USING AIRBORNE LIDAR TO MAP EXPOSURE OF COASTAL AREAS IN MARITIME CANADA TO FLOODING FROM STORM-SURGE EVENTS: A REVIEW OF RECENT EXPERIENCE

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ABSTRACT

Much of the coast in the Canadian Maritimes is susceptible to erosion and flooding from storm-surge events and long-term sea-level rise. In recent years significant damage has occurred during storms in both urban and rural areas of the region. LiDAR technology has been employed to develop high-resolution digital elevation models (DEMs) as a basis for production of flood-risk maps. These are required by coastal zone managers and emergency measures officials to plan for the future. This paper presents a summary of the LiDAR surveys conducted in the region to date and reviews the conclusions on exposure to flooding in each area. Although most of the areas considered lie above mean sea level, some areas are dyked and lie below mean sea level. These areas are assessed in terms of their susceptible to flooding by a storm surge overtopping or breaching the dykes.

Keywords: LiDAR, coastal hazards, flooding, storm surge, digital elevation models, digital surface models

1 INTRODUCTION

The coastline of Canada has been assessed for sensitivity to sea-level rise and many areas of the Maritimes were determined to be highly susceptible (Shaw et al., 1998). Projections of accelerated sea-level rise in the Third Assessment of the Intergovernmental Panel on Climate Change (IPCC) indicate an increase in global mean sea level from 1990 to 2100 between 0.09 m and 0.88 m with a central value 0.48 m (Church et al., 2001). The high sensitivity to sea level rise and projections of more rapid relative sea-level rise in future led to the initiation of several studies to develop detailed maps of storm-surge flood risk in coastal communities.

Relative sea-level rise at any one place is a combination of changes in regional sea-level and vertical ground motion. Subsidence in many coastal areas results in more rapid relative sea-level rise. This is of particular importance in Maritime Canada where postglacial isostatic adjustments are ongoing (Grant, 1980; Forbes and Manson, 2002). Superimposed on sea-level rise, coastal erosion and flooding associated with large waves and runup at high storm-surge water levels pose additional threats. A storm-surge is defined as the difference between observed water level and the level predicted for the astronomical tide. Storm surges are caused by high winds and atmospheric low pressure systems associated with storms (Parkes et al., 1997). Because storm-surges are typically up to 2 m in height for this region, technologies with vertical precision significantly finer than these values must be employed to generate terrain models of sufficient precision and resolution. Airborne LiDAR (Light Detection and Ranging) altimetry is a technology that offers the vertical precision and high spatial detail required for this purpose.

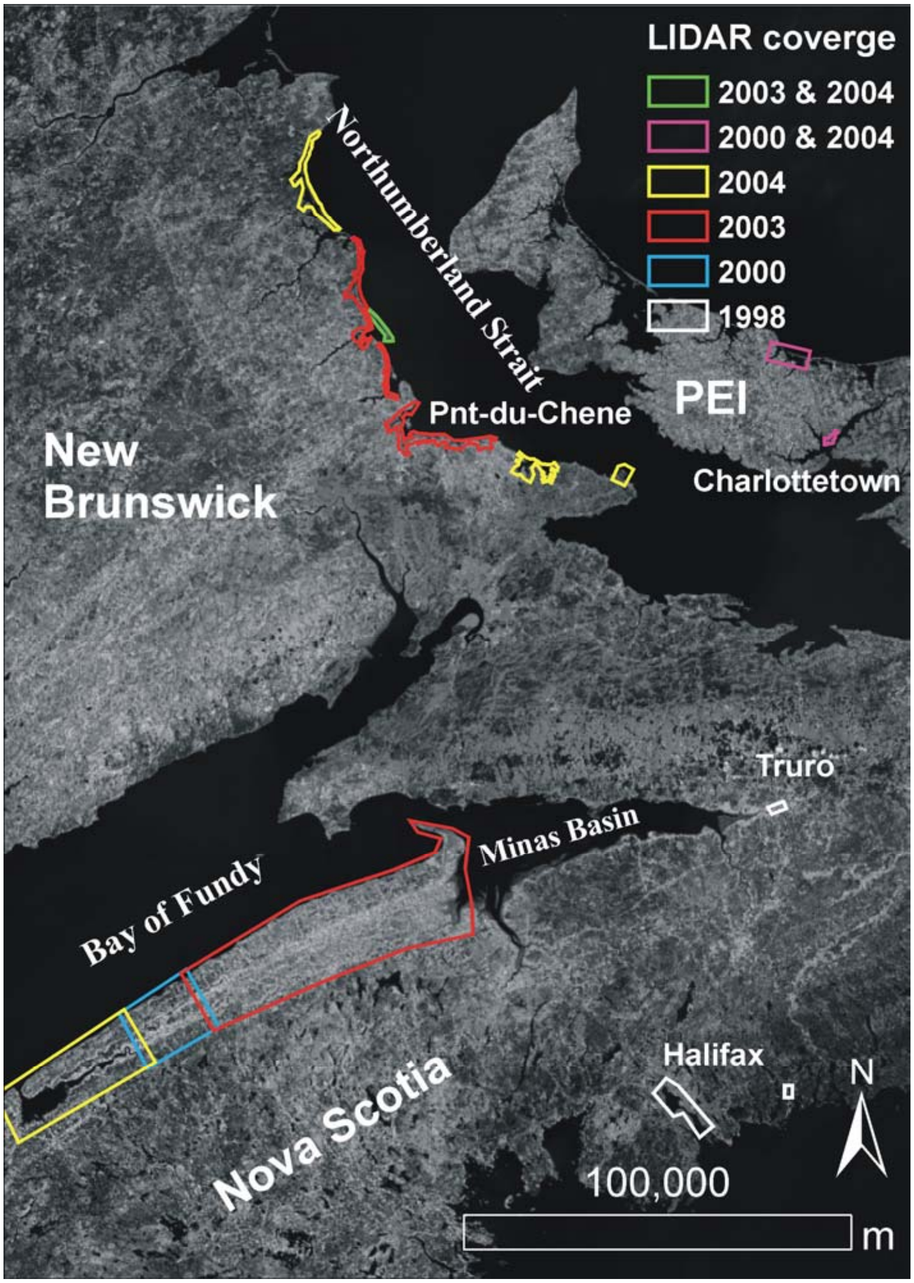

Figure 1. Greyscale Landsat mosaic of Maritime Canada with LiDAR survey polygons colour-coded by acquisition date since 1998.

Applications to coastal process studies in the USA have been reported by Sallenger et al. (1999), Krabill et al. (1999), and Brock et al. (2002), among others. Preliminary trials in Atlantic Canada were reported by O'Reilly (2000) and subsequent experience was described by Webster et al. (2002, 2004a, b), O'Reilly et al. (2005), Webster and Forbes (*in press*), and Webster et al. (2005, *in review*).

LiDAR surveys of coastal areas in the Maritimes were first conducted in 1998 (Fig. 1). In 2000, LiDAR technology was applied to storm-surge flood-risk mapping in Prince Edward Island (PEI) (McCulloch et al., 2002; Forbes and Manson, 2002; Forbes, Shaw, and Manson, 2002; Webster et al., 2002, 2003, 2004a; Webster and Forbes, *in press*). LiDAR surveys were conducted in the summer of 2000 for PEI and the Annapolis Valley of Nova Scotia (Figure 1). Flood-risk mapping was carried out for the low-lying areas in Minas Basin in the Bay of Fundy and reported by Webster et al. (2004b). Following from the PEI study, another project was undertaken to map flood risk along a large portion of the coastline in southeast New Brunswick (Fig. 1). LiDAR surveys for this project were conducted in April 2003 and April 2004 (Webster et al., *in review*). The Annapolis valley and sections of PEI near the City of Charlottetown and part of the North Shore were re-surveyed in 2004 to validate adjustments applied to the previous LiDAR surveys (see Webster, *in press*; Webster and Dias, *in press*; Webster and Forbes, *in press*). The LiDAR sensor employed in 2004 was capable of recording the intensity of the reflected laser pulse and has been used with height information to successfully map land cover and variations in inter-tidal sediments (Brennan and Webster, *in review*).

Recently, the Applied Geomatics Research Group (AGRG) of the Nova Scotia Community College acquired airborne topographic and ground-based LiDAR systems. One of the proposed areas of research using this new equipment is to map changes in coastal morphology following storm events (cf. Forbes et al., 2004).

The various areas surveyed with LiDAR in the Maritime Provinces show varying susceptibility to coastal flooding and erosion. This paper describes the areas surveyed, the precision of the LiDAR sensors for each survey, and the exposure of each area to coastal flooding.

2 LIDAR SURVEYS

2.1 Demonstration LiDAR Surveys

A series of demonstration LiDAR surveys was undertaken in December 1998 by the Canadian Hydrographic Service (CHS) in collaboration with the Geological Survey of Canada (GSC) at the Bedford Institute of Oceanography. The survey data were acquired by Optech using their ALTM 1020 system. The purpose of the surveys was to demonstrate the technology for deriving detailed height information along the coast. The areas surveyed were all within Nova Scotia and included: (1) the community of Truro (Salmon River estuary and associated floodplain), (2) parts of Halifax and Dartmouth in the Halifax Regional Municipality (HRM), and (3) Chezzetcook Inlet on the Eastern Shore, also in HRM (Fig. 1). Geomatics organizations, including the AGRG, were given access to these data in order to gain experience processing LiDAR and generating flood-risk maps.

2.2 Recent Experience with Operational Surveys

In the summer of 2000, Terra Remote Sensing used their Mark I sensor for an extensive set of LiDAR surveys in several parts of the region. This project included acquisition of LiDAR data over the Annapolis Valley for AGRG, and for the City of Charlottetown and the North Shore of PEI as part of a large multi-partner project (McCulloch et al., 2002) to assess potential impacts of rising sea level on the flood risk associated with storm-surge events (Fig. 1). Although the data from these surveys were adequate to conduct flood-risk mapping, there were vertical offset issues in the data (Webster et al., 2004) that had to be corrected prior to use in the creation of digital elevation models. Also in the summer of 2000, AGRG contracted GeoSurv to survey an area in the central Annapolis Valley and nearby coastal zone sing an ALTM 1020 system (see Webster, *in press*).

In 2003, Terra Remote Sensing re-surveyed sections of the PEI and Annapolis Valley study areas with an improved sensor (smaller beam divergence, more precise IMU and improved calibration procedures). Additionally, several polygons along the Northumberland Strait coast in New Brunswick were surveyed for flood-risk mapping. These data were determined to have a vertical accuracy better than 30 cm.

Figure 2. Example of flood-risk maps for the Truro area simulating the Saxby Gale storm surge. A perspective view of air photos draped over the LiDAR digital surface model (DSM) for lower Truro. Top image represents the water level extent simulated from the LiDAR at perigean high tide. The lower image represents the water level from the Saxby Gale event of 1869 draped over the air photo and LiDAR DSM.

In 2004, Terra Remote Sensing surveyed the remainder of the New Brunswick study area and the western region of the Annapolis Valley (Fig. 1). These areas were surveyed with their Mark II sensor, which has increased vertical precision of 15 cm and is capable of recording the first and last laser pulse returns and the intensity of alternating reflected pulses.

In the spring of 2005, AGRG used the new ALTM 3100 sensor to survey the coast of the Bay of Fundy. The purpose of this survey was to obtain a baseline data set for monitoring change in the future.

3 EXAMPLES OF FLOOD-RISK MAPPING

Initial experimentation with flood-risk mapping in the region using LiDAR was conducted jointly by CHS, GSC, and AGRG using the 1998 demonstration data for the Truro area (Fig. 2). LiDAR 'ground' hits were used to construct a *digital elevation model* (DEM) that was used to construct the flood-risk maps. A *digital surface model* (DSM) was also constructed from the LiDAR using all surface returns, including buildings and vegetation cover. The DSM was used for visualizing the results of the flood-risk mapping. The combination of the DSM and DEM were used to determine whether all coastal features were correctly coded as 'ground' points and included in the DEM. In a number of cases, LiDAR points representing steeply sloped coastal features such as wharves and armoured embankments were coded as 'non-ground' and not included in the DEM. These features are important in the generation of flood-risk maps and must be included in DEMs. The flood-risk maps were generated using a Geographic Information System (GIS) and standard processing tools. The assumption was made that the water level associated with a storm-surge or sea-level rise would form a flat plane originating from the ocean. As the water level was raised, only low-lying areas that had free connection with the ocean were selected as being at risk of flooding. On 5 October 1869, a storm known as the Saxby Gale tracked up the Bay of Fundy with hurricane force winds, generating a 2 m storm surge that caused extensive flooding (http://www.magma.ca/~jdreid/saxby_gale.htm) (Ruffman, 1999). This event was simulated using the LiDAR information for Truro (Figure 2). Low-lying areas in Truro are protected from the Bay of Fundy by dykes with crest elevations approximately 10.25 m above MSL. If the water level exceeds this height, a significant amount of low-lying land is vulnerable. In addition, these low-lying areas are often flooded during spring snowmelt and from heavy rainfall events.

Figure 3. Photograph of storm-surge damage at Margaretsville along the Bay of Fundy coast in Nova Scotia.

In January 2000, a major storm-surge event caused flooding in the city of Charlottetown and damage to coastal infrastructure throughout the region (Forbes et al., 2004), even along the coast of the Bay of Fundy (Fig. 3), which was thought to be less susceptible to such events because of the large tidal range. The storm surge coincided with high tide at Charlottetown, PEI, resulting in a record high water level and severe ice impacts along the coast (Parkes and Ketch, 2002; Forbes et al., 2004). This event demonstrated how vulnerable the waterfront of Charlottetown is to such events.

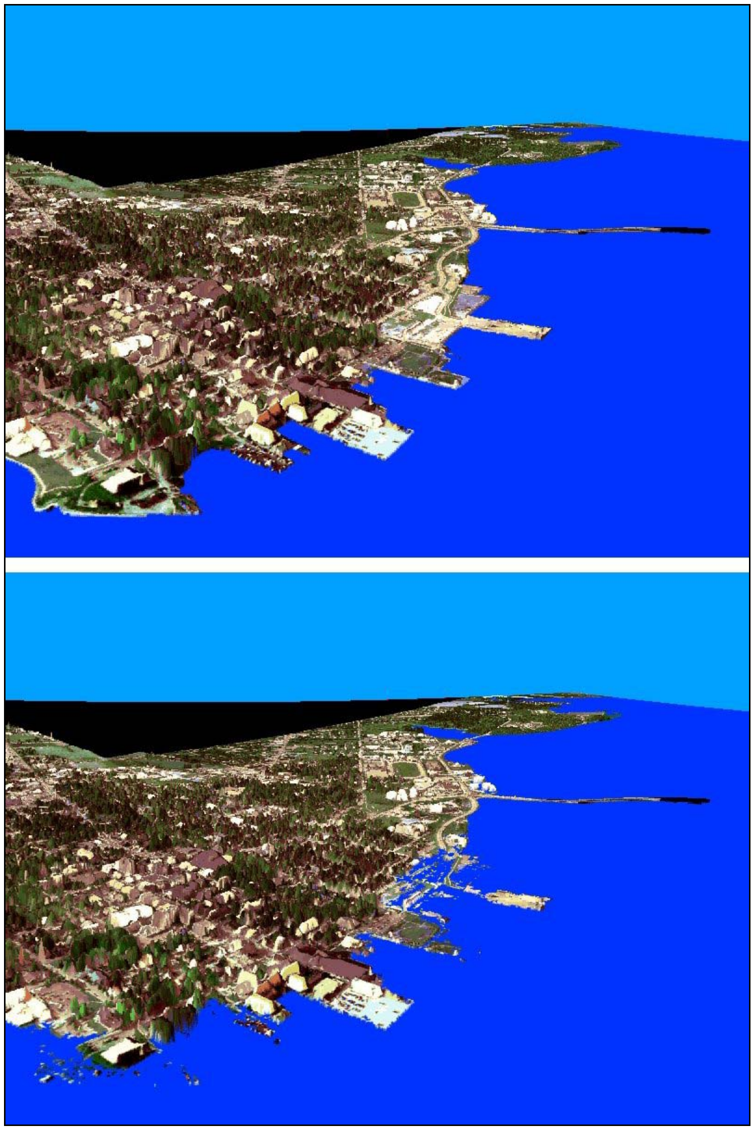

Figure 4. Flood-risk map for Charlottetown, PEI. Perspective view of CASI (compact airborne spectrographic imager) data draped over LiDAR digital surface model (DSM). Upper image: CASI true-colour composite image draped over DSM. Lower image: Simulated January 2000 water level overlain on the CASI image.

The tide-gauge record at Charlottetown was used to determine the water level relative to Chart Datum and, subsequently, the orthometric height of the maximum water level in order to simulate the flooding from this event using the LiDAR-derived DEM. The DEM was referenced to the Canadian Geodetic Vertical Datum of 1928 (CGVD28) that approximates mean sea level (MSL). Tide-gauge records dating back to 1904 indicate that relative sea level rose at a mean rate of 32 cm/century over this time interval at Charlottetown (Parkes et al., 2002).

Three sets of flood-risk maps were constructed for the city based on: (1) the January 2000 storm-surge water level (2.54 m above MSL) (Fig. 4); (2) the January 2000 storm-surge water level superimposed on a 47 cm rise in relative sea level; and (3) the January 2000 storm-surge water level superimposed on a 70 cm rise in relative sea level. The flood-extent map for the January 2000 water level was used to validate the results by consulting with city officials on the extent of the floodwaters (Fig. 4).

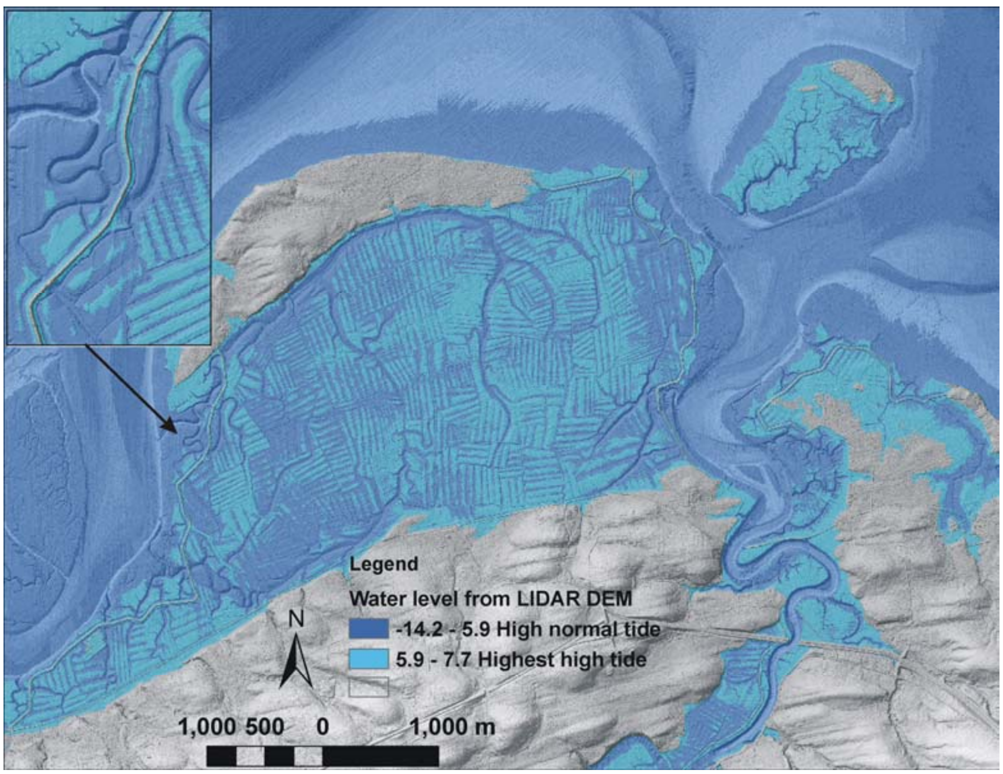

Figure 5. LiDAR image of the Grand Pré area of Nova Scotia, highlighting the dykes. The two shades of blue represent the water level at mean high tide (5.7 m MSL) and at highest high tide (7.7 MSL). This map shows that much of the area of Grand Pre is below sea level. The inset map in the upper left shows detail of the dyke structure (8.75-9.00 m MSL) that protects the low-lying areas from these tides and can withstand additional water levels up 1.0 m to 1.3 m occurring on a high spring tide.

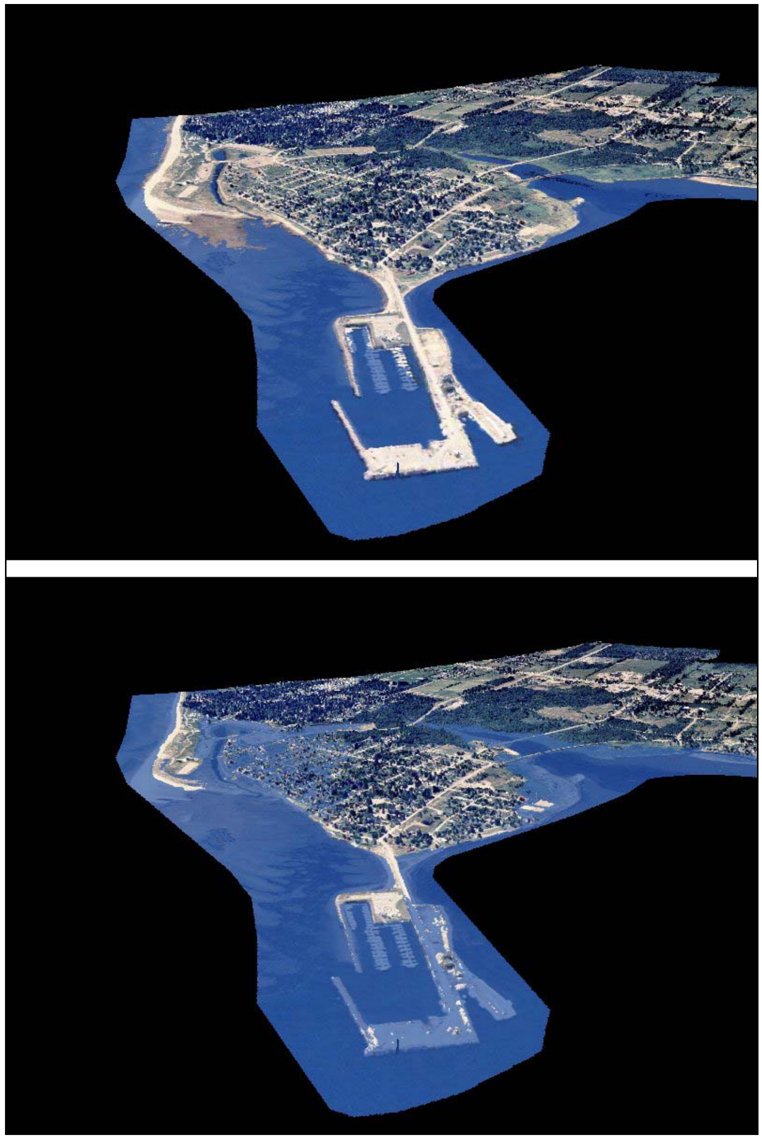

Figure 6. Perspective view of air photographs draped over the LiDAR digital surface model (DSM) for the Pte-du-Chêne area along the New Brunswick coast of the Northumberland Strait. The upper image represents mean water level. The lower image represents the water level of the January 2000 storm simulated using the LiDAR DEM (air photos courtesy of Services New Brunswick).

A similar flood-risk mapping exercise was conducted for the south shore of the Minas Basin in Nova Scotia (Webster et al., 2004). This region hosts the National Historic site of Grand Pre, a major centre of early Acadian settlement. Much of the area is below sea level and protected from tidal flooding by earth dykes (Fig. 5). The dykes protect the fertile low-lying land from normal and spring tide levels. Figure 5 shows the areas that would be affected by the tides if the dykes were breached. Breaching of dykes occurred during the Saxby Gale in 1869, but no breaching has occurred in recent times, including the January 2000 storm. However, the dykes have been set back because of sea-level rise since the time of the early Acadians (Bleakney, 2004). The high-resolution of the LiDAR data reveals the location of some of the historic dykes that have been abandoned. The current elevation of the dyke system is 8.75 – 9.00 m above MSL, and the largest high tides are 7.7 m MSL. Therefore, a storm-surge of 1.3 m superimposed on high tide could overtop the dykes and cause extensive flooding of the low-lying land behind.

Flood-risk mapping was conducted for the Northumberland Strait coastline of New Brunswick in 2004-2005. Maps showing flooded area were generated at 10 cm increments of water level from MSL to 4 m above MSL (Webster et al., *in review*). Where raised roadbeds on the LiDAR DEM prevented the simulation of flooding for low-lying areas on the landward side, notches were cut into the DEM across roadbeds where bridges or culverts in the real world allow free connection to the ocean.

The New Brunswick study area includes valuable ecosystems and areas of extensive coastal development (Hanson et al., 2005), both of which are affected by coastal flooding and sea-level rise. One of the most vulnerable sites in the area is the Pte-du-Chêne neighbourhood near Parlee Beach and Shediac. Residents had to be rescued using heavy equipment during the January 2000 storm-surge event and the area has been subject to evacuation alerts on other occasions since. Although the land is above MSL, the gentle slope inland makes this area susceptible to flooding (Fig. 6).

Salt marshes serve as important ecological functions, including provision of important breeding habitat for birds such as Willett and Nelson's Sharp-tailed Sparrow. Salt marshes exist in a horizontal and vertical 'window' between high and low tide. As sea level rises, the salt marsh must migrate landward, accrete vertically, or both in order to survive. The LiDAR DEM is being used to simulate sea-level rise under various scenarios and assumed accretion rates. The area available for marsh expansion up-slope depends on the slope of the backshore terrain and presence or absence of structures, such as roadbeds, that can act as barriers and limit migration, causing 'coastal squeeze'.

In the 2004 LiDAR surveys, the intensity of the returning laser pulse was recorded and used to construct maps of backscatter intensity. These maps provide valuable information on the nature of the sediments and other surface properties in the coastal zone. The water content and type of material in inter-tidal sediments influences the reflectance of the near-infrared laser pulse and can be used to differentiate materials (Brennan and Webster, *in review*). This is an area of continuing research, but shows promise as another source of information for coastal zone management.

4 CONCLUSIONS

Since the first LiDAR surveys in the region in 1998, local researchers have been improving their processing techniques and methodologies to generate accurate flood-risk maps for coastal regions in the Maritimes. LiDAR sensors have improved since that first survey in at least three important ways: (1) improved horizontal and vertical accuracy, (2) allowing a number of returns to be recorded from each laser pulse, and (3) recording of the intensity of the reflected laser pulse. The improvements to the technology have facilitated increased accuracy in the derived flood-risk and flood-depth maps. Nevertheless, validation surveys are still required and the use of LiDAR data requires an understanding of its strengths and limitations.

Large parts of the coast in New Brunswick and PEI have now been mapped, but large sections of the coast in those provinces and in Nova Scotia are similarly exposed and have no coverage. There is a growing awareness of the uses to which LiDAR data can be put among coastal managers and others in the region. Therefore we anticipate that the pace of LiDAR data acquisition and coastal DEM development is likely to accelerate in the future.

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