depressions nodes in a stack called Marked stack. For every node which is a sink, its eight adjacent neighbors are taken in an OPEN LIST and a heuristic function is applied.

The heuristic information consists of two elements, actual cost and estimated cost, according to:

$$f(n)=g(n)+h(n)$$

Where, f (n) is heuristic information of node n, g(n) is actual cost i.e. the difference of elevation between the starting node and the node n, h(n) is estimated cost, the cost to go from this node to the outlet with maximum heuristic information. The proposed algorithm always selects the node in the open list with the maximum heuristic information as the next node to be checked. This heuristic information ensures the proposed algorithm only tries to select nodes that most likely to lead to the direction towards the outlet. But the only limitation is that there is a need to develop an efficient heuristic function and the research is going further in its development.

Figure 8 shows how the accuracy is improved using heuristic algorithm and exact drainage lines are obtained [12].



i) Drainage lines delineated using ArcGIS 9.2 (J&d method for pit filling and D-8 and D-infinity)
ii) Drainage lines delineated using heuristic pit filling algorithm
iii) River Geospatial Data Presentation

We can see from the above figure that the drainage lines obtained by applying Heuristic approach are far much closer to the real river network extraction as compared to Arc-GIS which uses J&D approach with D-8 method.

III. Conclusion

Our main aim in the survey is to enrich the information content of digital elevation data by automatic sink removal, treatment of flat areas and Flow field derivation with accuracy. Various flow determination and pit filling algorithms have been introduced. Always a new algorithm is introduced with reduced time complexity and improved accuracy. The conventional approach which started in the early 80's could solve the problem but their methods are ineffective with high resolution large DEMs. It took hours and days to complete and the drainage lines obtained are far away from reality. Modern methods especially Priority- flood and quantile classification are much more effective. Heuristic approach improves accuracy but there is a need to build an efficient heuristic function. Moreover we also need to decide which heuristic information a node should contain. Decremental methods introduced in 2003 are not much efficient but there is a scope to come up with new hybrid approaches of intermixing these incremental and decremental approaches. Earlier we had limited sources of obtaining DEM, mainly SRTM (Shuttle Radar Topographic Mission), which is now obsolete. With new upcoming technologies like LIDAR based elevation model and ASTER DEM, we need to device new algorithms which can effectively remove the depressions of the terrain with minimum alteration and reduced time complexity. While devising an algorithm, we have to maintain a tradeoff between complexity and modifications since our aim is accuracy with less time requirement. Simple, efficient and less complex algorithms are implemented as a tool in GIS processing.

References:

[1]. Quinn, P.F., Beven, P., Chevallier, P., Planchon, O."The prediction of hillslope flow paths for distributed hydrological modelling using digital terrain models." Hydrological processes, Volume 5, Issue 1, pages 59–79, 1991.

[2]. Tarboton, D.G., 1997. "A new method for the determination of flow directions and upslope areas in grid digital elevation models." Water Resources Research, VOL. 33, no. 2, pages-309-319, February 1997.

[3]. Kun Hou, Jigui Sun, Wei Yang, Tieli Sun, Ying Wang, and Sijun Ma, "Extraction Algorithms for Using a Regular Grid DEMs", Jinggangshan, P. R. China, 2-4, April. 2010, pp. 112-115.

[4]. N. Senevirathne a and G. Willgoose, "A Comparison of the Performance of Digital Elevation Model Pit Filling Algorithms for Hydrology", 20th International Congress on Modelling and Simulation, Adelaide, Australia, 1–6 December 2013.

[5]. O. Planchon and F. Darboux, "A fast, simple and versatile algorithm to fill the depressions of digital elevation models", Catena, vol. 46(2-3), 2001 , pp. 1 59-176.

[6]. D. M. Mark, "Automatic detection of drainage networks from digital elevation models," Cartographica, vol. 21, pp. 168–178, 1983.

[7]. Q. Zhu, X. Tian, and Y. Zhang, "The Extraction of Catchment and Subcatchment from Regular Grid DEMs," Acta Geodaetica et Cartographica Sinica, vol. 34, no. 2, pp. 129–133, May 2005.

[8]. Jan Seibert and Brian L. McGlynn, 2007, "A new triangular multiple flow direction algorithm for computing upslope areas from gridded digital elevation models", Water Resources Research, VOL. 43, W04501, doi:10.1029/2006WR005128, 2007.

[9]. Richard Barnesa,Clarence Lehmanb, David Mullac -Priority-Flood: "An Optimal Depression-Filling and Watershed-LabelingAlgorithm for Digital Elevation Models" July 2013.

[10]. Pierre Soille, Ju¨ rgen Vogt, and Roberto Colombo- "Carving and adaptive drainage enforcement of grid digital elevation models", Water Resources Research, Volume 39, Issue 12, December 2003.

[11]. Ao Tianqi , Kuniyoshi Takeuchi , Hiroshi Ishidaira , Junich Yoshitani & Kazuhiko Fukami "Development and application of a new algorithm for automated pit removal for grid DEMs- (2010)", Hydrological Sciences Journal, 48:6, 985-997, DOI: 10.1623/hysj.48.6.985.51423.

[12]. Wei Yang, Tieli Sun1, Kun Hou14, Fanhua Yu and Zhiming Liu, "An adaptive approach for extraction of drainage network from shuttle radar topography mission and satellite imagery," International Journal of Innovative Computing, Information and Control, Volume 7, Number 12, Pg 6965-6978, December 2011.

[13]. Jan Seibert and Brian L. McGlynn,-" A new triangular multiple flow direction algorithm for computing upslope areas from gridded digital elevation models", Water Resources Research, Volume 43, Issue 4, April 2007**.**

[14]. Jingwen Xu , Wanchang Zhang , Chuansheng Liu –" A novel method for Filling the Depressions in Massive DEM Data", IEEE 2007. Geoscience and Remote Sensing Symposium, Publication Year: 2007 , Page(s): 4080 – 4083.

[15]. Wei-Bin Yu, Cheng Su, Chun-Na Yu, Xi-Zhi Wang, Cun-Jun Feng, and Xiao-Can Zhang - An Efficient Algorithm for Depression Filling and Flat-Surface Processing in Raster DEMs , IEEE Geoscience and Remote Sensing letters, vol. 11, no. 12, December 2014

[16]. S. K. Jenson and J. O. Domingue, "Extracting Topographic Structure from Digital Elevation Data for Geographic Information System Analysis," Photogramm. Eng. Remote Sens., vol. 54, no. 11, pp. 1593–1600, Nov. 1988.

[17]. L. Wang and H. Liu, "An efficient method for identifying and filling surface depressions in digital elevation models for hydrologic analysis and modeling," Int. J. Geogr. Inf. Sci, vol. 20, no. 2, pp. 193–213, Feb. 2006.

[18]. J. F. Ocallachan and D. M. Mark, "The extraction of drainage networks from digital elevation data," Comput. Vis. Graph. Image Process., vol. 28, no. 3, pp. 323–344, Dec. 1984.

[19]. Robert H. Erskine, Timothy R. Green, Jorge A. Ramirez ,Lee H. MacDonald- "Comparison of grid-based algorithms for computing upslope contributing area" Water Resources Research, VOL. 42, W09416, doi:10.1029/2005WR004648, 2006.

[20]. W. Yang, K.Hou, F.Yu, Z.Liu,T.Sun- "A novel algorithm with heuristic information for extracting drainage networks from raster DEMs." Hydrol. Earth Syst. Sci. Discuss., 7, 441–459, 2010,www.hydrol-earth-syst-sci-discuss.net/7/441/2010.

[21]. W. Yang, K.Hou, F.Yu, Z.Liu,T.Sun- "Extraction Algorithms for Using a Regular Gridded DEMs." Jinggangshan, P. R. China, 2-4, April. 2010, pp. 112-115.

[22]. Feifei Pan, Mark Stiglitz, Robert B. McKane- " An algorithm for treating flat areas and depressions in digital elevation models using linear interpolation." Water Resources Research, VOL.48, W00L 10, 2012.

[23]. Pierre Soille (2004) - "Optimal removal of spurious pits in grid digital elevation models", Water Resources Research,40, W12509, doi:10.1029/2004WR003060.

[24]. LIU Yong-He, ZHANG Wan-Chang, and XU Jing-Wen-" Another Fast and Simple DEM Depression-Filling Algorithm Based on Priority Queue Structure", Atmospheric and Oceanic Science letters, 2009, vol. 2, no. 4, 214−219.