Flood-risk mapping for storm-surge events and sea-level rise using lidar for southeast New Brunswick

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Abstract. Coastal flooding from storm-surge events and sea-level rise is a major issue in Atlantic Canada. Airborne light detection and ranging (lidar) has the spatial density and vertical precision required to map coastal areas at risk of flooding from water levels typically 1–2 m higher than predicted tides during storm surges. In this study, a large section of the New Brunswick coast along Northumberland Strait was surveyed in 2003 and 2004 using two lidar systems. Water levels from a major storm-surge event in January 2000 were surveyed using a global positioning system (GPS) and used as a benchmark for flood-risk maps. Maps of flood depth were also generated for all water levels and used for socioeconomic and ecosystem impact assessment. Flood-risk maps were constructed using standard geographical information system (GIS) processing routines to determine the spatial extent of inundation for a given water level. The high resolution of the lidar digital elevation model (DEM) captured embankments such as raised roadbeds that could prevent flooding inland. Where connectivity was present due to culverts or bridges, the DEM was notched across the roadbed to simulate the connection between the ocean and upstream low-lying areas in the GIS. An automated routine was then used to generate maps of flood extent for water levels at 10 cm increments from 0 to 4 m above mean sea level. Validation of the flood-risk and flood-depth maps for the January 2000 storm-surge water level by field visits indicates that the simulations are generally accurate to within 10–20 cm. The lidar data were also used to evaluate the potential for overtopping and dune erosion on a large coastal spit, La Dune de Bouctouche. This showed a high vulnerability to storm damage for critical habitats on the spit. The lidar-derived maps produced in this study are now available to coastal communities and regional planners for use in the planning process and to assist in development of long-term adaptation strategies.

Résumé. Les inondations côtières dues aux ondes de tempête et aux crues des eaux de la mer constituent une menace significative au Canada Atlantique. Les données levées par lidar (« light detection and ranging ») aéroporté ont la densité spatiale et la précision verticale nécessaires pour la cartographie de zones côtières exposées au risque d’inondation en raison de crues causées par des vagues de tempête qui, d’une façon générale, produisent des niveaux d’eau dépassant d’un ou deux mètres le niveau prévu de la marée. Au cours de cette étude en 2003 et 2004 et à l’aide de deux systèmes lidar on a effectué l’arpentage d’un assez grand tronçon de la côte du Nouveau Brunswick s’étendant le long du détroit de Northumberland. Les niveaux d’eau résultant d’une onde de tempête qui s’est produite en janvier 2000 ont été relevés à l’aide du GPS (« global positioning system ») et ont servi de repères pour la cartographie des zones exposées au risque d’inondation. Des cartes de la profondeur des crues ont été également dressées pour tous les niveaux d’eau afin de déterminer l’impact socio-économique et les répercussions environnementales des inondations. Les cartes des zones exposées aux inondations ont été dressées à travers un travail de préparation d’un système d’information géographique (SIG) ordinaire pour déterminer l’étendue spatiale de la zone inondée pour un niveau donné d’eau. La haute définition du modèle altimétrique numérique (MAN) lidar a permis de capter des levées de terrain, telles que des assiettes de voirie remontées, susceptibles d’empêcher l’inondation de l’arrière-pays. Là où il existait une connectivité due à la présence de busse ou de ponts, le MAN a été entaillé à travers l’assiette de voirie pour simuler le raccord entre l’océan et les zones de terrain bas se trouvant en amont dans le SIG. Nous nous sommes ensuite servis d’une routine automatisée pour dresser des cartes de l’étendue de l’inondation pour des différents niveaux d’eau augmentés de 10 cm à chaque incrément, partant de zéro jusqu’à quatre mètres au-dessus du niveau moyen de la mer. La validation de la cartographie des zones exposées aux inondations et de la profondeur des eaux d’inondations effectuée au cours de visites sur le terrain donne à entendre que les simulations sont en général exactes dans les limites de 10 à 20 cm. Des données lidar ont été utilisées pour évaluer la probabilité que les vagues de tempête puissent atteindre un niveau plus haut que celui de la crête de la dune ou qu’il y ait érosion du relief de sable à la Dune de Bouctouche, grande flèche littorale du Nouveau Brunswick. Il est apparu que des habitats essentiels de la flèche

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**Introduction**

For coastal communities, the risk of storm-surge flooding with long-term sea-level rise is a particular concern. The Intergovernmental Panel on Climate Change (IPCC) has predicted a rise in global mean sea-level from 1990 to 2100 of between 0.09 m and 0.88 m, with a central value of 0.48 m (Church et al., 2001). Relative sea-level rise at any one place is a combination of changes in regional sea-level and vertical ground motion. Subsidence in coastal areas will result in more rapid relative sea-level rise. This is of particular importance in the Canadian Maritimes, where postglacial isostatic adjustments are ongoing and much of the region is subsiding (Grant, 1980; Shaw et al., 1998). Superimposed on sea-level rise, large storm waves and runup riding on high storm-surge water levels pose additional coastal erosion and flooding hazards. Other factors being equal, coastal erosion will increase with a rise in mean sea-level (Cowell and Thom, 1994; Leatherman et al., 2003). On dune-backed coastal beaches and barriers, erosion often takes the form of dune-front scarping, and backshore flooding may occur if runup and overwash exploit low points in the dune crest to create breaches and washover channels. Sea-level rise can also threaten ecosystems, especially areas such as coastal wetlands and marshes that are dependent on specific tidal range conditions (Nicholls et al., 1999).

A storm surge is defined as the difference between observed water level and the level predicted for the astronomical tide. Surges are caused by atmospheric low-pressure systems and high winds associated with storms. Storm surges along the east coast of Canada can add 2 m or more of water to the predicted water level along the coast (Parkes et al., 1997; Parkes and Ketch, 2002). Coastal communities are most vulnerable if a storm surge peaks during a high-tide event, especially during large spring high tides. With accelerated sea-level rise, the extent and frequency of flooding will increase in the future, as will the impact of related factors such as shoreline erosion. Thus, there is a demand for information that predicts areas at risk from such events, at present and into the future, as a basis for sustainable coastal zone management, effective planning, and the development of appropriate adaptation strategies (McLean et al., 2001).

Because storm surges in eastern Canada are typically less than 2 m in height, technologies with vertical precision significantly finer than this must be employed to generate flood-risk maps of sufficient resolution. Airborne light detection and ranging (lidar) is a technology that offers the vertical precision and high spatial detail required for this purpose. A general overview of airborne laser scanning technology and principles is provided by Wehr and Lohr (1999). Applications to coastal process studies in the United States have been reported by Sallenger et al. (1999) and Krabill et al. (1999), among others. Preliminary trials in Atlantic Canada were reported by O’Reilly (2000), and subsequent experience was described by Webster et al. (2002; 2003; 2004a; 2004b), O’Reilly et al. (2005), and Webster and Forbes (2006). Most of the coast of the conterminous United States has now been mapped using this technology (Brock et al., 2002). Stockdon et al. (2002) used lidar to map the shoreline and detect changes.

In this paper we describe a recent study using two lidar systems to generate high-resolution digital elevation models (DEMs) and associated flood-risk maps for the coast of New Brunswick along Northumberland Strait (Figure 1) (MacKinnon, 2004). This region was highlighted in a national study by Shaw et al. (1998) as being vulnerable to sea-level rise. This paper represents one part of a multidisciplinary project led by Environment Canada to derive information to aid local resource managers in identifying areas prone to coastal flooding and erosion and the possible socioeconomic and ecosystem impacts of sea-level rise and storm-surge events. The maps depicting areas vulnerable to sea-level rise have been used to assess potential impact to ecosystems such as salt marshes and coastal dunes and cultural features such as homes, businesses, municipal infrastructure, and historic sites in low-lying areas. This project builds on the experience gained from the successful application of lidar technology to storm-surge flood-risk mapping on Prince Edward Island (McCulloch et al., 2002; Webster et al., 2001; 2003; 2004a; 2004b; Webster and Forbes, 2006).

**Methods**

**Lidar systems**

Lidar mapping systems consist of three components, the laser ranging system, an inertial measurement unit (IMU), and the global positioning system (GPS), integrated to provide the horizontal coordinates and elevation of each laser return. Earlier lidar systems were capable of recording a single return, either the first or last pulse reflected from the target. The latest lidar sensors are capable of recording multiple returns, typically at least the first and last pulse, with some sensors recording up to four intermediate returns, and in most cases the intensity of the reflected pulses.

Various studies have been reported on the calibration and systematic errors of lidar systems (Kilian et al., 1996; Burman, 2000; Filin, 2001; 2003a; 2003b; Katzenbeisser, 2003) and the accuracy of laser altimetry data (Huisings and Gomes Pereira, 1998; Kraus and Pfeifer, 1998; Crombaghs et al., 2000; Schenk et al., 2001; Maas, 2000; 2003; Ahokas et al., 2003; Artuso et al., 2003; Bretar et al., 2003; Elberink et al., 2003; Kornus and
Although lidar technology has improved over the years and systems are capable of providing elevations of the earth’s surface to decimetre-level precision, systematic and random errors can still occur and independent validation is recommended. Classification of the lidar returns into “ground” and “non-ground” (i.e., vegetation or buildings) points is an important aspect of the lidar processing stream and can affect the accuracy of derivative products such as a DEM. The correct definition of coastal features such as wharves and steep rock embankments in the lidar point data is critical to the derivation of an accurate DEM for flood-risk mapping.

Lidar surveys

In this study, Terra Remote Sensing Inc. (Sidney, B.C.) was contracted to acquire lidar data for coastal areas of southeast New Brunswick. The total study area consisted of 278 km². The requested lidar point density on open ground was a posting every 60 cm. The absolute accuracy of the lidar data for this study was specified to be ±30 cm in the vertical. Two lidar systems were used to acquire data during leaf-off conditions following snowmelt in the spring of 2003 and 2004. In 2003, the Mark I system was used to acquire data over four of the seven survey polygons (Figure 1). In 2004, the more sophisticated Mark II system was used to acquire data over the remaining three polygons (Figure 1). Surveys were acquired near low-tide conditions where possible, and GPS baselines were kept below 50 km to minimize aircraft trajectory errors. A large coastal spit, La Dune de Bouctouche, was surveyed in both 2003 and 2004 to assess changes in the morphology of the dune following a storm in February 2004 (Roberts et al., 2005).

The Mark I is a first-return lidar system that was originally designed for corridor mapping and was mounted on a pod fixed to the underside of a Bell 206L helicopter (Figure 2A). The lidar operated at a 10 kHz laser repetition rate along with the scanning mirror operating at 15 Hz to direct the laser pulses across the swath. At a flying altitude of 300 m, the laser beam had a ground footprint diameter of 9 cm and an average post spacing of 60 cm (Figure 2A). The narrow laser beam facilitated penetration to the ground in vegetated terrain. The survey was conducted from 23 May to 3 June 2003.

The Mark II system is capable of recording the first and last returns and the intensity of one of the returns and was mounted on a pod that was fixed to the underside of a Bell 206L helicopter (Figure 2B). It was decided to acquire the intensity on alternating returns, thus every second first and last return would record the intensity. The lidar operated at a 40 kHz laser repetition rate along with the scanning mirror operating at 17 Hz to direct the laser pulses across the swath. At a flying
altitude of 600 m, the laser beam had a ground footprint
diameter of 27 cm and an average post spacing of 45 cm
(Figure 2B). Because the Mark II sensor is capable of
recording the first and last returns, the wider laser beam could
still partially penetrate the vegetation canopy and reflect off the
ground or near-ground surface and be measured as the last
returning pulse. The survey was conducted from 26 April to
1 May 2004. The Mark II has improved precision to better than
±15 cm in the vertical as a result of the higher precision laser
ranging system and IMU.

Lidar preprocessing

Hodgson et al. (2005) provide an overview of the general
procedure used by many of the automated routines employed to
classify the lidar point cloud data. They point out that most
lidar data providers consider the details of this process
proprietary and do not report the specifics of the parameters
used for the classification. In this study, the lidar point cloud
was classified into ground and non-ground categories using
Terrascan™ software by the data provider, who did not provide
the parameters used in the classification.

For many coastal applications, including flood-risk mapping,
the lidar elevations are transformed from ellipsoid heights to
orthometric heights. Orthometric heights are based on the geoid,
an equipotential surface defined by the earth’s gravity field,
approximately equal to mean sea level. To obtain orthometric
heights, an adjustment must be made for the local vertical
separation between the ellipsoid and the geoid. The difference
between the WGS84 ellipsoid and the Canadian Geodetic Vertical
Datum of 1928 (CGVD28) is obtained using the HT1_01E model,
which has since been replaced by HTv2.0, with an accuracy of
±5 cm with 95% confidence in southern Canada (Geodetic Survey
Division, Natural Resources Canada, www.geod.nrcan.ca/
index_e/products_e/software_e/gpsht_e.html).

Lidar data are typically delivered in ASCII files consisting of
x, y, z information. There is no standard format for lidar data,
although a new proposed binary format known as LAS has
recently been published (Schuckman, 2003). In this study the
data were delivered as ASCII files separated into 4 km × 4 km
tiles based on the Universal Transverse Mercator (UTM) grid.
The 2003 data files have data fields for each lidar point,
including easting and northing positions based on UTM zone
20 (WGS84), ellipsoidal and orthometric heights, the GPS time
for every laser shot, and the flight line number. The last two
fields facilitated testing for systematic errors between adjacent
flight lines or strips (e.g., Maas 2000; 2002). The 2004 data
have the same fields as the 2003 data, with additional fields
including echo number and the intensity of alternating returns.
The echo number is an integer code that defines whether the
return was the first or last of multiple returns or a single return.

Lidar GIS processing

The ASCII lidar data were imported into the ESRI ArcGIS™
system (ESRI, Redlands, Calif.) utilizing Arc Macro Language
(AML) automated routines. Ground and non-ground point
layers were built in the GIS system. Various surfaces were
constructed from the lidar points. Digital surface models
(DSMs) were constructed from the lidar data by utilizing the
ground and non-ground points. The surface was linearly
interpolated to a 1 m grid from a triangular irregular network
(TIN). The ground points were used to construct a DEM using
the same method. The DSMs and DEMs were examined in
combination with the classified lidar points, and classification
errors were identified. For example, the edges of wharves were
classified as non-ground, therefore the initial DEM did not accurately represent these features. The non-ground points that were incorrectly classified for these areas were used to construct a new DEM that more accurately represented the coastal features following a method described in Webster et al. (2004a). It was determined that the most effective method to represent the intensity information was derived by interpolating the intensity values of all the lidar returns (ground and non-ground). The exploitation of the intensity data is beyond the scope of this paper; however, using these data in combination with the DSM, the DEM, the normalized height grid (DSM – DEM), and echo information, Brennan and Webster (2005) demonstrated that accurate land cover classification based entirely on lidar is possible.

One issue with lidar data collected in the coastal zone is the specular reflection over flat water and intertidal areas. Only returns within a narrow angle off nadir were recorded over these areas, often having anomalously high intensity values. The variable density of returns over water causes the lidar surfaces to have large triangles that do not accurately represent the surface. We have used a combination of lidar point density maps to constrain the surface over water and assign a constant elevation for the areas of no data between flight lines based on the water level observed from the nadir data.

DEM and DSM grids were imported into PCI Geomatica™ software (PCI Geomatics, Richmond Hill, Ont.) to construct colour shaded-relief models. Surfaces were “illuminated” from the northwest using an zenith angle of 45° with a five times vertical exaggeration applied. To ensure that adjacent lidar study area polygons (Figure 1) have a consistent colour range, the maximum elevation range of the surveyed region was determined and used to scale the data. The maximum elevation used was 38 m for the DEM and 58 m for the DSM.

**Lidar validation**

The accuracy of lidar data depends on the removal of the systematic errors associated with the system (Filin, 2001; 2003a; 2003b). Several researchers have examined the issues of lidar validation and have highlighted the potential for errors between flight lines or strips (Kilian et al., 1996; Huisings and Gomes Pereira, 1998; Crombaghs et al., 2000; Maas, 2000; 2002; Schenk et al., 2001; Latypov and Zosse, 2002; Ahokas et al., 2003; Bretar et al., 2003; Elberink et al., 2003; Kornus and Ruiz, 2003; Webster, 2005). Many of the studies have dealt with individual flight strips, where the overlapping areas are compared either as points or as interpolated surfaces. To evaluate the possible error sources between strips, the GPS time tag or flight line number for each lidar point is used in the validation procedure. In this study the absolute accuracy was required for accurate flood-risk mapping, therefore extensive ground control using GPS and traditional survey methods was used in the analysis. In all cases the HT1_01 model was used to transform the GPS ellipsoidal heights into orthometric heights for comparison with the lidar data. A methodology described in Webster (2005) was used for comparing the GPS validation data with the lidar ground points and derived DEMs. Coastal features (e.g., wharves) in the DEM were compared to digital orthophotographs to ensure an accurate representation.

The absolute accuracy of the lidar data was validated using two techniques: (i) comparing proximal lidar points to checkpoints, and (ii) comparing the lidar DEM to checkpoints (Webster, 2005). The validation checkpoints consisted of real-time kinematic (RTK) GPS surveys of roads and wharves and traditional surveys utilizing a total station for dune transects and under the forest canopy.

**Water levels for flood modelling**

The study area in southeast New Brunswick has sustained a number of damaging storms over the past few years (Forbes et al., 2004). The 21–22 January 2000 storm produced one of the highest storm-surge water levels on record for the Northumberland Strait region (Parkes and Ketch, 2002; Forbes et al., 2004). Unfortunately the tide gauge at Escuminac, the only permanent gauge remaining in the study area, did not capture this event, having frozen prior to the highest water level during the storm. This surge produced a record water level at Charlottetown, Prince Edward Island, where the tide gauge has been operating since 1911 and records exist back to 1904 (Parkes et al., 2002). Staff from Environment Canada visited several coastal communities in the aftermath of the storm and marked the high-water position using nails in power poles and other wooden structures. These high-water marks and others identified on buildings were surveyed with RTK GPS in 2002 and used to estimate the water level associated with the January 2000 storm-surge event. It is estimated that the water level associated with the January 2000 storm reached 2.5 m above CGVD28 (Figure 3). Three water levels were selected for initial flood modelling. These were the January 2000 storm level and 50 and 70 cm above that level. Tide-gauge records from Charlottetown indicate that mean relative sea-level is rising at a rate of 32 cm per century (Parkes et al., 2002; Forbes et al., 2004). This value is a combination of regional sea-level rise from global warning and crustal subsidence, estimated at 15 cm per century for this area. The rate of relative sea-level rise diminishes to the west and north along the New Brunswick coast as a function of lower rates of subsidence (Koozhare et al., 2005). Due to the uncertainties in the estimates of future sea-level rise, it was decided to construct additional flood-risk maps using water levels at 10 cm increments up to a maximum of 4 m above CGVD28 in addition to the three benchmark levels described previously.

**Flood-risk modelling**

In the present study of coastal flooding, it was decided to use existing GIS and image-processing capabilities combined with the lidar DEM to model the potential areas of flooding. Galy and Sanders (2002) presented a similar approach where they used a DEM derived from interferometric synthetic aperture radar (InSAR) data to map flood risk along the River Thames in the United Kingdom. It is assumed that a given water level from
the storm-surge event would form a horizontal flood surface extending landward from the open ocean. Thus hydraulic effects, associated time lags, or flood expansion or dampening were not considered in the modelling effort. This assumption is justified with the results of water levels measured by RTK GPS for the January 2000 storm which show a nearly consistent height of near 2.5 m above CGVD28 throughout most of the surveyed area (Figure 3). Mean sea-level is approximately 19 cm above CGVD28.

Webster et al. (2004a) discussed the requirement to ensure that areas in the DEM below a given flood level are included in the flooded polygon only if they have free connection to the ocean (i.e., low-lying areas behind an embankment would not be flooded unless there was a channel allowing water to enter). In the earlier Charlottetown study, engineers were consulted on the types of culverts used at different locations when deciding whether to include upstream low-lying areas in the flood extent (Webster et al., 2004a). In the present study, the area of interest was significantly larger, and specific information on culvert locations was not readily available during this phase of the project. As a result, we did a visual interpretation of areas along the coast where stream channels or valleys exist but appear in the DEM to be blocked from the ocean by the elevated roadbed, to determine if a bridge or culvert may be present. Where it was thought that a culvert or bridge exists, then the area upstream of the road was included in the flood extent (see MacKinnon, 2004). This proved to be a very time consuming task, especially when constructing flood extents for every 10 cm increment from 0 to 4 m above CGVD28.

In the present study, we modified this methodology to automate the computation of the 10 cm flood limits. The method involved visually evaluating the DEM using a criterion similar to that described by Webster et al. (2004a). The DEM was notched across the roadbed where bridges or culverts were thought to be present. The base of the notch was assigned an elevation equal to that of the nearest upstream part of the channel or basin landward of the road. The automated routine made use of this modified DEM with “hydraulic pathways” to ensure areas with free connection to the ocean were included. To determine the flood extent, a script was written in Python™ and executed in the ESRI ArcGIS™ system. The script involved applying a threshold to the modified DEM at a given

Figure 3. Reference marks for water levels associated with the January 2000 storm-surge event surveyed using RTK GPS. A water level approximately 2.5 m above CGVD28 was determined from the survey data.
flood level. The resultant binary raster was then vectorized and perimeter and area attributes were computed. Since the modified DEM always contained a significant portion of the area that represented the ocean, the largest polygon (area) generated for a given flood level would represent the continuously connected coastal flooded area. Smaller low-lying inland polygons would not have free connection to the ocean and thus would not be selected during this process. The original DEM, without the notches, was used again to evaluate each flood level to determine where the roadbed would be flooded at the various water levels. This was important because the water level at which a road will become impassable due to flooding is critical information for emergency-measures organizations and in the design of adaptation strategies. The results of this analysis are merged with the flood extents derived from the notched DEM to produce the final flood-extent maps.

In addition to the flood-extent maps, Webster and Forbes (2006) highlighted the importance of flood depth for the assessment of potential damage associated with storm-surge flooding. Flood-depth maps were generated for the various flood levels by subtracting the DEM from the flooding level over the area flooded.

**Flood visualization**

The flood extents at 10 cm increments are visualized as vector overlays in the GIS system for ease and convenience of use by the non-GIS specialist. In addition, because the surge events are dynamic, the 10 cm flood extents are used to construct animation sequences. The animations are created using both planimetric and perspective views of the terrain. The animation sequences involve overlaying the flood extents on colour shaded-relief models of the lidar DSM, orthophotography, or high-resolution satellite imagery such as QuickBird™. PCI Geomatica™ software is used for the visualization and to generate the individual frames for the animations. In previous studies (Dickie, 2001; Webster et al., 2004a; 2004b; MacKinnon, 2004), a solid colour was used to represent the water level. In this study we modified this method to allow the water to be transparent so that the underlying features affected by the floodwater are still visible. An EASI script is used to automate the process once a desirable perspective view is defined. The individual frames are annotated to describe critical water-level events such as the January 2000 storm surge and combined to build a Windows® AVI file.

**Evaluating the potential for coastal barrier overwash**

La Dune de Bouctouche is one of the largest natural barrier beach and dune systems along the coast of New Brunswick and hosts several species at risk, including Gulf of St. Lawrence aster (*Symphyotrichum laurentianum*) and piping plover (*Charadrius melodus*). Lidar data were acquired over this area in both 2003 and 2004 and used to generate DEMs gridded at 1 m horizontal resolution. To evaluate the potential for dune-face erosion or overtopping under storm conditions, the foredune crest elevation (or the beach crest where dunes are absent) was obtained from shore-normal transects superimposed on the DEM at 50 m intervals along the beach. The upper limit of the wave-formed beach was also determined by visual inspection of each transect profile. The resulting alongshore elevation profiles for barrier and dune crest and top of beach provide a basis for estimating the extent and location of flooding and overtopping under storm-surge conditions. The spit segments subject to flooding in the January 2000 storm, with sea ice present and no waves, can be determined by superimposing the surge water level on the barrier profile. For other storms, such as the storm on 29 October 2000, when large waves were present (Forbes et al., 2004), the water level provides a highly conservative estimate of overtopping potential. Although deepwater wave data are now available for some events from 2003–2005, we have no data on setup and breaking wave conditions from which to compute runup. For purposes of discussion, we add 1.5 m to the peak water level for large storm-surge events to obtain a conservative estimate of runup and the extent of overtopping. It should also be noted that where the resulting runup level lies above the top-of-beach profile, there is a high potential for dune-front erosion.

**Results**

The lidar surfaces, DSM, DEM, and intensity maps and the flood-risk extent and flood-depth maps have been passed to the other members of the project team who are currently using these data to evaluate potential socioeconomic and ecosystem impacts (e.g., Chouinard et al., 2004; Daigle, 2004; DeBaie, 2004; Hanson, 2004; Vasseur and Delusca., 2004) and to advise on possible adaptation strategies (Nichols and Sutherland, 2004). In the following section, we present examples of the flood-risk mapping from the lidar surveys with the validation results.

**Surface models and validation: 2003 lidar data**

MacKinnon (2004) inspected all of the lidar data acquired in 2003 and highlighted two main types of problems: (i) a few small missing areas within the survey polygons, and (ii) lidar point classification errors. The areas that were missed in 2003 were acquired during the 2004 mission. In addition to the absolute accuracy of the lidar information, classification errors between ground and non-ground targets along the coast are critical for this type of flood-risk mapping application. The classification errors are associated with coastal features that have abrupt vertical relief relative to that of the surrounding terrain. The erroneously classified points were integrated into the final DEMs used for flood-risk mapping. The data provider was informed about this error and instructed to carefully inspect the classification results along the coast to ensure such features are accurately classified in subsequent datasets. In subsequent data delivered, this problem was not observed and coastal features were accurately classified.
The 2003 lidar data met the specifications based on the comparison with the GPS and total-station survey data with the derived DEMs. A systematic pattern is observed in the data over flat areas such as water, however. This pattern, also found in lidar data from other systems and data providers (D. Whalen, Geological Survey of Canada, personal communication, 2005), has been termed the “wood-grain effect.” It is caused by a combination of the limited precision of the laser ranging system and the motion of the aircraft (Figure 4). The variance of the pattern is within the specifications of the survey, but the pattern detracts from the fidelity of the DSM. There were no systematic errors detected between strips or flight lines in these data.

The summary statistics for the lidar DEMs compared with GPS surveys are presented in Table 1. The mean difference in height between the GPS and lidar DEMs for the 2003 survey polygons is 0.11 m, with a mean standard deviation of 0.11 m and a mean root mean square (RMS) error of 0.16 m.

The results of the total-station transects across dunes within the Cap-Pele lidar polygon show general good agreement (Figure 5). Where the profiles differ, the lidar DEM is consistently too high by a few decimetres. We attribute this bias to the dense growth of dune grass (Ammophila breviligulata) growing on the backslope of the dune and to some accumulation of sand on the upper dune face between the dates of the survey and the lidar acquisition. The dune crest location and height are accurately captured by the lidar survey (Figure 5).

Surface models and validation: 2004 lidar data

The 2004 lidar data met the specifications based on the comparison with the GPS and total-station survey data with the derived DEMs (Table 2). The mean difference in height between the GPS and lidar DEMs for the 2004 survey polygons is 0.11 m, with a mean standard deviation of 0.08 m and a mean RMS of 0.12 m. No systematic patterns were detected in the 2004 lidar surfaces (Figure 6).

The horizontal accuracy of lidar data is challenging to evaluate if only height information is supplied. Data from sensors capable of recording the intensity of the return pulse can be used to assess the positional accuracy, however. In this study, field validation data concentrated on assessment of the height, and no data were collected specifically to validate the horizontal position of the data. The intensity surfaces were assessed for relative accuracy, however, and compared with 1 : 10 000 scale base maps. The relative accuracy was assessed qualitatively by examining linear features such as parking lots. In a few cases it appeared the motion of the aircraft was not completely resolved because the intensity images showed wavy features that should have been straight.

The intensity data were used in combination with the DEM and DSM to assess the moisture content and vegetation cover on the dune system in Kouchibougouac National Park. The lidar data were capable of highlighting spruce trees that occur on some lidar systems, the intensity values for these data are very consistent across the swath, with the exception of nadir scans over flat water, thus allowing intensity mosaics to be constructed without significant artefacts between flight lines.

Flood-risk maps

The notched lidar DEMs are used initially to construct flood-risk maps for three water levels. The levels are based on the January 2000 storm, determined to be 2.5 m above CGVD28, and the same storm superimposed on increased relative sea-level 50 and 70 cm above the mean water level in 2000. Initial flood modelling was carried out for the Pointe-du-Chêne area, near Shediac, because this built-up area was inundated during the January 2000 storm-surge event (O’Reilly et al., 2005) and people had to be evacuated in snowstorm conditions using front-end loaders. In the summer of 2004 this site was visited with the flood-risk maps to verify the extent of the flooding with local residents. The high resolution of the lidar DSM allows one to easily navigate to specific road intersections associated with the flood limit. The qualitative assessment indicated that the flood extent derived for this event matched the flood limit observed by the local residents (Figure 8A).

Flood-depth maps are constructed to better estimate the potential economic impact of storm-surge events (Figure 8B).

Table 1. Summary statistics of 2003 lidar DEMs and GPS checkpoints.

<table>
<thead>
<tr>
<th>Lidar polygon</th>
<th>Mean difference, GPS – DEM (m)</th>
<th>Standard deviation, GPS – DEM (m)</th>
<th>RMS error, GPS – DEM (m)</th>
<th>No. of GPS points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cap Pelé</td>
<td>0.04</td>
<td>0.11</td>
<td>0.11</td>
<td>20 748</td>
</tr>
<tr>
<td>Cormierville</td>
<td>0.21</td>
<td>0.12</td>
<td>0.24</td>
<td>2 426</td>
</tr>
<tr>
<td>Bouctouche</td>
<td>0.12</td>
<td>0.10</td>
<td>0.16</td>
<td>3 125</td>
</tr>
<tr>
<td>Cap Lumière</td>
<td>0.07</td>
<td>0.12</td>
<td>0.14</td>
<td>810</td>
</tr>
</tbody>
</table>

Table 2. Summary statistics of 2004 lidar DEMs and GPS checkpoints.

<table>
<thead>
<tr>
<th>Lidar polygon</th>
<th>Mean difference, GPS – DEM (m)</th>
<th>Standard deviation, GPS – DEM (m)</th>
<th>RMS error, GPS – DEM (m)</th>
<th>No. of GPS points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cap Jourimain</td>
<td>0.10</td>
<td>0.09</td>
<td>0.14</td>
<td>1645</td>
</tr>
<tr>
<td>Shemogue</td>
<td>0.11</td>
<td>0.07</td>
<td>0.10</td>
<td>3333</td>
</tr>
</tbody>
</table>
Figure 4. Example of 2003 lidar data with “wood grain” pattern and location of the GPS survey check data. (A) Lidar DEM of Bouctouche Bay with GPS checkpoints (magenta triangles). (B) DSM of Bouctouche Bay with the direction (arrow) of the perspective view of the sea-level rise simulation depicted in Figure 9.
Figure 5. Total-station dune survey transects at l’Aboiteau in the Cap Pelé lidar polygon. (A) Lidar DEM with transect locations (solid circles). (B) Comparison of survey and lidar DEM elevations for transect 1 at the east end of the dune. Vertical bars denote standard deviation (SD). (C) Comparison of survey and lidar DEM values at transect 3 on the central part of the dune.
The flood-depth maps also proved useful for validating the results of the flood modelling. Staff from Environment Canada visited several communities throughout the larger study area to evaluate the flood-extent and flood-depth maps. They reported a general agreement of within 10 cm of the flood depth simulated for the January 2000 storm compared with those measured in the field.

Additional flood-risk maps were generated for 10 cm increments in water level to allow for a more precise estimate of the areas potentially affected by future sea-level rise and storm-surge events. Other members of the project team are calculating return probabilities for the various water levels. Histograms of the area of flood extent are assessed to determine if there are specific water-level thresholds for specific regions. In addition, other ecosystem impacts can be assessed with these flood-risk map sequences.

The flood-risk map sequences at 10 cm elevation increments can be used for assessing ecosystem impacts. Salt marshes are sensitive to the tidal range and frequency and duration of inundation. They will migrate upslope as relative sea-level rises (Shaw and Ceman, 1999; Donnelly et al., 2004). The extent of landward migration is dependent on local slope and land-cover conditions as well as the species composition and habitat conditions (Donnelly and Bertnes, 2001; Bertnes et al., 2002). The flood-risk maps are used to determine the area available for salt-marsh migration as a function of the rising sea-level and associated tidal range.

Visualization of flooding

The 10 cm increment flood extents are available as vector polygons. We have created animations to visualize flooding as a result of a storm-surge event superimposed on sea-level rise. These have a background image consisting of a lidar colour shaded relief (CSR) or satellite image draped over the DSM to construct a perspective view. This is a very effective way to present the flood-risk modelling results in a way that is readily understood by the general public. Figure 9 presents an example from the community of Bouctouche in the New Brunswick study area.

Potential for overtopping and dune erosion

The alongshore profile of beach and foredune crest elevations was developed as described earlier using an approach similar to that presented by Elko et al. (2002a; 2002b). The dataset for La Dune de Bouctouche is almost 12 km in length, with a gap of about 1 km where the 2004 lidar coverage missed the outer beach (Figure 10). The x axis represents distance alongshore (downdrift) from the proximal point of detachment (at the Irving Eco-Centre) to the outer end of the spit (Figure 10A). Blue squares in Figure 10B represent transects without dunes, where the crest elevation is determined by wave runup dynamics. The orange squares and line denote the morphological break in slope at the base of the foredune, representing the top of the beach at the end of April 2004, at the time of the lidar data acquisition (Figure 10B). The blue-green triangles and line represent the foredune crest elevation, almost invariably the highest elevation on the transect (Figure 10B).
The highest dunes at La Dune de Bouctouche exceed 6 m above CGVD28, and the modal dune crest elevation is $4.0 \leq h_{DC} < 4.5$ m (mean = 3.94 m). Dune crest elevations below 3 m occur in some areas, notably between 7 and 8 km downdrift, representing a total distance of 1.45 km. The dune crest falls to below 2 m at the distal tip, where the minimum crest elevation is 1.8 m. Barrier crest elevations without dunes, representing 1.60 km of the spit, range from 2.0 to 3.3 m, with most lying between 2.2 and 2.8 m above mean sea level. The top-of-beach (base-of-dune) elevations range from about 1.3 to >3.0 m and show distinctive patterns of alongshore variability on various segments of the spit. The most common runup (base-of-dune) elevations are $1.5 \leq h_{R} < 2.0$ m (3.35 km) and $2.0 \leq h_{R} < 2.5$ m (2.75 km). Overall, the barrier crest elevations are bimodal,
with maxima in the classes $2.0 \leq h_C < 2.5 \text{ m}$ and $4.0 \leq h_C < 4.5 \text{ m}$.

Preliminary analysis of overtopping potential for La Dune de Bouctouche, based on the lidar DEM crest elevations (Figure 10B), shows that some sections were overtopped by storm-surge flooding to a level of 2.5 m in the storm of 21–22 January 2000 (when sea ice prevented wave development). Some of the lower parts of the spit near the proximal end had

Figure 8. (A) Flood-risk map of the three water levels for Pointe-du-Chêne area. Lidar DSM with water levels overlain. The water levels correspond to the January 2000 storm (red line); the January 2000 storm plus 100 years of sea-level rise at a rate of 50 cm per century (yellow line); and the January 2000 storm plus 100 years of sea-level rise at a rate of 70 cm per century (white line) (orthophoto provided by Service New Brunswick). (B) Flood-depth map of the Pointe-du-Chêne area for the January 2000 storm water level.
foredunes at least 3 m high in January 2000, prior to the damaging storm of 29 October 2000 (Forbes et al., 2004). In the latter storm, the surge peaked at 2.42 m chart datum at Escuminac (about 1.7 m above mean sea level) and was accompanied by very high waves that caused significant damage along the New Brunswick coast. Adding a conservative 1.5 m to the maximum storm-surge elevation to account for wave setup and runup, all parts of the spit below 3.2 m would have been subject to overtopping, and severe dune cut would have occurred almost along the entire length of the spit (Figure 10B). This is indeed what happened, as demonstrated by the complete removal of 3 m high dunes on the proximal spit (Forbes et al., 2004). This dataset highlights the increased vulnerability of barriers along the southeast New Brunswick coast following strong storm events in October 2000, November 2001, and December 2004, among others. The crest on parts of La Dune de Bouctouche is now considerably lower, leaving it exposed to potential overtopping in less severe storms.

Summary and discussion

The lidar surveys of 2003 and 2004 in southeast New Brunswick provided the high-resolution point sampling along the coast required to construct DEMs that enabled flood-risk and flood-depth maps to be built to model the impact of water levels up to 4 m above CGVD28. The data met the vertical specifications for the study. The flood extents and flood depths associated with the January 2000 storm surge have been qualitatively validated by field visits to sites where the water levels are known. The lidar DSM maps, in combination with the flood-extent and flood-depth maps, facilitated this work. The flood extents generally agree, and the flood depths are typically within 10 cm of observed water levels where observed in January 2000.

The modification of the lidar DEM by notching the roadbed to allow a hydraulic pathway to low-lying upstream areas has facilitated the use of automated scripts in the GIS to generate flood extents at water levels every 10 cm up to 4 m. This allowed near-continuous flooding simulations and animations. The ability to generate a full sequence of water levels allows the emergency-measures and planning officials access to more information for use in designing adaptation plans. The lidar DEMs proved valuable for analysis of flooding potential in natural estuarine settings as well, where the data are being used to evaluate the potential for salt-marsh migration or coastal squeeze.

The repeat lidar surveys for La Dune de Bouctouche highlighted the dynamic morphology of this system and changes that occurred over 1 year (Roberts et al., 2005). Extraction of crest elevations from the lidar DEM enabled an assessment of overtopping potential and risk of dune erosion under a variety of storm conditions. This analysis demonstrated that the sequence of storms since 2000 has partly cut down the crest elevation, resulting in higher vulnerability for the spit, including threats to low-lying areas occupied by the...
threatened Gulf of St. Lawrence aster. The impact on habitat availability for piping plover is less clear. Overall, at least 1.75 km of the ~12 km long spit has crest elevations below 2.5 m CGVD28, the peak surge level during the storm of 21–22 January 2000. The damaging storm of 29 October 2000, with runup estimated up to 3.2 m or higher, overtopped about 3 km of the spit and reached the base of dunes almost everywhere else. Very similar conditions pertained during the storm of 27 December 2004, but a concentration of slush in the nearshore may have reduced the runup height. Nevertheless, slush was deposited to a depth of at least 0.5 m over the barrier crest in the low area extending about 1 km from the start of the spit (Figure 10B).

In summary, this study demonstrates multiple applications of airborne lidar topographic mapping to assess flooding, overtopping, and erosion hazards. Furthermore, the resulting DEMs are valuable tools for assessing the potential impacts of accelerated sea-level rise under future climate change.

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