LiDAR APPLICATIONS
REMS6090

Assignment 2
HYDROLOGICAL APPLICATIONS of LiDAR DATA
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1.0 Introduction

High accuracy Digital Elevation Models (DEM) derived from Light Detection and Ranging (LiDAR) datasets are being increasingly applied in the fields of watershed analysis and management, where surface hydrological modeling represents a core component of the work flow. The ability of LiDAR point cloud data to generate high spatial accuracy DEM’s is a major advantage over traditional DEMs of courser resolution (~>20 m). The following report outlines three basic hydrological modeling procedures conducted on a LiDAR-derived 1 m DEM for a study area encompassing the town of Middleton, Nova Scotia (Fig. 1).

The goals of this project are to:

1. Carry out three hydrological processing procedures including Hydrological Flattening, Hydrological Enforcement and Hydrological Conditioning on the 1 m LiDAR DEM for the Middleton study area. The purpose of the processing is to prepare the data for subsequent hydrological modeling.

2. Conduct and compare Watershed Mapping completed on the 1 m LiDAR - derived DEM and a publicly available 20 m DEM for the same area.

3. Complete simple Flood Modeling on the 1 m DEM (No barriers), and 20 m DEM and compare the results of the output flood limit polygons.

All data processing and analysis was carried out ArcGIS 10.2.2 with the use of 9 pre-built processing models customized to assist automation of the various modeling steps. The models make use of key tools available in the ArcGIS Hydrology toolset. Presentation maps provided in the main body of the report and digital products accompanying the report were created in ArcGIS 10.2.2. A schematic outline illustrating the folder and file structure associated with the Hydrological Surface Modeling project data is provided in the Appendix, in additional to raw and reference metadata. All datasets used for analysis are in the NAD83 CSRS98 horizontal datum and projected using UTM zone 20. Elevation data are in CGVD 28 vertical datum.
Figure 1: Location of Middleton hydrological modeling project. Middleton LiDAR 1 m DEM superposed on satellite imagery. Reference world ocean and imagery basemaps accessed through ArcGIS online basemaps. 

*Geographic coordinate system - NAD83 CSRS, UTM zone 20.*
2.0 HYDROLOGICAL PROCESSING of LiDAR DEM

Digital elevation models, particularly high spatial accuracy, LiDAR-derived DEMs, cannot be directly used for hydrological modelling without prior processing of the data to remove features that impede or overly the drainage networks (e.g. roads, road fill, bridges). The DEM(s) involved in hydrologic surface modeling require processing to create a DEM that represents the actual water flow surface \(^2\). Three processing methods were conducted on the Middleton LiDAR-derived DEM to convert it to a Hydrologic DEM that would be used in subsequent watershed mapping and flood modeling. It is important to note that the resulting DEM is specific for hydrologic modeling purposes. Any derivative products from such a DEM (e.g. contours) will misrepresent the data due to the elevation modifications that have been enforced on the DEM.

Hydrologic Flattening was first applied to the 1 m DEM to flatten and level the Triangulated Irregular Network (TIN) modeled surface over lake bodies and the Annapolis River. The original modeled water surfaces have irregular elevation values mainly due to variable interaction of the incident laser beams with water (e.g. absorption, specular reflection). Two ArcGIS models (Flatten Lake, Flatten River; Figs. 2, 3) were applied to process the lakes and river surface and convert the existing irregular surface to a flat surface. In the case of lakes, flat and level surfaces are generated from the lowest elevation value extracted from the shoreline. Each lake is processed individually to ensure elevation differences present between lakes are preserved (Fig. 4). The flattened Annapolis River surface was created in a similar fashion to the lakes except an elevation gradient was modeled in the resulting surface, such that the new river DEM represents a flat interpolated surface between the highest and the lowest point on the river. Waterbody polygon reference data, representing the water features to be flattened, are used to extract elevation information to generate the new lake and river surfaces. The new water surfaces are then mosaicked into the original (parent) DEM to produce a Hydrologically Flattened DEM (MT_Ground_DEM_flat.img).

Hydrologic enforcement of LiDAR-derived DEM modifies elevations of artificial impediments to simulate how man-made drainage structures allow continuous downslope flow \(^2\). The ArcGIS model Remove Barriers (Fig. 5) was used to complete hydrologic enforcement of the Middleton LiDAR DEM. Priority road and drainage intersection points were initially identified as targets to conduct hydrologic enforcement. Polygons were digitized to link drainage networks on either side of man-made barriers that occur throughout the Middleton project area. These barriers were subsequently removed from the DEM by assigning a lower elevation value (e.g. 0 m) for the portion of the barrier overlying the drainage network (Fig. 6).

Hydrologic conditioning was the final processing step involved to convert the LiDAR-derived DEM to a Hydrologic DEM. Hydrologic conditioning involves defining un-drained depressions (sinks) in the elevation model and subsequently ‘filling’ it to a user-defined constant elevation level. The objective of hydrologic conditioning is to ensure that an inflow and outflow direction exists in the drainage network (Fig. 6).

The areas which change the most between the original and flattened DEM include the water bodies where the TIN interpolation surfaces were most noticeable. The Annapolis River and some of the larger lakes were most affected by the TIN interpolation problem and consequently show the most change (Fig. 4). The quality of the flattened DEM is limited by the accuracy of the reference water body polygon dataset, which in many cases does not faithfully reflect the shorelines as identified in the LiDAR dataset.
Figure 2: Custom model builder tool for hydrologically flattening lake surfaces.
**Figure 3**: Custom model builder tool for hydrologically flattening river surfaces.
Figure 4: Original and hydrologically flattened lake and river examples from the Middleton Project Area.
Figure 5: Model builder tool for barrier removal and creation of hydrologic enforced DEM prior to conditioning
Figure 6: Hydrologically enforced Middleton project area DEM with 3D visualizations of barriers removed from dataset. NOTE- DEM also conditioned. 3D visualization performed in ArcGlobe.
The result is a very abrupt change (and often inaccurate delineation of the shoreline) between the new flattened water surface and the surrounding terrain. A more gradational integration of the flattened water surface edge and the surrounding parent DEM would also yield a higher quality, seamless end product.

The procedures carried to process the LiDAR-derived DEM broadly adhere to those outlined in the USGS LiDAR Base Specification V 1.0. The hydrological flattening procedures carried out in this study meet the following requirements:

- **Water bodies of 8,000 m² (2 acres) or greater surface area at the time of collection shall be flattened.**
- **Flattened water bodies shall present a flat and level water surface**
- **The entire water-surface edge shall be at or below the immediately surrounding terrain**
- **Streams and rivers of a 30-m (100-ft) nominal width shall be flattened.**
- **Streams or rivers whose width varies above and below 30 meters will not be broken into multiple segments.**
- **Flattened streams and rivers shall present a flat and level water surface bank-to-bank**
- **Flattened streams and rivers shall present a gradient downhill water surface, following the immediately surrounding terrain.**
- **The entire water-surface edge shall be at or below the immediately surrounding terrain**
- **Stream channels shall break at culvert locations leaving the roadway over the culvert intact.**
- **Bridges in all their forms shall be removed from the DEM.**
- **Streams shall be continuous at bridge locations**

Similarly, the hydrologically enforced and conditioned DEMS produced in this study also follow the guidelines outlined in the USGS guide. Breaklines were created in the DEM to enable drainage systems to continue downslope flow through artificial impediments. Hydro-conditioning procedures also were consistent with the specifications are all sinks identified across the land and enforced water surfaces were filled.
3.0 WATERSHED MODELLING

Watershed mapping involves delineation of a region from which a drainage network will naturally flow to a single end point location (pour point) such as a lake, the ocean or a river system (e.g. Annapolis River in this study). The Watershed Model (Fig. 7) was used to map watershed extents in the Middleton study area using three different DEMs, including the 1 m LiDAR-derived DEM with and without barriers and the 20 m Geobase DEM with barriers removed.

The custom built watershed model involves preliminary water flow analysis using the Flow Direction and Flow Accumulation tools from the ESRI Hydrology toolset. The ‘Flow Direction’ tool uses the hydrologic DEM to generate a new raster showing the direction of flow out of each cell in the raster (Fig. 8). The Flow Accumulation tool calculates accumulated flow as the accumulated weight of all cells flowing into each downslope cell in the output raster $^3$ (Fig. 8). The flow accumulation image displays the number of cells that flow into each cell based on the flow direction dataset. Cells with a high flow accumulation are areas of concentrated flow and may be used to identify stream channels $^3$. Cells with a flow accumulation of 0 are local topographic highs and may be used to identify ridges $^3$. A review of the flow accumulation raster (Fig. 9) gives an indication of any barriers that remain in the hydrologic DEM. After inspection of this dataset, a watershed can be modeled using the watershed tool available in ArcGIS hydrology toolset. After creation of a single pour point at the lowest elevation on the Annapolis River, the watershed tool was ran on the three different DEMS outlined above. Note – the pour point location had to be moved further upstream for the 20 m Geobase DEM in order to successful run the watershed tool.

The results of the Flow Accumulation analysis (Fig. 9) indicate that neither the 1m LiDAR flattened nor the 20 m Geobase DEM reflect the true nature of waterflow in Middleton watershed area. The presence of artificial barriers in the flattened 1 m DEM causes the drainage to divert southwest once the creek systems encounter highway 1, which does not happen in reality. The 20 m DEM does allow some creeks to continue to flow downslope SSE towards the Annapolis River, but the coarse resolution of the DEM precludes identification of all stream systems that follow the same trajectory towards the river. The flow accumulation results in Figure 9 indicate that the 1 m hydrologically enforced LiDAR derived DEM represents the most realistic model of the three DEMs analysed in this study.

The final watershed maps presented in Figure 10a-c highlight several problems in all three models. The 1 m hydrologically enforced DEM represents the more realistic of the three, but is not without problems. The creeks to the east of the watershed (north east portion of Figure 10b) should also be incorporated into the watershed, however the truncation of the DEM on the east central side of the study area creates a discontinuity in the drainage system which isolates the northeastern creeks from the main watershed. This problem is inherent in all three models. Creating a more spatially continuous data would resolve this problem and generate a more accurate final product. The 1 m flattened DEM is inaccurate because it does not include creeks higher up the watershed as drainage is impeded by highway 1. Similarly, the 20 m Geobase DEM is also inaccurate because it does not preserve continuous water flow of all creeks north of highway 1.
Figure 7: Model builder tool for Watershed mapping

- **Input DEM**
- **Fill**
- **Filled DEM**
- **Flow Direction**
- **DEM Direction**
- **Flow Accumulation**
- ** DEM Accumulation**
- **Pour Points**
- **Snap Pour Point**
- **Pour Points Grid**
- **Watershed**
- **Output Watershed**

- Fill 'sink holes'
- Define the location in the watershed represents ultimate destination of all upstream drainage
- Calculate per cell flow direction
- Calculate per cell flow accumulation (cumulative addition of all cells upstream 'flowing' into the next adjacent cell downstream)
- Map watershed associated with defined pour point location
**Figure 8**: Schematic illustration of raster cell calculations associated with creation of FLOW DIRECTION and FLOW ACCUMULATION rasters. Modified after [http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#/How_Flow_Accumulation_works/009z00000062000000/](http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#/How_Flow_Accumulation_works/009z00000062000000/)
Figure 9: Flow Accumulation example of differences between flattened, enforced and Geobase DEM
Figure 10: Watershed mapping results for (a) 1m LiDAR flattened, (b) 1m LiDAR hydrologically enforced and (c) 20 m Geobase DEMs for Middleton project area.
4.0 FLOOD MODELLING

Simple flood modeling using the Flood to Level and Flood by Increment tools (Fig. 11) was conducted on both the Geobase 20 m DEM and the LiDAR 1m Hydrologic DEM (barriers removed). Three different flood levels were modeled; 12, 14 and 16 m, respectively. The method involves selecting all DEM cells below a certain cut-off elevation level (flood masking) and then removing any of this selection that is disconnected from the main river system by completing a spatial join to link the pour point locality to the main flood polygon. The results for the 20 m geobase and 1m hydrologically enforced LiDAR-derived DEM are presented in Figures, 12 and 13, respectively.

The 1 m LiDAR DEM produces the more realistic flood extents model of the DEMs processed. The greatest difference between the two modeling datasets exists in the 12 m flood extent model where the Geobase DEM grossly underestimates the 12 m flood extent, restricting it to a confined area near the pour point defined for that DEM. In contrast, the greater spatial accuracy of the 1 m LiDAR DEM allows for a more reliable model of the 12 m flood extent. Figures 12 and 13 illustrates how the 12 m flood levels cover a much greater area in the 1 m DEM compared to the 20 m DEM. The 14 and 16 m flood extents are somewhat improved in the 20 m DEM, however, they fail to replicate how flooding progresses upstream into north-trending drainages feeding into the Annapolis River. The problems inherent in the Geobase DEM flood models center on the lower spatial accuracy of the data set. The large pixel size forces unnatural, angular geometries to the flood margins to be created.

A final model comparison was made between the original unflattened vs. flattened LiDAR DEM for the same flood intervals 12, 14 and 16 m. No differences were observed between the two models for the 14 and 16 m intervals. The main difference occurred in the 12 m model where the presence of the bridge over the Annapolis River resulted in termination of the 12 m flood extents model (Fig. 14).
Figure 11: Model builder tool for incremental flood modeling
Figure 13: 12, 14 and 16m modeled flood levels derived from hydrologically enforced 1m LiDAR DEM.
Figure 12: 12, 14 and 16m modeled flood levels derived from 20 m Geobase DEM.
Figure 13: Unflattened and flattened 1m LiDAR derived DEM, 12 m flood extents comparison
5.0 MODEL BUILDER – HYDROLOGY TOOLSET

The custom models built for processing and carrying out preliminary surface hydrological modeling of the Middleton LiDAR DEM were highly effective in expediting what would otherwise me a tedious process. Improvements could be made to the Flatten Lake model to allow batch processing by allowing unique intermediary data names in the model. This would allow the user to load all individual lakes and set the model to process all lakes in one round of processing. Currently the Flatten Lakes model forces an overwrite of intermediary dataset names (e.g. extract by mask - extract_img1) which causes incorrect results when batch processing. Also, the use of the Split tool will automate the procedure to extract lakes into individual files for subsequent loading into the Flatten Lake Model.

The use of buffer and intersect tools may also help automate polygon creation associated with linking drainages across artificial impediments (roads, bridges). A buffer of fixed width could be applied to the creeks and the output could be intersected with the road_bridge reference vector file to isolated relevant parts of the creek buffer.

References

APPENDIX

i) LiDAR Raw & Reference Data
ii) Product Listing
**Middleton Project Metadata**

Note – All data uses UTM zone 20 NAD83 CSRS98 (horizontal datum) and CGVD28 for a vertical datum

**LIDAR data - Raw**

The LiDAR data encompassing the Middleton study area from the DEM was created to carry out the hydrology analysis in this report represents a portion of a large NW – SE oriented transect carried out by the Applied Geomatics Research Group (AGRG). Data acquisition took place on 18th of August, 2010. Data was acquired at a flying altitude of 1200 m at a pulse rate frequency of 70 kHz and a scan angle of 18°. The approximate resolution of the point data is 0.829 m. The data are in NAD 83 CSRS 98, UTM zone 20. Flight lines were oriented NW – SE and cover. The approximate area of the study area was 8 x 5 km. Output data were delivered as strips in LAS format. Survey metadata can be accessed via: [http://agrg.cogs.nscc.ca/projects/LiDAR_Metadata](http://agrg.cogs.nscc.ca/projects/LiDAR_Metadata).

**LIDAR data - DEM**

The LiDAR DEM provided with this lab was derived the LiDAR survey described above by. The DEM was produced from ground points using 1 m TIN interpolation and have been transformed into orthometric heights (CGVD28).

**GEOBASE data - DEM**

The GEOBASE DEM used in this study represents part of the GeoBase Digital Elevation data (http://novascotia.ca/natr/meb/download/dp055.asp). The data are hydrologically corrected and generated at a resolution of 20 m. The data has been trimmed to cover the Middleton study area.

**AirPhoto - Mosaic**

Air photo data was acquired concurrently with LiDAR data during the 2010 survey. The data were mosaicked and orthorectified and resampled to 0.5 m. The image has a spatial reference of NAD83 CSRS UTM zone 20. The LiDAR system used to acquire the data consists of an integrated Applanix POS-AV 510, ALTM 3100 and Rollei digital camera.

**Hydrology Vector Data**

The hydrological vectors (streams, rivers & lakes) were extracted from the Nova Scotia Geomatics Centre (NSGC) Base Data (1:10,000 scale). These vectors were derived from 1:40,000 scale aerial photography (from 1987 to 1997) through photo interpretation.

**Road Vector Data**

PRODUCT LISTING & DATA STORAGE STRUCTURE INFORMATION

Main Folder

HYDROLOGICAL REPORT.pdf

Subfolders

DEM

MT_Ground_DEM_flat.img
MT_Ground_DEM_no_barriers.img

WATERSHED

MT_Ground_DEM_ws.img
MT_Ground_DEM_nb_ws.img
Geobase_NS_DEM_was.img

FLOOD

Geobase_NS_flood.shp
MT_Ground_NS_flood.shp

Hydrologically Flattened, Enforced & Conditioned DEMS

Watershed Maps

12 m Flood Models