# Removal of artifact depressions from digital elevation models: Towards a minimum impact approach

**Short Title: Removal of artifact depressions from digital elevation models**

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ABSTRACT

Artifact depressions in digital elevation models (DEMs) interrupt flow-paths and alter drainage directions. Techniques for removing depressions should enforce continuous flow-paths in a way that requires the least modification of the DEM. Impacts on the spatial and statistical distributions of elevation and its derivatives were assessed for four methods of removing depressions, including: (1) filling, (2) breaching, (3) a combination of filling and breaching with breaching constrained to a maximum of two grid cells, and (4) a combination of filling and breaching based on an impact reduction approach (IRA). The IRA removes each depression using either filling or breaching depending on which method has the least impact, in terms of the number of modified cells (NMC) and the mean absolute difference (MAD) in the DEM.

Analysis of a LiDAR DEM of a landscape on the Canadian Shield showed significant differences in the impacts among the four depression removal methods. Depression filling, a removal method that is widely implemented in GIS software, was found to impact terrain attributes most severely. Constrained breaching, which relies heavily on filling for larger depressions, also performed poorly. Both depression breaching and the IRA impacted spatial and statistical distributions of terrain attributes less than depression filling and constrained breaching. The most sensitive landscapes to depression removal were those that contained large (i.e., >10%) flat areas, because of the occurrence of relatively large depressions in these areas.



**Keywords:** digital elevation models, terrain analysis, depression, error, pre-processing, flow routing, channel network extraction.

## 1. INTRODUCTION

Regular-grid digital elevation models (DEMs) commonly contain numerous topographic depressions, sometimes referred to as sinks or pits. Often these depressions may be artifacts that do not represent actual features of the landscape. Artifact depressions may occur in DEMs because of: (1) the limited horizontal and vertical resolution of elevation data, (2) operator error in the collection or entry of elevation data, and (3) error resulting from the interpolation of elevation data to generate a DEM (Qian *et al.*, 1990; Tribe, 1992; Martz and Garbrecht, 1998; Rieger, 1998; Florinsky, 2002). Despite their various origins, all artifact depressions artificially truncate hydrologic flow lengths and alter flow directions.

Although there is a current trend towards finer resolution and greater accuracy in digital terrain modeling (Lane and Chandler, 2003), artifact depressions will always be present in DEMs because they are an inherent characteristic of the tessellation of a continuous surface (Mark, 1988). Hutchinson (1989) describes a method of interpolating DEMs from point elevations and contour lines that uses a drainage enforcement algorithm to minimize depression occurrence. Although this interpolation scheme, known as ANUDEM (Hutchinson, 2000), effectively reduces the problem, very often artifact depressions are still present in the DEM. Furthermore, researchers frequently do not have access to the elevation source data directly and must rely on published DEMs that are created without hydrological conditioning. As such, depression removal will always be an important pre-processing step for modeling geomorphic and hydrologic phenomena that rely on flow routing (Burrough and McDonnell, 1998). Often the choice to use a particular depression removal method, such as filling (Jenson and Domingue, 1988; Fairfield and

Leymarie, 1991; Planchon and Darboux, 2001) or breaching (Rieger, 1998), is made because of computational efficiency or algorithm availability. However, recent developments in depression removal techniques offer very different solutions, which may yield dissimilar DEMs. For illustration, consider the following two extreme cases:

*Scenario 1:* In the process of removing a depression with a narrow outlet (e.g., a lake or wetland) that has been obscured by the DEM grid, depression filling will raise the entire lake surface while depression breaching will modify one or two cells at the site of the obscured outlet.

*Scenario 2:* In the process of removing a pit (i.e., a single-cell depression) that has been severely underestimated, depression filling will modify the underestimated cell, while depression breaching will modify grid cells in a long breach channel following the path of steepest descent to the DEM edge.

Clearly, the impacts of depression filling and depression breaching on the DEM can be very different. There is also potential for these dissimilarities to magnify in the terrain attributes derived from DEMs (Wise, 2000). Therefore, consideration of the impacts of depression removal methods on the quality of DEMs and derived terrain attributes is needed.

Ideally, each artifact would be removed using a method that is appropriate given the feature's origin. That is, depression artifacts that are caused by underestimation of elevations should be filled and those features that result from elevation overestimation should be corrected by breaching. Unfortunately, the origin of depressions is rarely, if ever, apparent. Because there is seldom justification for using a particular depression removal method based on feature origin, the best alternative is to minimize the error introduced to the DEM by inappropriately filling or breaching a depression. Therefore, the goal of depression removal methods should be to enforce continuous flow-paths descending from catchment divides to outlets in a way that requires the least modification of the DEM.

This study assesses the impacts of depression removal methods on the spatial and statistical distributions of terrain attributes. We ask the following questions:

1. Are there significant differences in the impacts of depression removal methods on DEMs? If so, which methods perform best under various geomorphic settings?
2. Is there a systematic manner in which terrain attributes derived from DEMs are affected by depression removal?
3. To what extent can the impacts of depression removal on terrain attributes be reduced?

## 2. BACKGROUND

Direct depression removal methods, that is, schemes that explicitly eliminate depressions, can be classified according to Fig. 1. Depression filling and breaching occupy opposite ends of a spectrum of methods. Filling raises the elevations of cells in the DEM grid, essentially flooding the feature. Breaching lowers grid cell elevations along a breach channel, essentially trenching the impoundment dam in front of the depression. In the middle of the spectrum, there are ‘combination approaches’. These schemes for depression removal work by both lowering and raising grid cell elevations. Some criterion must be used in combination approaches to decide which depressions, or parts of depressions, to fill and which to breach. For example, in the combination approach developed by Martz and Garbrecht (1998) the breach channel length is limited to a maximum of two grid cells; all remaining depressions are filled.

De-pitting is the process of filling single grid cells that are surrounded by neighbors with higher elevations. Although de-pitting does not remove all depressions from a DEM (i.e., depressions that are larger than one grid cell remain), it can reduce the processing required by other depression removal schemes. Thus, de-pitting is a common pre-processing procedure (O'Callaghan and Mark, 1984; MacMillan *et al.*, 1993). It is not known if de-pitting affects the impact of the depression removal process.

## 3. METHODS

### *3.1 Depression Removal Methods and the Impact Reduction Approach*

This study examined the impacts of four depression removal methods (with and without de-pitting) on the spatial and statistical distributions of terrain attributes. These methods included:

1. Filling (F) (Planchon and Darboux, 2001);
2. Breaching (B) and de-pitting followed by breaching (D/B) of remaining depressions (Rieger 1998);
3. Constrained breaching (CB) and de-pitting followed by constrained breaching (D/CB) (modified from Martz and Garbrecht, 1998);

4. Selectively filling and breaching based on the impact reduction approach (IRA) and de-pitting followed by the IRA (D/IRA).

De-pitting followed by depression filling was not examined because it is essentially a two-staged filling procedure that yields identical results to filling depressions in one step. The constrained breaching algorithm was similar to the algorithm described by Martz and Garbrecht (1998). However, if the grid cell that represents the overflow point for a depression is in an adjacent catchment, the Martz and Garbrecht (1998) criterion that outlet cells have neighboring cells in adjacent catchments that are at a lower elevation, may overestimate the overflow elevation and depression extent. Thus, outlets were defined in the constrained breaching algorithm used in this paper as the lowest grid cell along a depression's catchment boundary, or an adjacent grid cell in a neighboring catchment, from which flow continues into a neighboring catchment.

The IRA is a new combination depression removal technique that selects filling or breaching depending on which method results in the least modification of the DEM. The IRA algorithm (1) makes two copies of the DEM, one for filling and one for breaching, (2) measures the number of modified cells (NMC) and mean absolute difference (MAD) in elevation for depressions using both removal methods, (3) makes a decision to fill or breach depressions, and (4) performs the appropriate depression removal method in the original DEM. The decision to fill or breach depressions is based on an impact factor (IF) such that:

$$IF = \frac{1}{2}\left(\frac{NMC_f}{NMC_b} + \frac{MAD_f}{MAD_b}\right) \quad \text{If } IF \geq 1 \text{ then } \textit{breach}\text{, else } \textit{fill} \qquad (1)$$

Where the subscripts *f* and *b* denote filling and breaching respectively.

Ideally, the depression removal method that results in the minimum impact could be used to remove each individual depression in DEMs. In practice, however, the inter-dependence among depressions does not allow for this optimal solution. Fig. 2A shows a series of cascading depressions. Cascading depressions occur frequently along narrow valley bottoms in DEMs (Burrough and McDonnell, 1998; Rieger, 1998) because flow-paths are easily interrupted by spurious grid cell elevations in convergent topography. If the removal method that resulted in the least modification of the DEM were chosen to remove each depression artifact in this group of cascading depressions, the upper two depressions would be breached and the downslope depression would be filled (Fig. 2B). However, the breach channels from the upper two depressions are obstructed by the filled depression downslope, resulting in an interruption to the flow-path. To prevent such damming, the IRA considers the impacts of groups of cascading depressions as a whole rather than the impacts of individual features (Fig. 2C).

*3.2 Data*

The Turkey Lakes Watershed (TLW) is a 10.5 $km^2$ experimental watershed located approximately 60 km north of Sault Ste. Marie, Ontario (Fig. 3). There is approximately 410 m of relief in the watershed from the basin outlet (243 m a.s.l.) to the summit of Batchawana Mountain (653 m a.s.l.). Topography and hydrography in the TLW are controlled by bedrock, which is dominantly composed of Precambrian silicate greenstone (metamorphosed basalt) with some outcrops of granite (Semkin and Jeffries, 1983). The

TLW contains a chain of five small headwater lakes, which eventually drain into Lake Superior via the Batchawana River.

This study utilized a high resolution DEM of the TLW and surrounding areas created using LiDAR (light direction and ranging). LiDAR is a type of active remote sensing that uses the round-trip time of a laser onboard an airborne platform to measure the elevation of Earth's surface (Measures, 1984). The DEM was based on the 'last return' of the laser altimeter, thereby estimating the ground surface elevation rather than the top of the forest canopy. The grid resolution of the DEM was 5.0 m and the vertical precision was ±0.15 m.

The TLW DEM was partitioned into 149 catchments (Fig. 3) using an automated watershed extraction algorithm. These catchments represent a range in catchment area, relief, slope, and in the number and coverage of depressions (Table 1). Each catchment was categorized based on the percent of the catchment area with topographic flats, defined as a ≤ 5° slope. This independent variable was deemed important given the observation that depressions occur frequently on flatter sites (Martz and Garbrecht, 2003). Three slope classes were established including: upland-dominated catchments (< 10% flats), intermediate catchments (10% to 25% flats), and bottomland-dominated catchments (> 25% flats). The class boundaries were selected to ensure that a representative number of catchments were assigned to each category. The depressions in the DEM were removed using the four depression removal schemes previously described.

*3.3 The Spatial Distributions of Terrain Attributes:*

The impact of depression removal was defined as the difference in the terrain attribute derived from the original and depressionless terrain models. The horizontal extent of depression removal impact was measured for each catchment using the NMC and the vertical extent of impact was measured using the MAD in elevation. A repeated-measures MANOVA was performed to evaluate differences in the impacts of the depression removal methods on the spatial pattern of elevations in the three catchment slope classes. The within-subjects main effect of depression removal method, the between-subjects main effect of catchment slope class, and the interaction effect of depression removal method by slope class were tested for significance in the model. Because the distributions of the NMC and the MAD were skewed, log transformations were performed and $\log_{10}$(NMC) and $\log_{10}$(MAD) served as the dependent variables. Bonferroni tests were used to assess pairwise differences for significant statistical differences identified in the MANOVA analysis.

*3.4 The Statistical Distributions of Terrain Attributes:*

Kolmogorov-Smirnov (K-S) two-sample tests were used to evaluate whether depression removal significantly affected statistical distributions of elevation and other terrain attributes. The K-S test determines whether the maximum absolute difference ($D_{max}$) between the cumulative probability distributions of two samples is larger than would be expected as a result of random sampling (Earickson and Harlin, 1994). Thus, the K-S test is sensitive to differences in the general shape of the samples' distributions, rather than differences in their means or medians. This is important, given that depression removal often affects the tails of statistical distributions of terrain attributes because depressions frequently occur in low-elevation sites (e.g., along valley bottoms). The K-S test is also a distribution free statistic, which is advantageous because many distributions of terrain attributes are not normally distributed.

Tests were conducted to evaluate whether the statistical distributions of elevation, slope (4-neighbor calculation), and profile curvature (8-neighbor calculations) derived from depression-removed DEMs significantly differed from the original distributions of these attributes. Additionally, comparisons were stratified by slope class by lumping catchments of equal slope class and comparing the distributions of terrain attributes within these area. A total of 36 K-S tests were conducted (i.e., 3 terrain attributes × 4 depression removal methods × 3 slope classes).

## 4. RESULTS AND DISCUSSION

### *4.1 Depression Removal Schemes and Spatial Distributions of Elevation*

Catchment averages and standard deviations of the NMC and the MAD in elevation are presented in Table 2 for each depression removal method. The NMC ranged among the techniques and slope classes from 98.5 ±353.7 cells to 373.5 ±1982.6 cells. The MAD in elevation ranged among the depression removal methods and slope classes from 0.128 ±0.89 m to 0.236 ±0.211 m. Upland-dominated catchments had the fewest NMCs and bottomland-dominated catchments had the greatest NMCs for each depression removal method. Similarly, the MAD in elevation was smallest in the upland-dominated catchments and largest in the bottomland catchments for each depression removal method except constrained breaching (with and without de-pitting) for which this trend was reversed.

MANOVA analyses were used to evaluate the significance of differences in the NMC and the MAD in elevation among the removal methods. The multivariate main effect of the depression removal method on the NMC and the MAD was significant ($p < 0.001$, Table 3), as were the univariate effects of the depression removal method on the NMC [F (df = 1.64, 239.60) = 103.336, p < 0.001, $\eta^2 = 0.414$] and the MAD [$F$ (df = 2.05, 299.48) = 59.242, $p < 0.001$, $\eta^2 = 0.289$]. These results supported the premise that there were differences in the impacts of the depression removal methods on elevations in the TLW catchments. Bonferroni tests were conducted to identify significant pairwise differences (i.e. $p < 0.05$) among depression removal methods. To summarize the finding with respect to the NMC: IRA < breaching ≈ IRA (with de-pitting) ≈ breaching (with de-pitting) < constrained breach (with de-pitting) < constrained breaching ≈ filling. With respect to the MAD in elevation Bonferroni pairwise tests indicated that: IRA (with de-pitting) ≈ breaching (with de-pitting) < filling ≈ IRA ≈ constrained breaching (with de-pitting) ≈ breaching < constrained breaching.

The multivariate main effect of slope class on the NMC and the MAD was also significant ($p < 0.001$, Table 3). Univariate tests showed that the effect of slope class on the NMC was significant [$F$ (df = 2, 146) = 22.899, $p < 0.001$, $\eta^2 = 0.239$], while the effect of slope class on the MAD was not [$F$ (df = 2, 146) = 1.095, $p > 0.05$]. Bonferroni pairwise comparisons indicated that each the mean NMCs significantly differed by slope classes (p < 0.05) such that: upland-dominated catchments < intermediate catchments < bottomland-dominated catchments.

The multivariate interaction effect of the depression removal method by slope class was significant (Table 3), accompanied by a significant univariate interaction effect on the NMC [$F$ (df = 3.28, 239.60) = 5.737, $p$ = 0.001, $\eta^2$ = 0.073] and on the MAD [$F$ (df = 4.10, 299.48) = 9.480, $p$ < 0.001, $\eta^2$ = 0.115]. The interaction effects of the depression removal method and slope class on the NMC and the MAD are presented in Fig. 4A and Fig. 4B respectively. If no interaction effect were present, the relative performance of each of the removal methods would be the same in each slope class and the lines in Fig. 4A and Fig. 4B would be parallel. In terms of the NMC, the differences in the performance of the depression removal methods relative to one another are exaggerated in bottomland-dominated and intermediate catchments and are subdued in upland-dominated catchments (Fig. 4A). With respect to the MAD, all of the depression removal methods except constrained breaching (with and without de-pitting) yielded higher MADs in bottomland-dominated and lower MADs in upland-dominated. Constrained breaching (with and without de-pitting) performed most poorly in terms of the MAD in upland-dominated and intermediate-type catchments. These differences in performance of the depression removal methods under varying catchment slope classes resulted in the significant interaction effect observed in Table 3.

A priori de-pitting of the DEM had varying effects on the NMCs resulting from the depression removal methods. De-pitting significantly reduced the NMC of constrained breaching, did not significantly alter the NMC of depression breaching, and significantly increased the NMC of the IRA (Table 4). De-pitting consistently reduced the MADs in elevation resulting from each of the three removal methods with which it was tested (Table

4). Depression breaching (with de-pitting) and IRA (with de-pitting) resulted in the lowest MADs of the tested algorithms (0.128 ± 0.089 m). Constrained breaching (with de-pitting) had a lower MAD in elevation than constrained breaching (without de-pitting). Therefore, it appears that de-pitting can benefit the depression removal processes by reducing the impacts on DEMs, particularly in terms of the MAD in elevation.

*4.2 Depression Removal Schemes and Spatial Patterns of Other Terrain Attributes*

Every modified grid cell in a DEM corresponds to one or more modified grid cells in a derived terrain attribute. Therefore, the impacts of depression removal are always greater in terrain attributes than in the DEM. Surface derivatives (e.g., slope, aspect, and curvature) are calculated using neighboring cells in a three-by-three window. The degree to which a surface derivative is affected by depression removal is related to the number of neighboring cells used to calculate the derivative and the spatial distribution of modified cells in the DEM. The first of these factors is determined by the specific algorithm used to calculate the derivative. For example, given identical depression-removed DEMs, algorithms that use four neighboring cells are affected by the error introduced by depression removal to a lesser extent than algorithms that use all eight neighboring cells.

Fig. 5 illustrates how the spatial distribution of modified cells in the DEM influences the NMC resulting from depression removal in a surface derivative. When modified elevations are widely spaced (e.g., Fig. 5A), there are many unmodified cells in the DEM that can be modified in the surface derivative, depending on the algorithm used. In contrast, when modified elevations are clumped (e.g. Fig. 5B), there are fewer unmodified cells in the DEM that are adjacent to modified elevations, and therefore, fewer potentially modified cells in the surface derivative. Thus, the number of unmodified cells in a DEM adjacent to modified elevations is an important factor in determining the potential impact of depression removal on a surface derivative.

Fig. 6 presents the number of cells adjacent to modified elevations in the TLW DEM resulting from each of the depression removal schemes. Breaching and the IRA yielded approximately 20% more grid cells adjacent to modified elevations than the filling and constrained breaching algorithms (Fig. 6, solid line). This difference reflects the fact that depression filling tended to modify elevations in clumps while breaching modified elevations in elongated patches along breach channels. However, although depression breaching and the IRA modified more derivative cells per modified elevation than depression filling and constrained breaching, their overall impact on terrain derivatives was smaller because breaching and the IRA modified far fewer elevations in the DEM.

### *4.3 Impact of Depression Removal on Statistical Distributions of Terrain Attributes*

K-S tests were used to evaluate whether depression removal significantly altered statistical distributions of terrain attributes. Table 4 presents the $D_{max}$ values (i.e., the maximum absolute differences) between the probability distributions of each terrain attribute derived from a depressionless and the original DEM, as well as the significance of these differences. For each depression removal method and terrain attribute, $D_{max}$ values were largest in bottomland-dominated catchments and smallest in upland-dominated catchments. The largest $D_{max}$ values occurred with depression filling and the smallest values resulted from the IRA. Each of the four depression removal methods significantly altered the distributions of the three terrain attributes in bottomland-dominated catchments. No significant differences were identified in upland-dominated catchments.

Most of the changes in the probability distributions of terrain attributes that resulted from removing depressions were very small. Even significant differences in the cumulative probability distributions were generally found to be less than 3.5% (Table 4). The notable exception was depression filling and constrained breaching in bottomland-dominated catchments, where probability distributions of terrain attributes differed from the original DEM attributes by between 7.92% and 17.60%. The IRA modified the statistical distribution of elevations, slope, and profile curvature the least.

### *4.4 The Overall Performance of Depression Removal Methods*

The performance of each of the depression removal methods is summarized in Fig. 7 in terms of the NMC and the MAD in elevation. Depression filling, the most common method for removing depressions from DEMs, is among the worst choices in terms of impacting DEMs. This is particularly true when depressions are more than a few grid cells in extent. Constrained breaching (with and without de-pitting) also performed poorly. Although constrained breaching effectively removes smaller depressions with two-cell breach channels, it relies heavily on depression filling when depressions are larger. Depression filling and constrained breaching were also found to impact statistical distributions of terrain attributes more than depression breaching and the IRA.

Depression breaching and the IRA had similar impacts on the TLW DEM (Fig. 7). However, the IRA was found to impact statistical distributions of terrain attributes to a lesser degree than depression breaching (Table 4). Depression breaching (with de-pitting) and the IRA (with de-pitting) plotted in nearly the same location in Fig. 7. De-pitting reduced the MAD substantially for the breaching and IRA algorithms, although the NMC increased slightly in both cases. Therefore, a compromise exists between the dual objectives of minimizing the NMC and the MAD in elevation resulting from the depression removal process. If a researcher chooses to accept larger elevation changes over a smaller extent, the IRA (without de-pitting) would be the appropriate method of removing depressions. If, however, a researcher chooses instead to favor smaller elevation changes over a larger modified area, either the IRA (with de-pitting) or depression breaching (with de-pitting) would be appropriate.

Differences in the impacts of the four depression removal methods on DEMs and statistical distributions of terrain attributes were more pronounced in catchments containing greater than 10% flat areas. Therefore, the choice of an appropriate DEM pre-processing algorithm is particularly important in catchments containing a large proportion of flat areas, which tend to have larger depressions. When depressions are small in extent, depression filling and breaching have similar impacts on DEMs. As depression size increases, breaching and the IRA become evermore advantageous in terms of reducing the NMC.

It should be noted that the LiDAR DEM used in this study represented a best-case scenario. The dominant cause of depressions in the TLW DEM was random error, and therefore, the majority (62%) of the depressions consisted of one or two grid cells. The differences in the relative performance of the depression removal methods may be exaggerated in DEMs that are generated by other means, which contain larger depressions resulting from errors associated with interpolation and the spatial distribution of elevation data.

This paper has assumed that all depressions in a DEM are artifacts, and therefore, are justified in being removed. However, actual topographic depressions do occur in certain landscapes. Removing these real features from DEMs may not be appropriate for particular applications (Gallant and Wilson, 2000). Topographic depressions store water, collect windblown snow and nutrients, attenuate flood peaks, and focus groundwater recharge and evapotranspiration (Hayashi *et al.*, 1998; Hayashi and van der Kamp, 2000). Several researchers have presented alternatives to removing depressions from DEMs when these features are deemed to be significant (e.g., Martz and deJong, 1998; MacMillan *et al.*, 1993; McCormack *et al.*, 1993); however, considerable work is still needed in this area. Future research will focus on developing methods for distinguishing real depressions from artifacts in DEMs and evaluating the significance of real depressions as controls on local hydrology.

## 5. CONCLUSIONS

Our evaluation of several schemes for removing artifact depressions under a variety of geomorphic conditions revealed the following main findings:

1. Depression removal can significantly alter spatial and statistical distributions of terrain attributes. Therefore, greater consideration of DEM pre-processing algorithms is needed, particularly in research that utilizes DEMs to model hydrological and geomorphic processes.
2. There are significant differences in the degree of impact among the various schemes for removing depressions. Depression filling, although widely implemented in

commercial GIS software and commonly used in environmental research, can severely impact DEMs and derived terrain attributes. Depression breaching and the IRA are both better alternatives for removing depressions. The IRA, however, impacted the spatial and statistical distributions of terrain attributes less. De-pitting prior to depression breaching or applying the IRA effectively reduced the mean absolute elevation difference resulting from depression removal, yet increased the number of modified grid cells. If a researcher chooses to accept smaller elevation changes over a slightly larger area, then either depression breaching or the IRA is recommended.

3. The error in regular-grid DEMs that results from depression removal is magnified in the spatial and statistical distributions of terrain attributes derived from DEMs. The degree to which depression removal introduces error into surface derivatives such as slope, aspect, and curvature, is controlled by the number of neighbors used to calculate the derivative and the arrangement of modified cells in the DEM. The impacts of depression removal on DEM and derived terrain attributes are most severe in catchments containing large bottomland areas (i.e., > 10% flats). In addition, the advantages of depression breaching and the IRA over depression filling and constrained breaching are more pronounced in these bottomland-dominated catchments.

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**Figure Captions:**

Fig. 1: Spectrum of depression removal schemes.

Fig. 2: Longitudinal profile along narrow valley bottom showing how choosing the method of least impact to remove depression artifacts from DEMs can obstruct flow-paths. (B = breaching, F = filling)

Fig. 3: Shaded relief image depicting Turkey Lakes experimental watershed area. Catchments delineated in thin black lines.

Fig. 4: Interaction effect of depression removal method and slope class on NMC (A) and MAD (B). Abbreviations are defined in text.

Fig. 5: Arrangement of modified cells in surface derivative map resulting from five widely spaced (A) and clumped (B) modified cells in DEM. Figures assume use of an algorithm that uses all eight neighbors to calculate surface derivative.

Fig. 6: Number of cells adjacent to modified elevations in the TLW DEM resulting from seven depression removal methods. Each adjacent cell can be modified in a surface derivative if all eight neighbors are used in the calculation. Combining unmodified adjacent cells with the number of modified elevations gives the overall NMC for a surface derivative. Abbreviations are defined in text.

Fig. 7: Comparison of depression removal methods in terms of the impact on the TLW LiDAR DEM.