A Voronoi diagram approach to defining surface hydrography using LIDAR-generated bare earth sample points

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Abstract

Geographic Information Systems (GIS) typically rely on raster grid data structures to define surface hydrography and define watershed boundaries. The interpolation of grids from sample points and the algorithms used to define flow directions introduce error and compromise data quality, especially in areas of low relief. This research proposes a new approach in hydrographic geomorphometry, using Voronoi diagrams generated from airborne laser altimetry data points to determine flow direction and define watershed boundaries for the Lummi Indian Reservation in Whatcom County, Washington State. In theory, the Voronoi diagram approach will bypass the errors introduced by the raster grid by constructing a connected network expressing flow direction generated directly from sample point data. The Voronoi surface output will be compared with the raster grid output and measured for accuracy based on a field survey of selected water courses.

Keywords: Geographic Information Systems, LIDAR, watershed, data structure, hydrography, geomorphometry, Voronoi

Introduction

In 2004 the Lummi Indian Nation procured LiDAR-generated surface elevation data for the Reservation and adjacent areas that contribute overland flow to the Reservation. The legal, cultural, and economic implications of surface water quality and ground water availability necessitate an accurate delineation of watershed boundary along with a flow direction model for the watershed. The current watershed boundary is based on a manual inspection of United States Geologic Survey (USGS) topographic maps and calculated from USGS raster based 10 meter digital elevation models (DEM). The error introduced by this surface model data structure and associated processing algorithms leads to inaccuracies in the final hydrologic calculations and therefore the contributing watershed boundary for the Reservation. With the improved accuracy and precision of topography derived from LiDAR data, there is an opportunity to improve the watershed boundaries. Typically, LiDAR data is used to generate a DEM by interpolation, which then serves as the input for the flow direction algorithm. In this paper, I shall discuss the DEM error introduced by the interpolation from sample points, and how the flow direction algorithm fails to capture flow in areas of low spatial relief, such as the Lummi Indian Reservation. In response to these concerns, I propose an alternative surface tessellation approach that employs Voronoi cells generated around each LiDAR sample point to calculate overland flow direction; outputs from this approach will be compared with the outputs using standard raster-based surface models in a geographic information system (GIS). This paper is motivated by the following hypothesis:

The alternative approach described above will produce a more accurate flow direction model than that derived from raster DEM for low relief areas of the Lummi Indian Reservation.

Background

The generation of DEMs requires some form of interpolation to generate cell values for those cells that do not contain sample points (Wood and Fisher 1993) and the raster resolution generated by the interpolation methods has a significant impact on the resulting flow direction calculations (Crosby 2006; Garbrecht and Martz 2000; Horritt and Bates 2001; Kienzle 2004; Barber 2005; Changqing et al. 2005; Haile 2005; Aguilar 2006; Callow 2007). Figures 1 and 2 depict the flow paths generated from a sub-set of the Lummi LiDAR data using standard procedures from interpolated DEMs at two different cell resolutions (1ft. and 3ft.). The same methods and parameters were used, and the differences in flow paths are a result of raster resolution and interpolation.

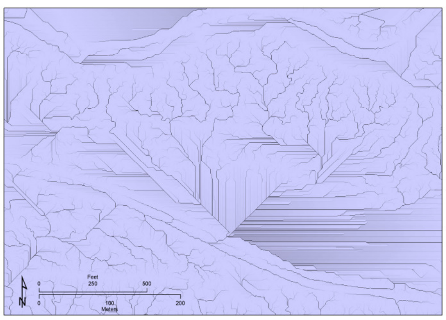

Figure 1. Flow paths from a 1 ft. DEM

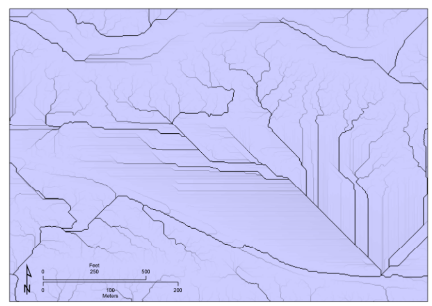

Figure 2. Flow paths from a 3 ft. DEM

Flow direction error is also introduced by the processing algorithm, the D8 flow direction algorithm used to calculate flow direction across the raster surface. The D8 selects a cell, and compares the z value with the eight adjacent cells. Flow direction from the D8 is restricted to one, and only one, of eight cardinal directions. As a result, the D8 fails to capture stream bifurcation, for example braided or anastamosing stream channels (Burgholzer 2005; Garbrecht 1997; Blaszczynski et al. 1999; Garbrecht and Martz 2000; Barber 2005; Callow et al. 2007). Similarly, the D8 is unable to accurately capture flow direction on flat areas that occur as a result of interpolation, filling (Wechsler 2007), or breaching and stream burning (Soille 2003). The stream flow direction in figures 1 and 2 demonstrate the limitations of the D8 on filled areas where flow directions are constrained to 45 degree angle increments.

Methods

In response to the DEM limitations described above, I propose an alternative tessellated surface/Voronoi diagram approach to reduce the error in watershed boundaries and flow directions associated with interpolation and the D8 flow direction algorithm. The proposed method loosely follows the Voronoi Bucket approach used by Drakowicz (Dakowicz 2007). Voronoi cells will be calculated representing the area around each LiDAR sample point that is closest to only that point. The proposed algorithm will iterate through the polygon file, select polygon P_1, return the polygons adjacent to P_1, and compare z values for the points bound by the polygons. The process will then use the x and y values of the sample points and create a network of lines representing the flow paths between adjacent sample points. This method is roughly based on the same processing method used by the D8, but flow connections can be established to more than one downhill cell and therefore capture stream bifurcation. Similarly, this method permits the bypass of the fill procedure since sinks can be identified during the iteration, computationally flooded, and flow connectivity can be established to the flow network.

Conclusion

There are important legal implications for the Lummi Nation to accurately identify lands that are contributing to overland flow on the Reservation, and identify the homes and wells that are bound within that boundary. Both the Lummi Reservation and western Whatcom County are characterized by low relief, low elevation Puget Sound floodplains. Established GIS-based watershed delineation and flow direction tools that are based on raster-based data structures fail to accurately model flow direction in this type of terrain, and therefore affects the accuracy of watershed boundaries. Modern advances in file storage capacities and improvements in processing time provide the foundations to facilitate new approaches which may bypass the constraints imposed by the raster model. By using a Voronoi data structure to identify areas most likely equal to LiDAR bare-earth sample points in elevation, and using the relation of Voronoi cells to define flow relationships, it may be possible to define surface hydrology that is not constrained by the raster model.

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