Three Dimensional Flood Modeling with High Resolution LIDAR

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Abstract

Airborne LIDAR systems obtain high resolution elevation data that can be processed to produce accurate topographic representations. The sensor emits laser pulses toward the surface and records the time difference between the contact with the surface and the return after reflection. A high precision global positioning system (GPS) and an inertial measurement unit (IMU) are used to determine the location and orientation of the aircraft so that the ground location of the return laser pulse can be accurately determined. This project used LIDAR technology to produce three dimensional representations of the landscape and to provide accurate hydrological dimensional digital elevation models (DEM) to perform accurate flood risk modeling.

Water levels from a January 2000 storm, that caused significant coastal flooding, were used to construct flood maps. Sea level increases of 50 and 70 cm per century were also modeled to show the potential impacts of such a storm in 100 years of expected sea level rise. In addition to the flood risk maps depicting areas that would by inundated, flood depth maps and continuous flood risk maps were also generated.

The study area was located along the coastal area of south-eastern New Brunswick from Kouchibouguac National Park south to Jourimain Island and included areas of highest scientific interest and significant priority. This project covered six of ten study areas that were surveyed in May-June, 2003 and contained 40 tiles of LIDAR data, covered about 165,500 square kilometres and contained over 45 million points.

Keywords

LIDAR, validation, digital elevation model (DEM), digital surface model (DSM), flood modeling

1. Introduction

This paper and presentation summarizes an extensive graduate technical report that detailed the methodologies and issues involved with mapping areas at risk to coastal flooding from storm surge events. Data acquired from an airborne LIDAR sensor was used to interpolate DEMs of the coastal topography and to accurately model flooding events for selected areas in southeast New Brunswick in support of the Climate Change Action Fund (CCAF) Project A591. The aim of the CCAF project was to collaborate together and generate accurate maps and information that could quantify the future impacts of climate change, sea level rise, storm surge events and coastal erosion in support of sustainable management and the development of adaptation strategies.

1.1 Study Area

The study area consisted of the coastal Gulf Shore region of south-eastern New Brunswick and comprised the areas of highest scientific interest and significant priority for governments and coastal stakeholders. Four of the ten study areas had to be excluded from this graduate portion of the project due to technical difficulties that Terra Remote Sensing experienced with their LIDAR Mark II system.

1.2 Sea Level Rise

Coastal sensitivity to sea level rise has become a major issue in Canada and a nation wide overview published by the Geological Survey of Canada (Shaw, 1998) demonstrated that there are low, moderate, and high sensitivity regions. Some of the most severely threatened coastal areas and high sensitivity regions in Canada are parts of the Atlantic Coast, including most sections of south-eastern New Brunswick. Factors contributing to this include soft sandstone bedrock, a sandy and dynamic shore zone, an indented shoreline with extensive salt marsh, low terrain behind the shore with significant flooding potential, documented high rates of shore retreat, and ongoing submergence of the coast (Webster et al., 2003).

Impacts of sea level rise vary from location to location and often lead to many physical changes to the coastal environment. These changes, in turn, affect human and wildlife uses of the coast such as settlement, tourism, fishing, and agriculture. The most serious physical impacts of sea level rise on coastal zones are inundation and displacement of wetlands and lowlands, coastal erosion, increased vulnerability to coastal storm damage and flooding, and salinization of surface water and ground water.

1.3 Storm Surges

The change in sea level produced by strong winds and low atmospheric pressures that cause coastal waters to flood inland regions are known as a storm surge event. Storm surges are extremely powerful when they coincide during peaks of high tides and can cause extensive coastal flooding. Unlike the tides, storm surges are hard to predict in advance because weather conditions change on a regular basis, and are often only accurately forecast up to a few days in advance.

The predicted tidal height plus the surge are used to determine if a flooding event is likely to occur. Changes in sea level generated by extreme meteorological events, such as winter storms and hurricanes, can cause extensive flooding and massive damage to coastal features, and could occur more frequently as the climate changes and sea level continues to rise. Thus, predicting the timing of storm surges relative to tides is an important goal of meteorologists.

Many areas in Atlantic Canada on January 21, 2000 experienced severe impacts at numerous coastal locations due to a storm surge event. With a minimum central pressure of 94.5 kPa at 1800 UTC 110 km south southeast of Halifax, the storm passed 55 km east of Charlottetown at 0000 UTC and then north across the Gulf of St. Lawrence. Coincidence of a 1.2 m storm surge with perigean high tides intensified the impact of the storm at many sites (Environment Canada Website, 2002) including the Point-du-Chene area of New Brunswick shown in figure 1.

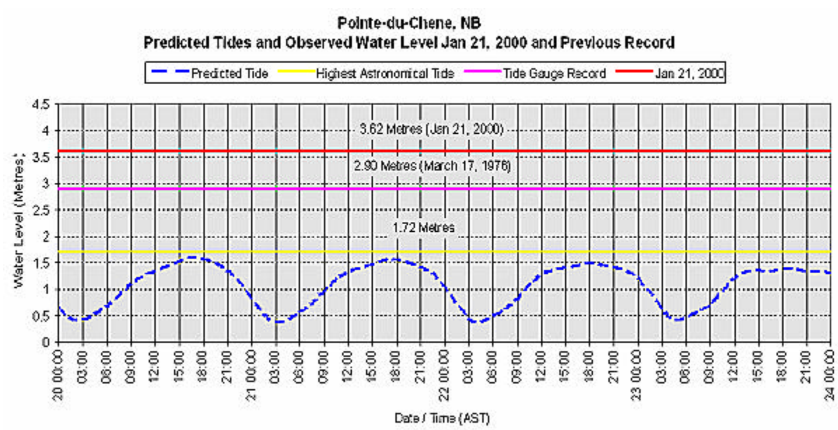

Figure 1This graph from a tide gauge on the Pointe-du-Chene, NB wharf demonstrates the large difference in predicted tides and the observed water level experienced during the January 21, 2000 storm surge event. The blue line represents the predicted water level and the red line represents the storm surge water level (Image: D. Forbes).

1.4 Airborne LIDAR

An airborne LIDAR system was used to obtain high resolution elevation data that was processed to represent the topography, and was perfect for predicting areas that are at risk to coastal flooding associated with sea level rise and storm surge events.

The LIDAR system combines a single narrow-beam near-infrared laser with a high tech receiver system. The laser emits a pulse that is transmitted towards the surface, reflected off an object, and returned to the receiver. The laser scan is acquired by rapid repetition of the laser pulse transmitter and cross track zigzag pattern of laser hits on exposed surfaces below the aircraft (Krabill and Martin, 1987). The receiver accurately measures the travel time of the pulse from its origin to its return. The laser pulse is travelling at the speed of light, and since the speed of light is known (and assumed constant); the travel time can be converted to a range measurement.

Combining the laser range, scan angle, position from GPS, and orientation of the aircraft (pitch, yaw, and roll) from an IMU, accurate ground coordinates can be calculated for each laser pulse. When combined into one system, they allow the positioning of the footprint of the laser beam as it hits an object, to a high degree of precision. As advancements in commercially available GPS and IMU occur, it is becoming possible to obtain a high degree of accuracy using LIDAR from moving platforms such as an aircraft.

Typically LIDAR data contains a series of point measurements that consists of geographic location and height of both natural and man-made features above the ellipsoid, and can be further processed to produce several different products. The point data can be separated into two types, a file containing only points that interact with the ground surface and a file that contains all of the rest of the points (known as non-ground points).

This separation of data allowed for the construction of a "bald earth" DEM with all forest, vegetation and other non-ground features removed, providing a true ground representation of the surface. Traditional DEMs are typically derived from photogrammetry, and do not have the vertical accuracy or resolution suitable for most scales of regional flood risk mapping. Good flood simulation must be modeled on a surface that best represents the actual ground elevation.

The LIDAR data for this project was collected by Terra Remote Sensing during the spring of 2003 and 2004. Their sensor was a first return sensor (Mark-I) with a diode pumped scanning laser operating in a wavelength of 1047 nanometres, and had a swath scan of 56 degrees. Its pulse repetition frequency was typically up to 10 kHz and resulted in relative accuracies in the horizontal and vertical axes at normal flying altitudes of up to 30 cm depending on the nature of the ground cover.

The data arrived in the form of ASCII text files and each file contained the following information: GPS week, GPS time, flight line number, easting, northing, and ellipsoidal height. The reference system of the data was WGS 84, Projection: UTM Zone 20 N, and with ground spacing (XY) of 0.6 meters in open areas. The relative accuracy was approximately ± 0.15 meters and the absolute accuracy was ± 0.3 meters. The high accuracy and high data point density achieved by LIDAR improves the accuracy of flood hazard mapping (Christian, 2001).

Man-influenced changes to the ground surface were represented in the ground only data if they were judged to be of a permanent nature. As an example, the earthen land forms that made up an approach ramp on a highway were captured while the actual overpass bridgework was not. A bridge that spanned a river/stream was not classified as ground but an earthen structure with a culvert that crosses a river was classified as ground.

Because the LIDAR was used for flood modeling, it was decided that having wharfs and piers should be included with the ground layer since this layer would be used to model the flood data. The vendor had already separated these features out along with other man-made features, thus the point coverages had to be edited and points representing wharfs and break water structures had to be moved into the ground coverages prior to a proper DEM being built and used to map flood risk.

2. GPS Validation Survey

Differential carrier phase GPS data, known to provide accurate orthometric heights was used to validate the accuracy of the airborne LIDAR data. An extensive high-precision GPS survey of the study areas took place in May of 2004 and coincided with the LIDAR survey to ensure that exact conditions at the time of LIDAR survey were measured. The timing was crucial for features such as the heights of vegetation and coastal features such as sand dunes. An important step in ensuring accurate representation of the topography involved comparing the processed data with ground validation points positioned to a higher accuracy than the LIDAR.

The accepted tolerance level for the vertical accuracy of the LIDAR data provided by Terra Remote Sensing was set at +/-30 cm, so it was important that the GPS validation data have a higher accuracy. A Leica real time kinematic (RTK) GPS system was used to provide sub decimetre accuracy and save time by avoiding any post processing of the data. The system was made up of two GPS receivers; one was setup (base station) over a survey monument from a high precision network (HPN) with known published coordinates and the second was a mobile receiver that collected unknown points. The base station was used to process the GPS data that it received from satellites and then sent corrections to the rover unit via a high frequency radio signal. This trigonometric GPS setup provided precise orthometric measurements up to 2 cm with ideal conditions.

Two different setups were used to collect the GPS data; a RTK setup on a 2 m pole and a RTK unit setup on top of a moving vehicle. The vehicle setup was used to provide GPS data of hard surface features, including roads and parking lots. This method of GPS data collection provided a means of gathering precise measurements over a larger coverage area. The pole setup was used to provide GPS measurements where a vehicle could not get access to (coastal dunes, wharf edges, etc.).

The WGS84 ellipsoid, a smooth mathematical surface representing the earth, is used as the reference datum with GPS navigation. Elevations found on most topographic maps are measured to a vertical datum based on the geoid (in Canada known as CGVD28). To relate the height measurements to proper sea level, an adjustment had to be made for the local vertical separation between the ellipsoid and the geoid. This adjustment was done using the HT1-01 model provided by the geodetic survey of Canada, Natural Resources Canada.

3. LIDAR Processing

The LIDAR which was separated into ground files and non-ground files was extremely large, covered 165, 500 square kilometres and contained over 45 million points, therefore the data was divided into smaller tiles that made the data easier to manage.

Importing of the ASCII LIDAR data was accomplished using ESRI ArcINFO software. Point coverages were created using automated procedures developed in an Arc Macro Language (AML). The scripts generated ground-only and non-ground spatially referenced point coverages for each LIDAR tile.

ArcINFO contains several different methods suitable for creating grid cell based surface representations from point coverage data. After several visual examinations of the surface models derived from the LIDAR points, and considering all available resources, it was determined that the best representation of a true ground DEM surface was using the ESRI triangular irregular network (TIN) method based on the orthometric height with a quintic interpolation (MacKinnon, 2003).

The TIN method, which is a topological data model, interpolated a continuous surface using all of the available points. The mass points consisting of X, Y and Z values become nodes and triangle facets are constructed between them. The output created a rectangle area and areas with no data from outside the zone of interpolation were represented by a null value also known as a convex hull.

The TIN was then transformed into a lattice grid using a quintic interpolation with a 1 m pixel resolution. A lattice is a surface interpolation of a grid, represented by equally spaced sample points referenced to a common and a constant sampling distance in the X and Y direction. Each mesh point contains the Z value of that location. Surface Z values of locations between lattice mesh points were approximated by interpolation between adjacent mesh points. The quintic method provided a smoother surface than the linear method, and was used to create ground surface DEMs. A linear interpolation method was used with the non-ground hits to create the digital surface models (DSM) because it was known to better interpolate sharp corners (such as buildings).

Each individual LIDAR raster grid was then mosaicked together to provide larger continuous surface models for each study area and the erroneous surface values were clipped to avoid areas of no data. Combining both the ground and the non-ground grids together resulted with an all-hits grid, better known as a digital surface model (DSM). A DSM is an actual surface representation that included all of the possible LIDAR points. Features such as fields and clear cuts were easily distinguished with the DSMs.

4. Color Shaded Relief Models

Geomatica image software was used to visualize and create 3D models of the DEMs and DSMs. The grids were imported and color coded using chromo stereoscopic techniques, illuminated to create a shading effect, and then combined to produce a Color Shaded Relief Model (CSR).

Shaded relief models were produced to give the images a texture look by making the slopes facing the user-specified light source (315, 45) appear bright and those facing away appear dark. The shaded grey level at a point was calculated from the cosine of the angle between the normal vector to the surface (slope and aspect) and the direction of illumination. All surfaces that were not illuminated by the light source were set to zero. An elevation exaggeration of 5 was applied to enhance the 3D of the surface.

Custom pseudo color tables (PCT) were then derived with colors that ranged from blue (representing low elevations) to green, to yellow, and to red (representing high elevations). The PCT was then fused together with the shaded relief model to create a color shaded relief model. This gave the surface a more pleasing visual appearance and made it easier to depict the elevations of the image.

5. LIDAR Validations

The LIDAR points and the interpolated surface models were all validated to ensure that the quality of the data was acceptable and that the vendor maintained the accuracy that was specified in the initial contract. This was done utilizing several methods. A visual process involved checking each DEM for artifacts and other processing errors. A second validation method involved comparing the GPS to proximal LIDAR points. A two meter search radius was applied to the GPS points and the LIDAR points from within this buffer region was selected and compared with the GPS orthometric heights. The points were evaluated and validated individually before being used to generate any surface models. Because all the LIDAR data was acquired at once then later separated into two types, it was necessary to examine the separation provided by the vendor since this is often problematic in LIDAR data. A third validation method involved comparing the GPS points with the surface derived from the LIDAR data to identify any key problems such as missing data or any artifacts that were present within the data. Statistics for the errors encountered were generated and summarized to ensure the vendor's data met all specifications.

The GPS elevations were converted from ellipsoid heights to orthometric heights using the HT1_01E geoid/ellipsoid separation model so that comparison could be done between the GPS orthometric heights and the LIDAR-derived DEM ground surface orthometric heights. The GPS points were overlaid upon the DEM surface in a GIS and the orthometric height difference was calculated between GPS and the LIDAR surface.

The orthometric heights for the LIDAR DEM and the GPS measurements were used to calculate the difference and the absolute difference in elevation for each point. The mean was calculated from the average of difference values, and the magnitude of deviation was calculated from the average of all the absolute difference values. Standard deviation was calculated with the difference values and the average magnitude was calculated from the difference values. A root mean square was calculated from the square root of the average of all the difference values.

Histograms were graphed from the results that plotted the difference in orthometric heights with the frequency of points. Ideal histograms had bell shaped curves centered on the X axis. If all graphs were off by a similar amount, it would have indicated that there was a problem with the LIDAR or the validation data. The 2000 AGRG LIDAR study in Charlottetown, PEI had a systematic vertical bias problem. During the validation, it was determined that the DEM was 0.9 m too low, therefore the DEMs were adjusted by adding a value of 0.9 m to raise the entire surface (Webster et al., 2004).

Scatter plots compared the height difference between the LIDAR DEM and the GPS with the Distance from the GPS point for each file plotted. The expected result for this style of graph was that there should be a larger variance with the results the further you go away from the GPS point. In other words, the tighter the formation of points the more accurate the data was.

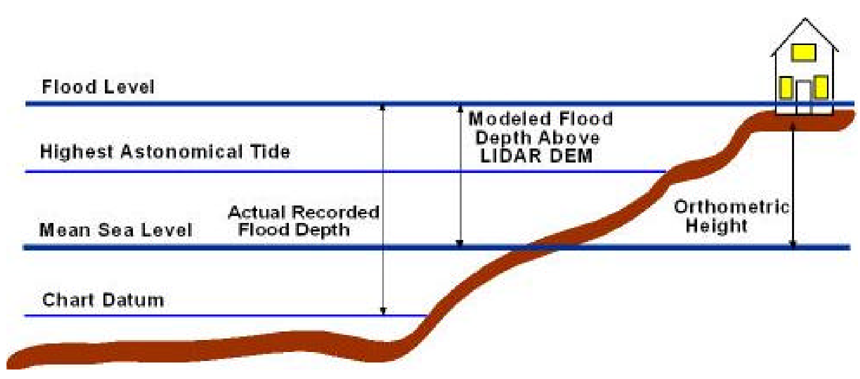

Figure 2 The flood levels provided for this project had to be converted from heights above chart datum to orthometric height so that the flood levels modeled would be consistent with the orthometric heights of the digital surface models.

6. Flood Simulations

Water level data resulting from existing storm surge events and predicted events with respect to height above chart datum (figure 2) was used to simulate the flood data. Chart datum was locally defined as the vertical reference that represented the lowest water level at lowest tide. The three water levels used in the modeling scenarios were: 3.6 m, 4.1 m, and 4.3 m above chart datum. The first level was actually observed during the January 21, 2000, storm surge event, in which significant coastal flooding occurred. The 4.1 m level represented the January storm event plus a 100 year predicted 50 cm relative sea level rise. This represented a moderate case scenario for 100 years of relative sea level rise. The 4.3 m level represented the January storm event plus a 100 year predicted 70 cm relative sea level rise. This represented an extreme case scenario for 100 years of relative local sea level rise. These flood levels were converted to heights above geodetic datum because the LIDAR surface represented orthometric heights above the geodetic datum.

Flood modeling of the three defined flood levels were done on the ground only DEM because it best represented a true earth surface. Using the ground only LIDAR "bald earth" DEM allowed modeling of accurate flood limits that incorporated hydrological features that most DEMs did not include. The ground only LIDAR had all vegetation removed and clearly distinguished features of stream channels and other features in detail that traditional DEMs could not.

It was assumed that a storm surge affected all parts of the DEM that contained a direct connection to coastal waters. Flood extents maps, flood depth raster surfaces and flood risk raster surfaces were generated and, when combined, provided a valuable tool for supplying information for strategic planning that will help prevent future damage.

6.1 Flood Extent

Flood extent map layers define how far a given water level will extend inland. These layers were derived mathematically using the orthometric heights of the ground only DEM, by separating the DEM into regions below the flood level and regions above the flood level. This procedure was done using conditional statements in the ArcINFO GRID environment, which would compute new raster grid values defining all regions that would be flooded by the flood level and all regions not affected. The method selected all values that were below the flood level including low lying areas inland that were not connected to the water source and did not address the connectivity issue of flood modeling. Manually editing for connectivity to the flooding source was necessary because this flood modelling method did not incorporate connectivity issues. Computed flooded areas that were not connected to the ocean and did not have a visible culvert from topographic map data were changed from a value being flooded to a value not being flooded.

6.2 Flood Depth

When assessing the damage and severity of a flood, it was important to know the depth of the flood water as well as how far it extended. Flood depth grids were generated mathematically from the ground only DEMs, by starting with the flood water level and the LIDAR ground only DEM; adjusting the zero value of the DEM to the flood water level so that the new grid would have the flood level represented by zero and flood depths would become positive values.

Flood extent levels were used to clip the flood depth raster to ensure that only flood depth values existed for areas that were within the flood extents. A final flood depth GRID represented only depth values that lied within the flood extent after the connectivity was edited. Risk grids were generated by reclassifying the depth grid values together into groups that represented areas with 1m of water, areas with 2m of water and so on. This was very useful for quickly identifying depth of flooding. The flood layers were then integrated with topographic data and orthophotos to determine the amount of damage that would have occurred.

6.3 Flood Animation

Three dimensional animation sequences were created to help envision how the flood would encompass the study areas. Animation is a valuable tool for helping people quickly visualize how serious a flood can be to a region. To be most effective, the animated sequence had to be able to show ample detail, thus it was better to be zoomed in on an area while demonstrating the flood.

The animation processing was accomplished with both PCI Geomatica and Jasc Animation Studio software packages. Scripts were written to aid with the creation of flood images and perspective views were created to show a unique 3D visualization of the regions. Each flood level was then modeled similar to the process that was used to generate binary image flood extent images where the DEM would be either flooded or not flooded. The flood images were coloured blue to represent water and modeled together with color shaded relief images. Images were created at 10 cm increments and weaved together to represent a gradual increase in water level up to the January 2000 storm surge flood level. The output animation clearly demonstrated the effects that the storm surge had as it increased from sea level up to the flood level which figure 3 clearly illustrates. This flood tool was extremely valuable because it helped visualize (in a 3D environment) the area that the flood maps were actually depicting.

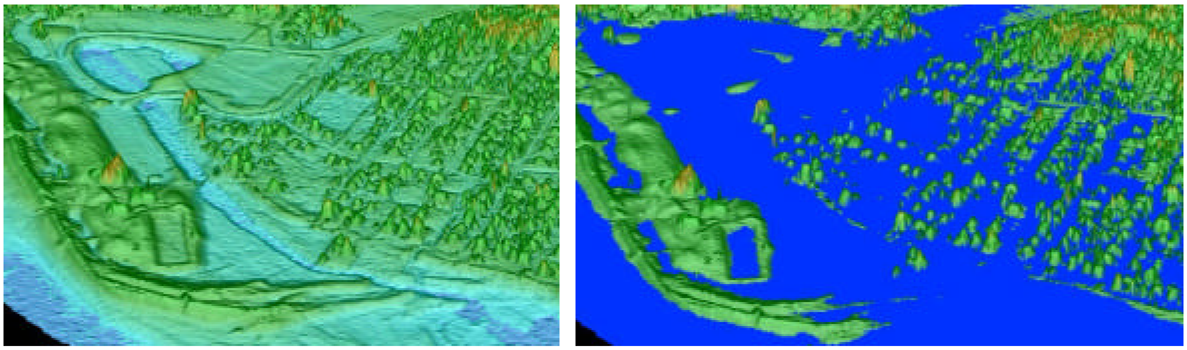

Figure 3 These images are two single frames from one of the animation sequences; the image on the left is a three dimensional view at mean sea level (0 m), and the image on the right demonstrates the severity that the January 2000 flood (3.6 m CD).

7. Results

Validation of the data revealed that the LIDAR was within the accuracy specifications in both vertical and horizontal values. The validation of the LIDAR points resulted in a standard deviation of ? z between 9 and 10 cm, and an average mean between 12.5 and 34 cm. The mean ? z value of 34 cm was from the Cormierville study area and the value was carefully examined and it was determined that the relatively higher error value was a result of some minor GPS data collection errors (MacKinnon, 2004).

Validation of the LIDAR surfaces produced a standard deviation of between 10 and 13 cm and a mean ? z of 3 to 20 cm for all of the study areas. The mean value of 20 cm was once again from the Cormierville study area. The result of this area having the more significant error value was again related to the error propagated with the GPS field survey and not the actual LIDAR data (MacKinnon, 2004).

More precise editing would be required to determine if all reasonable topography had been properly identified. It was possible that some ground data could have been unclassified due to the LIDAR density and the practical impossibility of addressing each hit. A well-classed file would have a DEM that described sufficiently the finer relief across the study area. Thus, heavy vegetated areas that were known to impair laser penetration, limiting the ability to determine subtle relief characteristics in sub-canopy conditions, would require more study to ensure that they indeed were represented well.

Maps of the Flooding results were produced and brought to show residents of the study areas during the spring of 2004 to ensure that the extent and flood depth representations actually represented the flood levels that the area had experienced during the January 2000 storm. The majority of the individuals that responded agreed that the modeled flood level maps were correct and that indeed the simulated flood was an adequate representation of the storm surge event that happened.

The connectivity issue of the flood models required accurate information to determine if an area was flooded or not. The topographic data that was provided by Service New Brunswick could not provide sufficient data for all areas, thus there were perhaps areas in the flood extent areas that could be better refined. Using a GPS to locate all culverts and relevant structures would be a more reliable source of obtaining information to help ensure the model was more accurate.

8. Conclusions

This study has summarized the methodologies that were involved from the geomatics based approach that involved the production of simulated flood products using high resolution LIDAR data. LIDAR technology and these methods has the potential to become a fundamental tool in coastal studies, comparable to established techniques such as aerial photogrammetry and ground surveys (Webster et al., 2004).

Detailed ground validation of the resulting DEM is essential to ensure that the LIDAR data meets adequate specifications in vertical and horizontal accuracy and precision to enable reliable mapping. Proper validation and communication with vendors is essential to ensure that the data is of the highest quality.

Airborne topographic mapping of flood limits through the use of LIDAR derived high resolution DEMs can provide an efficient method for defining flood risk hazard zones as a basis for precautionary planning climate change adaptation and emergency response measures. Careful validation of the LIDAR data in relation to orthometric elevations enabled simulated flooding of the DEM of the observed water level from the January 2000 storm surge event and two higher estimated flood levels.

These methods, although highly accurate in creating flood maps, were based solely on ideal conditions and should not be taken as absolute maps but guides; features such as wind speed and temporary obstacles such as snow banks have not been included into the scenarios and would definitely affect the outcome of flooding. Accurate locations of culverts are needed to ensure that the connectivity issue is accurately represented. The AGRG in conjunction with an AIF project are currently developing software that will incorporate such variables of a coastal storm surge flood.

In summary, this project has demonstrated the effectiveness and varied utility of LIDAR for the analysis of storm surge flooding in coastal regions. LIDAR is already becoming a main staple in the Geomatics industry and is clearly a valuable tool in flood mapping, and will continue to get better as data acquisition and processing technology advances. The full LIDAR project report that this paper has summarized can be obtained at http://tmackinnon.com.

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