Automation of DEM Cutting for Hydrologic/ Hydraulic Modeling

Final Report
February 2015

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16. Abstract Hydrologic analysis is a critical part of transportation design because it helps ensure that hydraulic structures are able to accommodate the flow regimes they are likely to see. This analysis is currently conducted using computer simulations of water flow patterns, and continuing developments in elevation survey techniques result in higher and higher resolution surveys. Current survey techniques now resolve many natural and anthropogenic features that were not practical to map and, thus, require new methods for dealing with depressions and flow discontinuities. A method for depressional analysis is proposed that uses the fact that most anthropogenically constructed embankments are roughly more symmetrical with greater slopes than natural depressions. An enforcement method for draining depressions is then analyzed on those depressions that should be drained. This procedure has been evaluated on a small watershed in central Iowa, Walnut Creek of the South Skunk River, HUC12 # 070801050901, and was found to accurately identify 88 of 92 drained depressions and place enforcements within two pixels, although the method often tries to drain prairie pothole depressions that are bisected by anthropogenic features.			
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EXECUTIVE SUMMARY

Hydrologic analysis is a critical part of transportation design because it helps ensure that roads are not frequently inundated and that hydraulic structures are able to accommodate the flow regimes they will likely see. This analysis is currently conducted using computer simulations of water flow patterns, and the wide availability of data from one such technique, light detection and ranging (LiDAR), is expected to revolutionize the analysis process. Survey techniques such as LiDAR now resolve many natural and anthropogenic features that were not practical to map and, thus, require new methods for dealing with depressions and flow discontinuities.

The method proposed for depressional analysis and enforcement involves multiple processes. The first process involves creating a digital elevation model (DEM) from the raw LiDAR data. Elevation points are imported into a terrain using custom pyramid and thinning settings to reduce unnecessary resolution. The terrain is then converted into a DEM, and elevation differences smaller than 1 centimeter are truncated. This centimeter-resolution DEM is then analyzed for flow characteristics to remove one-cell sinks, or depressions of one-cell extent.

The second process, termed “hole punching”, involves defining depressions that are significant enough to warrant analysis via the enforcement algorithm. This involves iteratively filling the DEM, defining regions where the DEM was filled, and calculating the maximum fill depth and total area filled of each region. Regions deeper than the 18 centimeter root mean squared error (RMSE) of the LiDAR data on unvegetated surfaces or greater than 100 square meters in area are currently considered significant depressions. The deepest point in these significant depressions is set to “null” so that water can “flow” out the null value, and the process of filling the DEM is repeated until no significant depressions remain. The depressions for consideration are then further refined by removing those that are drained via channelized flowpaths.

The final process, termed “cutting”, identifies depressions that are likely created via an embankment and would drain if the embankment were removed. Depressions where the distance from the deepest points in a depression to the local watershed boundary is greater than a 5 percent slope have the embankment removed and tested for a decrease in the filled DEM elevation. The depressions that are provisionally drained are then tested for enforcement by trying to connect the deepest points in the depression with lower points outside the depression. Successful linear connections are converted into rasters and then used to modify the DEM elevation appropriately, creating the final enforced DEM.

This procedure has been evaluated at a 3 meter resolution on a small watershed in central Iowa, Walnut Creek of the South Skunk River, HUC12 # 070801050901. It was found to accurately identify 88 of 92 drained depressions and then place enforcements generally accurate to within two pixels, although the method often tries to drain prairie pothole depressions that are bisected by anthropogenic features.

INTRODUCTION

Hydrologic analysis is a critical part of most major infrastructure projects as well as watershed planning and modeling efforts. Knowledge of peak flow and flow recurrence intervals is key to designing culverts, bridges, agricultural drainage ditches, and drainage pipe systems as well as estimating flood extents and peaks. Because hydrologic analysis is based on modeling the flow of water across the landscape, knowledge of the underlying topography is essential for conducting these types of analyses. The steady march of progress has now brought light detection and ranging (LiDAR) technology into widespread use throughout the geographic information system (GIS) community, and this brings with it a new set of challenges that must be solved before it can be commonly used as a model input.

High-resolution digital elevation models (DEMs), such as those created by LiDAR, interferometric synthetic aperture radar (IfSAR), or intensive traditional photogrammetry, have inherent challenges for hydrologic analysis that have been well documented (Poppenga et al. 2010). In a nutshell, high-resolution DEMs capture many high-frequency manmade features, such as roads, bridges, ditches, and terraces, as well as some natural features, such as vegetation, that create hydrologic obstructions during the hydrologic enforcement process. Also compounding the problem is that some landform regions have significant amounts of natural depressions, such as the prairie potholes of the late Wisconsinan glaciation or areas of sinkholes in karst terrain that are also not handled well by traditional DEM enforcement. Regardless, high-resolution DEMs are seen as the future of hydrologic analysis because these high-frequency features and natural depressions are part of the hydrologic landscape and any realistic solution must incorporate these complexities. This research project endeavors to develop an automated process for hydrologic enforcement that both respects natural depressions and correctly enforces flow in areas that are drained.

LITERATURE REVIEW

Numerous articles have dealt with the subject of hydrologic enforcement of high-resolution DEMs throughout the past decades. Rieger (1998) established that most of the depressions in high-resolution DEMs are physically based and are created as a phenomenon of the use of incomplete sampling and regular grids to define a surface. Other errors result from the lack of return data, resulting in the use of incorrect interpolation algorithms in areas of channelized flow. Taken together, these issues result in many depressions being purely the result of data processing errors. Poppenga et al. (2010) have documented the inaccuracies inherent in various conventional methods of enforcement and they, along with Hans et al. (2003), document the improvement that can result from the use of high-resolution DEMs in areas of low topographic relief.

Multiple different methods have been proposed for conducting the hydrologic enforcement process. Some methods incorporate the use of ancillary transportation and other anthropogenic feature data (Duke et al. 2003, Duke et al. 2006, Dhun 2011) to define modifications, while others adopt a minimum impact approach (Lindsay and Creed 2005). Both of these approaches have their own merits because the use of anthropogenic feature data often results in highly accurate modifications to the elevation model, but these feature data are not always available, especially for privately owned and constructed features. The minimum impact approach often has difficulties in areas of low topographic relief.

It is hypothesized that an appropriate search radius for downstream connections can typically be determined from the morphology of the depressions. Depressions that slope back at less than 5 percent slope from the watershed edge are not representative of human construction activities and will not be drained. Depressions that slope back at greater than 5 percent may be drained, and the downstream search radius can be determined by the distance from points greater than 80 percent of the maximum depth to the local basin boundary. However, in areas of transportation features such as divided highways or railyards it is sometimes necessary to increase the default search radius by the width of the transporation feature. A new cutting process was also devised that matches upstream and downstream points and connects them linearly. This option, although likely slower than minimum impact approaches, allows more flexibility in defining optimum connections using distance, slope, direction, connectivity by curvature, and other metrics. The cutting process is evaluated for accuracy by looking at enforcements that cross transportation embankments (federal, state, county, and local roads, railroads, and runways) and comparing those to the presence, location, and direction of actual culvert and bridge locations that cross actual transportation embankments (federal, state, county, and local roads, railroads, and runways).

METHODOLOGY

The initial phase is DEM generation and pit filling. The second phase is termed “hole punching”, and the final phase is termed “cutting”. The accuracy of this process will be assessed on HUC12 070801050901, Walnut Creek of the South Skunk River watershed, just south of Ames, IA (Figure 1). This watershed has a wide range of topographic conditions over about 70 meters of elevation difference. The uplands consist of prairie potholes running into a well-incised stream channel into the South Skunk River floodplain, making it ideal for accuracy assessment. It also has numerous anthropogenic surface modifications, including a divided highway, abandoned railroad beds, lagoons, drainage ditches, terraces, water and sediment control basins (WASCOBs), and a small town. Areas where the flowpath crosses transportation features (i.e., roads, railyards, and runways) and where a bridge or culvert has been installed will be analyzed for placement accuracy. The enforcement was conducted using a 3 meter resolution DEM because this provides an average of three to four elevation returns per cell from the 1.4 meter LiDAR return density.

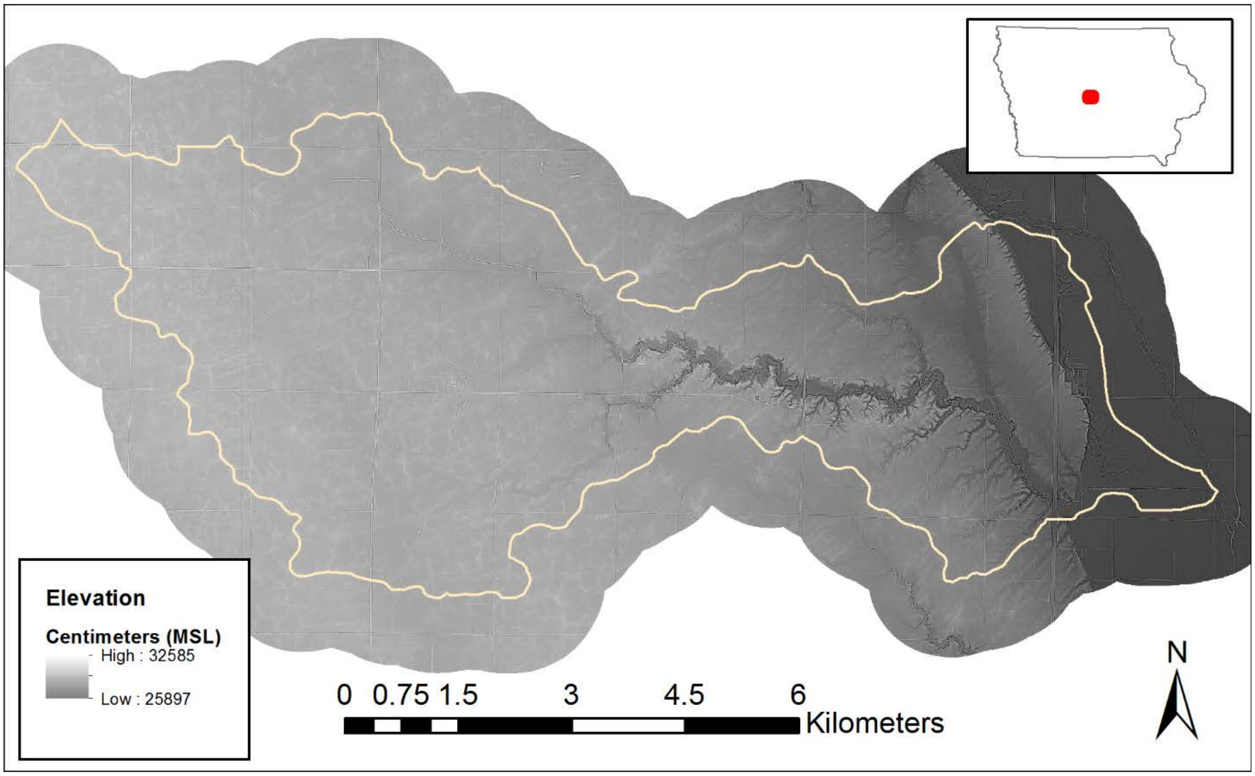

Figure 1. One kilometer buffer of Walnut Creek of South Skunk River watershed

DEM Generation and Pit Filling

The overall goals of the DEM generation and pit filling stage are the creation of a high-accuracy DEM at the single-cell level and defining the areas where the DEM was created by interpolation. The initial LiDAR data are stored in .las file format (ASPRS 2013), which contains information about the number, location, and intensity of returns. This process begins with full-resolution .las files of the watershed plus a 1 kilometer buffer to allow for boundary error in low-relief landscapes. This buffer is re-evaluated after processing is complete to determine if 1 kilometer was sufficient. The .las files are filtered to only bare earth points and processed into multipoint features which are added to a terrain. Custom pyramid levels as well as centimeter-level truncation are used to help reduce errors caused by unreasonable precision. The resulting terrain is then converted into a 3 meter resolution DEM with centimeter-level elevation precision to reduce quantization errors. A raster of return counts per cell is also created at this time. After the DEM is generated, one-cell sinks are removed. For this project, one-cell sinks are defined as cells that are lower than all surrounding cells and have no surrounding cells draining into them. Figure 2 shows the cells altered by the one-cell sink removal. The small ridge and change in image texture represents a LiDAR collection boundary between two subcontractors and demonstrates the difference between LiDAR collection systems.

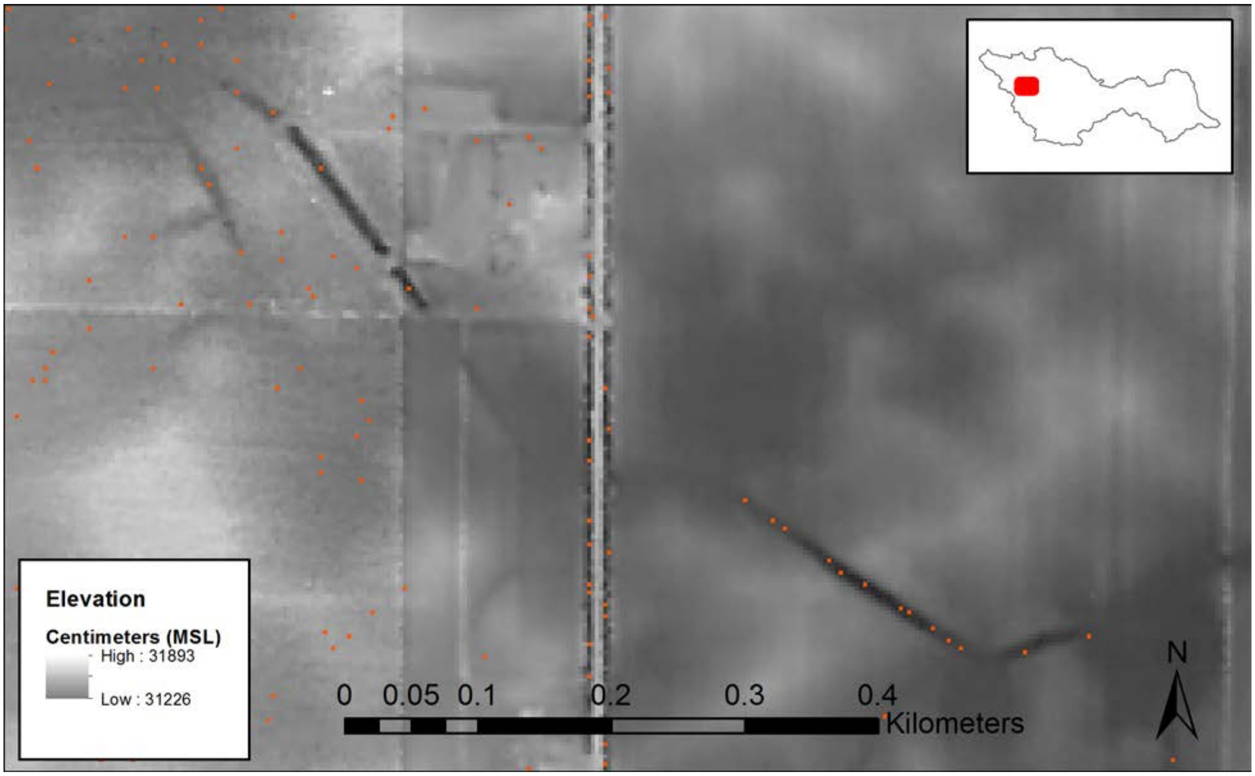

Figure 2. Highlighted cells altered by removal of one-cell sinks

DEM Hole Punching and Cutting

Originally the hole punching and cutting programs were entirely separate. However, to optimize for processing speed the two programs were combined to allow fill region characterization to occur at the same time as fill region delineation. Overall, the goal of the hole punching phase is to define only those depressions that one wishes to consider for further enforcement processing. This is done by a combination of the depression characteristics depth and area. All depressions smaller and shallower than the criteria are removed from the DEM via a fill operation and are not considered for enforcement in the cutting process. The objective of the cutting phase is to create a DEM that represents flow through obstructions such as roads, railroads, other embankments, or vegetation cover as close as possible to actuality, ideally without changing the DEM in other, unnecessary places. The allowable connection distance is defined as a multiple of the distance from the local watershed boundary to the deepest points in the local watershed.

Preprocessing

Before the cutting process begins, a number of preprocessing steps are conducted. The first step involves defining areas where the normal search radius prediction algorithm will likely not be sufficiently effective. These include areas where medians divide highways, railyards, runways, and drainage ditches. These first three areas are identified from statewide transportation feature classes clipped to the watershed of interest, where an additional search distance equal to the width of the feature will be added to the estimated search radius. The last areas, ditches, are identified from the DEM by the confluence of three topographic characteristics that indicate a high likelihood of channelized flow (Figure 3):

1. Aspect that deviates more than 1.05 radians
2. Profile curvature greater than 1.0
3. Elevation less than the 3x3 kernel mean

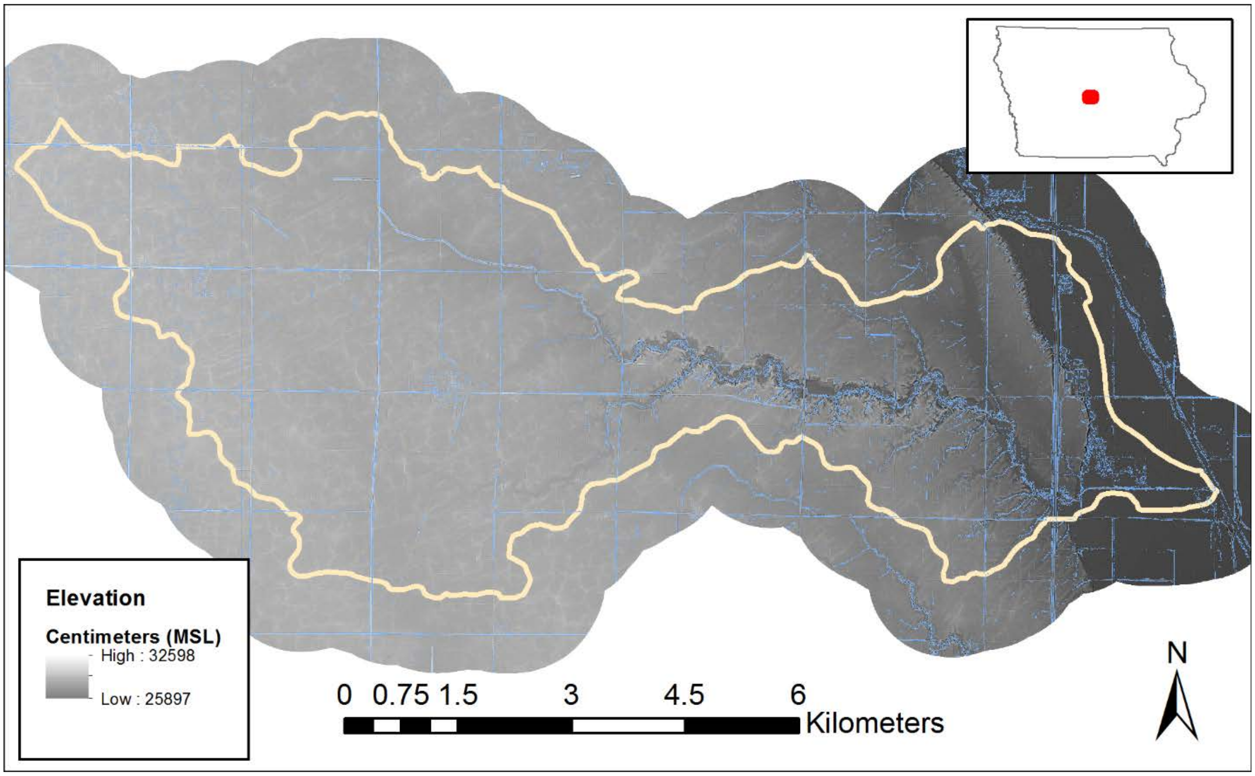

Figure 3. Areas of likely channelized flow

Additional analysis is also conducted on the areas where the initial DEM was interpolated to determine whether a fill region is likely an area of open water. This is done by finding cells that have no returns and those that have only one return and border a cell of zero returns. These “no data” areas must have a minimum thickness of seven cells and a boundary that is more than 50 percent channelized flow cells.

Hole Punching and Fill Region Characterization

The hole punching process begins with defining all sinks in the DEM. It then proceeds as follows:

1. Define “fill regions” as areas of positive fill depth by filling the DEM and subtracting the filled result from the initial DEM to calculate fill depth (Figure 4) and then grouping the results by connectivity.

2. Define fill regions to punch by calculating the area and maximum depth of depressions.

3. Punch fill regions at the sink of maximum depth within the respective fill region.

4. Repeat steps one through three until no “fill regions” remain. The final result with all fill regions is shown in Figure 5.

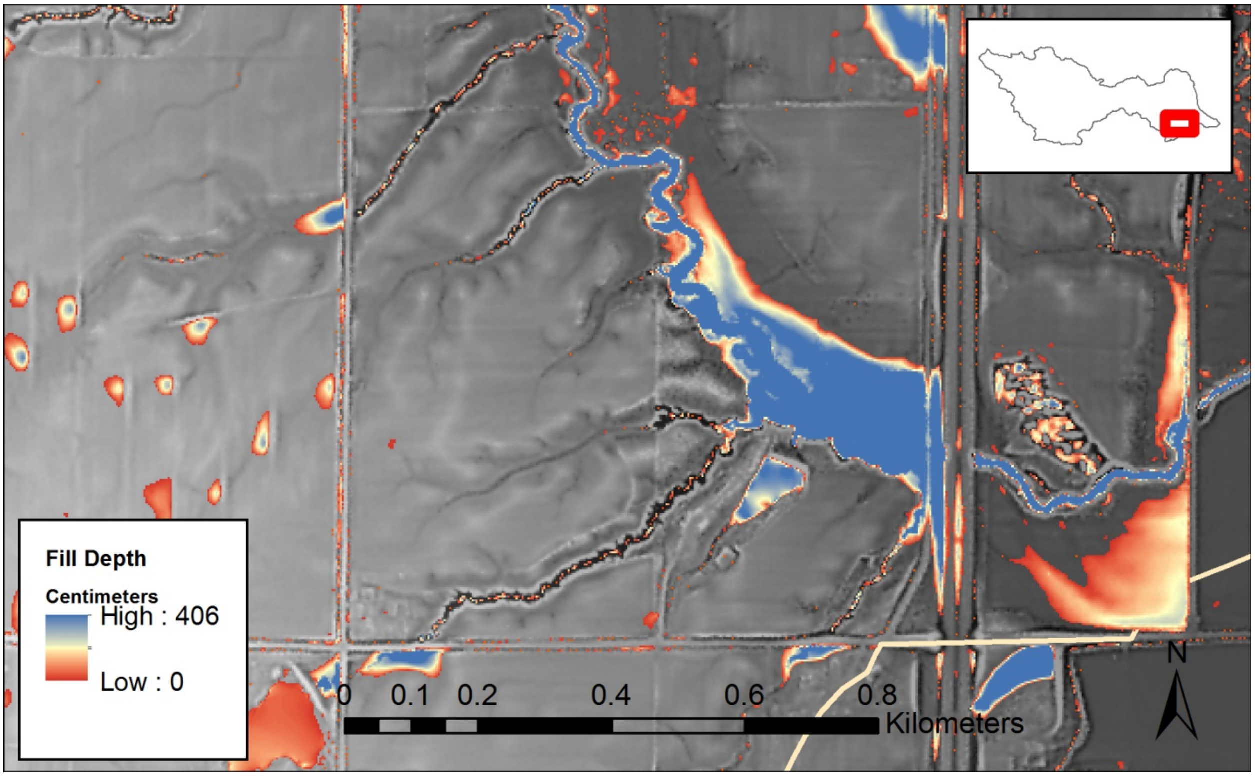

Figure 4. Fill depth required to make DEM flow

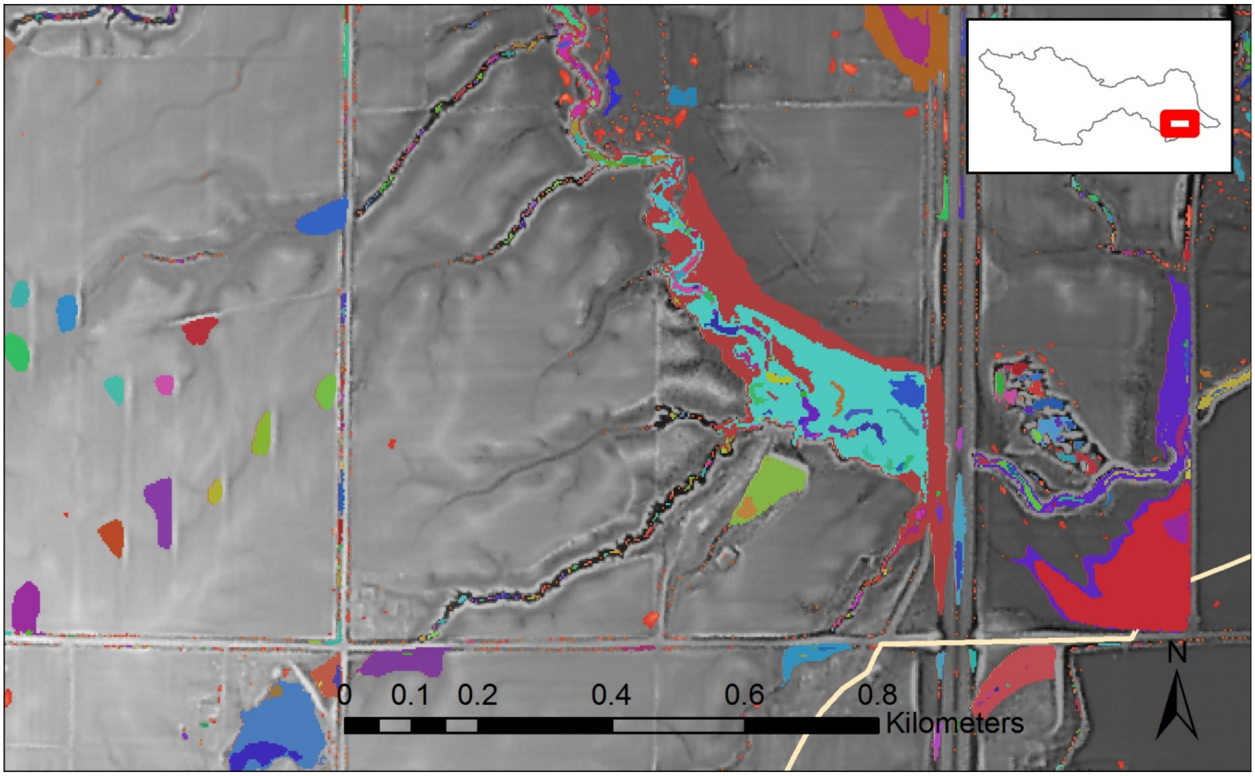

Figure 5. Fill regions after all iterations

During the hole punching process, a number of fill region characteristics are calculated to help classify depressions into two categories: those that might flow and those that do not. These characteristics include the following:

- Assignment of a unique reference number consistent across sinks, fill regions, and watersheds
- Fill region minimum elevation, minimum effective elevation (the third minimum elevation found in a 9x9 kernel around the minimum), and 80 percent of maximum effective depth
- Distance of all fill region cells from the local watershed boundary
  - Distance of nearest minimum effective elevation and 80 percent of maximum effective depth cells
- Possibility of fill depth reduction via cutting – This initial assessment of flow/no flow is made by determining whether the deepest points (those within 80 percent of the maximum depth) are within a 5 percent slope of the local basin (i.e., the basin defined by those deepest points). Essentially, this determines if the deepest points are close to the local watershed boundary. The actual distance from the deepest points to the boundary is

then used to define a DEM alteration radius around the deepest points. Within this region, the elevation is reduced to the local basin minimum, and then a check is performed to see if the basin will flow with this alteration. If the depth of fill in the basin is reduced after this alteration, the depression will be further evaluated for cutting.

- The total fractional extent of the fill region that is
    - In an area of likely channelized flow, or
    - In an area of “no data” or no LiDAR returns

Identification of Ponds

To reduce the number of fill regions to be considered for enforcement, a determination of whether a fill region is open water is made. Fill regions that are determined to be open water and are not the deepest open water fill region (i.e., the first fill region punched in that area of open water) are noted and removed from further enforcement consideration.

Fill Region Aggregation

After removing extra depressions in ponds, the remaining depressions are evaluated to determine if a cut needs to be made to enforce connectivity or whether filling the depression is the most appropriate solution to force flow downstream. This determination is made by assessing whether a depression and its overflow pathway is entirely contained within the area of channelized flow. If the depression leaves this area of channelized flow or is deeper than 1 meter, it will not be filled; otherwise, it will be filled and only the deepest depression in a channelized flow section is retained. This connection evaluation reduces the number of depressions resulting from channel definition via regular grids, as suggested by Rieger (1998).

Assigning Search Radius

After fill regions have been filtered via the above steps to only those most likely to require enforcement, the calculation of search radius for the remaining fill regions begins. If the distance from the local watershed boundary to the nearest minimum effective elevation cell is within two times the distance from the local watershed boundary to the nearest 80 percent of maximum effective depth cell, the average of these two distances is used. The square root of the cell size is added to all minimum calculated distances because cell-based cost distance is used and this is less than the distance from the watershed polygon boundary. The default search radius is limited to a maximum of 150 meters.

$$\text{Default SR} = 1.41 \times \text{CS} + 3 \times (\text{MD80} + \text{MDM}) \div 2 \tag{1}$$

where CS is cell size, MD80 is the minimum distance to 80 percent of maximum effective depth, and MDM is the minimum distance to minimum effective depth. If MD80 is not less than one-half of MDM, the default search radius is calculated as follows:

$$\text{Default SR} = 1.41 \times \text{CS} + 3 \times \text{MD80} \tag{2}$$

Finally, all depressions are identified that abut a transportation feature that has a median (e.g., divided highways). These depressions have their search radius increased via the width of the median. The final, total search radius is then calculated as follows:

$$\text{Total SR} = \text{Default SR} + \text{Median Width} \tag{3}$$

Enforcement

The enforcement process connects upstream and downstream cells with a line and then replaces the elevations along this line with an elevation equivalent to the upstream cell. Enforcement takes place in one of three steps, each of which relaxes the criteria used to define upstream cells from the previous attempt. This approach was found to produce the best enforcement results by using only very deep upstream cells located near the local watershed boundary in the first iteration, allowing less deep upstream cells to be used in the next iteration, and using deep downstream cells to match with upstream cells in the final iteration.

Define Upstream Cells

The enforcement process begins by first defining upstream cells, which are those cells deeper than the 80 percent maximum effective depth located in the fill region to be enforced. All potential upstream cells are first defined based on elevation alone and then filtered to those that are within the total search radius of the watershed boundary (Figure 6). The upstream cells to be used are defined in the following priority:

1. Those deeper than the minimum effective elevation of the fill region to be enforced, or any subsequent fill regions that are deeper than the minimum effective elevation of the fill region that are deeper than the 80 percent maximum effective depth of the fill region to be enforced (i.e., the deepest parts of a nested fill region)

2. Those deeper than the 80 percent maximum effective depth of the fill region

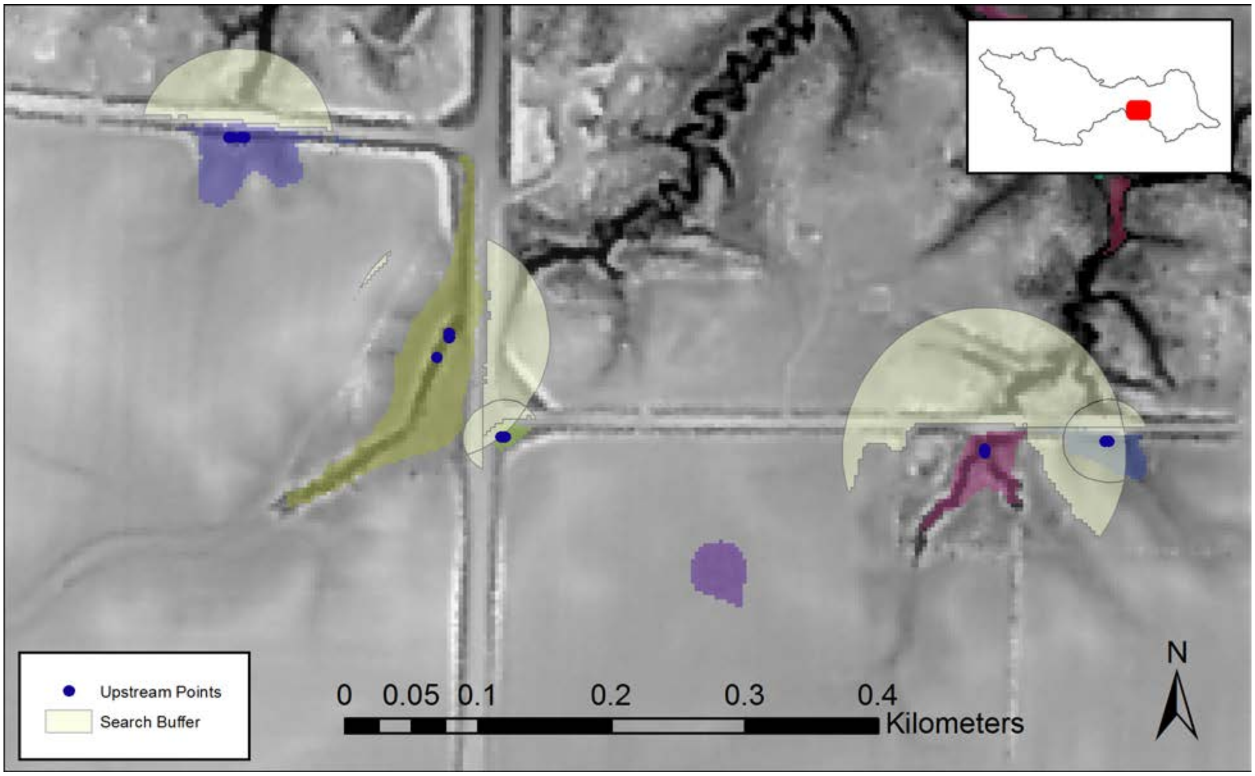

Figure 6. Uniquely colored fill regions, upstream points, and search buffers

Define Downstream Cells

Downstream cells are defined as those cells that are deeper than the minimum effective elevation of the fill region to be enforced. These must also be within the search radius distance of the upstream cells to be enforced. Example cells after conversion to points are shown in Figure 7.

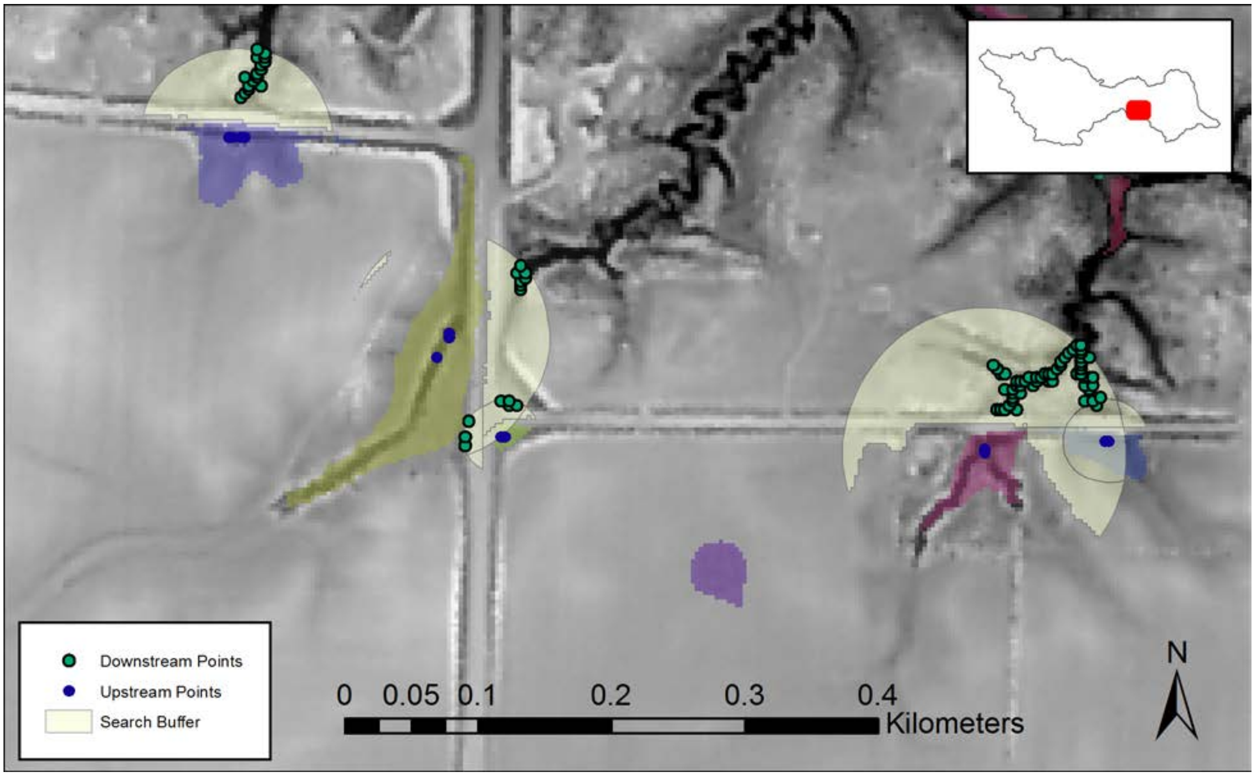

Figure 7. Eligible downstream connection points

Filter Upstream and Downstream Cells

If there are numerous upstream or downstream cells in a fill region, the cells are filtered using a focal mean filter to determine the 3x3 mean flow accumulation. Only cells greater than the 3x3 mean will be used as upstream or downstream cells.

Match Upstream and Downstream Cells

Upstream and downstream cells are matched by first turning the cells into points and then generating a table of all matches within the maximum search radius. These results are then filtered to those within the search radius for that fill region and those that would enable downhill water flow. The results are further filtered to the "best" results by choosing those that are at least one-half the maximum slope of that fill region's matches (if greater than 1 percent) or within 1 percent of the maximum (if less than 1 percent). These results are again filtered to those that are the minimum remaining match distance for the fill region, and this match will then be used for enforcement. A line feature class is then created to join the upstream and downstream points, and its elevation is set at that of the upstream point (Figure 8). The elevation of these lines are then converted into raster cell values and used to replace the elevation found in the DEM at the overlapping cells.

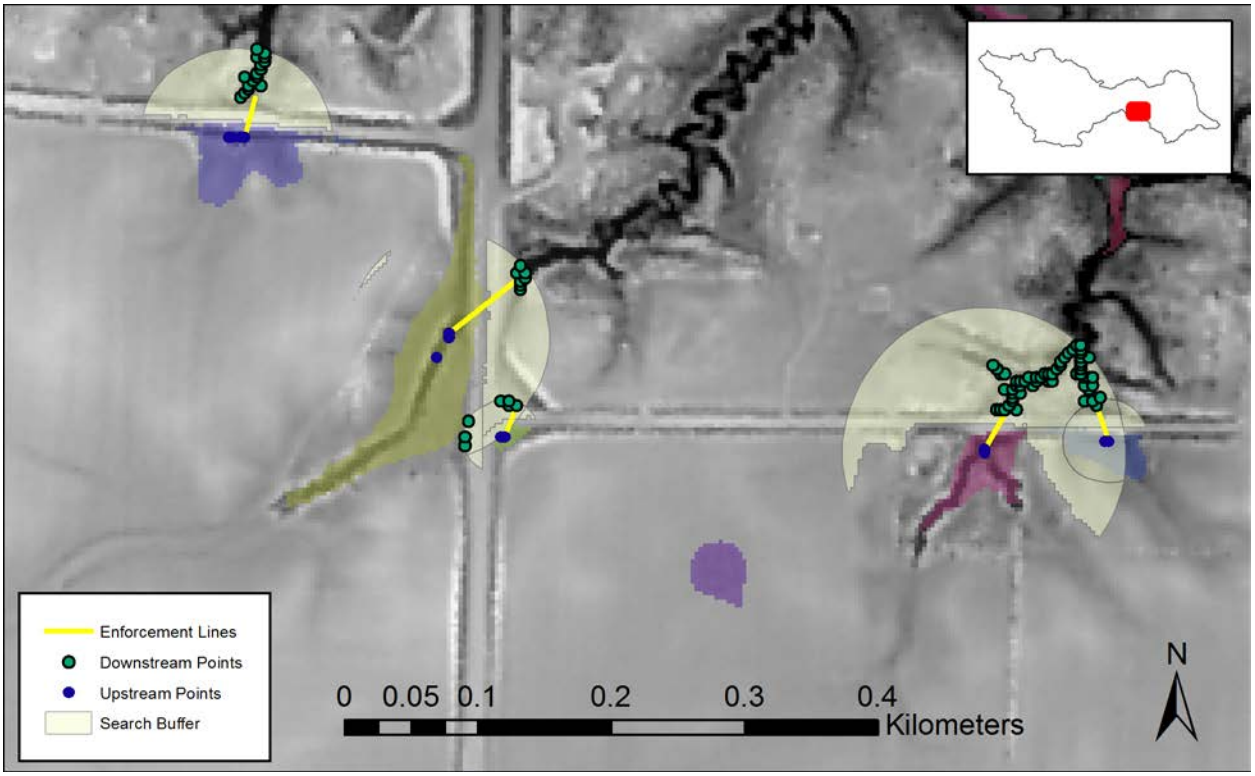

Figure 8. Enforcement lines connecting upstream and downstream points

Final Matching Iteration

After two iterations of upstream to downstream matching have failed, a fill region is attempted to be cut from the downstream to the upstream by defining downstream cells within the search radius that are deeper than the 80 percent maximum effective depth. Upstream cells as defined above are then attempted to be matched with the relaxed definition downstream cells. If a match is made, it is evaluated as above with respect to slope and distance and then converted from a line to a raster and placed into the DEM.

Flow Testing for Enforcement Retention

After the enforcement process is complete, the enforcements are tested to see if they decrease the depth of ponding. If the enforcement decreases the amount of water that must be stored by filling, the enforcement process is considered to be successful and will be maintained. Other enforcements will be removed before the final, enforced DEM is created.

Reference Dataset

A reference dataset of culvert and bridge locations was developed through a combination of methods. The database began with an Iowa Department of Transportation culvert database for federal and state roads (Blaesing-Thompson et al. 2013). The database was then extended by field investigations of areas where the cutting program indicated potential hydraulic structure locations. If these enforcements were correctly situated near a bridge or culvert, an enforcement line was then digitized to within one pixel (3 meters) on the DEM with the aid of aerial photography. This database of bridge and culvert locations was then used to create a manually enforced DEM by replacing the DEM elevations from the start to the end of the structure. This manually enforced DEM was then used to create reference flowpaths where flow accumulation was greater than 640 acres.

RESULTS AND DISCUSSION

Accuracy Assessment

Enforcement accuracy is assessed through a variety of different measures. First, the accuracy of the placement algorithm is analyzed by determining whether the program is correctly selecting depressions near transportation features for enforcement. Next is assessing the enforcement accuracy of the entire channel network by tracing downstream from defined channel initiation points and determining what percentage of the test network falls within a three-cell accuracy radius of the reference network. This method is referred to as the coefficient of linear correspondence and is derived from work presented by Goodchild and Hunter (1997). The determination of enforcement necessity can be assessed with an omission/commission matrix, and the locational accuracy of each line can be assessed by the average positional error of the culvert or bridge centroid, inlet, or outlet. Culvert directionality can also be assessed by assessing average directional error. Overall watershed boundary changes are analyzed as well.

The results of the classification accuracy assessment show that there were 1,232 depressions that abut transportation features in this watershed. Of those, enforcements were attempted on 378. The transportation feature survey indicates that there were 92 depressions actually drained via structures. Of these 92, all were identified except for 4. These results are displayed graphically in a pie chart in Figure 9. Two of the errors resulted from shallow depressions that were bisected by a road, and the resulting slope from the edge of the local watershed to the deepest points in the depression did not exceed 5 percent. The other two errors resulted from the fill region aggregation step, where depressions in the ditches along a divided highway were allowed to overflow when they should have been forced to flow across the road.

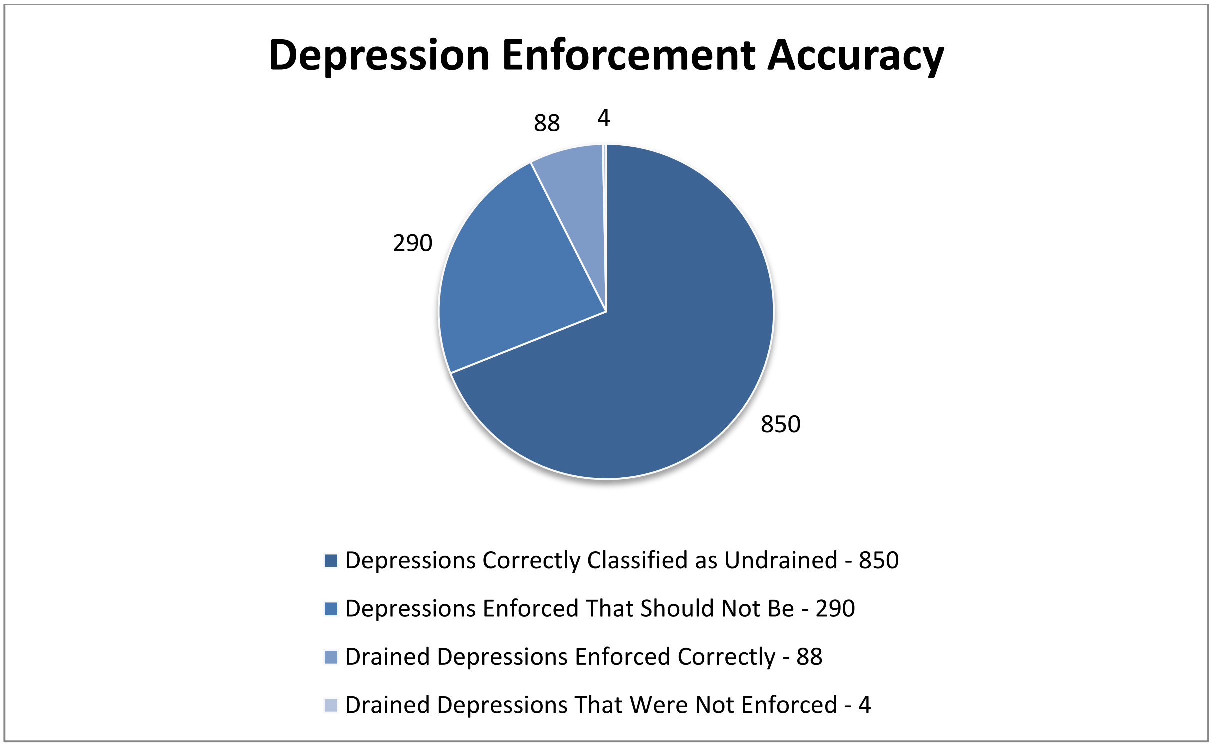

Figure 9. Depression classification accuracy assessment

The results of this analysis indicate that the enforcement program classifies the vast majority of depressions correctly. This is evident in the reduction in fill depth that can be seen when comparing the fill depth after enforcement (Figure 10) with fill depth in the same area before enforcement (Figure 4). However, it often places enforcements where none are necessary, because there are approximately four times as many enforcements as actual hydraulic structures. These errors occur almost exclusively in the upland portion of the watershed that is dominated by prairie potholes. These depressions are often bisected by roads, and the enforcement program often tries to reconnect the bisected basins (Figure 11).

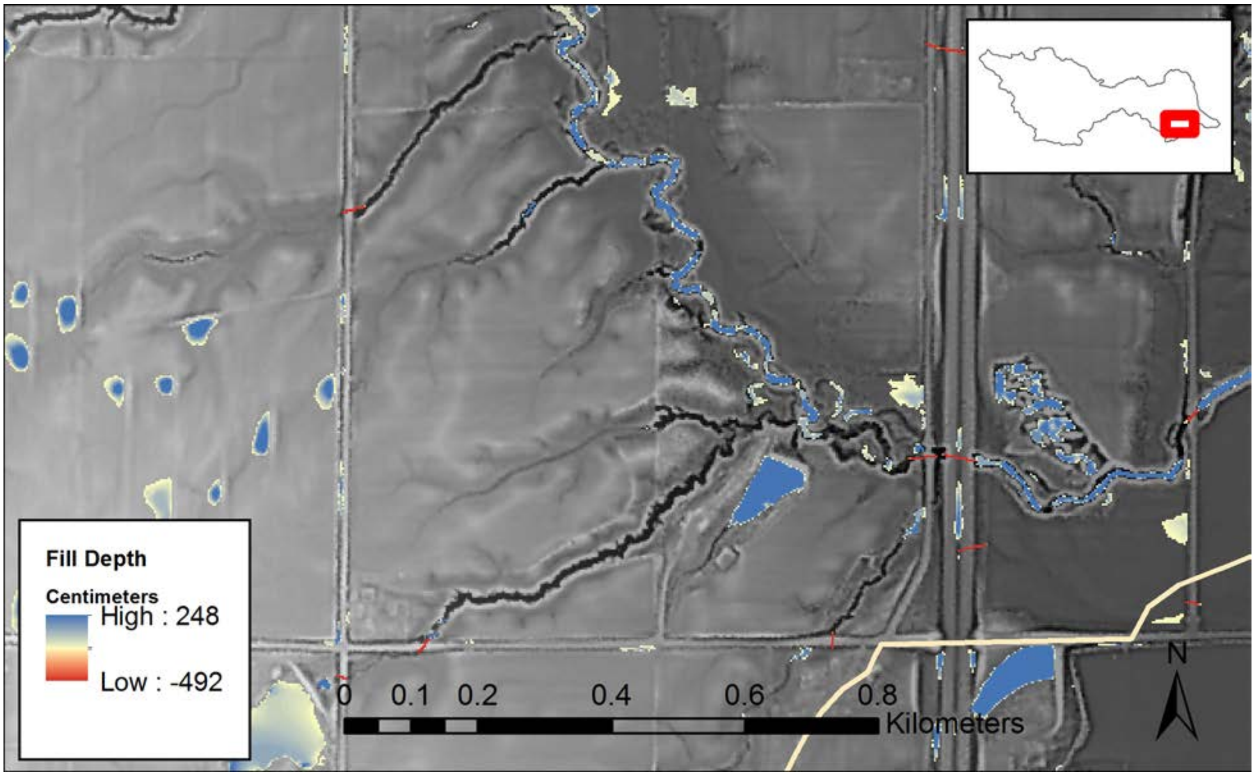

Figure 10. Fill depth required to make DEM flow after enforcement

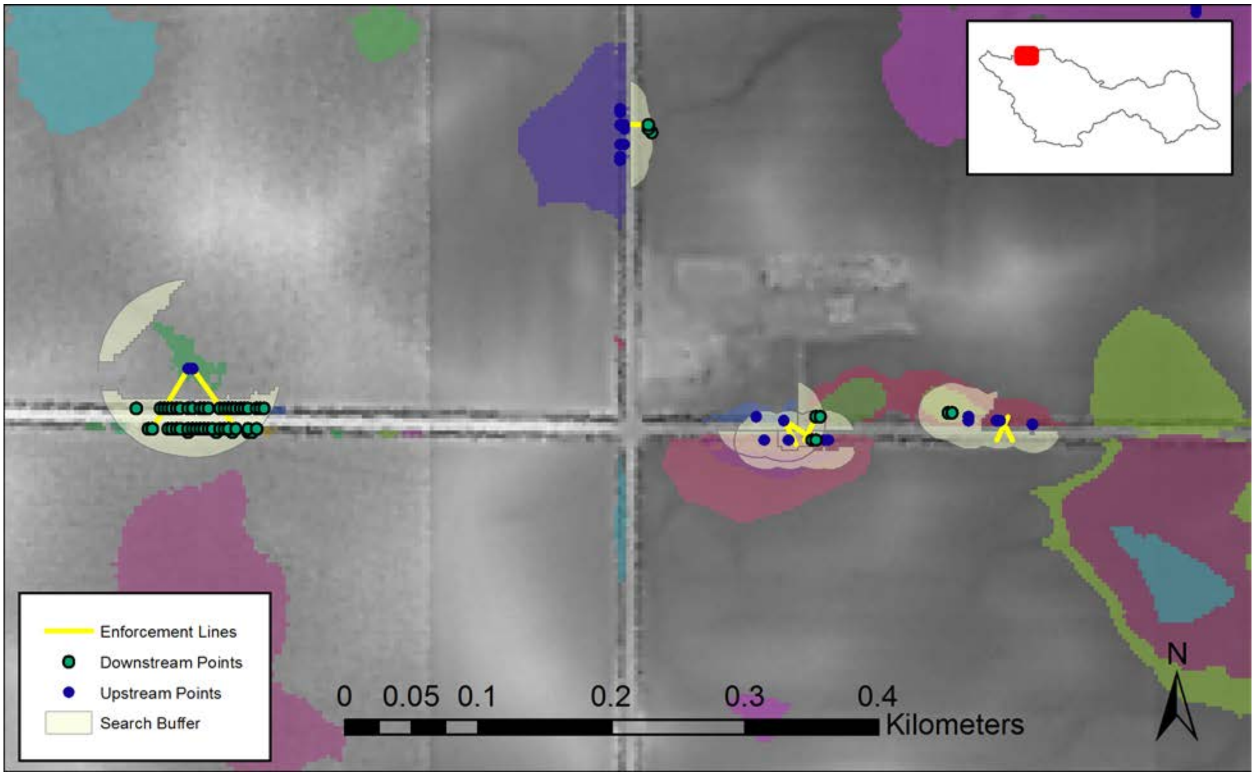

Figure 11. Multiple bad enforcements and one good one (northernmost)

These errors should be easy to filter out with additional logic because these depressions are not fully drained by the enforcement; the water just transfers from one side to the other. Other commission errors are due to the enforcement process cutting to the other side of the road to drain a depression when the enforcement should be occurring along the right of way, not across it (Figure 12). These errors could be improved by using road directionality to help preferentially select downstream points that are on the same side of the road as opposed to across the road.

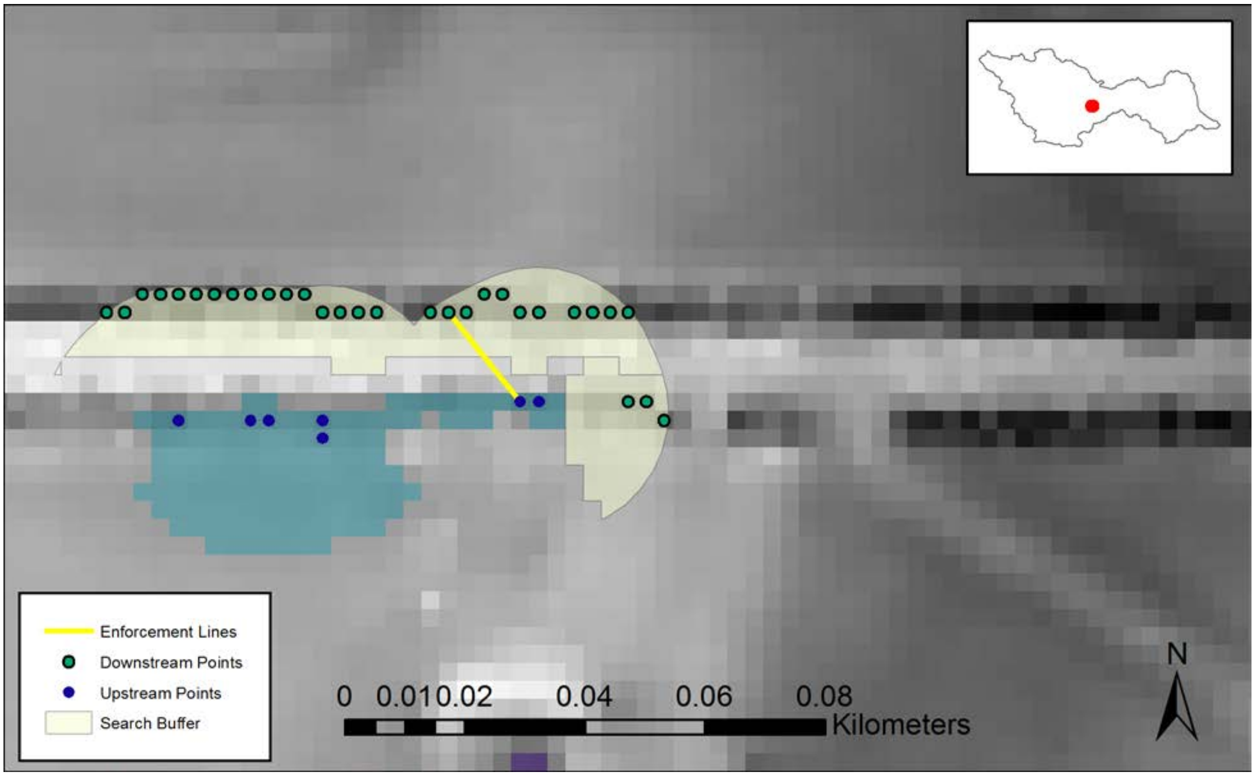

Figure 12. Cut that should parallel the road

The coefficient of linear correspondence analysis is shown in Table 1. This analysis shows that there were 33,115 meters of reference flowpaths derived from the DEM enforced by the structure database, and there were 32,819 meters of enforced flowpaths within the allowable error radius of three pixels or 9 meters. This results in a coefficient of linear correspondence of 0.991, which, although high, can be increased even more by only looking at the channelized flowpaths. If one looks at only the channelized portions of the flowpaths, the correspondence coefficient increases to 0.999 because, except for a few small errors in enforcement directionality at the structure location, the enforced flowpath exactly follows the reference flowpath. The deviations in the non-channelized flowpaths occur almost entirely in the low-relief prairie pothole uplands and floodplain lowlands of the watershed.

Table 1. Coefficient of linear correspondence for enforcements

	Overall	**Channelized**
	33,115 m	**22,214 m**
Enforced Flowpaths	**0.991 (32,819 m)**	**0.999 (22,196 m)**

Centroid position, length, and directional error are shown in Table 2 for those depressions that are both drained by a structure and had an enforcement placed because a reference is needed from which to define an error. The mean positional error was 3.8 meters, with most of that error occurring in the Y direction. This makes sense because the watershed is primarily drained by structures that are oriented east-west. The mean length error of -3.6 meters indicates that the average enforcement length was about one pixel longer than it needed to be, on average. The mean directional error was about 0.10 radians, or 6 degrees.

Table 2. Mean error of enforcement position, length, and direction

Error Type and Units		
Mean Centroid Position	**Mean Length**	**Mean Direction**
meters	**meters**	**radians**
3.85	**-3.6**	**0.10**

Watershed Boundary Changes

The pre-LiDAR and post-enforcement watershed boundaries can be seen in Figure 13.

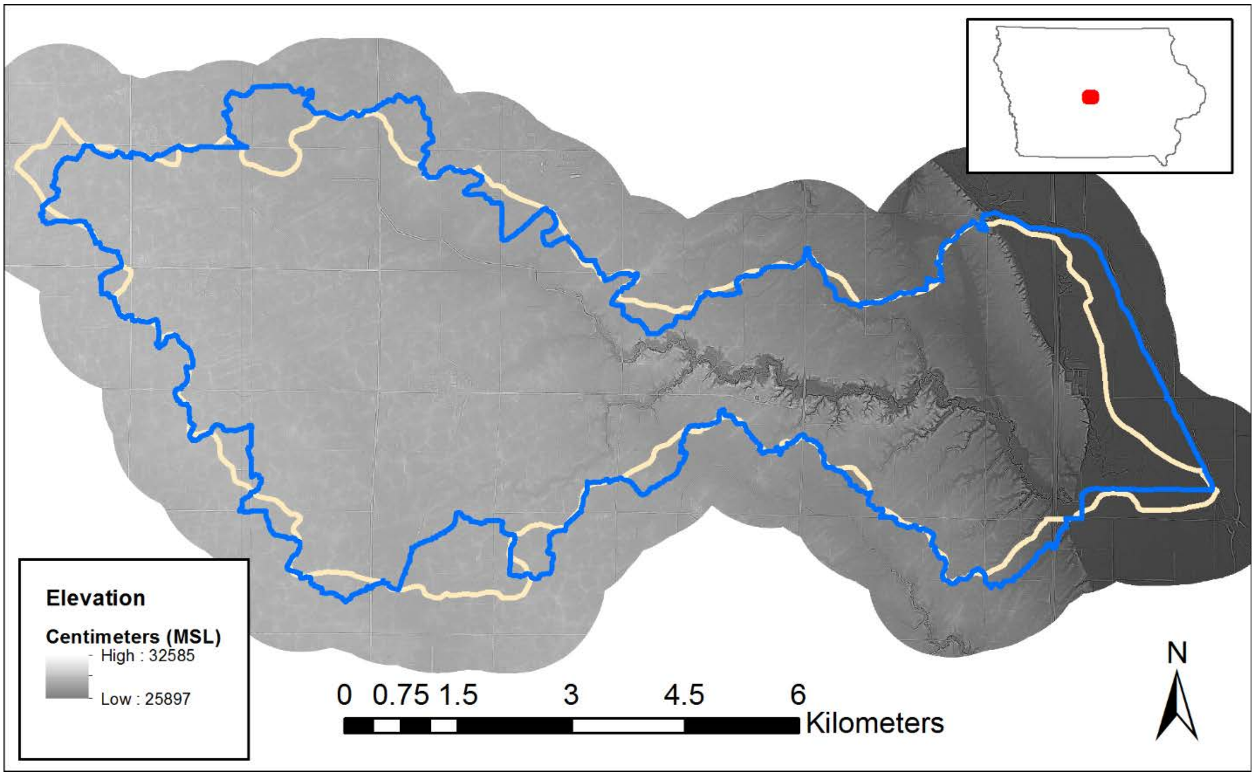

Figure 13. Final watershed boundaries overlaid on initial boundaries

The watershed boundary moved up to a maximum of 1 kilometer from the original boundary, but many changes were offsetting. Changes were more common and of larger magnitude in areas of the lower relief upland and floodplain parts of the watershed. On average, more area was added to the watershed than removed, with the final watershed boundary being 103 percent of the area of the initial watershed.

Suggestions for Additional Work

The program currently does a very good job of enforcing flow where flow direction is well defined, i.e., where channelization has already occurred. It also does a good job of preserving natural and anthropogenic depressions. However, there continues to be room for improvement in poorly defined areas that flow. The large number of extra enforcements indicate that either a different philosophical approach or additional line filtering is needed. One possibility that could remove more depressions from the beginning would be to use a new interpolation method in areas of no LiDAR returns that will help remove as many false depressions as possible. These areas then need to be enforced with a DEM inversion process to help enforce downstream flow on rivers and major streams. This approach is currently used on shallow, thin depressions in areas of channelized flow and needs to be expanded. After removing as many false depressions as possible, the depressions must continue to be evaluated for flow, as is currently done. An additional step needs to be developed that classifies all non-flowing depressions as terminal depressions. These terminal depressions would include prairie potholes, lagoons, and borrow pits. Coping with the problem of there being too many enforcements and the fact that in most of these cases filling the DEM would be the most appropriate solution will require developing a new metric to detect areas where enforcements are appropriate, such as when flow significantly leaves the channel and when it does not move downstream to the lowest points.

CONCLUSIONS

The depression classification and enforcement algorithms presented were tested on a watershed representative of most of the diverse landscapes found across Iowa. The classification algorithm correctly identified about 95 percent of the depressions drained via hydraulic structures as such. It also identified about three times as many depressions as drained that were not drained, although most of these enforcements reconnected a depression bisected by a road or cut across a road when the enforcement should have paralleled the road. The enforcements that were placed were generally accurate with a mean centroid and length error of approximately one pixel and a directional error of about 0.10 radians. Based on these results, the enforcement method proposed can provide relatively accurately enforced DEMs with relatively little effort.

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