This is the submitted version of **Lindsay, J.B., 2016. Efficient hybrid breaching-filling sink removal methods for flow path enforcement in digital elevation models, *Hydrological Processes*, 30(6): 846–857**, which has been published in final form at: doi:10.1002/hyp.10648. This article may be used for non-commercial purposes only.

Efficient hybrid breaching-filling sink removal methods for flow path enforcement in digital elevation models

John B. Lindsay*[1]

*Corresponding author; email: jlindsay@uoguelph.ca, phone: +1 519 824-4120 ext. 56074

1. Department of Geography, The University of Guelph, 50 Stone Road East, Guelph, N1G 2W1, Canada

Abstract

Digital elevation models (DEMs) that are used in hydrological applications must be processed to remove sinks, mainly topographic depressions. Flow enforcement techniques include filling methods, which raise elevations within depressions, breaching, which carves channels through blockages, and hybrid methods. Despite previous research demonstrating the large impact to DEMs and subsequent analyses of depression filling, it is common practice apply this technique to flow enforcement. This is partly due to the greater efficiency of depression filling tools compared to breaching counterparts, which often limits breaching to applications of small- to moderate-sized DEMs.

A new hybrid flow enforcement algorithm is presented in this study. The method can be run in complete breaching, selective breaching (either breached or filled), or constrained breaching (partial breaching) modes, allowing for greater flexibility in how practitioners enforce continuous flow paths. Algorithm performance was tested with DEMs of varying topography, spatial extents, and resolution. The sites included three moderate sized DEMs (52,000,000 to 190,000,000 cells) and three massive DEMs of the Iberian Peninsula, and the Amazon and Nile River basins, the largest containing nearly one billion cells. In complete breaching mode, the new algorithm required 87% of the time needed by a filling method to process the test DEMs, while the selective breaching and constrained breaching modes, operating with maximum breach depth constraints, increased run times by 8% and 27% respectively. Therefore, the new algorithm offers comparable performance to filling and the ability to process massive topographic data sets, while giving practitioners greater flexibility and lowering DEM impact.

Keywords Topographic depression; digital elevation model; surface flow-path modeling; flow enforcement; sink removal

1.0 Introduction

A DEM sink is a grid cell, or group of cells, that have no lower neighbor. DEM sinks include flat areas, which are often artifacts of inadequate elevation precision, and closed topographic depressions (O'Callaghan and Mark, 1984; Jenson and Domingue 1988). Large topographic depressions are common in previously glaciated and karst terrains. Although fluvial incision and sediment deposition make large depressions rare in landscapes with long fluvial histories, at smaller spatial scales many processes operating within landscapes can result in closed depressions (Lindsay and Creed, 2006). Nonetheless, most depressions within DEMs are artifacts resulting from the failure of the source data to capture the topography's natural break lines (i.e. ridge and valley bottom networks), inadequate grid resolution, random errors that have caused apparent flow blockages, and the inability of a surface model to properly represent infrastructure such as culverts and bridges (Lindsay and Creed, 2006; Lindsay and Dhun, 2015; Rieger, 1998). Large DEMs can contain millions of sinks.

Regardless of their origin, the assumptions underlying topographically driven flow routing methods break down within sinks because flow entering the feature cannot be routed further downslope. Therefore, sinks are problematic for many common applications of surface drainage modeling including watershed mapping (Band, 1986; Liang and MaCkay, 2000), automated stream network extraction and analysis (Heine et al., 2004; O'Callaghan and Mark, 1984; Tarboton et al., 1991), and the estimation of numerous flow-path based terrain indices. This is the reason why most hydrological applications of DEMs begin with sink removal, which is a process that ensures continuous flow paths extending from ridges to the edges of the DEM data (Martz and Garbrecht, 1998; O'Callaghan and Mark, 1984).

There are various methods for enforcing flow paths through flat areas in DEMs most of which involve routing flow away from surrounding uplands and towards outlets (Garbrecht and Martz, 1997; Jenson and Domingue, 1988). Many sink-removal algorithms combine the flat area flow enforcement and depression removal components into one process (Planchon and Darboux, 2002). There are two distinct approaches for removing topographic depressions, including filling and breaching (Rieger, 1998). Depression filling involves raising the elevations of grid cells interior to the closed depression. This simulated flooding leaves behind a flat area that must be removed for surface drainage modeling applications. Depression breaching involves lowering grid cell elevations along a single-cell wide breach channel connecting the bottom of a closed depression to some downslope point (Rieger, 1998). If breach channels are constructed in a way that ensures a monotonic downward gradient, depression breaching will not introduce flat areas into the DEM. Hybrid sink-removal algorithms have also been developed to combine filling and breaching approaches (Lindsay and Creed, 2005; Martz and Garbrecht, 1999, 1998; Soille, 2004a).

For reasons that will be further explored in this paper, many practitioners continue to favor depression filling for sink removal, despite evidence that breaching-based and hybrid approaches are more accurate, are better aligned with the causes of artifact depressions in DEMs, and impact subsequent analysis to a lesser extent (Grimaldi et al., 2007; Lindsay and Creed, 2005; Rieger, 1998; Soille, 2004a). The objective of this paper is to present a new hybrid sink removal algorithm and to evaluate the method with respect to the criteria that have previously restricted widespread adoption of depression breaching methods, specifically issues of algorithm performance and implementation details.

2.0 Background

Research in the area of flow enforcement has suffered from overlapping use of terms. In particular, the terms *sink*, *depression*, and *pit* are often used interchangeably. To clarify this situation, Figure 1 presents a typology of features that are typically involved in flow enforcement. The word *sink* is herein used to describe any group of grid cells in a DEM with undefined lateral flow direction due to a lack of downslope neighbor as well as areas of internal drainage. This includes both flat areas and closed topographic depressions. The word sink is well suited to this usage because of its connotation that lateral surface flow has been interrupted. *Depressions* are bowl-like features, denoted by an area of internal drainage, and completely surrounded by grid cells of higher elevations. The extent of a depression is defined by the elevation of its outlet, also called a spill. All depressions have at least one outlet and multiple outlets are also possible, particularly within integer-precision DEMs. Depressions are often referred to in the literature as pits, but the term *pit* will be used in this paper specifically to refer to a single DEM grid cell that is surrounded by eight neighboring cells of higher elevation. Pits can be isolated or can be located at the bottom of a larger closed depression. An *isolated pit* is a type of depression consisting of a single cell, while *depression-bottom pits* are themselves part of a larger multi-celled depressional feature. A complex depression containing multiple smaller nested depressions may contain multiple pits and each cell within the interior of a depression will be connected by a flow path to one of its bottom pits. Depressions may also be flat bottomed although these features are commonly restricted to integer-precision DEMs. While pits and flat areas can be identified in DEMs by examining the 3×3 neighborhood around each grid cell in a single-pass scan, identifying the extent of larger topographic depressions is much more complex.

2.1 Previous Sink-Removal Methods

The earliest sink removal algorithms used depression-filling approaches and were designed to work with the small-extent, large-resolution and highly

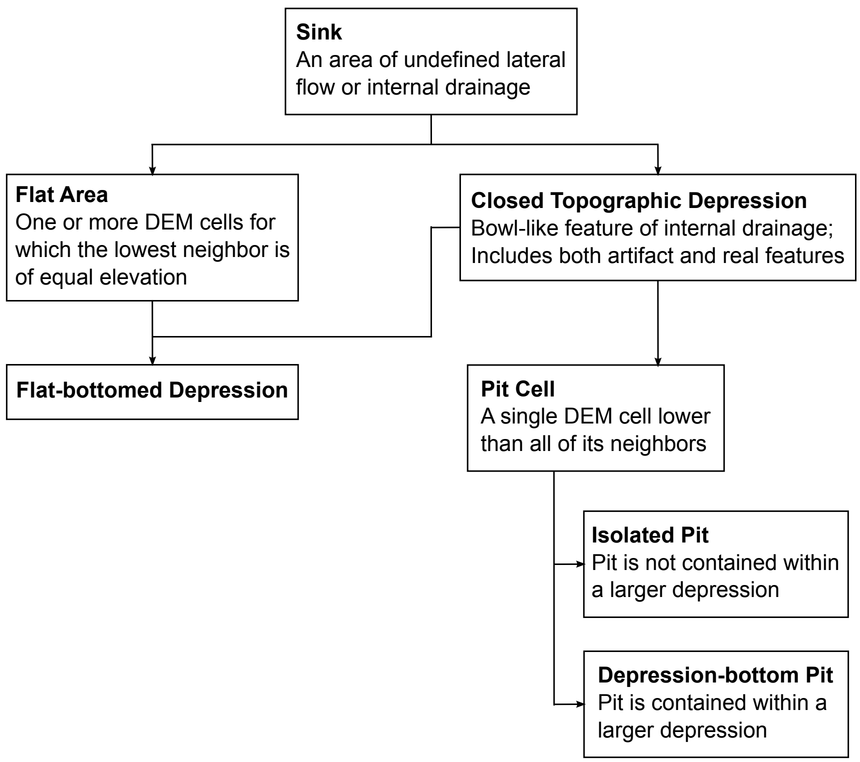

Figure 1: A typology of features found within DEMs that interrupt modeled flow paths and require flow enforcement.

smoothed DEMs available at the time (O'Callaghan and Mark, 1984; Jenson and Domingue 1988). These algorithms suffered from poor performance in part because they required the identification of each depression's outlet and because nested depressions were handled hierarchically. More efficient depression filling can be achieved through flood simulation approaches (Vincent and Soille, 1991). Two notable improvements in depression filling algorithms included the flood-water shedding method of Planchon and Darboux (2002) and the priority-flood method proposed by Wang and Liu (2006), which itself was similar to the method developed more than a decade earlier by Soille and Gratin (1994) (It is interesting to note that the priority-flood algorithm appears to have been independently re-discovered in the literature multiple times). Several commonly used geographical information systems (GIS) have implemented the efficient methods of Planchon and Darboux (2002) and Wang and Liu (2006). Since the publication of these two influential algorithms, the recent academic literature has focused on further improving efficiency of depression filling algorithms based on flood-water shedding (Wallis et al., 2009) and the priority-flood method (Barnes et al., 2014; Liu et al., 2009; Yu et al., 2014). For example, the refinement of combining a priority queue data structure (the basis of the priority-flood algorithm) with a more efficient First-In-First-Out (FIFO) queue for handling depressions was independently discovered by Barnes et al. (2014) and by Yu et al. (2014).

The first description in the published literature of a sink removal algorithm involving the lowering of elevations near dam-points in DEMs, i.e. breaching, is given by Rieger (1993). This early paper describes a hybrid solution in which depression outlets are partially lowered while interior areas are raised. Martz and Garbrecht (1999, 1998) later described a similar hybrid approach, with the novel contribution of constraining breach channels issuing from depression outlets based on their length. Rieger (1998) developed a complete breaching solution in which elevations are lowered along a flow path extending from the depression's outlet to the pit cell and along a second flow path exterior to the depression and extending toward the first downslope grid cell lower than the pit. The need to locate depression outlets, combined with the hierarchical handling of nested depressions, make these early breaching method ill suited to applications with large DEMs.

Soille et al. (2003) and Soille (2004b) proposed a breaching method based on the efficient priority-flood method previously used for depression filling. This method offers the advantages of not requiring outlet locations or special handling for nested depressions. Soille (2004a) further modified this approach to provide a hybrid solution that attempts to minimize the impact of flow enforcement through an optimal combination of depression breaching and filling. Minimizing the impact of the sink-removal process on the DEM was also the intent of the impact reduction approach (IRA) described by Lindsay and Creed (2005), although unlike the Soille (2004a) algorithm, the IRA solves individual depressions with either complete breaching or complete filling but not a partial solution involving both methods.

Breach channels that result from each of the previous methods are determined by the flow paths dictated by the topography in the original unmodified DEM and always pass through depression outlets. Lindsay and Dhun (2015) proposed an alternative method for finding potential breach channels based on the least-cost pathway, where the cost surface was determined by the accumulated elevation decrement needed to connect pits to nearby grid cells with breach channels. The resulting breach channels can differ substantially from alternative methods. For example, if an artifact dam in a DEM is higher than the surrounding terrain, such as is often the case with road embankments in flat areas, this approach can correctly breach through the embankment while other breaching methods may not. Thus, the method was found to be suited to sink-removal in fine-resolution DEMs of flat, heavily altered landscapes. Although Lindsay and Dhun (2015) demonstrated that the technique could be used with large DEM data sets, computational efficiency remains an issue in its application and the method is significantly slower than many modern filling methods. Because not all depressions in a DEM will have lower cells within a specified distance, filling must be used as a final sink-removal step; thus the technique is best thought of as a hybrid breaching method.

2.2 The prevalence of depression filling in practice

Breaching and hybrid methods have been shown to impact modeled flow paths significantly less than depression filling (Lindsay and Creed, 2005; Lindsay and Dhun, 2015; Soille, 2004a). It might be expected that breaching methods would therefore dominate usage but this is not the case; filling is far more favored among practitioners. There are several likely reasons why depression filling is so prevalent in surface flow-path modeling applications despite its shortcomings. Filling algorithms have had a longer history and much of the development effort has focused on improving algorithm efficiency. This is a response to the need for a robust and efficient means of removing the vast number of sinks that are found in fine resolution DEMs, such as those provided by LiDAR, and the recent availability of global topographic datasets such as the Shuttle Radar Topography Mission (SRTM 1-arcsecond), GDEM, and WorldDEM products. Although there are multiple potential breaching solutions for each depression in a DEM, all filling algorithms, regardless of how they operate, produce the same result. When a case is made that one filling method is an improvement over another it is solely on the basis of its efficiency and algorithmic issues, e.g. the ability to process larger data sets, the handling of floating-point precision elevations, ease of implementation, etc. These are however important factors that strongly affect the adoption of a sink-removal method in practice.

Depression filling also benefits from greater availability in common GIS software, which almost ubiquitously offer depression-filling tools. Currently, the most widely available depression breaching tools include the GRASS GIS module r.hydrodem, which is an implementation of the Lindsay and Creed's IRA, and an implementation of Soille (2004a) optimal hybrid breaching method developed at the Center for Research in Water Resources (University of Texas) as a third-party plugin for ArcGIS (Esri). The ArcGIS tool is limited in application to moderate-sized DEMs with fewer than 25,000,000 grid cells. The open-source GIS Whitebox GAT (Lindsay, 2014) also has built-in support for the breaching method of Lindsay and Dhun (2015). Some specialized software, such as TopoToolbox (Schwanghart and Scherler, 2014), also offer breaching-based solutions. Since breaching alternatives are less commonly found in widely available GIS software packages, it is likely that many practitioners are unaware that filling has a greater impact on their surface drainage modeling analysis. Thus, depression breaching suffers from availability and implementation issues, as well as poorer awareness, which have prevented this approach from gaining wider usage in the field.

2.3 When to breach and when to fill?

Soille (2004a) and Lindsay and Creed (2005) both compared the modifications to DEMs made by filling, breaching, and hybrid approaches. These studies showed that hybrid solutions offer the lowest impact on modeled flow paths but that the improvements are only marginally better than a breaching-only solution. Thus, when breaching and filling approaches are combined for sink removal, the breaching component of the solution will result in the lower impact in most cases. When is breaching not a good sink removal option? Isolated pits are usually better handled by filling, i.e. raising the single elevation value to the elevation of its lowest neighbor. De-pitting is recommended by Lindsay and Creed (2005) and Lindsay and Dhun (2015) as an efficient pre-processing step to sink removal to counter the effects of the speckle-type error that is common in LiDAR and InSAR DEMs.

In addition to isolated pits, very deep depressions are also problematic for breaching algorithms. Most larger-sized depressions in DEMs of fluvial landscapes result from artifact damming within the confined topography of incised valleys and gullies (Lindsay and Creed, 2006; Rieger, 1998). While these artifact depressions can be extensive, they are typically shallow and are well handled by breaching methods, which tend to reinforce natural drainage pathways along existing stream networks. Extensive deep depressions within DEMs tend to indicate actual landscape features such as sinkholes, pothole wetlands, lakes, and quarries and other types of open-pit mines. Breaching these deep depressions results in long and deeply incised breach channels. For example, Figure 2A shows a breached DEM of an area located south of Montreal, Canada, which contains several deep quarries. This type of depression tends to be more appropriately removed using depression filling (Figure 2B), which mimics the inundation of the feature. It is important to note, however, that DEM-based flow-path modeling attempts to simulate lateral flow at or near the surface. The presence of actual topographic depressions in the landscape implies that local flow patterns are dominated by vertical movement, either into the subsurface groundwater or as evaporative losses vertically into the atmosphere (Antonić et al., 2001; Rosenberry and Winter, 1997). In cases where these features are prevalent, the use of topographically driven flow path modeling to depict lateral flows becomes dubious (Lindsay and Creed, 2006). Robust flow enforcement methods should allow for the optional retention of these types of deep depressions for applications with special handling of areas of internal drainage.

Situations in which breaching algorithms provide an inadequate solution for sink removal are conspicuous because of the resulting unusually deep and long breach channels (Figure 2). One hybrid sink-removal approach therefore is to favor breaching as a solution except in cases where the resulting breach channel necessary for solving flow through a sink would be deeper and/or longer than some specified thresholds. These special cases are then resolved using subsequent depression filling. This breach-first hybrid solution is referred to here as *selective depression breaching*. In selective breaching each sink is solved completely either using breaching or filling. This is similar to the IRA (Lindsay and Creed, 2005), except that the breaching solution is given priority rather than using an impact-based criterion for choosing which approach to apply. The breach-first method can be further modified to provide a partially breached solution (Martz and Garbrecht, 1999, 1998; Rieger, 1993; Soille, 2004a), such that depressions that can not be fully eliminated by breach channels within the specified limits of length and/or depth have their outlets lowered by a carved channel meeting these criteria. This partial breaching solution reduces the interior size of the depression that must then be subsequently filled. This is similar to the constrained breaching approach described by Martz and Garbrecht (1999) except that the breach channel length threshold is allowed to have any specified value (instead of a maximum of two grid cells used by Martz and Garbrecht) and a maximum breach depth constraint is also added.

3.0 Methods

3.1 Algorithm description

Like several of the depression filling/breaching algorithms described above, the new flow enforcement algorithm is based on the priority-flood operation (see Barnes et al., 2014 for a recent review of the history the priority-flood method). The priority-flood algorithm provides an efficient method for visiting DEM grid cells in their flood order, i.e. the order in which cells would be inundated by the rising waters of a water-body surrounding the terrain in the area extending beyond the DEM edges. The priority-flood algorithm determines flood-order by entering DEM grid cells into a priority queue, a data structure in which grid cells can be added and subsequently removed based on an assigned priority value. The priority metric is determined by cell elevation such that lower cells are assigned highest priority. The process begins by entering the grid cells along the DEM edges into the priority queue. The lowest cell within the queue (highest

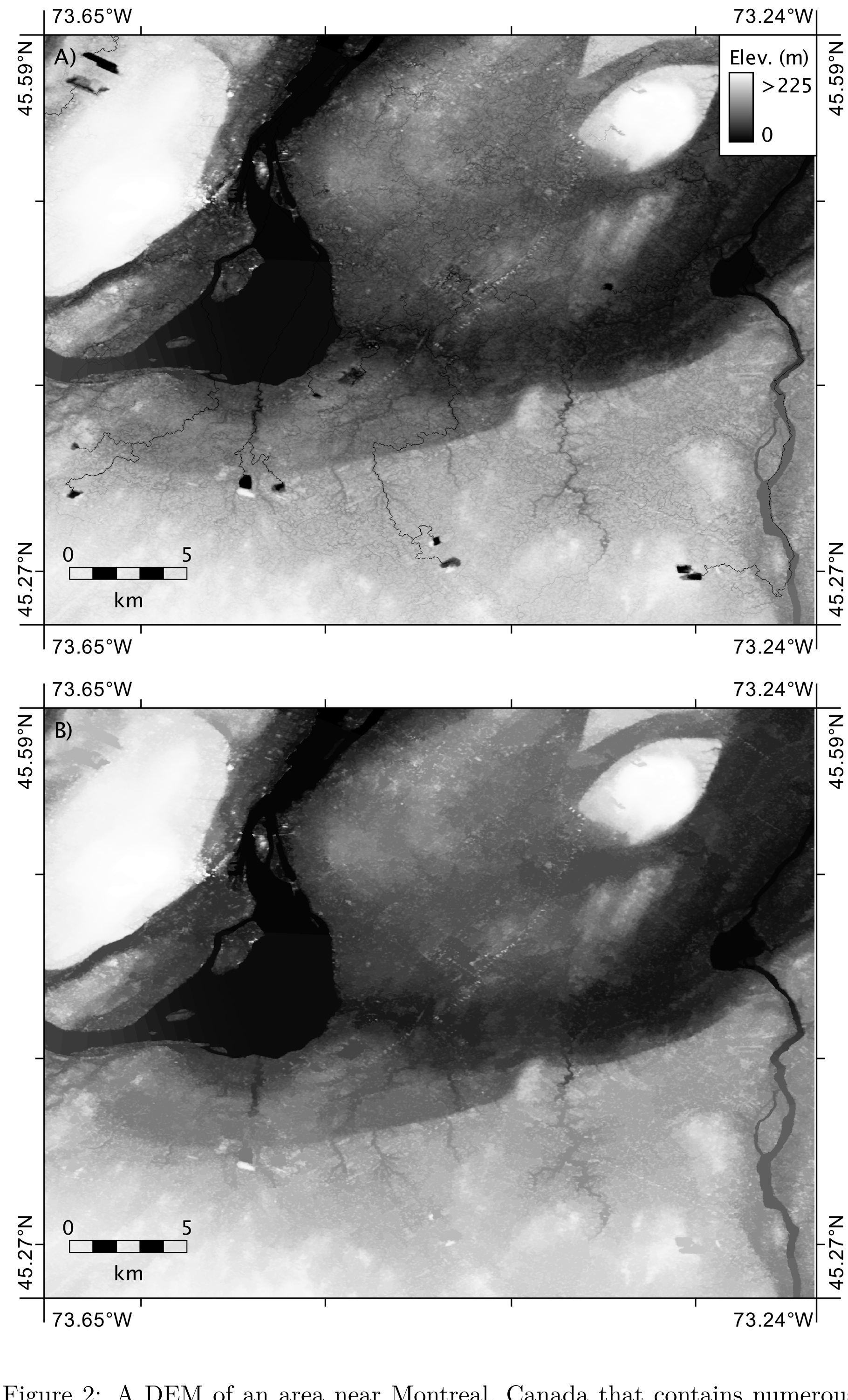

Figure 2: A DEM of an area near Montreal, Canada that contains numerous deep quarries. Sinks in the DEM have been treated with depression breaching (A) and filling (B).

priority) is then removed and its eight neighbors are scanned. Any newly found neighbors are added to the priority queue and the process iterates until each cell in the DEM has passed through the queue. A grid cell effectively becomes inundated by the progressing flood wave when it is removed from the queue. Thus, cells are visited in order from lowest to highest and inward from the data edges.

Although the priority-flood algorithm has been more widely associated with depression filling (Barnes et al., 2014; Soille and Gratin, 1994; Wang and Liu, 2006; Yu et al., 2014), Soille et al. (2003) demonstrated how the technique can also be applied to depression breaching. The key modification is the incorporation of a back-link grid, which specifies the neighboring cell from which a grid cell was discovered by the progressing flood wave. When a pit/flat grid cell is encountered, the back-link raster is used to trace the flow path downslope and towards a raster edge until either a lower grid cell is found or the edge is encountered. Elevations in the output DEM are lowered along these traced flow paths such that the path is monotonically descending. In this way, flow paths can be enforced through both depressions and flat areas.

The new flow enforcement algorithm has three basic components (Figure 3). The first component is an initialization step in which various required grids are established including a grid to store back-link values, a Boolean grid used to mark cells as they pass through the priority queue, and the output DEM grid. During initialization, the input DEM is scanned to identify pit/flat cells, which are also marked in a Boolean grid, and to identify grid cells located along the data edges, which are then placed into the priority queue. Importantly, DEM data are frequently irregularly shaped and do not fully occupy their rectangular shaped rasters (e.g. LiDAR DEM data often have irregular boundaries associated with flight-lines). Thus mapping the data edges to initialize the priority queue involves identifying valid-valued grid cells that are either located along a raster edge or that have a NoData (null) valued neighbor.

During the initialization step, each cell in the output DEM grid is assigned the elevation of the corresponding cell in the input DEM. However, any identified pit cells are shallowed in the output grid. That is, pit elevations are raised to a value very slightly below (e.g. 0.0001 m) that of their lowest neighbor. This operation is completed during the initial scan of the DEM just after a pit is identified. Shallowing significantly reduces the length and depth of breach channels, and therefore lowers the impact of breaching on the corrected DEM. While isolated pits could be effectively removed at this point by raising their elevations to a value slightly above their lowest neighbor (and below the second lowest neighbor), this same procedure applied to depression-bottom pits will simply introduce new pits elsewhere, which would then require a second initialization scan of the raster to identify. Thus, pit shallowing represents a good compromise.

The second component of the algorithm is a priority-flood based depression breaching operation (Figure 3). This is the most computationally intensive part

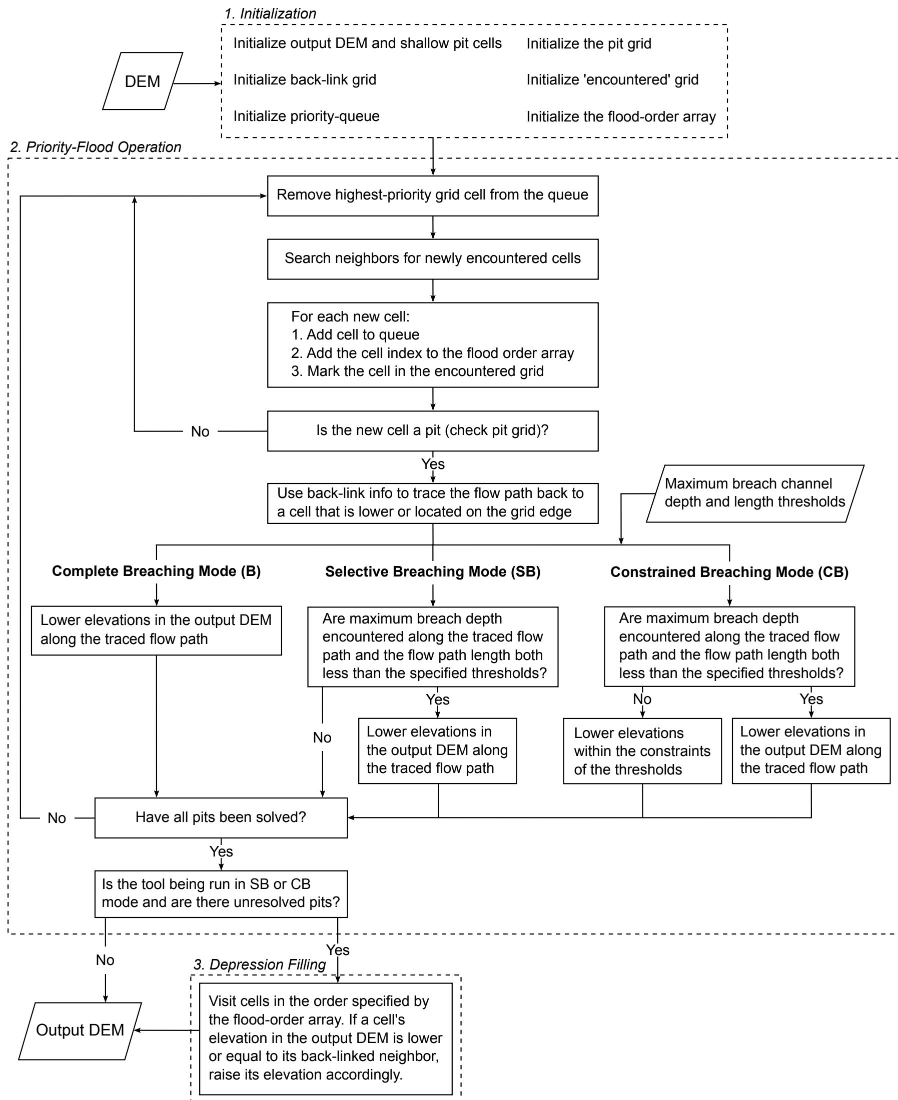

Figure 3: The new sink-removal algorithm. The three main components described in the text are highlighted with dashed-line boxes.

of the process. The algorithm can be run in three user-specified modes, which determine how the breaching operation is carried out. In the complete-breaching mode (B) all sinks are removed through a combination of pit shallowing and carving breach channels. The stopping condition for the priority-flood operation in complete-breaching mode is when every pit/flat cell has been visited. This is an early stopping-condition compared with other priority-flood based flow enforcement algorithms (e.g. Wang and Liu filling method), which stop when the priority queue is empty and every grid cell has passed through the queue. In the selective-breaching mode (SB), only sinks that can be breached within the specified criteria of maximum breach channel depth and/or length will be carved, leaving the remaining sinks unmodified. Any remaining sinks can be optionally removed through a subsequent filling operation described below. Selective breaching requires tracing the back-linked flow path from each pit/flat twice: once to measure the maximum breach depth and length required to remove the feature and once to perform the elevation decrements if the breach channel meets the specified criteria. The breaching operation may also be run in a constrained-breaching mode (CB), i.e. partial breaching. If this option is chosen, then when a pit/flat is located with a breach channel that does not meet the specified criteria, a restricted breach channel will be used to reduce the interior depression size by lowering the cells along a restricted flow path around the depression outlet. A sink's outlet is identified as the cell of maximum breach depth along the back-link flow path connecting the sink to its downslope data edge cell.

The last component of the algorithm is a filling operation (Figure 3), and is only executed 1) if either the selective or constrained breaching modes are used, 2) if pits/flats are encountered during the breaching operation that cannot be resolved within the specified limits of breach depth and channel length, and 3) if the user specifies that all depressions should be removed. The filling operation proceeds by visiting each cell in the DEM in their flood order. A cell's elevation is compared with that of the cell to which it points in the back-link raster calculated from the previous breach operation. If a grid cell is lower than its back-linked neighbor, its elevation is raised to the elevation of its neighbor plus a small value (e.g. 0.0001) to ensure a shallow gradient along filled depressions. Because the flood order is already determined during the previous breaching component, there is no need to re-run the priority-flood operation a second time. Instead, if it is determined from the outset that depression filling will be needed then a flood-order array is created to store the index number of grid cells (Index = Row $\times$ NumberOfColumns + Column) in their flood order. In this way, the second flood-wave progression can be carried out very efficiently and the processing cost of the subsequent filling operation is low compared with running the priority-flood operation twice (i.e. once for breaching and once for filling).

3.2 Implementation

The character of the priority queue strongly affects the overall computational performance of any priority-flood algorithm. A binary search-tree (min-heap) based priority queue is used in this work because it offers efficient data insertion and removal combined with ease of implementation. Priority values are based on a combination of grid cell elevation and the distance of the cell relative to the last non-sink cell (insertion order). Using insertion order in priority value calculation aids with the handling of flat areas; without including this additional criterion very irregular and convoluted flow paths often result within the extensive flat areas common in integer-precision DEMs. Elevation and insertion order are combined using fixed-precision concatenation. Elevation values are multiplied by a constant (e.g. 10000), truncated, and concatenated with a five-digit representation of insertion order. The resulting value is stored in the priority queue as a 64-bit integer. For example, a grid cell with an elevation of 538.9678 m and an insertion order of 4 would be assigned a priority value of 5389678000004. The use of this combined elevation/insertion order priority simplifies the sorting logic within the priority queue, which increases the performance of the priority-flood operation.

The new hybrid flow enforcement tool has been implemented as a standalone program developed using the Go programming language. Native binary files, compiled for MS Windows, OSX and Linux operating systems, and the raw source-code, are distributed under an open-source license (http://www.uoguelph.ca/~hydrogeo/software.html). The single executable file can be run either by command line interface or called through shell scripting automation. The tool could therefore be embedded into GIS software through scripting, or the developers of GIS software could implement plugin tools using the source code.

The tool outputs a hydrologically corrected DEM, with each grid cell connected by a continuous flow path to the raster edge. Both floating-point and integer precision DEMs are handled and the tool can read and write GeoTIFF, Esri (binary and ASCII), GRASS GIS ASCII, Whitebox GAT, SAGA binary, Golden Software ASCII, and IDRISI binary raster formats. The output DEM is of floating-point precision (32-bit) because of the need to represent small elevation increments along breach channels and flat areas. The maximum DEM size that the tool can process is largely determined by the available memory in the computer system. Because the entire input and output DEMs, priority queue, and several smaller grids (e.g. the back-link grid, and various grids of Boolean data) must be held in memory during processing, memory requirements must be a consideration in the application of the tool.

4.0 Case Studies For Performance Testing

Six DEMs (Figure 4) of varying sizes (Table 1) were used to test the performance of the new flow enforcement algorithm. The DEMs were each derived from the SRTM InSAR data (Jarvis et al., 2008) and include three DEMs derived from the 1 arc-second (approximately 30 m) SRTM product and three DEMs derived from the 3 arc-second (approximately 90 meters) data set. Individual 1° data tiles were seamlessly mosaicked using nearest-neighbor resampling to form each of the final test DEMs. Although the original data contained elevations stored as 16-bit integers (nearest meter), the mosaicked DEM rasters used 32-bit precision floating point values to store elevations. The three largest DEMs, the Nile and Amazon River basin and Iberian Peninsula data sets (Table 1), were each more than 3 GB in size. All six of the test DEMs contained millions of pits and flat grid cells, with the Nile basin DEM possessing the largest number with over 79 million sinks.

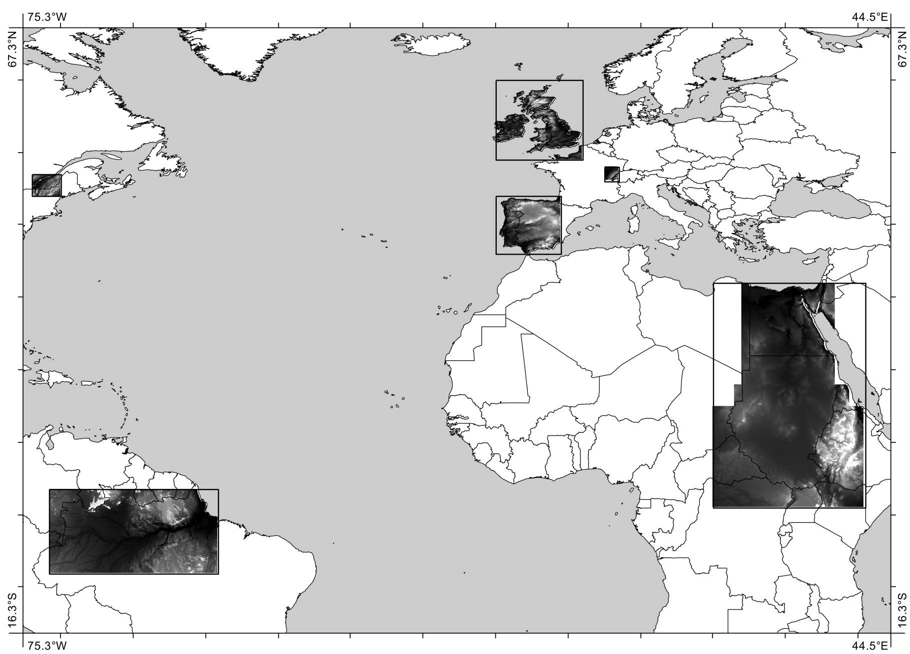

Figure 4: The six test DEMs used to evaluate the performance of the new sink-removal algorithm. The thick black boxes show the extent of the DEM raster grids.

Table 1: Characteristics of the test DEMs.

Region	**Res.**[1]	**Rows × Columns**	**Num. Pits/flats (%)**[2]	**% NoData**
Western Alps	1.0	7201 × 7201	5,216,899 (10.1)	0.0

Region	Res.[1]	Rows × Columns	Num. Pits/flats (%)[2]	% NoData
Quebec, Canada	1.0	10,801 × 14,401	16,194,960 (10.7)	2.5
British Isles	3.0	13,201 × 14,401	4,678,482 (7.1)	65.4
Amazon Basin	3.0	14,001 × 28,001	38,996,584 (10.2)	2.7
Iberian Peninsula	1.0	28,801 × 32,401	43,368,323 (6.3)	26.4
Nile Basin	3.0	37,201 × 25,201	79,240,286 (10.9)	22.3

1. Grid resolution in arc-seconds; 2. Percent is of the valid (non-NoData) area.

Table 2 shows the times required to process each of the six test DEMs with the new flow-enforcement algorithm using the B, SB, and CB modes. The tests were run on a computer system with a 3.0 GHz 8-core Intel processor with 64 GB of 1866 MHz DDR3 memory. The results for the Wang and Liu depression-filling algorithm are also presented in Table 2 for comparison. Efforts were made to ensure that the implementations (e.g. the programming environment, priority queue, priority metric, etc.) were similar between the Wang and Liu tool and the new flow enforcement method to ensure that the comparison reflected algorithmic differences rather than differences in the implementations. Table 2 also presents the geometric mean of the relative processing times, expressed as percentages of the Wang and Liu algorithm run times.

Table 2: A comparison of processing times for the Wang and Liu and new sink-removal algorithm for the test DEMs. Stated processing times are averages of ten runs and exclude data input/output time.

Region	F[1]	B[1]	SB1[1]	SB2[1]	CB1[1]	CB2[1]
Western Alps	35.4	29.6	34.9	36.8	35.3	136.9
Quebec, Canada	104.5	94.8	113.5	118.3	116.1	147.5
British Isles	57.9	48.7	59.1	59.0	58.4	62.1
Amazon Basin	344.9	310.6	365.1	367.5	363.8	909.3
Iberian Peninsula	586.4	519.2	657.9	659.8	658.5	689.9
Nile Basin	627.9	519.3	780.3	658.6	2012.3	2434.5
Mean Percent of F	100.0%	86.6%	108.3%	107.1%	127.2%	203.2%

1. Notes: F = Wang and Liu depression filling algorithm; B = new algorithm; complete depression breach mode; SB1 = new algorithm; selective breaching mode, 20 m max. depth; SB2 = selective breaching mode, 20 m max. depth, 100 cell max. length; CB1 = constrained breaching mode, 20 m max. depth; CB2 = constrained breaching mode, 20 m max. depth, 100 cell max. length

Unsurprisingly, the tests demonstrated that the new flow enforcement tool operating in complete breaching (B) mode offered better performance than either SB or CB modes, which involved the additional step of subsequent filling (Table 2). The new flow-enforcement tool (B mode) had execution times that were on average 86.6% of the equivalent times required by the Wang and Liu filling tool and ranged from 0.5 minutes for the smallest DEM to 8.7 minutes for the multi-gigabyte Iberian and Nile DEMs. The improved performance compared with the Wang and Liu filling method may partially reflect the early-stopping condition of the priority-flood simulation of new tool when operating in B mode.

The added complexity of the SB mode, due to the need to measure breach channel length and depth and the cost of subsequent depression filling (which necessarily removes the early-stopping condition of the breaching component), was found to increase computation times by approximately 7-8% compared to Wang and Liu filling-only method. Execution times of the selective breaching mode were not strongly affected by application of a breach channel depth constraint versus the combination of depth and length constraints (Table 2). In fact, experimentation showed that the execution times of the algorithm were largely unrelated to the specific threshold values of maximum breach channel depth and length used.

The partial breaching solution provided by the CB mode showed greater sensitivity to the breach channel depth and length constraints. While use of a maximum depth constraint alone was found to offer similar performance for most of the test DEMs (Table 2), the inclusion of an additional maximum breach channel length criterion increased execution times substantially for several of the test DEMs. This was most notably for the Nile Basin, where execution time increased to nearly 40 minutes (compared to 8.7 minutes in B mode), and the Alps DEM where processing times increased by nearly 465% with the addition of a maximum breach length constraint. This was likely due to the costs of creating partial breach channels, which requires identifying sink outlets and is particularly challenging where there are extensive low-lying flat areas. While the CB mode demonstrated the longest computation times of the tested sink-removal methods, this partial-breaching solution was still found to be an efficient means of flow path enforcement even for the massive DEMs used in this study. For example, the depth-only CB execution times were on average only 27.2% slower than the Wang and Liu filling algorithm.

5.0 Discussion

The past focus on developing breaching algorithms that minimize the impacts of the sink removal process on DEMs has resulted in many algorithms that are not as performant as comparable modern depression filling algorithms. Given the current trend towards applications of massive DEMs derived from LiDAR and InSAR data sources, performance and robustness issues are critical factors affecting the adoption of a flow enforcement method by spatial hydrology practitioners. This study however demonstrated that depression breaching based solutions can offer similar computational performance to that of traditional depression-filling methods, can be applied to large topographic data sets, while also offering advantages of lower impact to the DEM and greater flexibility in how depressions are treated. Future research efforts should be invested in continued improvements in breaching based solutions similar to the past focus on performance improvements made for depression filling algorithms. Development efforts should also focus on making breaching and hybrid sink removal tools more widely available to practitioners in the GIS software platforms that are commonly used in the field. In this way, breaching-based solutions may eventually supplant filling-only algorithms as the default flow enforcement method used in flow-path modeling applications, finally resolving the disconnect that exists between recommendations within the academic literature and common practice. There will always be a need for depression filling methods because of their use in topographic depression mapping; however, breaching-based solutions should be more widely applied in most surface drainage pattern modeling applications where filling currently dominates.

The three modes of operation of the new flow enforcement tool offer the user highly flexibility solutions for sink-removal. If it is known *a priori* that the DEM does not contain large depressions (open-pit mines, lakes, or wetlands, etc.), and the modeled landscape is high-relief and dominated by fluvial processes, then the greater computational performance of the complete-breaching mode is likely the preferred method. If these features are present, the breaching-only solution will result in long, deeply incised breach channels and one of the hybrid modes is likely preferable. If the focus is on reducing the impact on the DEM then the partial solution of the CB mode is likely most suited to the application and the associated performance penalty can be justified. If actual depressions are known to exist in the landscape and the user intends to model the impacts of areas of internal drainage on the local hydrology then the SB mode enables the user to retain larger depressions. The SB mode also has a logical advantage in that if it is assumed that artifact topographic depressions are likely to be introduced into the DEM as a result of either over-estimation (damming) or under-estimation errors, but not both, the solution for their removal should also reflect this characteristic.

Both of the hybrid modes require the user to specify thresholds of the maximum depth and/or length for breach channels. Setting appropriate values for these two parameters may require some experimentation. The physical nature of the depth and length parameters aids somewhat in this process. For example, both the Quebec (Figure 2) and the Iberian Peninsula DEMs contained multiple large open-pit mines that were many tens of meters in depth. These features were much deeper than any of the artifact depressions in the DEMs that resulted from the speckle-type noise that causes erroneous damming of flow paths and isolated pits. The fact that these natural features and the artifact depressions in DEMs are often widely separated in terms of their typical depths helps in setting a threshold value, i.e. a range of values are equally appropriate.

The logic of the new hybrid flow enforcement method is attractive. Small topographic depressions, i.e. isolated pits, can be easily handled by filling. The pit-shallowing that takes place during the initialization step ensures that deep isolated pits do not result in long breach channels where they could be better handled simply by raising their single interior grid cell. Previous work has demonstrated that most large artifact depressions result from erroneous damming along convergent topography and these features are best handled by breaching methods. In relatively rare cases (i.e. compared with the abundance of artifact depressions in DEMs), a depression represents a real feature that is best handled through filling. These cases are often easily identified because of the exceptionally deep and/or long breach channels that would be necessary to remove the feature using breaching based methods. Thus, the hybrid flow-enforcement approach described in this study can be described as a breach-first/fill-last solution applied to a pit-shallowed pre-processed DEM. This approach provides a flexible means of flow enforcement that reflects the causes of sink presence in DEMs.

The tests performed in this study demonstrated that the breach-only and hybrid-breach/fill approaches to flow enforcement can offer broadly similar performance characteristics to that of existing depression filling methods. This is largely the result of the fact that the the new algorithm relies on the same priority-flood operation applied in many of the most efficient filling algorithms. The priority-flood operation is used to calculate the flood order (i.e. the order of inundation of grid cells), to calculate flow directions, and to modify DEM elevations to remove sinks. Most of the computational effort during the priority-flood operation is spent in calculating the flood order and this component of the operation is identical between the new algorithm and some filling methods. The two broad approaches of priority-flood based breaching and filling differ only in the way they modify elevations to remove sinks, where breaching requires a flow-path traverse downslope from pit cells to a lower cell and filling raises the elevation of depression interior cells. By storing the flood-order calculated during the initial breaching priority-flood operation, the new algorithm is able to perform the secondary filling step, when it is needed, with little additional computational cost—much less than would be needed to perform two independent priority-flood operations, one to breach and one to subsequently fill the remaining unresolved depressions in the DEM.

When run in any of the three modes of operation, the new flow-enforcement method reduces the impact on a DEM compared with a filling-only solution. However the new method does not ensure optimally minimal impact sink-removal like that provided by the algorithms of Soille (2004a), Lindsay and Creed (2005), or Lindsay and Dhun (2015). The new method does not find the lower impact of the filling or breaching solution for individual depressions like the IRA (Lindsay and Creed, 2005), it does not find the optimally low impact partial solution of a combined breach/fill of depressions (Soille, 2004a), and it does not compare among the numerous potential breach paths to find an optimally low-impact breach channel for depressions. Instead, the hybrid method breaches all depressions with an incised channel path determined by the priority-flood operation, except for depressions where the impact of a breach channel is too high, in which case the algorithm will use a filling-based or combined filling/breaching solution. Each of the optimal approaches provides lower-impact solutions for many DEM, particularly in low-relief landscapes. For most moderate- to high-relief landscapes, however, the difference between the new algorithm and these optimal approaches is likely quite small. Furthermore, the optimal solutions may show advantages in terms of lower impacts to the DEM but this benefit comes at a computational cost that restricts their practical application to smaller data sets.

6.0 Conclusions

The standard practice of using depression-filling algorithms for DEM sink removal has been criticized in the academic literature for its greater impact on DEMs and subsequent surface drainage pattern modeling. While breaching based and hybrid sink removal methods have been demonstrated to reduce impacts compared with depression filling, performance and robustness issues and the lack of availability have limited their use. The new flow enforcement tool introduced in this paper has demonstrated that these shortcomings are not inherent in breaching and hybrid approaches to sink removal and that the issues affecting the widespread application of these methods in common practice can be resolved. This new tool has been developed as an open-source library that can be readily integrated into existing GIS systems.

The tool was applied to six test DEMs of widely varying grid size and extent, including large multi-gigabyte topographic data sets of the Nile and Amazon River basins as well as the Iberian Peninsula. The hybrid flow enforcement method offered similar performance to a widely used and efficient depression filling method, requiring between 87% and 203% of the processing time, depending on the specified constraint values and operation mode. The tool was found to be capable of processing massive DEMs containing millions of sinks. The approach is highly flexible, allowing for breaching-only, selective breaching (i.e. either/or breaching and filling) and constrained (partial) breaching solutions using threshold constraints of breach channel depth and length. Large depressions in the DEM, often associated with real and hydrologically salient landscape features, can also be retained in the corrected DEM, thereby enabling the inclusion of areas of internal drainage within flow path modeling applications.

7.0 Acknowledgements

This work was partially funded through a grant provided by the Natural Sciences and Engineering Research Council of Canada (NSERC; grant number 400317).

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