ASSESSING THE EFFECTS OF HYDROLOGIC ENFORCEMENT METHODS IN A CENTRAL TEXAS WATERSHED

by

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I. INTRODUCTION

The ultimate goal of hydrologic modeling is to predict the occurrence, circulation, and distribution of water resources on earth. For example, a city government or watershed management agency would use watershed modeling to determine watershed boundaries, identify sinkholes, or estimate total discharge from the watershed (Cederstrand and Rea 1996, Hart, Mills and Li 2009, Richter 2016). Emergency managers would use flood modeling to predict inundated areas from large storm events (Perotin et al. 2009). Engineering companies would use stormwater models to gauge a client's compliance with federal and local stormwater regulations (McGill Associates 2018, Streamline Environmental 2013, Terraphase Engineering 2018).

All of these hydrologic applications require an important input: the Digital Elevation Model (DEM), a digital representation of the topography. In a Geographic Information System (GIS), a common representation of a DEM is a raster grid, where each cell in the grid has an elevation value. Light Detection and Ranging (lidar) is an advanced remote sensing technology used to produce DEMs with fine spatial resolutions. At the time of writing, lidar data is commonly collected with a NPS (Nominal Post Spacing) of 1 meter (m) or finer. Without the extensive effort of filtering, a lidar dataset can be used to produce DSMs (Digital Surface Models) that include surface features (e.g. vegetation, structures) on the ground. While these fine resolution DEMs have many benefits over the coarser resolution DEMs (e.g. the 10 m or 30 m National Elevation Dataset from U.S. Geological Survey), a main drawback, however, is that these fine resolution DEMs also capture fine-grained landscape features, both natural and man-made, that may disrupt water from flowing downstream (Barber and Shortridge 2005).

Although these landscape features may not appear to block the flow of water in the real world, they practically “block” the simulation of a water droplet from flowing downstream (hereafter blocking features). Much effort has been focused on the development of lidar filtering algorithms to produce a bald-earth representations of the terrain, known as Digital Terrain Models (DTMs) (Meng et al. 2009). However, lidar-derived DTMs at fine spatial resolutions still often contain these blocking features that affect hydrologic modeling (Lindsay and Dhun 2015).

The first type of blocking features are sinkholes. In the real world, if water flows into a sinkhole, it may infiltrate into the ground through an opening in the lowest point of the sinkhole or accumulate as a pool and eventually overflow. In many modeling schemas, however, sinkholes can act as bottomless blackholes; cells flowing into a sinkhole can result in erroneous flow directions, hampering subsequent modeling. To avoid this, a common solution is to either breach or fill the sinkhole, so that the modeled water can continue to flow downstream. If the sinkhole is breached, then a small cut is made in the downstream “wall” of the sinkhole, effectively connecting the lowest point in the sinkhole to the next lower elevation point adjacent to the sinkhole. If the sinkhole is filled, the interior cells are raised to the spill elevation—where water would begin to spill over the rim of the sinkhole. In this way, water would no longer pool in the sinkhole, but rather would continue downstream.

A second type of blocking feature is a dam. A dam generally contains a culvert or opening on the downstream side, allowing water to flow downstream at specific times, and at a regulated rate. Again, in the flow direction step of hydrologic modeling, all cells with inflow must have outflow, so this dam either needs to be breached, or the area behind it needs to be filled to the spill elevation.

One may now notice that blocking features create depressions that need to be drained in order for hydrologic modeling to be successful. Other blocking features include elevated roadways, detention basins, stormwater ditches, and bridges. Note that these blocking features do not completely block the flow of water in real life, because they contain culverts, or some sort of opening to allow flow to continue downstream. But, these openings are not captured by the lidar collection and represented in the resulting DEM, so all blocking features can be thought of as a type of "digital dam." While depressions created by these blocking features can be drained by breaching or filling, both involve altering the elevation of the digital topography.

The process of altering the elevation values in a DEM in order to ensure the continuous flow of water downstream is called hydrologic enforcement. Filling and breaching are the two most common methods. In general, filling alters flow paths significantly more than depression breaching, yet it remains the most popular method (Lindsay and Creed 2005, Lindsay and Dhun 2015). John Lindsay speculates that this is because filling has a longer history of development, and because it is included in common GIS software (Jenson and Domingue 1988, Lindsay 2016a).

A third type of hydrologic enforcement method is the hybrid approach. This approach combines both filling and breaching. There are multiple types of hybrid hydrologic enforcement algorithms (Lindsay and Creed 2005, Lindsay 2016a, Martz and Garbrecht 1999, Rieger 1993, Soille 2004). One type, called constrained depression breaching, breaches all depressions where the breach channel would be shorter than a user-specified threshold length (Martz and Garbrecht 1999). Any depressions not breached are filled. This is to avoid unnaturally long breach channels created by breaching deep, natural depressions. Another hybrid algorithm is the Impact Reduction Approach, or IRA (Lindsay and Creed 2005). As reviewed in the next chapter in greater detail, this algorithm either breaches or fills a depression; the method chosen is the one that has the lowest impact on the DEM.

Hybrid methods do not have to only breach or only fill—some methods combine filling and breaching in each depression. Rieger (1993) developed the earliest of these methods. His procedure raised the interior of the depression, but also breached the depression's boundary. Later, Soille (2004) developed a similar but modified hybrid breaching-filling method.

There is one final category of hydrologic enforcement algorithms: flow direction enforcement. These algorithms do not alter the elevation values in the DEM. Instead, they utilize ancillary data to alter the flow direction raster (Kenny and Matthews 2005, Kenny, Matthews and Todd 2008). Algorithms that utilize ancillary data are outside the scope of this study, but they will be examined briefly in Chapter 2.

The selection of an appropriate hydrologic enforcement method is important for multiple reasons. First, hydrologic enforcement affects the topographic properties of the DEM, such as minimum elevation and mean slope (Lindsay and Creed 2005, Callow et al. 2007). Second, and more importantly, flow paths are affected (Duke et al. 2003). Finally, hydrologic enforcement affects higher order variables, such as flow accumulation, flow length and even the shape and size of the watershed (Callow et al. 2007, Gelder 2015, Martz and Garbrecht 1999). However, recently developed algorithms, such as those from Brian Gelder and John Lindsay, have not been studied or compared in depth (Gelder 2015, Lindsay 2016a). These algorithms are promising alternatives to traditional enforcement techniques, but their effects on flow direction and the higher order watershed variables mentioned above have not been corroborated. Therefore, this research will implement and compare four different recently developed hydrologic enforcement algorithms and one traditional method, in hopes of understanding how these new methods handle blocking features present in lidar DTMs and consequently impact watershed modeling.

The methods to be tested are listed below.

- Traditional Method: ArcGIS's Fill Tool (Jenson and Domingue 1988)
- Gelder's Method: A breaching method developed by Brian Gelder (2015)
- Lindsay's Whitebox GAT "Breach Depressions" Tool (2012)
- Lindsay's Whitebox GAT "Breach Depressions (Fast)" Tool: Designed to decrease processing time (2014)
- Lindsay's WhiteboxTools Constrained Breaching Tool: An efficient hybrid breaching-filling tool (2016)

Research Questions:

1. How effective are the five different hydrologic enforcement methods in accounting for specific blocking features (e.g. detention basins, roadside ditches, bridges, and dams)
2. How does the resulting hydrologically enforced DTM affect watershed shape and watershed area?

The following null and alternate hypotheses will be tested to answer the first question:

$H1_0$: There is no significant difference in enforcement effectiveness among the five enforcement methods, measured in terms of a) correctness of enforcement method chosen b) flow length from depression to outlet c) breach channel accuracy d) overall elevation change.

$H1_1$: There is a significant difference in enforcement effectiveness among the five enforcement methods, measured in terms of a) correctness of enforcement method chosen b) flow length from depression to outlet c) breach channel accuracy d) overall elevation change.

The following null and alternate hypotheses will be used to answer the second question:

$H2_0$: There is no significant difference in a) watershed shape, and b) watershed area among the five enforcement methods.

$H2_1$: There is a significant difference in a) watershed shape, and b) watershed area among the five enforcement methods.

II. LITERATURE REVIEW

This chapter examines how the fundamental concepts of filling, breaching, and flow direction have been implemented in hydrologic enforcement algorithms. A general outline or "pseudocode" will be presented for the major algorithms. Additionally, algorithms which made massive improvements to their respective category, such as those which increased processing speed, improved breach locations, or improved identification of natural depressions, will be highlighted. Finally, the literature review will finish with a brief discussion of enforcement's impact on the slope of DEM cells, and its impact on the delineation of the watershed.

Hydrologic Enforcement Algorithms

Hydrologic enforcement algorithms often follow the same basic procedure that involves a moving window, such as a 3x3 or 5x5 roving window. This roving window iterates through every cell in the DEM, reading the elevation values within the window, and determining the size and location of any depressions. The algorithm usually gives each depression a unique identifier. Next, if the hydrologic enforcement method utilizes breaching, the algorithm searches for cells outside of the depression to which the breach channel will extend. Finally, the depressions are iteratively filled, breached or some combination of the two.

S.K. Jenson and J. O. Domingue (1988) developed one of the earliest and most influential hydrologic toolsets. The toolset includes tools for sink filling, flow direction, flow accumulation, and watershed delineation (Jenson and Domingue 1988). Environmental Systems Research Institute (Esri) eventually implemented these tools in the ArcGIS Hydrology Toolset, which is one of the most widely-used hydrology toolsets. The most relevant tool for this research is the Fill tool, because it provides a good overview of how a fill-type algorithm operates. First, the Fill algorithm identifies all single-celled depression (i.e. cells where each of the eight neighbor cells have a higher elevations), then it eliminates the single-celled depressions by filling them to the height of their lowest neighbor. Second, it computes flow directions based on the D8 algorithm, and then assigns "undefined" flow direction to connected groups of cells that would require flow uphill to drain (i.e. depressions). Third, the algorithm finds the watershed (i.e. upstream drainage area) in which each undefined block of cells resides. If the watershed drains back to itself (i.e. a loop), the algorithm compares the lowest pour point of itself and adjacent watersheds. Watersheds are merged if they form an endless loop of drainage; then pour points between them are deleted and the lowest pour point is recomputed. Finally, the algorithm enforces the DEM by filling all watersheds to their threshold values. The threshold value is equal to the elevation of the lowest pour point that is the highest among the cells in each watershed's path of lowest pour points (Figure 1; interested readers can see the complete pseudocode in Jenson and Dominique (1988)).

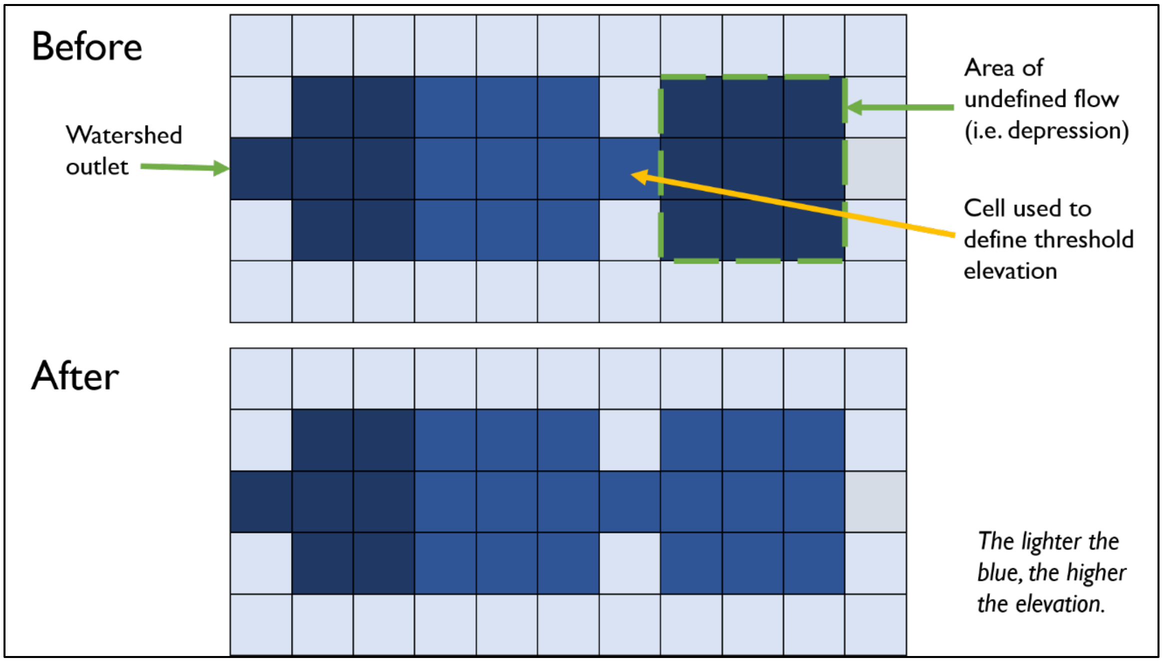

Figure 1**.** Filling enforced the depression by raising it to the threshold elevation of the depression (Jenson and Domingue 1988). The threshold elevation is the cell immediately left of the depression, because this cell is the watershed's pour point that is highest in elevation.

As an alternative to filling, breaching algorithms were proposed because filling depressions assumes that "all depressions are caused by elevation underestimation" (Martz and Garbrecht 1999). After identifying depressions, Martz and Garbrecht's breaching algorithm identifies the "sink contributing area" by growing outward from the lowest point in the depression (1999). Next, the lowest ridge cell (termed "the outlet") from the sink contributing area is flagged. Third, the algorithm determines if the depression can be breached. To breach, a channel must connect two candidate cells; both must be lower in elevation than the outlet, but one candidate cell should be located within the sink contributing area, and one outside. Additionally, the breach channel must be less than a pre-specified maximum breach length. If such a combination exists, then the depression is breached by lowering the cells along the breach channel to the elevation of the exterior candidate cell. Finally, the algorithm eliminates any remaining depression cells within the sink contributing area by raising them to the elevation of the breach channel (Figure 2). If no breach was made, then the depression cells are raised to the elevation of the outlet. The authors reported that their method “reduced the number of cells to which elevation changes were applied” by 25%. In addition to reducing the number of altered cells, the overall elevation change was also reduced (Martz and Garbrecht 1999).

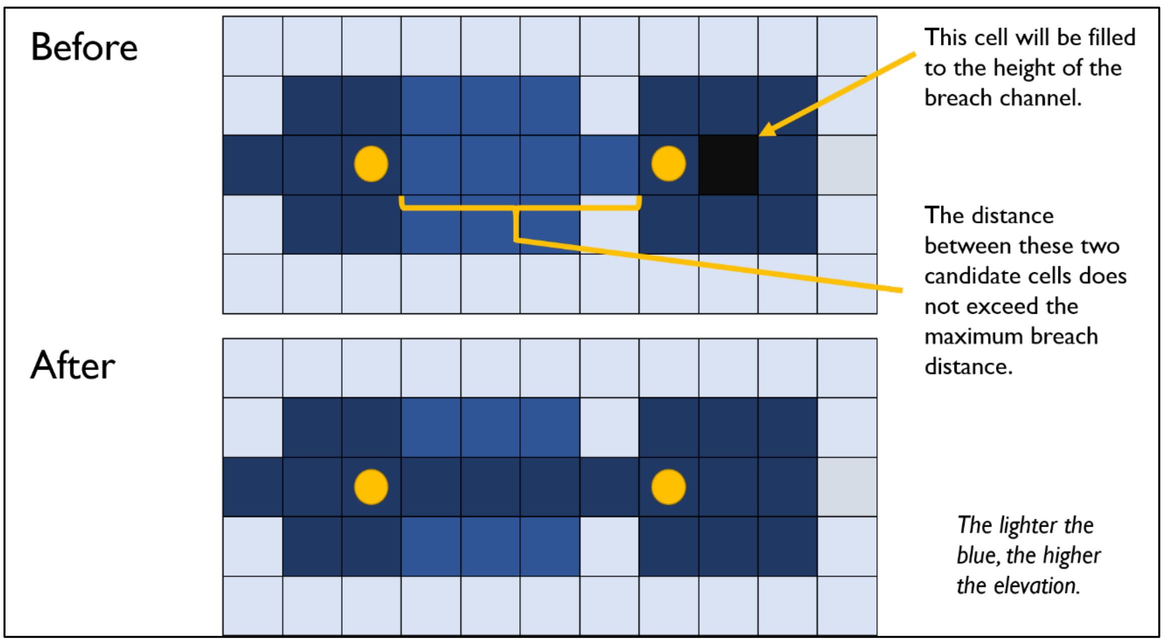

Figure 2. An illustration of Martz and Garbrecht’s breaching algorithm. First, the cell marked with the yellow circle on the left was identified as a candidate cell because it is outside the sink contributing area, and is lower than the depression’s outlet. Next, the cell marked with the yellow circle on the right was identified as an interior candidate cell because it is on the interior of the sink contributing area, is lower than the depressions outlet, and is within the maximum breach distance (e.g. 5 cells). Finally, the depression is breached, and any remaining cells are filled to the height of the breach.

Wang and Liu (2006) built upon the original filling algorithm by introducing the concept of spill elevation, which is the “minimum elevation value that the cell needs to be raised by to make water spill out from that cell to an outlet on the border of the DEM”.

By coupling this concept with a least-cost search for the lowest spill-elevation path, they ensured that the algorithm fills depressions only to the *actual* spill elevation; filling is not overestimated. The time complexity of their algorithm for a “DEM with N cells is $\boldsymbol{O(N \log N)}$ in the worst case” (Wang and Liu 2006). The authors go on to note that Jenson and Domingue’s algorithm’s time complexity is $\boldsymbol{O(N^2)}$ (1988). This translates to the new algorithm enforcing a DEM 30 to 90 times faster than the original filling algorithm.

As with filling algorithms, researchers have improved breaching algorithms drastically in recent years. The newest developments are from Lindsay and Dhun (2015) and Gelder (2015). Lindsay and Dhun noted that filling lidar DEMs containing road embankments causes major artefacts (2015). They argue that a breaching approach is better in these cases, but do not want to rely on ancillary data, such as in the algorithm developed by Duke et al. (2003). Their new algorithm uses least-cost path (LCP) analysis to determine where the breach channel should be located. Cost, in this case, is the amount of elevation change the DEM will undergo by finalizing the breach channel at a given location. Lindsay and Dhun (2015) argue that their algorithm is superior to previous breaching algorithms because the least-cost path approach more accurately enforces existing roadside ditches. For example, when other algorithms might erroneously breach across a road at the wrong location, the LCP breaching algorithm is more likely to trench along the ditch because of the lower elevation cost. Their algorithm would only breach across a road when doing so would be the only downstream option. This cost-surface approach frequently results in accurate breaches at culverts.

Gelder’s technical report (2015) written for the Iowa State University Institute for Transportation contains one of the most recent developments in breaching algorithms.

His aim was to both "respect natural depressions and correctly enforce flow in areas that are drained" (Gelder 2015). The algorithm he developed relies on some assumptions in order to achieve this goal. Depressions are first identified by filling the DEM using the Fill tool (Jenson and Domingue 1988, Planchon and Darboux 2002). Then, the algorithm thins the depressions to only those that should be enforced (i.e. candidate depressions) by testing them off five criteria. First, significant depressions are defined as regions "deeper than 18 centimeter root mean squared error of the lidar data on unvegetated surfaces or greater than 100 square meters in area." To enforce these significant depressions, the algorithm sets each depression's deepest point to null, so that water can "flow" out (during the flow direction stage of his algorithm), and they are removed from consideration for breaching. Second, the remaining candidate depressions are thinned to those that are not drained via channelized flow paths. Third, the slope between the deepest point in the candidate depressions and their nearest boundary is calculated. If the slope is greater than 5 percent, the candidate depression remains. If not, it is removed from consideration for breaching. Fourth, the candidate depressions are pre-cut, and then filled, to see if each fill depth has been reduced. If the cutting reduced the fill depth of a depression, it remains a candidate. Finally, if a candidate depression and its overflow pathway are fully within an area of channelized flow, and the candidate depression is shallower than one meter, the depression is filled. Any depressions that pass the five criteria are breached.

These strict criteria effectively identified depressions that should be breached in the study area. After an extensive accuracy assessment, the author found that his algorithm accurately identified 88 of 92 drained depressions. Furthermore, the algorithm breached channels with a mean centroid and length error down to one pixel (at 3 x 3 meter resolution) and a directional error of 0.10 radians. His algorithm required numerous assumptions to achieve this accuracy. Some of the assumptions are study-area dependent; they may not accurately identify candidate depressions outside of his Central Iowa study area. However, he introduced a useful framework. The parameters can be can be tweaked for other study areas.

Beside the common strategies of hydrologic enforcement algorithms, such as filling and breaching, there are also variations on these concepts, such as hybrid methods (filling + breaching) and algorithms that require ancillary data.

Lindsay and Creed developed one of the first hybrid methods of hydrologic enforcement called the Impact Reduction Approach (IRA), because the algorithm either fills or breaches each depression base on the least modification the DEM (2005). The algorithm makes this decision by first making two copies of the DEM, then filling one and breaching the other. Then, the algorithm calculates the Impact Factor (IF) for each depression using Equation 1.

Equation 1: $\mathrm{IF} = \frac{1}{2}\left(\frac{\mathrm{NMC_f}}{\mathrm{NMC_b}} + \frac{\mathrm{MAD_f}}{\mathrm{MAD_b}}\right)$ If $\mathrm{IF} \geq 1$ then breach, else fill

where NMC is Number of Modified Cells, MAD is Mean Absolute Difference, and the subscripts f and b are filling and breaching, respectively. When the IF is greater than or equal to one, the depression is breached; otherwise, the depression is filled. Note that the algorithm treats cascading depressions as a whole instead of individual depressions, in order to reduce enforcements that cancel each other out.

Their algorithm was innovative in its approach, but it was not very different from breaching in its results, especially when de-pitting (i.e. filling single-celled sinks) was performed before each algorithm. The mean and standard deviation NMCs, and the mean and standard deviation MAD for de-pitting + IRA and de-pitting + breaching were identical. Additionally, the authors reported a finding that "de-pitting minimizes the MAD for any breaching type method--and in most cases, quite significantly". De-pitting was a common preprocessing step well before their study, but their finding cemented de-pitting as a breaching best practice for future algorithm development.

More than a decade after the results of his study with Creed, Lindsay (2016a) noted that it was still a common practice to utilize filling methods, even though it had been demonstrated numerous times in the literature that breaching methods have a lesser impact on most DEMs (Grimaldi et al. 2007, Lindsay and Creed 2005, Soille 2004). He surmised that this reluctance to switch to breaching could partially be due to breaching's inefficiency for large DEMs. Thus, he created a highly efficient and versatile breaching tool, and included it in his open-source GIS software, Whitebox GAT (Lindsay 2016b). This tool combines a priority flood algorithm with a back link grid. In short, this algorithm first finds the lowest-elevation cell along the exterior of the DEM, and then reads each of its neighbor cells into a queue. It continues reading each neighboring cell into the queue, working its way uphill, but at the same time, remembering the path back downslope that it took to get to the current cell. When a pit cell or flat cell is discovered, the algorithm searches back through the previous cells in the backlink grid for a lower cell, then breaches the DEM along that path. This efficient breaching method can be combined with selective breaching (SB), which fills a depression if it would require too deep or long of a breach channel, or constrained breaching (CB), which breaches a depression up until a threshold depth and length, then fills the remainder if needed.

Lindsay's efficient hybrid breaching algorithm is faster than Wang and Liu's (2006) filling algorithm by 14% on average (Lindsay 2016a). The SB and CB variations were 7% and 100% slower than the filling algorithm, respectively, but the latter can be greatly improved by removing the max breach length constraint. All tests in his study were performed on massive, 3-GB DEMs from different continents, demonstrating that his tool is indeed as efficient and versatile as the filling methods.

Recent research in hydrologic enforcement has been focused on the development of hybrid methods, but another algorithm category that has seen recent development is enforcement that incorporates ancillary data. Algorithms in this category may utilize filling, breaching, or some combination of the two, which could lead to some confusion about what category these algorithms belong to. However, various researchers (e.g. Dhun, Duke, Gelder) have separated enforcement algorithms that heavily utilize ancillary data (i.e. vector data of canals, bridges, culverts, roads, etc.) into their own category (2015, 2003, 2015).

M.F. Hutchinson pioneered hydrologic enforcement algorithms that utilize ancillary data by presenting his new approach in a 1989 paper (Hutchinson 1989). The algorithm is primarily an interpolation algorithm, but one that incorporates a long list of ancillary data into the interpolation, if available. Data inputs can be sinks, streamlines, boundary polygons, contour lines, lake boundaries, cliff lines, or data mask polygons. The hydrologic enforcement aspect of the algorithm involves iterative interpolation that identifies and remove spurious sinks in the landscape by connecting a given sink to a lower sink via the first sink's lowest saddle point. The Australian Division of National Mapping adopted his algorithm in 1986.

This early algorithm is notable for a few reasons. First, it can produce hydrologically-correct surfaces from sparse input elevation points. Second, it is "computationally optimal in the sense that computer time is essentially proportional to the number of interpolated grid points" (Hutchinson 1989). The algorithm is also notable because it requests three tolerances from the user: the data's elevation accuracy; the contour interval; and a maximum connection length—designed to "prevent nonsensical drainage clearances" (Hutchinson 1989). This requesting of tolerances is found in many later algorithms.

Duke, Kiensle, Johnson, and Byrne developed a distinct ancillary hydrologic enforcement method in 2003 (Duke et al. 2003). Their method is called the Road Enforcement Algorithm, or REA, and was prompted by the realization that roads create a significant blocking effect on flow direction in flat landscape. Ditches are common on one or both sides of rural roads, and the flow direction in these ditches can be used to determine where overland flow might occur, or a culvert may exist. The algorithm requires ancillary data for the roads in the study area, and for these roads to be classified by their ditch types. See the three possible road classifications in Figure 3.

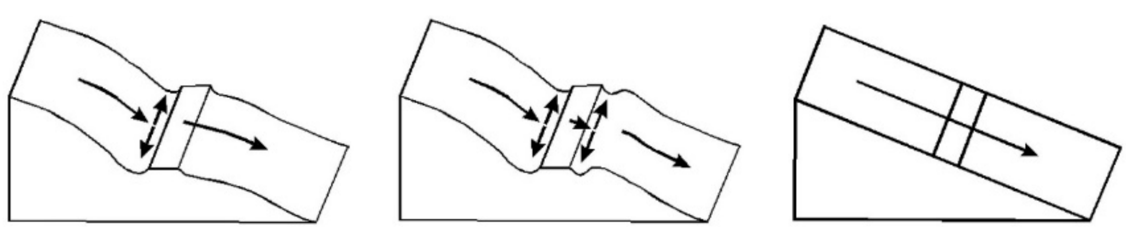

Figure 3**:** Illustrations of road classifications from Duke et al. 2003. Left: road with ditch only on upslope side. Center: road with ditches on both sides. Right: road without ditches.

For the roads that have some type of ditch, the algorithm accepts values for the depth of the ditch compared to the road. It can accept these depths according to three schemes, or “levels”:

1. Level 1 applies user-specified depths for “road to deepest ditch point” and “deepest ditch point to ground level” to all roads for which these values are relevant.
2. Level 2 is similar to Level 1, but allows the user to specify categories of roads, and then applies custom depth values to the roads in each category.
3. Level 3 allows fully variable ditch depths for each cell in each ditch in each category. Depth values might come from cross-section surveys.

First, the algorithm calculates the "collector network"; that is, the contributing area for each ditch. Next, flow directions are calculated for each collector network. Using an overflowing pools schema, the flow direction is modified for each collector network. Finally, breach locations (or overland flow locations) are identified using the lowest point in each collector network. The authors found that, for a large study area (~100 km^2), the algorithm was effective at identifying breach locations; only 5% were considered erroneous.

Instead of incorporating ancillary road data, Allen and Howard utilized ancillary ditch data (Allen and Howard 2015). In coastal North Carolina, old agricultural ditches and canals strongly influence hydrology. However, these features are sometimes so narrow that they are eliminated during the DEM interpolation process. To ensure that canals are represented in hydrologic models, Allen and Howard developed a method that burns vector canals and ditches from the National Hydrography Dataset (NHD) into lidar-derived DEMs. Although their stream burning method was not new (see W.K. Saunders in Maidment and Dojokic 2000), and their enforcement of the study area did not greatly affect the flood inundation model, it did greatly affect the delineation of sub-watersheds. The significance of this is described as follows:

> Better representation of functional sub-watersheds could improve the targeted application of best management practices, such as retention ponds, prescription of discharge and flow capacities for culverts, or selection of low-impact development alternatives (LIDs) such as vegetated swales. (Allen and Howard 2015)

Their method and findings have broad impact to practitioners because NHD data is available country-wide. Study areas where prominent hydrological structures might be omitted or underrepresented could utilize their method.

The final hydrologic enforcement category, flow direction enforcement, contains algorithms that are fundamentally different than the algorithms that have been discussed so far. Flow direction enforcement algorithms do not alter the elevation values in the DTM; instead, they alter the flow direction raster. Kenny and Matthews (2005) developed the first of these methods. Their algorithm relies on a key piece of auxiliary data: photogrammetrically-derived vector stream lines and waterbody polygons. Their method can produce a flow direction raster that aligns perfectly with photogrammetrically-derived vector data. The first step in their algorithm is to generate flow direction for an unenforced DTM using the typical D8 algorithm. Next, the algorithm converts the vector streams layer to raster, then calculates flow direction for this new layer. The algorithm creates flow direction for waterbodies in the third step. To assign flow directions to water body cells, there must be at least one stream line (in the other vector dataset) running through the center of the water body. Then, the algorithm “dilates” (i.e. grows outward) from the previously-created stream line flow direction cells (Kenny and Matthews 2005). In this way, each cell in the water body area is assigned a flow direction iteratively. Each iteration populates an adjacent set of cells from the original stream line “seed”. Finally, the algorithm replaces the corresponding cells in the DTM flow direction raster with their counterparts in the new stream and waterbody flow direction layers. The final product is a single “topologically enhanced” flow direction raster (Kenny and Matthews 2005).

Kenny and Matthews (2005) compared their new method with three other enforcement methods. To produce the DTM to be fed into their algorithm, they used ArcGIS’s TOPOGRID (AKA ANUDEM 4.4) combined with their vector streams and waterbodies. This means that the interpolated DTM would already be somewhat hydrologically enforced, because TOPOGRID accounts for these vector inputs when interpolating. The other three methods were: 1. TIN + Breaklines; 2. TOPOGRID + Vectors; 3. TOPOGRID + Stream Burning. The four flow direction layers produced by these four methods were compared in four areas of interest: 1. Waterbodies 2. Complex drainage areas 3. Meandering streams and 4. Stream junctions. The authors found that their flow direction layer most accurately represented the known hydrology in each circumstance.

In 2008, the two authors collaborated with Kent Todd to improve on their algorithm’s performance in flats and depressions (Kenny et al. 2008). The resulting solution, once again, outperformed competing algorithms (IRA, Constrained Breaching, Fast Breaching, Regular Breaching, and Filling) in accuracy, but also in terms of number of modified elevation cells and number of modified flow direction cells. Nevertheless, the impressive feats of these two algorithms cannot be achieved without highly accurate ancillary stream and water body data.

Table 1. Summary of articles discussed in this section (in order of appearance).

Algorithm Type	**Author**	**Year**	**Contribution**
Filling	Jenson & Domingue	1988	Foundational filling approach
Breaching	Martz & Garbrecht	1999	Foundational breaching approach
Filling	Wang & Liu	2006	Improved filling speed 30-fold
Breaching	Lindsay & Dhun	2011	Improved breach locations with LCP
Breaching	Gelder	2015	Improved identification of natural sinks
Hybrid	Lindsay & Creed	2005	Foundational hybrid approach ("IRA")
Hybrid	Lindsay	2016	Improved breaching speed
Ancillary	Hutchinson	1989	Foundational ancillary approach ("ANUDEM")
Ancillary	Duke et al.	2003	Improved road/ditch representation ("REA")
Ancillary	Allen & Howard	2015	Improved coastal modeling via canal burning
Flow Direction	Kenny & Matthews	2005	Foundational flow direction approach
Flow Direction	Kenny et al.	2008	Improved flow direction in flats and sinks

Impact on Hillslope

Slope is a primary attribute of Digital Elevation Model. The slope of a DEM cell is the angle between the vertical axis perpendicular to the horizon and surface normal based on the focal cell and its eight neighbors. Watersheds can be characterized by various slope metrics, such as mean, standard deviation, minimum, and maximum. However, hydrologic enforcement methods that affect the elevation values in the DEM will, naturally, affect the slope metrics of each watershed.

Roadside ditches with gentle gradients would cause problems for the algorithm developed by Lindsay and Dhun (2015). Their algorithm would often breach across roads instead of maintaining flow laterally in the ditch. This is because these gently sloped ditches created ambiguous flow direction. Despite this undesirable result, the authors noted that breaching across roads at the wrong location is still preferable to filling. Filling would allow water to spill over the whole road, which is unrealistic.

The measurement of slope played a crucial role in the algorithm developed by Gelder (2015). One of the central steps of his algorithm was to calculate the slope from the deepest points in a depression to the depression's local boundary. If the slope from these two points is greater than 5%, the depression's embankment is removed, the depression is filled, and a test is preformed to see if this procedure decreased the fill elevation compared to before the embankment removal.

Next, Lindsay and Creed (2005) compared before-enforcement and after-enforcement slope for 4 different hydrologic enforcement algorithms: filling, breaching, constrained breaching, and the Impact Reduction Approach (IRA). Furthermore, they categorized the 149 catchments in their study area into "upland" (<10% flats), “intermediate” (10-25% flats), and “bottomland” (>25% flats), so that they could determine which topography was most affected by each type of hydrologic enforcement. They found that there was a significant difference in maximum slope between the enforced and unenforced DEMs for filling and breaching in the intermediate and bottomland catchments but not upland. For constrained breaching and the IRA, there was only a significant difference in maximum slope for the bottomland catchments. Based on these results, one can conclude that hydrologic enforcement has a greater effect on slope in areas with low relief than areas with high relief.

Since bottomland catchments had significantly different max slope after being enforced by all four enforcement methods, some additional conclusions can be drawn. In order from the least to greatest change in maximum slope, the enforcement methods are: IRA, Breaching, Constrained Breaching, Filling. Note that the difference between IRA and Breaching was very small, and so was the difference between Constrained Breaching and Filling. However, the difference between these two pairs was great. With this information, we can draw one final conclusion; the breaching component of a hybrid algorithm causes far less change to the maximum slope for bottomland areas than the filling component.

Finally, Callow et al. (2007) also performed a comparison study that examined slope. They reported the mean and max slope of DEMs enforced by stream burning as well as the algorithms AGREE, ANUDEM v4, and ANUDEM v5. Between these, the least changed mean slope was from AGREE; its mean slope was only 0.1% higher than the original DEM. For max slope, the least change occurred with ANUDEM v5; its max was 23.15%, compared with 16.9% in the original DEM.

Unfortunately, these results cannot be easily compared to the results from Lindsay and Creed (2005). This is because all methods compared in the former study are fundamentally different than simple filling vs. breaching. Additionally, after each enforcement method was implemented in their study, remaining pits were filled (stream burning, AGREE and ANUDEM are not "complete" enforcement methods). If one method in the 2007 study stood out as being predominately breaching or filling, then a researcher could test Lindsay and Creed's finding that breaching methods have a lower effect on slope (2005). But, the methods do not fall cleanly into one category. Stream burning is fundamentally different than breaching because it can produce large, evenly deep channels along major water ways, but does not affect off-network depressions. AGREE and ANUDEM (both versions) recondition large sections of the landscape; they do not cut narrow channels like a strict breaching method. Therefore, the assertion that breaching methods have a lower effect on slope still needs to be corroborated. It is also notable that the findings of Lindsay and Creed (2005) were limited to maximum slope but not mean slope as in Callow et al. (2007).

The four papers above showed how slope is addressed in hydrologic enforcement studies. However, note that enforcement can either bring a depression closer or further from the true slope, depending on the polarity of interpolation error. If the elevation values in part of a hillslope are underestimated in the interpolation phase, then filling that depression will make the slope more accurate (i.e. breaching would be less accurate). However, if some elevation values on a slope are overestimated, then filling would cause the hillslope calculation to be further from the truth; in this case, breaching would result in a better representation of this hill (Figure 4). As mentioned in the previous section of this chapter, the rules Gelder developed for classifying depressions come a long way in solving this problem of which types of depression to fill or breach (2015).

The first research question of this paper asks, “how effective are the five different hydrologic enforcement methods in accounting for specific blocking features (e.g. detention basins, roadside ditches, bridges, and dams)?” The discussion of slope in this section can help in predicting what affect each type of algorithm has on slopes in different terrain types. However, the fact that no authors have examined slope changes surrounding specific drainage features/depressions is a gap in knowledge—one which this study hopes to answer.

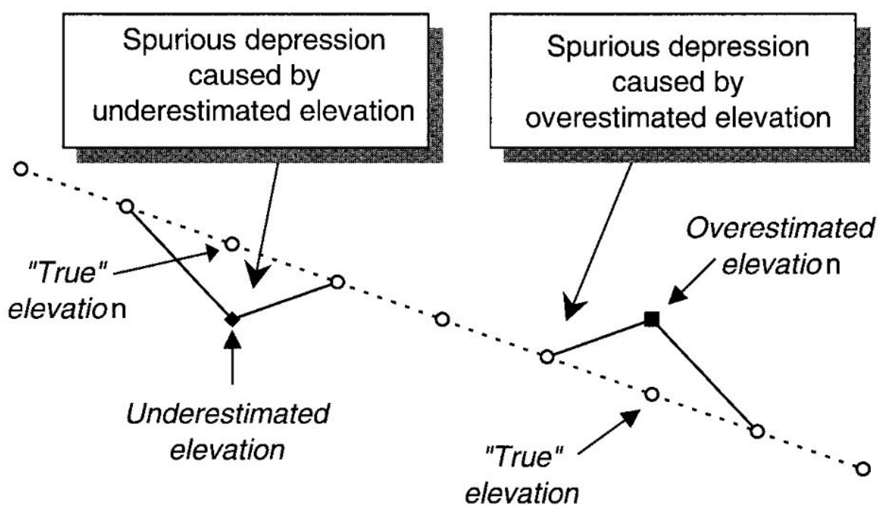

Figure 4: This figure from Martz and Garbrecht (1999) introduces the concept of elevation estimation errors, but it can be used to explain how hydrologic enforcement affects slope. The dotted line represents the true slope of this hypothetical hill. Correcting the two errors by means of filling or breaching can either bring the DEM values closer or further from the true elevations, depending on the direction of the original error.

Impact on Watershed

Since hydrologic enforcement procedures modify the terrain, they can also affect the shape/size of the delineated watersheds. Martz and Garbrecht (1999) addressed specifically how their algorithm affected the delineation of the watershed. Their algorithm allows the user to specify no breaching (i.e. all filling), breaching constrained to only one cell, or breaching constrained to a length of 2 cells. They noted the following.

> The increase in breaching length from one to two cells did produce an increase in the watershed area of 34 cells. This was the result of a single closed depression, which was filled and partitioned across the divide under the one-cell or no-breaching options, becoming incorporated into the watershed under the two-cell breaching option. Although the magnitude of the change in watershed size and the associated shift in divide position were minor, they do demonstrate that breaching can affect watershed delineation. (Martz and Garbrecht 1999)

This statement was echoed in a study preformed 8 years later. Besides examining the effect of different drainage enforcement algorithms on slope, Callow et al. (2007) also studied how these algorithms affect catchment area. AGREE and ANUDEM v4 were tied for the smallest change in area, with each only increasing and decreasing the total area by 3%, respectively. Figure 5 is an illustration from their paper. It is evident that watershed shape, as well as area, was affected.

Unfortunately, the conclusion that that filling or breaching affects watershed boundaries more cannot be made based on these studies. As stated in the previous section, this is because the methods used in the present study do not fall strictly into one category, so Martz and Garbarecht's (1999) finding that breaching may cause a larger watershed than filling cannot be corroborated. This study will help to answer this question by comparing both true breaching and true filling methods. Keep in mind, however, that breaching may only result in a larger watershed area when a large depression is on the edge of the catchment. Thus, an increase in watershed area as a result of breaching is highly dependent on the local topography, and, presumably, not a monotonic relationship.

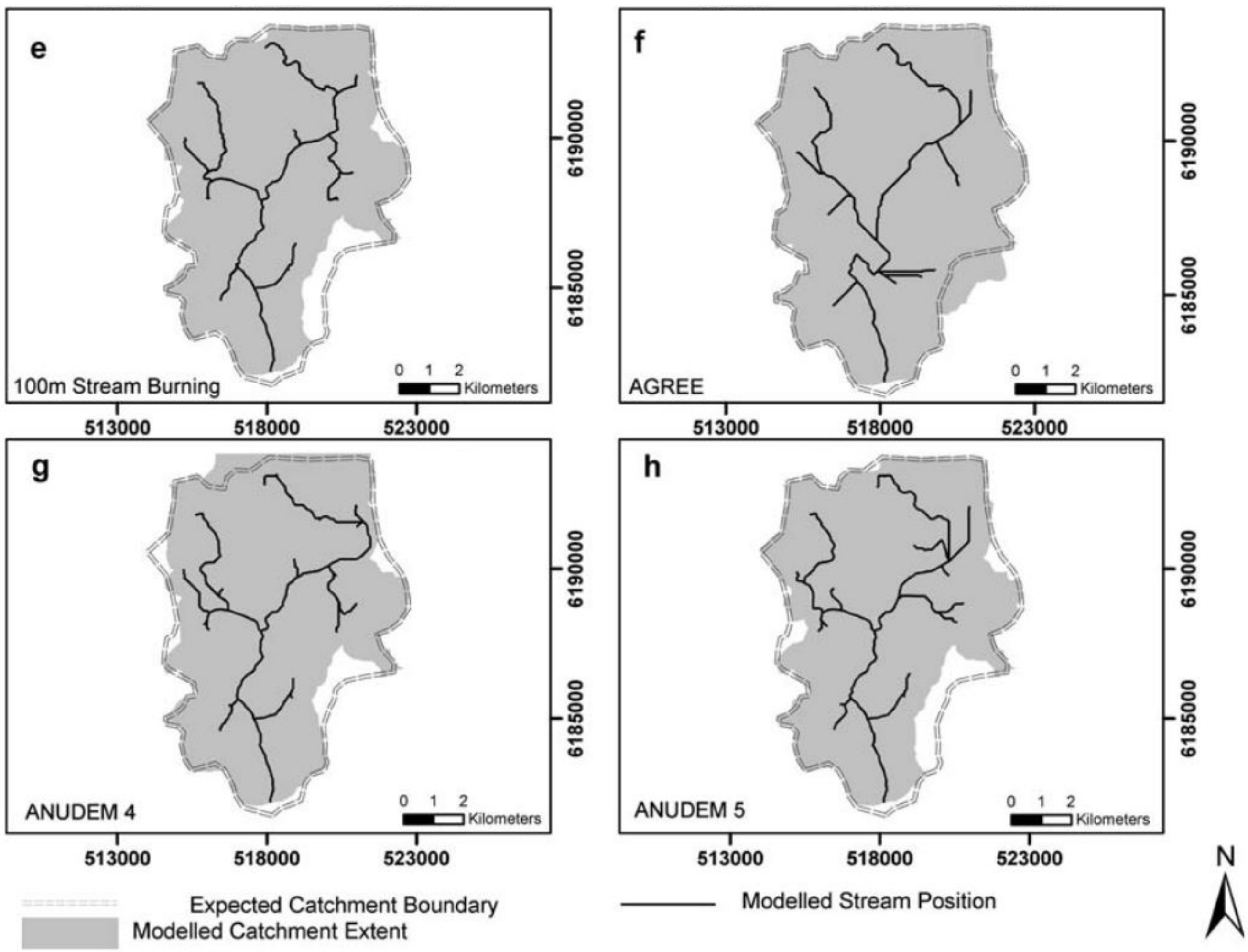

Figure 5: This figure from Callow et al. (2007) shows the difference between the modeled catchment boundary and expected catchment boundary for four different hydrologic enforcement methods used on a study area in Western Australia.

Summary

As hydrologic enforcement evolves, it has become more hybrid-focused and ancillary-focused. Recently developed algorithms from Gelder and Lindsay are promising; they compete with filling in speed and surpass it in accuracy (Gelder 2015, Lindsay 2016a). However, in terms of how hydrologic enforcement methods affect specific drainage features, the research is lacking. Some studies have been done which lightly touch the subject of how enforcement methods affect slope and watershed area. However, the findings in both categories are too few to form a complete picture. What is apparent is that enforcement increases max slope in low relief areas more than high relief areas, and that breaching methods may affect slope less than filling methods. Yet, the important linkages of how enforcement affects flow direction surrounding depressions, flow length from depression to outlet, and watershed area/shape remain unknown. A procedure that attempts to answer these questions is outlined in the next chapter.

III. METHODOLOGY

The general framework for this project is as follows.

1. *Download lidar data and interpolate it into a DTM.*

   1.1 Identify, classify, and digitize depressions

2. *Apply one of five hydrologic enforcement methods to the DTM.*

   2.1 Compare depressions in DTM with their representations in the 5 Enforced DTMs (EDTMs): enforcement method chosen and breach channel accuracy

3. *Run the Flow Direction, Flow Length, and Basins tools on each EDTM*

   3.1 Compare depressions in DTM with their representations in the 5 EDTMs: flow length from depression to outlet

   3.2 Numerically and statistically inspect the watershed size and shape for each EDTM

The remainder of this chapter will explain each of these steps more thoroughly.

Study Area

The study area for this project is the Smith Branch Watershed of the San Gabriel River. This watershed covers 56 square km (~13,853 acres) and is centered on Georgetown, TX. It is considered by the USGS a HUC12 watershed, which is one of their smallest classifications of watershed. The City of Georgetown contracted Sanborn Mapping Company to fly and process lidar for the city and surrounding area in May 2015, and the NPS (nominal point spacing) of the flight was 50cm.

Data Acquisition and Preprocessing

1. *Download lidar data and interpolate it into a DTM.*

First, the lidar point data was downloaded from TNRIS (Texas Natural Resources Information System). Sanborn classified each point into one of 14 classes (Bare Earth, Low Vegetation, Medium Vegetation, High Vegetation, Buildings, Water, etc.), and delivered quadrants of the data as .LAS tiles. This study's watershed was buffered by 1 km (Gelder 2015), and any LAS tile that intersects this buffer was downloaded from TNRIS. This buffer is used so that the shape of the watershed can vary widely, if, for example, one of the hydrologic enforcement methods drastically affects the elevations, flow direction, and thus watershed delineation.

After the data was downloaded and organized, it was filtered to only include points classified as "Class 2: Bare Earth/Ground". Then, the bare ground points were used to create a DTM with a cell size of 2 meter. It was created by interpolation using the Inverse Distance Weighted (IDW) algorithm with a power of 0.5.

1.1 Identify, classify, and digitize depressions

Before enforcing the DTM, depressions in the study area was identified and tabulated. This was done by filling the DTM, then subtracting original DTM from the filled DTM. Each depression was coded based on its type (e.g. detention basin, retention pond, ditch, embankment, etc.) Using aerial imagery, elevation values, and some field verification, the best enforcement method for each depression was determined. The best method was based on the existence and location of drainage structures (culverts, etc), as well as how water flows over the land during a rain event. Finally, the boundary of each depression and its proper enforcement were digitized. The depression boundary was created by converting the contiguous filled cells to vector, and if the most appropriate enforcement method is filling, this was noted in the table. If the most appropriate enforcement method was breaching, the breach channel was digitized by hand.

<u>Hydrologic Enforcement</u>

2. *Apply one of five hydrologic enforcement methods to the DTM.*

In step two, the DTM was hydrologically enforced, creating an enforced DTM (EDTM). The details of this step depend on the method used. Some, such as the Fill tool in ArcGIS, or the "Breach Depressions (Fast)" tool, were simple to implement; they only required one input and had minimal customizable parameters. On the other end of the spectrum, there was Gelder's Method, which is still in the testing stage of development. Regardless of the implementation, the result for each method was one EDTM. Procedures for implementing each of the five enforcement methods are outlined below.

i. Traditional Method: ArcGIS's Fill Tool (Jenson and Domingue 1988)

The parameters for Fill are input surface raster, output surface raster, and z-limit. The z-limit was left blank. The z-limit parameter allows the user to specify a maximum fill depth. If a filling a depression would mean exceeding the z-limit, that depression is left unfilled. Leaving some depressions unfilled is desirable if one's procedure involves enforcing the unfilled depressions by breaching, etc., but since this EDTM will only be enforced by filling, the z-limit parameter was kept blank.

ii. Gelder's Breaching Method (2015)

This breaching method spans two arcpy scripts. Together, they perform the following procedures: creating a DTM from raw lidar points; truncating small elevation differences, removing one-cell depressions (de-pitting); and enforcing drainage via hole-punching and cutting. The scripts contain many parameters which can be tweaked to better fit the study area, such as the threshold for slope between a depression bottom and its ridge that constitutes a non-natural depression. Since the method is still in the testing phase of development, Dr. Gelder ran the tool on his workstation and delivered the results and a technical summary via a cloud file sharing service.

iii. Lindsay's Whitebox GAT "Breach Depressions" Tool (2012)

Lindsay developed a full-featured open-access GIS program called Whitebox Geospatial Analysis Tools (Whitebox GAT) in 2009. Contained within the program are renditions of classic geospatial tools, but also some tools Lindsay himself developed. The Breach Depressions tool is one of those tools. It finds the optimal path for breaching by considering the cost (in elevation) of breaching through different paths out of each depression. The path with the lowest cost will be breached. The tool requires an in-and-out raster, as well as values for maximum breach channel length, maximum elevation decrement value, and minimum elevation decrement. The last two parameters are optional. For this study, the max breach length was set to 50, the maximum elevation decrement was set to 10 m, and the minimum elevation decrement was left blank.

iv. Lindsay's Whitebox GAT "Breach Depressions (Fast)" Tool: (2014)

Breach Depressions (Fast) is a breaching tool which has been optimized for speed. Instead of finding the cost of breaching through different pathways, the tool finds the flood order of the DEM cells, then, when a depression is encountered, the algorithm works backward along the flood order to find a breaching path. Breach Depressions (Fast) compares favorably in processing time to the ArcGIS Fill tool. It requires only an input and output raster, but optionally, a maximum breach length can be set. For this study, no maximum breach length was specified. Throughout the paper, this tool will be referred to as "Fast Breaching" to maintain clarity.

v. Lindsay's Constrained Breaching Tool: An efficient hybrid breaching-filling tool (2016)

The constrained breaching tool has all the speed benefits of the Breach Depressions (Fast) tool, because it utilizes the flood order queue to determine breach channel path. However, the tool has parameters that allow the user to specify varying combinations of breaching and filling; they can breach in complete, selective, or constrained modes. This study will utilize the constrained breaching mode, with a value of 50m for the maximum breach channel length threshold, and no maximum breach depth. Please see Figure 6, which is taken from Lindsay (2016a), for a flowchart of this tools different modes.

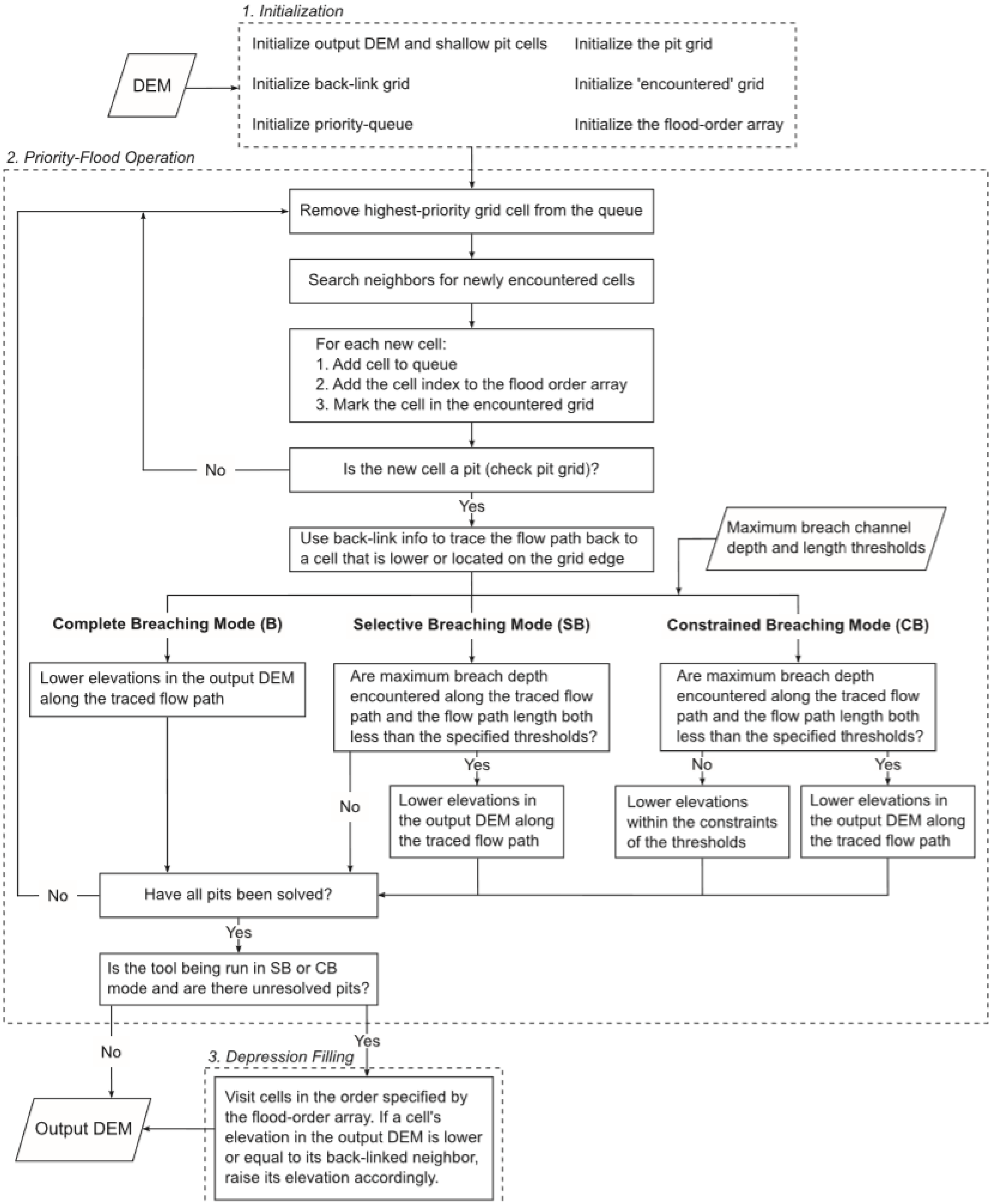

Figure 6: Flowchart from Lindsay (2016a), which describes the procedure for the hybrid tool used in this study.

2.1 Compare depressions in DTM with their representations in the five Enforced DTMs (EDTMs): enforcement method chosen and breach channel accuracy

In this step, null hypothesis H1(a) “enforcement method chosen” and null hypothesis H1(c) “breach channel accuracy” were tested. After each EDTM had been created, it was possible to compare the “best” enforcement method for each depression (determined in step 1.1) and the enforcement method used in each EDTM. For example, Lindsay’s Constrained Breaching tool is a hybrid method that may fill or breach a depression. The enforcement method chosen for each depression was marked as correct or incorrect. For the non-hybrid methods—Fill and Breach Depressions (Fast)—the correctness will depend on the type of depressions in the study area, as these methods apply either all breaching or all filling. Thus, null hypothesis H1(a) is most useful for examining Gelder’s Method, Breach Depressions, and Constrained Breaching.

For all the algorithms except Fill, breach channels were assessed for positional accuracy to test null hypothesis H1(c). First, the DTM were subtracted from each EDTM. This left cells with a non-zero value as cells that were changed by the enforcement process. Next, the cells representing the breach channel for each depression were identified and reclassified as one. After that, the raster pixels labeled as breach channels were converted to feature lines. Finally, each breach channel was compared to the digitized true enforcements (created in step 1.1) using a buffer overlay technique (Goodchild and Hunter 1997). A pseudocode, adapted from Tobar (2012), is outlined below:

```
For each digitized breach channel
    Buffer from 50 cm to 10m in 50cm intervals
    Clip the nearest modeled breach channel by the buffer
    Drop dangling nodes (where length = buffer)
    (CP = Length of clipped modeled channel / length of digitized channel)
    Calculate CP
    If CP >= 1
        Horizontal accuracy is +/- buffer distance
    Else if CP <= 0.999 and buffer < 10m
        Next buffer
```

This code will return the horizontal accuracy of each modeled breach channel as a probability curve. The curve's x-axis would be the buffer distance, and the y-axis would be the percentage of modeled breach channel that is within the buffer. For an illustration of these curves, see the figure from Goodchild and Hunter in Figure 7 (1997). Note that the maximum buffer distance is set as 10m; this is to limit processing time, while still providing sufficient information about the positional accuracy of the modeled breaches.

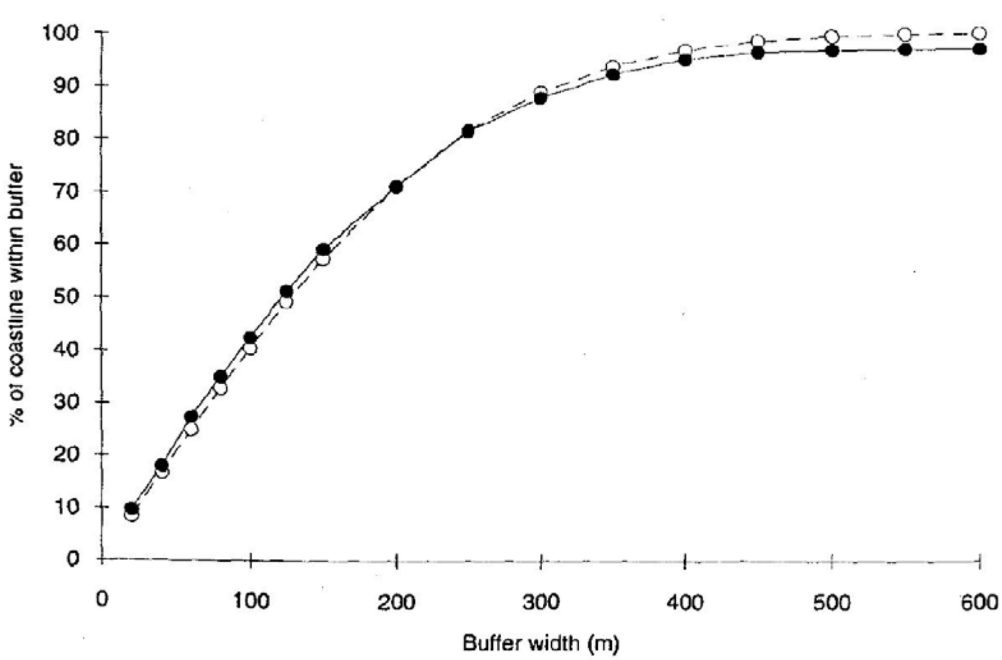

Figure 7: In this figure from Goodchild and Hunter, the Gaussian distribution (white) is plotted alongside an example application of buffer overlay: coastline accuracy (1997).

Flow Direction, Flow Length, Basins, and Final Calculations

3. *Run the Flow Direction, Flow Length, and Basins tools on each EDTM*

The EDTMs were used to derive flow direction, flow length, and delineate watersheds. The flow direction framework used in this paper is the eight-direction model (D8). Flow direction is represented by a raster grid, where each cell has a value of either 1, 2, 4, 8, 16, 32, 64, or 128. These values correspond to the possible directions that water might travel after falling on a central cell. Water traveling directly to the East would mean that the central cell is given a value of 1. If Southeast, the central cell is numbered 2. This continues to each of the cells 8 neighbors in a clockwise direction, so that the Northeast cell corresponds to the number 128.

3.1 Compare depressions in DTM with their representations in the 5 EDTMs: flow length from depression to outlet

Flow length was calculated for each enforced DTM. Then, the 250 sample depressions were thinned to just 142; only depressions which were completely within the delineated watershed with the smallest footprint (Fast Breaching – 5082.44 Ha) were retained. This way, flow length calculated from depression centroid to outlet is comparable across enforcement methods. For example, the outlet of depression #1 may be a distance of 429.8 river-meters from the outlet of the watershed when the depression is filled. When the depression is breached using Gelder’s Method, perhaps there are only 411.6 river-meters from outlet to outlet. These distances for each depression in the subset will be tabulated and compared statistically using an ANOVA test.

After completing steps 3.1, it will be possible to answer fully the first research question in this study, “1) how effective are the five different hydrologic enforcement methods in accounting for specific blocking features (e.g. detention basins, roadside ditches, bridges, and dams)?" In step 2.1, the modeled enforcements in each EDTM were compared to the correct (digitized) enforcements in terms of (a) enforcement method, and (c) breach channel accuracy. In step 3.1, the enforcements were compared in terms of (b) flow length. Finally, the number of cells with modified elevations and the total elevation change were calculated to answer (c) overall elevation change. If there is at least one significant difference among the enforcement methods in one of these categories, the null hypothesis must be rejected.

3.2 Numerically and statistically inspect the watershed size and shape for each EDTM

The second question of this study, "2) how does the resulting hydrologically enforced DTM affect watershed shape and watershed area?" is a two-part question. The first part of the second research question refers to the watershed shape. To see if there are any differences in this variable, polygon compactness was calculated using the Polsby-Popper test. See Equation 2 for the details of this test.

Equation 2: $$PP(D) = \frac{4\pi A(D)}{p^2}$$

In formula 2, D is the district (i.e. watershed), p is the perimeter of the district, and A(D) is the area of the district.

Additionally, the watershed perimeter was calculated, and boundaries were inspected manually by overlaying the original boundary and each new watershed boundary. The final question refers to watershed area. The area of a polygon is automatically calculated in ArcGIS, so these values can simply be compared. The null hypothesis will be rejected if each of the two parts of research question two (watershed shape, watershed area) show that there are differences among the hydrologic enforcement methods' generated watersheds.

Limitations

One limitation of this study is the study area itself. Because of the constraints of the availability of recently-collected lidar data, time, and processing power, the methods described in this section can only be tested on one study area. Therefore, any differences between enforcement methods at the watershed scale can only be said to be true for other watersheds that have similar topography, i.e. they are predominately urban or suburban and high-relief.

Another limitation of the study is the enforcement methods that are compared. There are multiple ancillary hydrologic enforcement algorithms currently available, but this study is limited to non-ancillary algorithms in order provide a fair comparison. However, modern ancillary algorithms such as ANUDEM 5.3 or Kenny, Matthews, and Todd's Flow Direction Enhancement algorithm (2008) may provide superior hydrologic representation, at the expense of a high input data requirement.

IV. RESULTS

Results in this section are divided in to two categories. First, the DTM interpolation and sample depressions results will be discussed. Then, data related to each sub-question of both hypotheses will be presented sequentially.

DTM Interpolation Results

A power of 0.5 was chosen for the IDW interpolation after trial and error. The smaller the power, the more weight distant points are given in the interpolation calculation, resulting in a smoother DTM. Visual inspection showed that 0.5 created a DTM where the edges of significant depressions are preserved, while the tiny depressions that create a pock-marked landscape are smoothed and often eliminated. Additionally, a cell size of 2m was chosen for the DTM, because ESRI recommends a cell size of 4 times the point spacing (ESRI 2018). See Figure 8 for a map of the final interpolation juxtaposed next to its landcover.

Sample Depression Selection and Locations

The 250 depressions were drawn from a total of 4,983 depressions that are > 4 m^2 and > 21cm deep (see Figure 9). Auxiliary culvert locations (both point and line) were available from the City of Georgetown and Williamson County. To ensure that the sample utilized this data, a proportional number of near-known-culvert depressions were selected by dividing the 4,983 depressions into 2 strata: (1) within 2m of a Georgetown (line) culvert or 10m of a Williamson Co (point) culvert, and (2) not near a verified culvert. Note that there is a large search distance for point culverts, which are often placed on road centerlines. Based on verification from orthophotos, the point culverts can be >8m from the roadside ditches they drain. This large distance cannot be used for the line culverts because depressions not drained by the culvert would be selected. Stratum (1) had 455 depressions and stratum (2), 4,528. Thus, the sample of 250 is comprised of 23 depressions from stratum (1) and 227 from stratum (2). However, visual inspection showed that culverts drained 64 depressions in the sample. The discrepancy stems from the fact that some culverts are privately maintained, and thus to not exist in neither the county's nor the city's data. The breakdown of sampled depressions by proximity to hydrographic features and land cover types are shown in Table 2.

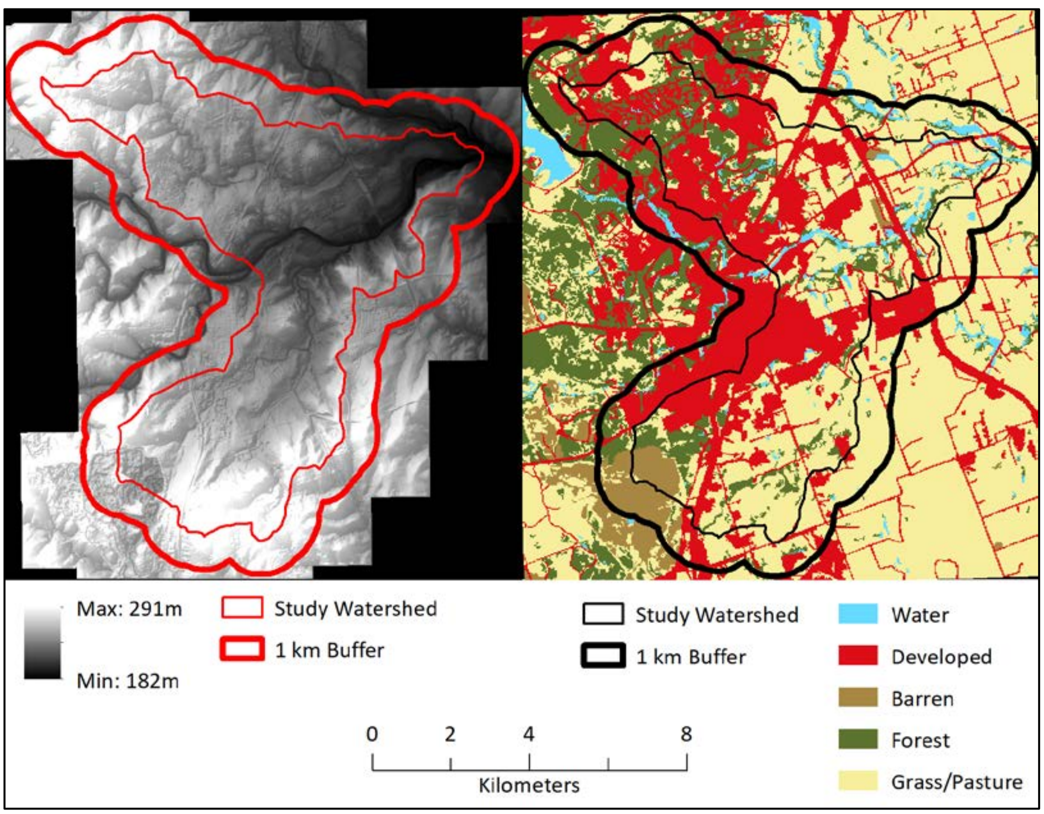

Figure 8: (a) A topographic map (left) of the watershed boundary (data source: USGS) and a 1km buffer. (b) Land cover map (right) overlaid with the watershed buffer. Note the major highway, Interstate 35 (North-South red line). Three out of five enforcement methods did not breach through I-35 (see text for more details).

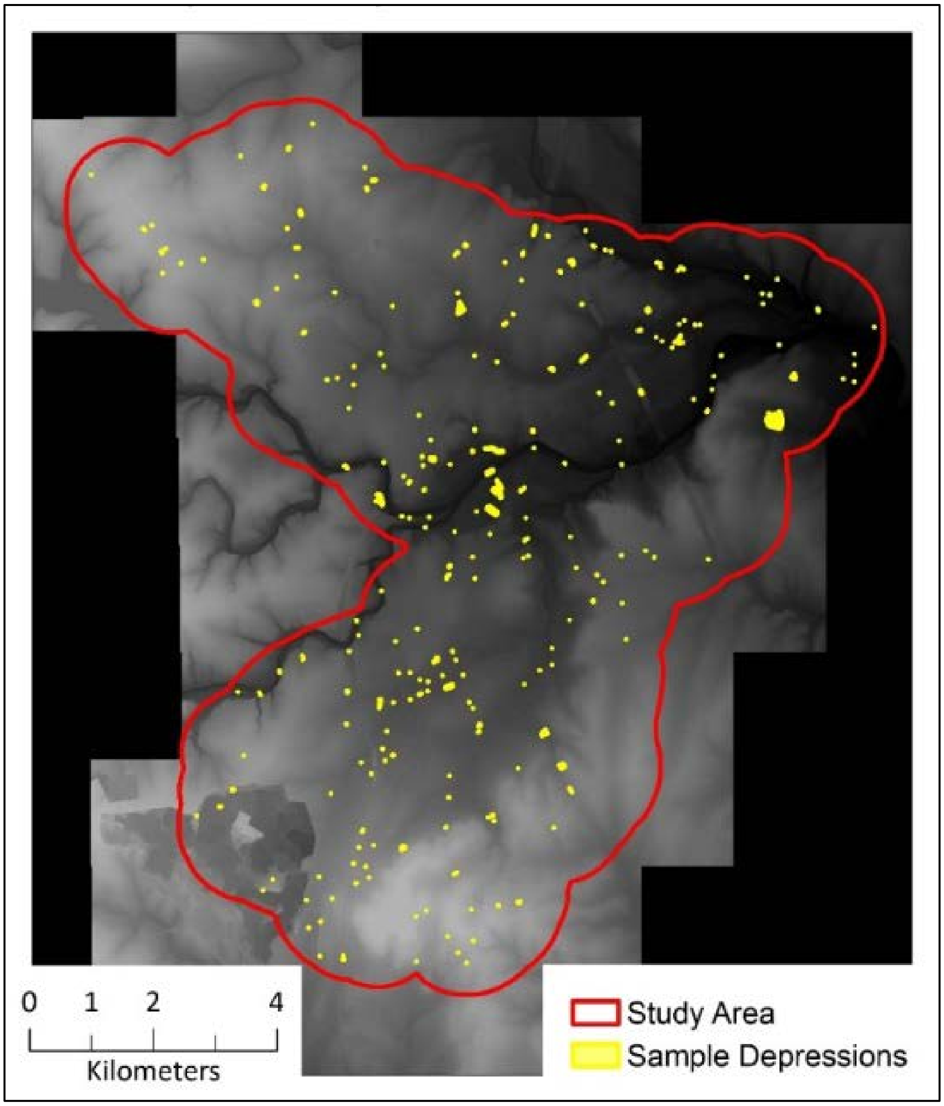

Figure 9: Locations of the 250 sample depressions.

Table 2: Summary of sample depression landcover and proximity to features

Depression Sample Information		
Depressions that are > 4 m^2 and > 21cm deep in study area	4,983	Depression area as percentage of area per class
Depressions in sample	250	
Drained by culvert(s)	64	
Within 20 m of NHD flowline	58	
Within 10 m of roads or rail	79	
In NLCD class: barren	6	0.028%
In NLCD class: urban	122	0.062%
In NLCD class: forest	23	0.023%
In NLCD class: grass/pasture	70	0.161%
In NLCD class: water	29	1.862%

Q1a) Correctness of Enforcement Method Chosen

If a depression is drained by a culvert, its most appropriate enforcement method is breaching. Filling most appropriately enforces all other depressions, because this mimics the spilling over of water from the depression at the lowest point along its rim. The numbers of depressions which were enforced correctly for each method are listed in Table 3.

Table 3: Number of depressions (n = 250) where an algorithm chose the "correct" enforcement

Enforcement Appropriateness *Number of depressions in the sample where the algorithm applied the "correct" enforcement method, be it breaching or filling*	
Gelder's Method	187 (75%)
Constrained Breaching	109 (44%)
Breach Depressions	91 (36%)
Fast Breaching	63* (25%)
Fill	186* (74%)
**non-hybrid methods (i.e. all breaching or all filling)*	

Table 3 is most useful for examining the hybrid methods, which are listed in the first 3 rows. Gelder's method performed best in this comparison, with 187 out of 250 depressions enforced correctly. The Constrained Breaching tool had the second highest number of correctly enforced depressions (109), and Breach Depressions had the fewest correctly enforced depressions among the hybrid methods (91). Note that, although biased in the respect that it filled depressions indiscriminately, Filling performed second best when all methods were considered.

Breaking down the number of correct and incorrect enforcements per aggregated land cover class allows for analysis with a chi-squared test (Table 4). The results of chi-square test (χ^2 = 46.08; df = 16; p < 0.001) revealed that there is significant difference between the observed number and expected number of correct enforcements per class. In other words, land cover class and enforcement correctness are not independent.

Table 4: Observed values for the chi-squared test. Note that the first row was not used in the calculations; it is only provided for reference.

Correct Enforcements Per Land Cover Class Observed Value (Expected Value)					
	Barren	Urban	Forest	Grass	Water
Depressions Per Class	*6*	*122*	*23*	*70*	*29*
Gelder's Method	4 (2.9)	87 (98.8)	19 (15.6)	52 (48.8)	25 (20.9)
Constrained Breaching	0 (1.7)	68 (57.6)	7 (9.1)	24 (28.4)	10 (12.2)
Breach Depressions	0 (1.4)	60 (48.1)	4 (7.6)	20 (23.8)	7 (10.2)
Fast Breaching	0 (1.0)	47 (33.3)	1 (5.3)	13 (16.4)	2 (7.0)
Fill	6 (2.9)	74 (98.3)	22 (15.5)	57 (48.5)	27 (20.8)

Patterns emerge when comparing the observed and expected cells individually. The observed values for both Gelder's Method and Fill exceeded expected values for the Barren, Forest, Grass, and Water classes. Conversely, Breach Depressions, Constrained Breaching, and Fast Breaching exceeded expectations for only the Urban class. In summary, the Whitebox tools, which rely heavily on breaching, are more suited to Urban cover, while Gelder's Method and Fill, which primarily Fill, are more appropriate for natural land cover.

<u>Q1b) Flow Length from Depression to Outlet</u>

Flow length was calculated from the centroid of each depression to the outlet of the watershed for the sample of 142 depressions that are within the smallest delineated watershed boundary. According to the descriptive statistics (Table 5), The longest mean flow length was produced by the Fast Breaching tool (12,825 m), and Breach Depressions produced the shortest (11,041 m). However, the mean flow length for

Gelder's Method and Fill were only 111 and 166 meters greater than Breach Depressions. Figure 10 shows the locations of depressions used in the subset.

Table 5: Flow length descriptive statistics

Flow Length Sample Depression Descriptive Statistics					
	Gelder's Method	Constrained Breaching	Breach Depressions	Fast Breaching	Fill
Flow Length: Mean (m)	11,151.39	12,038.21	11,040.63	12,824.72	11,206.22
Flow Length: St. Dev. (m)	4,229.60	4,389.93	4,276.90	4,529.77	4,122.14

The Kolmogorov-Smirnov normality test (K-S = 0.05; n = 710) revealed that the flow length variable is normally distributed. Hence, an Analysis of Variance test (ANOVA) was used to determine if there is a significant difference in flow length among the enforcement methods. The result of the ANOVA test F(4, 705)=4.482, p=0.0014) indicated that there is a statistically significant difference in flow length among the enforcement methods. Further investigation with Tukey HSD post-hoc test shows that the significant differences are between Fill and Fast Breaching, Fast Breaching and Breach Depressions, and Fast Breaching and Gelder's Method (Table 6).

Table 6: Tukey HSD pairwise comparison results

Tukey HSD Flow Length Results Q-statistic (P-value)					
	G.M.	C.B.	B.D.	F.B.	Fill
G.M.	X	2.17 (0.53)	0.31 (0.90)	**4.62 (0.01)**	0.15 (0.90)
C.B.		X	2.76 (0.29)	2.17 (0.53)	2.30 (0.48)
B.D.			X	**4.93 (<0.01)**	0.46 (0.90)
F.B				X	**4.47 (0.01)**
Fill					X

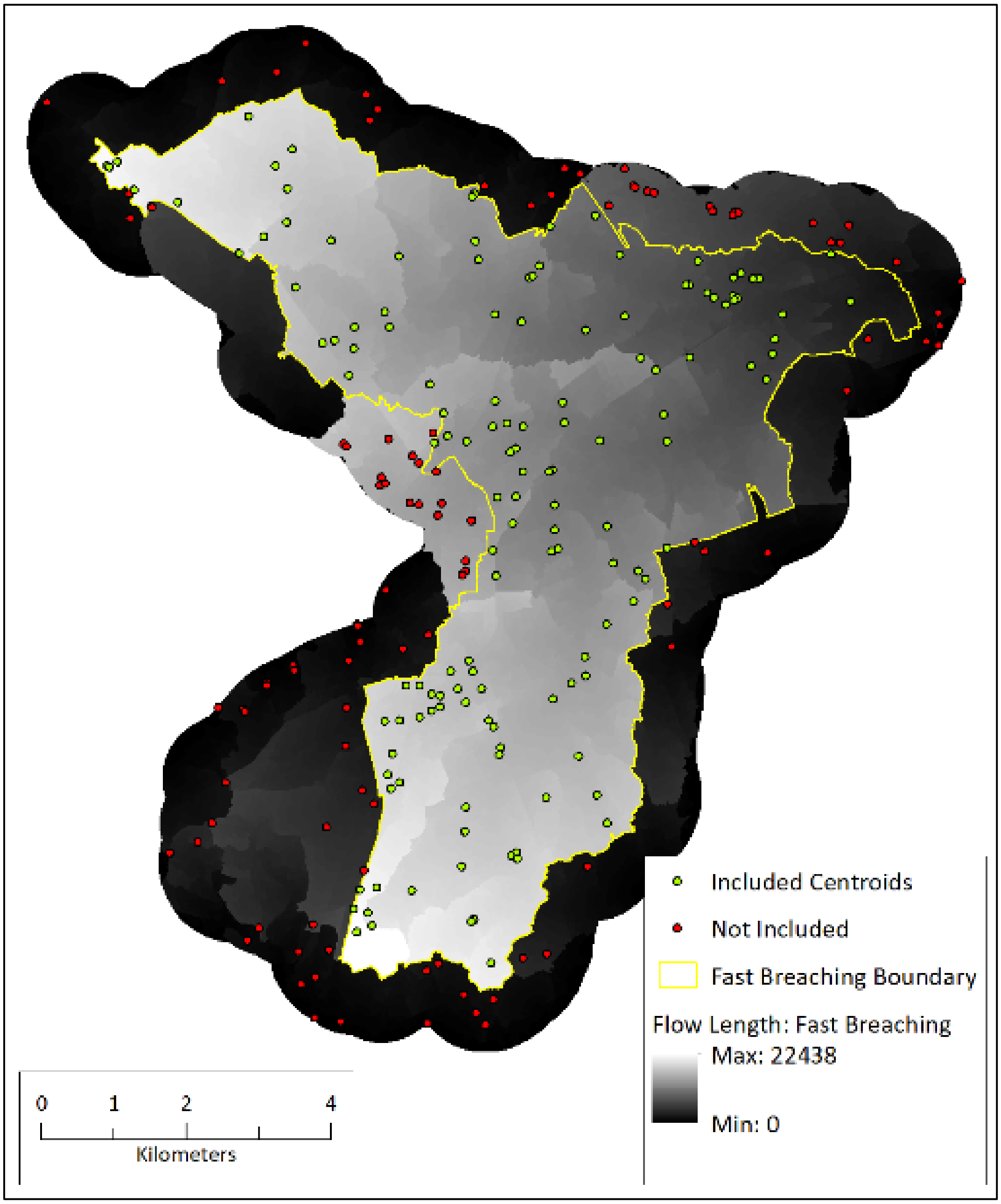

Figure 10: Locations of the 142 sample depressions used for flow length statistics

Q1c) Breach Channel Accuracy

The pseudocode in section 2.1 of the previous chapter was implemented through ArcGIS's model builder, a graphical scripting interface (Figure 11).

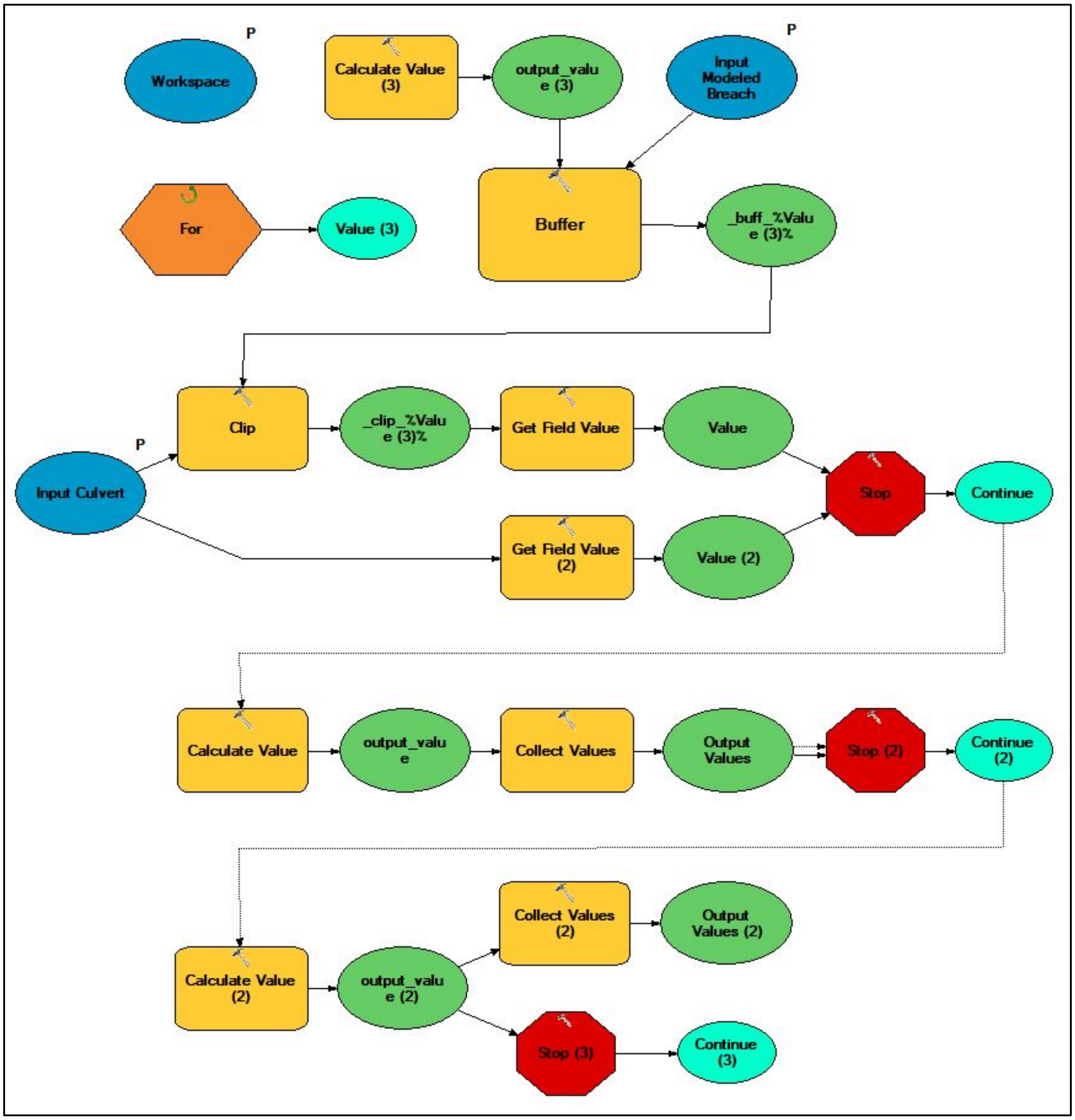

Figure 11: The workflow to calculate breach channel accuracy through buffer overlay.

This model requires 3 input parameters: workspace, input culvert, and input modeled breach. The model buffers the input modeled breach in intervals of 0.5 meters until the buffer completely encompasses the true culvert—or the buffer reaches 10m; whichever occurs first is recorded. The status of the buffer fully encompassing the true culvert is determined by clipping the true culvert line with the buffer, and checking to see if the clipped line is equal in length to the true culvert length. Table 7 summarizes the results of this breach accuracy tool. Note that the numbers for Constrained Breaching and Fast Breaching are nearly identical, because, for breaches up to 50 meters in length, both algorithms produce the same results.

Table 7: Breach Channel Descriptive Statistics and Accuracy

Breach Channel Descriptive Statistics and Accuracy *Best values in each row bolded*				
	Gelder's Method	Constrained Breaching	Breach Depressions	Fast Breaching
Depressions that should be breached (*N*)	64			
Depressions breached by the algorithm (*n*)	37	57	61	**63**
Breaches >10 m from culvert ($n_{>10}$)	**12**	26	17	29
Breaches ≤10 m from culvert ($n_{\leq 10}$)	25	31	**44**	34
Breach accuracy: proportion of depressions correctly breached ($n_{\leq 10} / n$)	0.676	0.544	**0.721**	0.540
Breach accuracy: mean (m)	**3.188**	4.935	3.932	4.853
Breach accuracy: median (m)	**2.50**	4.00	3.25	4.25
Breach accuracy: standard deviation (m)	**1.805**	2.713	2.217	2.723
Breach accuracy statistics are calculated from only breaches that are ≤10m from the culvert				

Breach accuracy statistics are calculated only for the subset of depressions where the enforcement method creates a breach that is ≤10 m from a culvert (Poppenga and Worstell 2016). Therefore, it is important to note the proportion of breaches that are ≤10m from the real culvert location compared to the total number of depressions which the enforcement method breached (Table 7). In simpler terms, this number represents the proportion of breaches that the enforcement method created that were reasonably close to the real culvert. The Breach depressions tool preformed best in this category, with 72% of breaches ≤10m from the real culvert.

Among the descriptive statistics of breach accuracy (Table 7), Gelder's method performed the best in terms of mean (3.2m), median (2.5m) and standard deviation (1.8m). The next best method in terms of mean breach accuracy was Breach Depressions at 3.9m. Although Gelder's method only breached 37 out of 64 depressions that should be breached, it performed well when the all sample depressions are considered; it used the correct method for 187 out of 250, for the most overall (Table 3). A K-S test of the breach accuracy values indicated that the data was not normally distributed.

Q1d) Overall Elevation Change.

The last part of research question one refers to the overall elevation change. To obtain the metrics shown in Table 8, first, a pit-filled DTM was subtracted from each EDTM. Then, cells were reclassified based on their elevation change. At this stage, the number of cells in each class (e.g. > 1-centimeter positive elevation change AKA filled cells) are totaled and recorded in rows 2-5 of Table 8. Concerning only elevation difference, an absolute value function was run on each "difference" raster to calculate the mean and standard deviation of elevation change (Table 8). Note that Gelder's Method truncated elevation differences smaller than 1 cm, so +/- 1 cm was used as a threshold when defining breached vs. filled cells, to provide a consistent comparison. As expected, Filling produced the most positive elevation change, Fast Breaching caused only negative change, and Fast Breaching also resulted in the lowest mean and standard deviation absolute difference.

Table 8: Number of Modified Cells and Mean Absolute Difference

Number of Modified Cells and Mean Absolute Difference *Based on (EDTM – Pit-Filled DTM)* *Best values bolded*					
	Gelder's Method	Constrained Breaching	Breach Depressions	Fast Breaching	Fill
Total Cells	24,616,859				
> +1 cm change (filled cells)	890,518	846,342	739,039	0	2,015,383
< - 1 cm change (breached cells)	12,604	254,787	252,312	305,010	0
"Punched" cells (set as NoData)	117,610	N/A	N/A	N/A	N/A
Total number of modified cells	1,020,732	1,101,129	991,351	**305,010**	2,015,383
-1 < x < 1 cm change	23,596,127	23,515,730	23,625,508	24,311,849	22,601,476
Mean Absolute Difference (m)	0.076	0.139	0.139	**0.003**	0.160
Absolute Difference St. Dev. (m)	0.784	1.122	1.137	**0.077**	1.146

Q2a) and Q2b) Watershed Shape and Watershed Area

The output from delineating a watershed is in raster format, but it is converted to polygon vector so that its dimensions can be easily obtained. Additionally, polygon compactness is calculated to represent watershed shape (see Equation 2, Chapter 3). These numbers are summarized in Table 9 and their geometries in are displayed in Figure 12. Finally, Figure 13 shows the two largest delineations (Gelder's Tool and Breach Depressions) in relation to the NHD boundary.

Table 9: Delineated Watershed Dimensions

Delineated Watershed Dimensions			
	Area (Hectares)	Perimeter (m)	Compactness
NHD	5,604.1	49,386*	0.289*
Gelder's Method	5,278.4	88,120	0.085
Constrained Breaching	5,098.7	82,200	0.095
Breach Depressions	5,400.9	86,124	0.092
Fast Breaching	5,082.4	82,216	0.094
Fill	5,099.0	82,256	0.095

* *These values should not be compared to others in their columns; the NHD boundary is less detailed than the delineated boundaries.*

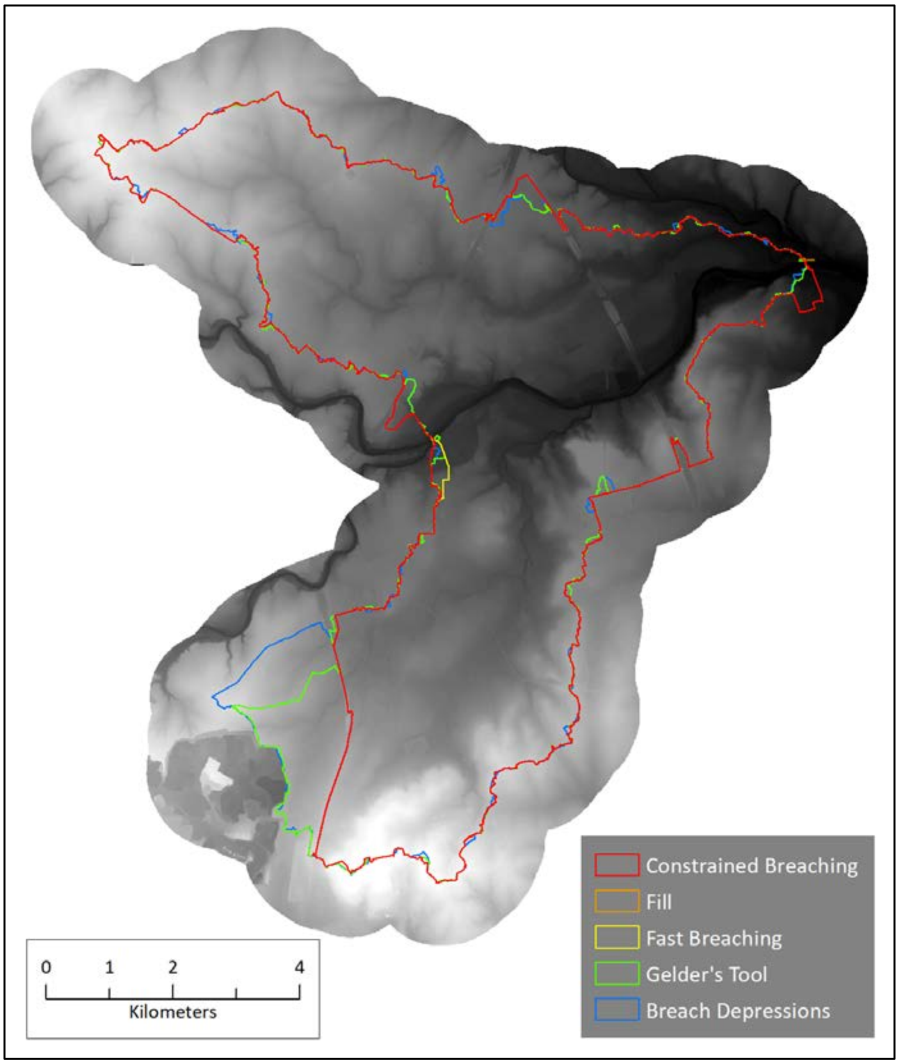

Figure 12: Delineated watershed boundaries overlaid.

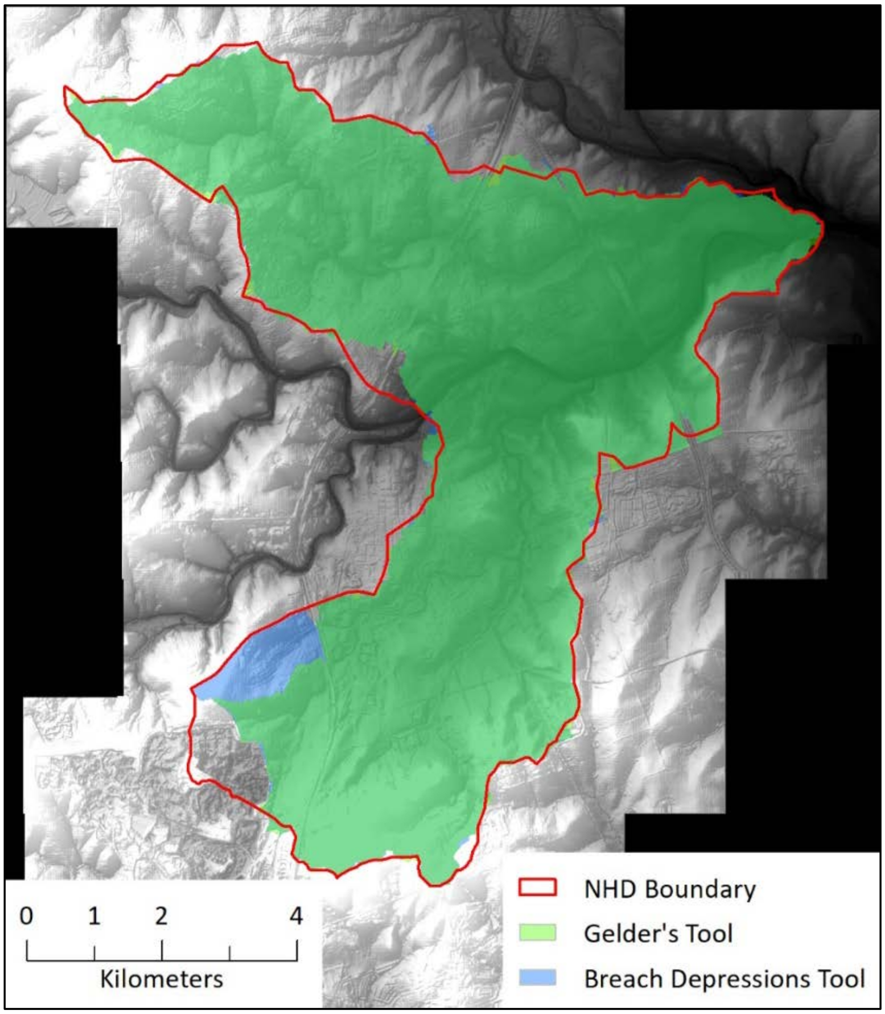

Figure 13: Delineations from the two algorithms whose breaches are based on a least cost path approach.

The largest watershed boundary is from the NHD; it is 5,604 ha. The second and third largest delineated watersheds in area are from the Breach Depressions tool and Gelder's Tool at 5,401 ha and 5,278 ha, respectively. Fast Breaching created the smallest watershed: 5,082 ha. These substantial differences in area can largely be attributed to the ability of the enforcement method to breach through I-35 as it runs through the lower half of the study area. In the southwest corner of the red (Constrained Breaching) outline, the nearly straight north-south line perfectly follows I-35. A little over halfway to the top of that straight line, a large stream passes under the highway through a series of culverts;

water is directed under 4 lanes of frontage roads and 6 lanes of highway. If this area is not breached, flow is directed north alongside the interstate until emptying into the South Fork of the San Gabriel before its confluence with the North Fork. This means that any area upstream of those culverts will not be considered as part of the watershed in question, reducing the total area. This occurs for all methods except Breach Depressions and Gelder's method. Additionally, the comparatively small but still visible differences in the northern tip of the study area are also because of a lack of breaching. In this instance, Gelder's Method and Breach Depressions cut through both the north and southbound lanes of highway TX-130 at the exact location of the culvert, while the other three methods only breach through the northbound lanes, resulting in their delineated watersheds including an extra 16 hectares that should be apart of an adjacent watershed. The underlying algorithm that decides where to enforce flow—a flood-based algorithm for Fill, Constrained Breaching and Fast Breaching, and a least cost path algorithm for the other two—is responsible for these differences in the delineated watershed boundaries. The least cost path approach, although more computationally intensive than the flood-based approach used in the other three enforcement methods, has resulted in more realistic enforcements throughout this study.

The two best delineations are similar in shape to the NHD boundary, but there is still a gap in the extreme southwest tip of the study area (Figure 13). The delineated watersheds extend up to the rim of a quarry located here, but the NHD boundary cuts across the pit, including an extra 150 hectares in the watershed. This quarry was founded in 1958, so if the NHD boundary was delineated from US Topo maps pre-1958, the difference is explained. Alternately, the NHD boundary could be based on some expert knowledge that the drainage in that part of quarry is pumped north and should be included in the watershed.

Besides area, Table 9 shows watershed perimeter and compactness. Although this watershed is only one sample and a statistical test cannot be performed, there seems to be no significant differences in watershed perimeter nor compactness among the enforcement methods.

V. FINDINGS

The aim of this research was to answer two questions. First, how effective are the five different hydrologic enforcement methods in accounting for specific blocking features? Second, how does the resulting hydrologically enforced DTM affect watershed shape and watershed area?

In Q1a), some methods (e.g. Fill, Gelder's Method) resulted in more than twice as many appropriate enforcements compared to the worst preforming method (Breach Depressions). Furthermore, the chi-squared test showed that enforcement correctness was not independent from land cover class. It was found that Gelder's Method and Fill exceeded the expected number of correct enforcements for natural land cover while the remaining three enforcement methods were more suited for urban cover.

In Q1b), the ANOVA test found a significant difference in flow length between the enforcement methods, and Tuckey HSD revealed that the significant differences were between 1) Fast Breaching and Fill 2) Fast Breaching and Gelder's Method, and 3) Fast Breaching and Breach Depressions.

The results from Q1c) showed that the Breach Depressions tool or Gelder's Method are the most accurate in terms of breach channel location. The former breached a high number of depressions (that should have been breached) while at the same time creating the most breaches that were less than or equal to ten meters from the actual culvert. Alternately, Gelder's method breached nearly 40% fewer depressions in the sample than the Breach Depressions tool, but the breaches it made were much closer to existing culverts on average than any other method.

Finally, different hydrologic enforcement methods can have vastly different numbers of modified cells and mean absolute elevation changes. Filling modified 1.7 million more cells than Fast Breaching, and the mean absolute difference varies just as widely. Considering these results, we reject the null hypothesis that there is a significant difference among the five enforcement methods in terms of the four factors listed previously.

While there is not as strong of a difference in watershed shape and area among the enforcement methods as compared to the factors in question one, there is nevertheless one main difference: the southwest corner of the watershed. Constrained Breaching, Fill, and Fast breaching all rely on a flood-based algorithm for enforcing the DTM. Thus, their delineated watersheds differ nominally. However, Gelder's Method and the Breach Depressions tool both breached through a major interstate and included 180 and 300 more hectares in the watershed, respectively. This is a notable increase considering the watershed is only around 5,600 hectares at the upper estimate. The results from question two suggest the rejection of null hypothesis: there is a difference, although there are too few samples for meaningful statistical analysis, in a) watershed shape, and b) watershed area among the five enforcement methods.

The remainder of this chapter is divided into sections for the components of the first null hypothesis. Each section lists some findings that were not noted previously.

Q1a) Correctness of Enforcement Method Chosen

This sub-question of the null hypothesis was mainly designed to assess the ability of hybrid methods to choose an appropriate enforcement, either breaching or filling. However, considering that the random sample of 250 depressions was comprised of only 64 depressions that should be breached, filling all depressions produces a comparable result to the top hybrid method. If all depressions were filled, 186 would have been enforced correctly; this is only one fewer than Gelder's Method. Thus, if a researcher knows that a large majority of depressions in his or her study area are natural, and their main goal is to choose the correct enforcement method for each depression, filling might be the best option. Gelder's method could be used the same circumstances. Since his method uses a stringent list of parameters to decide if and where to breach, the number of erroneous breaches is limited, especially in comparison with the other breaching and hybrid methods. Finally, the chi-squared test showed that there is a statistically significant difference between the observed number of correct enforcements per land cover class and their expected values. This is another reason for researchers to be mindful of their study area's land cover type when choosing a predominately breaching enforcement method or a predominately filing method.

The original papers that presented these enforcement algorithms may clarify why some algorithms perform better in certain cover types than others. One of the main goals of Gelder's Method was to respect natural depressions by not breaching them unnecessarily (Gelder 2015). It appears he achieved his goal, if not at the expense of limiting the number of breaches in developed areas. Additionally, his method was tested in the Walnut Creek of the South Skunk River watershed in Central Iowa, which contains prairie potholes. Perhaps an effort to distinguish these potholes from anthropogenic depressions cause some of the latter to be filled instead of breached. Breach Depressions "inherently prefer[s] solutions that require less modification to the DEM," according to Lindsay and Dhun (2015). This explains why their algorithm exceeded the expected number of expected correct enforcements in urban areas; breaching methods cost less elevation change than filling, and the most appropriate enforcement for urban depressions is frequently breaching.

The papers that introduced Breach Depressions and Gelder's Method contained findings that were close enough to this study's findings to warrant comparison. In the original study (Lindsay and Dhun 2015), the Breach Depressions tool was found to have breached 87.8% of bridges and major culverts in a Southwestern Ontario study area. This study found that Breach Depressions breached 96.9% of depressions that should be breached in the sample, but only 72.1% of those breaches were within 10m of the actual culvert. Since the random sample of 64 depressions that should be breached contained many minor depressions, the results of this study seem comparable to that of the original paper. Gelder's original paper also reported accuracy in regard to correctness of enforcement method (Gelder 2015). Adding up the values in Figure 9 of his technical report shows that the Gelder's Method correctly enforced 75.77% of depressions in his Central Iowa study area. This paper found that Gelder's Method chose the correct enforcement for 187/250 sample depressions, or 74.8%. These findings corroborate the accuracy stated by the original authors and should further provoke researchers to consider a breaching or hybrid method when enforcing drainage in their next project. Additionally, the accuracy statistics found in these papers are comparable to the findings from two major enforcement algorithms which utilize ancillary data: REA and CEA breached correctly in 72% and 77% of cases, respectively (Duke et al. 2003, Duke et al. 2006)

Q1b) Flow Length from Depression to Outlet

Filling and Gelder's method seemed to the best option when considering only the correctness of enforcement method chosen, but there are more ways that enforcement effectiveness can be assessed. Question 1b) is concerned with flow length from each depression to the watershed outlet. The Tukey HSD post-hoc test showed that there are significant differences in flow length between Fast Breaching and all the other methods besides Constrained Breaching. This indicates that flow length is highly sensitive to the enforcement method chosen. Since Fast Breaching and Constrained Breaching use the same underlying flood order algorithm to decide where to breach, we would not expect any differences in flow length except for where the Constrained Breaching channel would exceed the 50m threshold. But, the fact that the remainder of the enforcement methods were significantly different than Fast Breaching shows that researchers should be wary of the enforcement method they choose if modeled flow length is relevant to their study.

One way in which flow length may be relevant to a researcher is modeling flow rates from storm events. A factor in this type of modeling is time of concentration, or the amount of time a drop of water takes to travel from the most hydrologically remote point in the watershed to its outlet. Flow length is a factor in the watershed lag method for estimating time of concentration. In this equation, the longest flow length is used in conjunction with the average watershed land slope, the total drainage area, and the curve number (NRCS 2010). Longer flow lengths, such as those derived from the Constrained

Breaching or Fast Breaching EDTMs, increase time to concentration and can produce a lower peak discharge.

Both Filling and Breach Depressions have low mean flow lengths, but Breach Depressions is the lowest of any method (Table 5). This is evident when examining local areas, such as the industrial yard shown in Figure 14. Breach Depressions correctly breaches through the embankment at the north end of the yard, while the flow path in the Filled DTM takes a longer route around the warehouse.

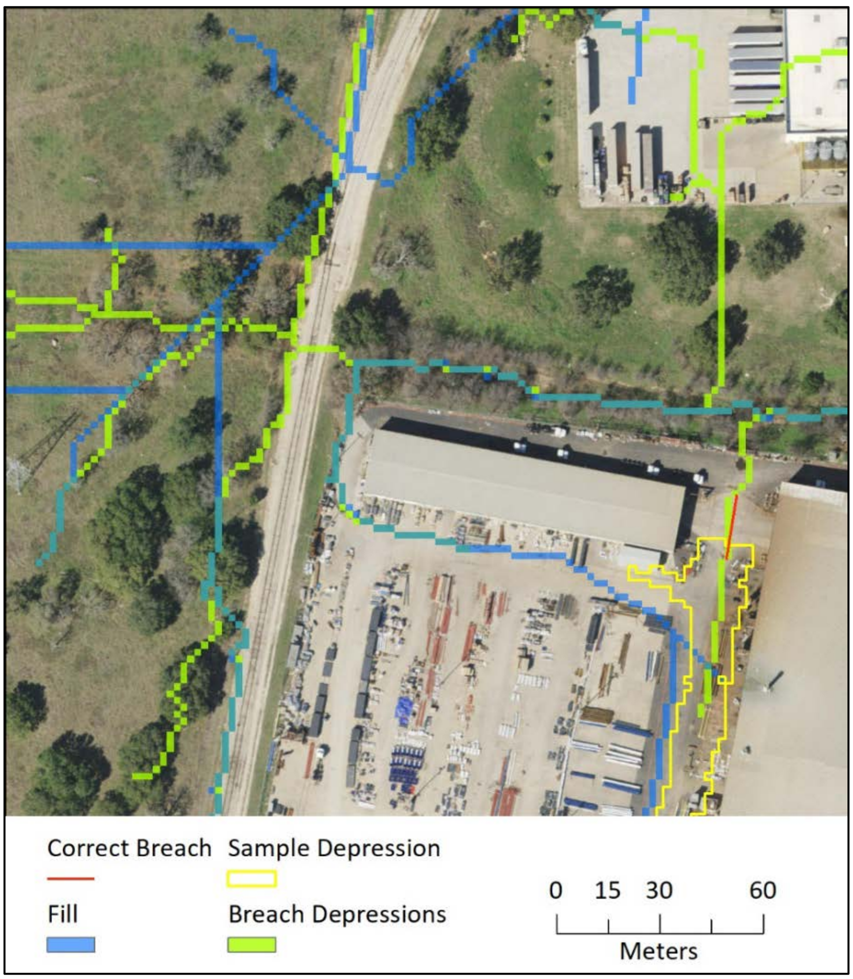

Figure 14: Streams (i.e. cells of high accumulated flow) generated by the Breach Depressions and Fill tools. Flow length is longer for the Fill tool in this area because it does not breach through the embankment. Note that the streams in this image are partially transparent, so that overlapping can be observed.

Q1c) Breach Channel Accuracy

Another way to gauge the differences among hydrologic enforcement methods is by looking at breach channel accuracy. As noted previously, the results do not lend themselves to statistical analysis, but large differences in Table 7 still prompt us to reject the null hypothesis for Question 1c. For instance, the mean and median breach accuracy both differed by nearly two meters between the best performing algorithm (Gelder's Method) and worst performing algorithms (Constrained Breaching and Fast Breaching, respectively). The answer as to which algorithm provides the most accurate breach channels is either Gelder's Method or Breach Depressions in every category, so researchers should choose either of these methods if breach accuracy is a concern. If auxiliary culvert data is not available for the study area, using Breach Depressions is recommended because it breaches a much higher number of depressions, while still maintaining a good ratio of close breaches (≤10 m from culvert) to total breaches.

In addition to correctness of enforcement type, this study's findings for Gelder's Method's mean breach accuracy can be directly compared to his original paper. This study found a mean breach accuracy of 3.188 meters for Gelder's Method, while Gelder reported a mean centroid position of 3.85 meters (Gelder 2015) . It is notable that this study found Gelder's method to be 0.662 meters more accurate than its original paper. For comparison, another paper which measured breach accuracy found a weighted mean offset of 3.91 meters between modeled breaches and field-surveyed culvert (Poppenga and Worstell 2016). The hybrid breaching method that was assessed in that paper was developed by the authors for the USGS (Poppenga et al. 2010, Poppenga et al. 2012).

Gelder’s Method created many similar breaches to the tools developed by Lindsay, but there were some minor differences. In Figure 15, the correct breach location is at the culvert located on the south side of the sample depression. Gelder’s method, however, breaches the steeper embankment on the North side, connecting the depression to the railroad underpass. So few of these types of differences can be seen that is hard to determine a pattern. The sample presented in Figure 15 is more the exception than the rule, however; the breach channels from Gelder’s method are more accurate than those made with Lindsay’s tools in terms of breach accuracy (Table 5).

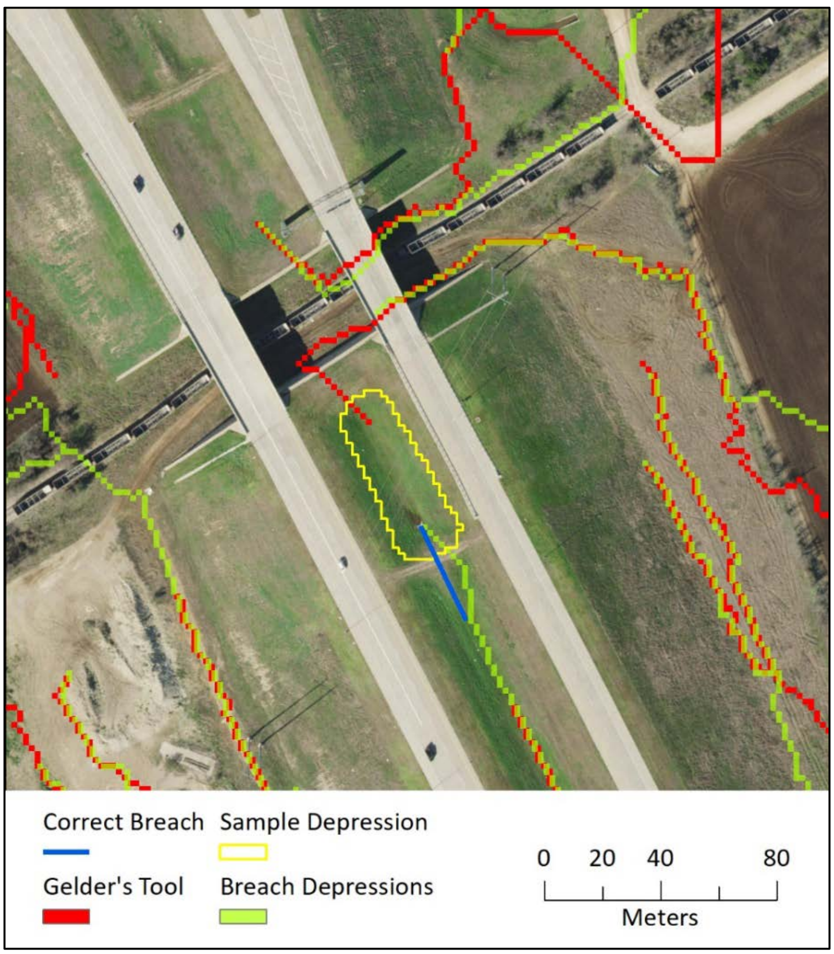

Figure 15: Streams generated from Gelder’s Method and the Breach Depressions tool.

Q1d) Overall Elevation Change.

The final aspect of null hypothesis one states that there are no significant differences in overall elevation change. This project used number of modified cells and absolute elevation difference to gauge overall change. The results of this section corroborate the findings of Martz and Garbrecht (1999); breaching methods result in fewer cells altered, as well as less absolute change to the DTM. In fact, the Fast Breaching method, which is a breaching-only method, resulted in a mean absolute difference of less than a centimeter for the whole DTM. A future study might strengthen this corroboration by examining each depression a zone, so that a zonal summary could reveal any significant differences in relative or absolute elevation change.

Strict breaching preforms well when looking at the whole DTM, but a consequence of strict breaching can be long, unrealistic breach channels. Thus, hybrid methods are preferred when the goal is to limit overall change to the DTM but also retain realistic drainage at a local scale. Among the hybrid methods, Breach Depressions has the lowest number of modified cells (991,351/23 million), and Gelder's method has the lowest mean absolute difference (0.076 m). It is also notable that Gelder's Method has a very low number of breached cells when compared with the other hybrid methods (12,604 vs. 250,000-300,000). One previous study examined NMC and MAD per slope class (e.g. uplands, bottomlands, etc.) (Lindsay and Creed 2005). In that study, the authors found that bottomland catchments see the most improvement in NMC and MAD when breached instead of filled. The presence of large depressions in flatter catchments means that the differences in these two metrics between filling methods—which modify a large number of cells—and breaching methods is exacerbated.

Finally, Gelder's method alters elevation in a way that no other method does: it sets the lowest points in some depressions to "NoData" (see Figure 16). Gelder calls this method "hole punching". Flow direction tools will treat these NoData cells as edges of the raster—effectively outlets for drainage. This is an innovative solution for representing some depressions as being internally drained. However, the drawback is that the elevation values are no longer present in these 117,610 cells, which is 0.47% of cells in the study area. Since the cost per GB of hard drive storage space continues to fall, it is not difficult to store unaltered DTMs as well as enforced DTMs, in case the elevation values of NoData cells are needed for later analysis. Although the elevation values from lidar are as close as researchers can frequently get to "true" elevations, they may be incorrect in terms of the flow paths in hydrologic modeling. Thus, there is a balance between limiting the modifications to the original DEM and enforcing "correct" drainage. Considering the fact that Gelder's Method and Breach Depressions have performed the best in nearly all other measures (e.g. enforcement correctness, breach channel accuracy, etc.) it is even more significant that they also have low numbers of modified cells and mean absolute differences.

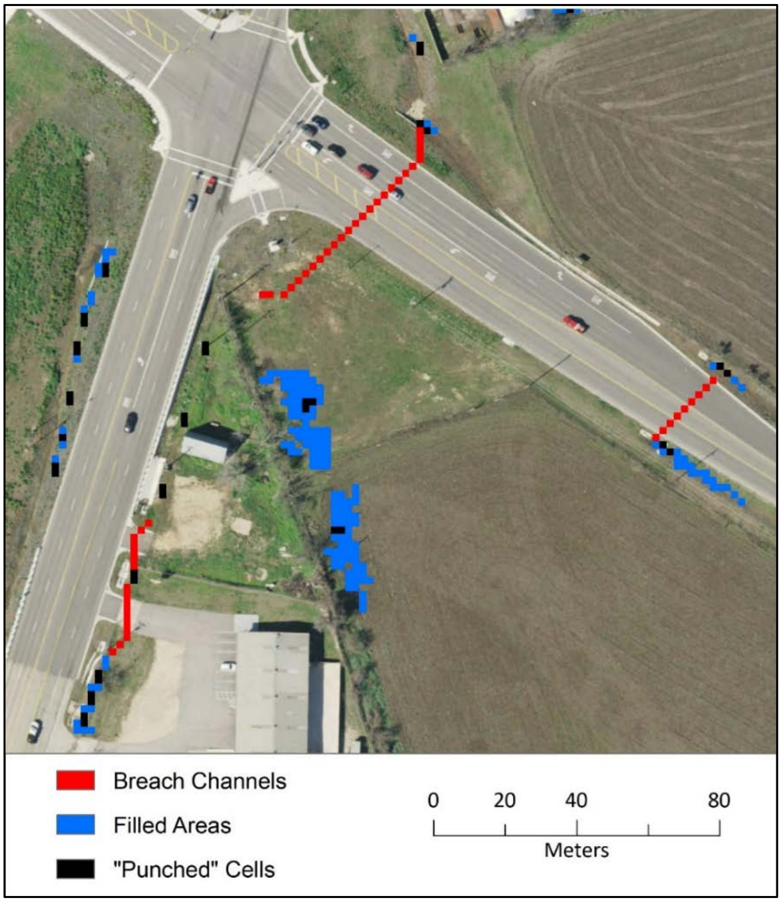

Figure 16: Different types of elevation changes made with Gelder's tool. Punched cells are set to "NoData."

Q2) Watershed Delineation Differences

In addition to investigating any differences in watershed delineation among the five hybrid enforcement methods, this study sought to investigate the claim that breaching methods can increase the size of the delineated watershed (Martz and Garbrecht 1999). In the literature review it was noted that a later study also compared the effects of hydrologic enforcement methods on watershed delineation, but since the methods compared were not strict breaching/filling methods, the claim that just breaching can increase the size of the watershed cannot be addressed (Callow et al. 2007).

However, this study did compare strict filling and breaching methods, and found that Filling resulted in a watershed that was 16.6 hectares *larger* than strict breaching (i.e. the Fast Breaching method) and 0.3 hectares larger than the Constrained Breaching tool. The remaining two methods produced watersheds nearly 200 and 300 hectares larger than Filling. The 16.6 hectare difference between breaching and filling is too small in a 5000 hectare watershed make the claim that breaching alone had any significant effect on watershed delineation. Additionally, Filling produced a watershed that was larger than breaching, which is the opposite of what Martz and Garbrecht found (1999). Rather, the meaningful finding from this study, as elaborated in the previous chapter, was that the underlying algorithm (least cost path or priority flood) can have a large effect on watershed shape and area.

VI. CONCLUSIONS

Since the enforcement method chosen will have an effect on subsequent modeling, it is important to consider the pros and cons of each method. This study found that there is a significant difference among hydrologic enforcement methods in terms of a) correctness of enforcement method chosen b) flow length from depression to outlet c) breach channel accuracy d) overall elevation change e) watershed shape and f) watershed area. Table 10 summarizes this study's findings in relation to each method.

Table 10: Strengths of each enforcement method in this study.

Method	Strengths
Gelder's Method	• Overall best in terms of correctness of enforcement method chosen per depression (breach vs. fill) • Second to Breach Depressions in shortest mean flow length • Lowest standard deviation flow length • Overall best in terms of breach channel accuracy • Lowest MAD among hybrid methods
Constrained Breaching	• Provides more customizability than Fast Breaching
Breach Depressions	• Shortest mean flow length • Highest proportion of depressions breached with 10m accuracy • Lowest NMC among hybrid methods • Largest delineated watershed (most similar to NHD boundary)
Fast Breaching	• Statistically significantly longer flow lengths for sample depressions than all other methods except constrained breaching • Lowest NMC and MAD by far
Fill	• Good for enforcing study areas of natural landcover

This study has some limitations. First, the threshold max breach length and max breach depth (for Breach Depressions and Constrained Breaching) were set based on knowledge of the study area, but could have been calibrated further. Future studies should optimize these values by running multiple iterations until realistic draining is achieved in known sample depressions. Second, Gelder's Method was implemented on a different workstation than other enforcement algorithms. Although Dr. Gelder delivered all necessary data, a technical write-up, and answered questions about the results, the use of a different machine for the DTM preprocessing could have introduced some error. However, Gelder's Method should soon be ready for widespread use, so this limitation should not be a problem for future studies. Third, the descriptive statistics for the breach channel accuracy assessment was biased by only including breaches that were less than 10 m from the actual culvert location. The 10 m threshold was chosen to limit processing time while still providing 0.5 m precision, but it resulted in 28-46% of breaches per enforcement method being left out of the analysis. A future study could either change the precision or utilize more processing power to limit the number of disregarded breaches.

Finally, this study was limited to a sample of only one watershed, so watershed-scale statistical analysis could not be performed. A future study might utilize the same high-resolution lidar data but for multiple watersheds of varying topographies. The topographic rules used by each enforcement algorithm in this study should apply equally to any raster DTM, but some conclusions are more extrapolatable than others. For instance, the best enforcement methods for flow length and enforcement correctness might differ in a study area with different morphology or different sample depressions, but breach channel accuracy and overall elevation change should be consistent with this study. Watershed modelers may utilize the recommendations above, as well as the tables and maps in the Results and Findings chapters of this paper to 1) decide which DTM characteristics are most relevant in their study and 2) decide which enforcement methods best preserve those characteristics.

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