# An Assessment of Hydrologic Enforcement Methods on Various Drainage Features

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## 1. Introduction

Lidar typically acquires high level of topographic details representing both the terrain and surface features by a mass cloud of *x*-, *y*-, and *z*-points at a fine resolution of ground sample distance. Much effort in lidar post-processing was to separate the ground features from the non-ground features to produce a bald-earth Digital Elevation Model (DEM). An essential component of lidar post-processing is to enforce the integrity of hydrographic features as water travels through the landscape. This process typically involves the insertion of breaklines to ensure the resulting terrain model will be "hydrologically correct". Despite the best effort in post-processing lidar data, the resulting DEM would still require hydrologic enforcement prior to topographic-based hydrologic modeling, such as determining flow direction and delineating the watershed. Little is known about their effectiveness and consequences on subsequent terrain analysis. The purpose of this research was to assess the impact of common methods of hydrologic-enforcement on the resulting DEM and their effectiveness in maintaining the integrity of various hydrographic features. This research utilized the 3-m lidar post-processed to derive hydrologically enforced DEMs by pit filling, stream burning, surface reconditioning and feature alignment methods.

## 2. Methodology

### 2.1 Study Areas and Data

In this research, the study areas were located in Genesee County, Michigan, USA (figure 1). Genesee County is part of the The four selected study areas cover various drainage features, including lakes/ponds, rivers, dams, ditches, culverts, bridges and road crossings. The first study area is a 1-mile segment along the Flint River that goes through the campus of University of Michigan – Flint. This urban floodplain is characterized by the levees fortified by the U.S. Army Corps of Engineer and the presence of Mansfield dam which obstructed the free-flowing water. The second study area is the Genesee County Park, a rural floodplain with a mix of meandering and braided rivers. The third study area is the Kearsley Lake, a reservoir created by the Kearsley dam located downstream. The Shiawassee River flows through downtown Fenton, Michigan, USA, and is interfaced with many urban drainage features, including ditches, bridges, road crossing and locks.

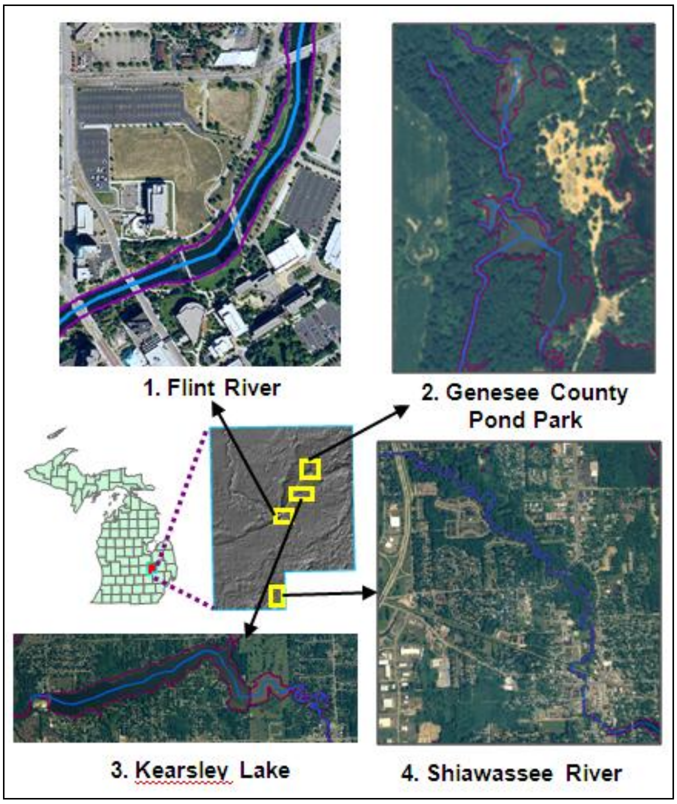


Figure 1. The study areas in Flint, Michigan, USA.

The lidar data was acquired by Sanborn during 2002 along with high resolution digital orthophoto in true color. The data vendor post-processed the lidar by removing ground features and inserting hard and soft breaklines, resulting a bald-earth DEM, or a digital terrain model (DTM). The filtered lidar data was delivered at 3-m nominal density. The lidar data was interpolated to a grid-based DEM by using Inverse Distance Weighted method with a variable neighbourhood of 12 nearest observations and a power of 2.

## 2.2 Algorithms

The lidar-derived DEM was used as primary input to represent topography. Based on the high resolution orthophoto, important hydrographic features, such as stream centreline and banks, were identified and digitized in all 4 study areas. The hydrologic enforcement algorithms examined in this research include: 1) pit filling, 2) stream burning, 3) surface reconditioning, 4) surface interpolation with feature enhancement, and 5) feature alignment (Euclidean direction and cost direction).

The selected algorithms reflect varying spatial extent of DEM modification (Kenny and Matthew 2005). Pit filling is a pre-requisite procedure in many topographic-based flow algorithms to determine flow direction by assuming flow occurs along the steepest slope (O'Callaghan and Mark, 1984; Jensen and Dominique, 1988). Pit filling applies to all cells in a DEM to remove pit holes and depressions. However, filling the pits does not necessarily alter the elevation within a river. Stream burning is a technique attempts to ensure continuous flow downstream by lowering the elevation along the stream centreline. The concept of stream burning is similar to trenching the stream bed to encourage flow convergence along the stream centreline (Saunders, 2000). However, this algorithm often modifies the DEM permanently, which cause steeper slope across the banks and greater stream volume. Surface reconditioning is an improved technique that applies a linear interpolation between the burned stream centreline and adjacent banks to create a smoother surface (Hellweger 1997). In this case, the affected cells would be extended from the stream centreline to the entire stream bed within the river banks. In fact, some advanced hydrologic enforcement algorithms, such as the Australian National University Digital Elevation Model (ANUDEM), take a step further by incorporating hydrographic features into surface interpolation and ensure the entire surface would be "hydrologically correct" through parameter optimization (Hutchison, 1989; Hutchison, 2009). As opposed to these topographic-based methods that focus on changing the terrain to ensure correct stream flow, another philosophy of hydrologic enforcement is to align flow direction grid directly to hydrographic features without altering the DEM. Kenny and Matthews (2005) proposed a feature alignment method that route water flow through flat terrains based on the closest Euclidean direction to the centreline. This research also tests an alternate method of feature alignment based on cost direction. This work examines the effectiveness of these 6 hydrologic enforcement algorithms on various drainage features and assesses their impacts on the resulting DEMs.

### 2.3 Assessment

The hydrologic enforcement algorithms were applied to the lidar-derived DEM to derive primary hydrologic variables, including slope, flow direction and watershed area. This research attempts to answer the following questions:

1. What are the impacts of hydrologic enforcement in the river bed (e.g. elevation, slope, volume)?
2. How effective is the hydrologic enforcement algorithm(s) in routing water through various drainage features and delineating the watershed?

The first research question used the original lidar-derived DEM as reference data, assuming that the unaltered DEM (i.e. original) approximates the actual terrain surface the best. Residuals were calculated between the hydrologically-enforced DEMs and reference DEM, and their significances were determined by using repeated-measure ANOVA. The research hypotheses are stated as follow:

**H1**: $Elevation_{x,y,reference} = Elevation_{x,y,i} = Elevation_{x,y,i+1} = \ldots$

**H2**: $Slope_{x,y,reference} = Slope_{x,y,i} = Slope_{x,y,i+1} = \ldots$

where $x$ and $y$ are the spatial coordinates of a pixel derive by algorithm $i$. Descriptive statistics of slope (e.g. min, max, mean) were computed to evaluate the magnitude of slope difference. Volume difference was also calculated by multiplying the elevation difference with cell area for each hydrologic enforcement method.

The second research question evaluates the effectiveness of hydrologic enforcement algorithms based on routing water flow through various drainage features covered in the 4 study areas. A challenge in this task originates from the absence of any hydrologic products that can be referenced as "ground truth". Hence, the original DEM with standard pit filling was used as the benchmark to assess any significant differences in the flow direction and watershed area determined by the hydrologic enforcement algorithms. Similarly, the corresponding research hypotheses are:

**H3**: $Flow\ Direction_{x,y,pit\text{-}filling} = Flow\ Direction_{x,y,i} = Flow\ Direction_{x,y,i+1} = \ldots$

**H4**: $Watershed\ Area_{x,y,pit\text{-}filling} = Watershed\ Area_{x,y,i} = Watershed\ Area_{x,y,i+1} = \ldots$

## 3. Results

By comparing to the original DEM, the results showed that all hydrologic enforcement methods would improve the determination of flow direction consistent with the hydrographic features, including meandering/braided streams, dams, bridges, lakes etc.

However, all methods except feature alignment increased slope and permanently altered the elevation and volume of catchment terrain. The methods of feature alignment demonstrated superior performance in hydrologic enforcement while preserving the original elevation. This research reflected the usefulness of hydrologic enforcement in modeling known hydrology and the importance in acknowledging their magnitude and spatial pattern of landscape modification.

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