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elevation

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Contains a reprint of the artcle entitled:

Mapping Storm Surge Flood Risk Using a LIDAR-Derived DEM

by Tim Webster, Steve Dickie, Charles O'Reilly, Don Forbes, George Parkes, Don Poole, Rick Quinn

A Supplement to Geospatial solutions GPS WORLD

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ADVANSTAR COMMUNICATIONS

Mapping Storm Surge Flood Risk
Using a LIDAR-Derived DEM

Using a multidisciplinary approach, researchers produced flood-risk maps that the city of Charlottetown's Planning Department will use to assess the economic impact of storm surge events and develop adaptation strategies.

FIGURE 1 Charlottetown, Prince Edward Island, and part of maritime Canada.

Tim Webster, Steve Dickie, Charles O'Reilly, Don Forbes, George Parkes, Don Poole, and Rick Quinn

For the past 6,000 years, sea level around Prince Edward Island, Nova Scotia, Canada, has risen by about 0.2–0.3 meter per century (Parkes et al. 2002). With increasing concentrations of greenhouse gases, sea-level rise is expected to accelerate. In fact, the Intergovernmental Panel on Climate Change (IPCC) predicts that global average sea level may increase by 0.09–0.88 meter by the year 2100, placing the lives and property of 46 million people at risk (Houghton et al. 2001).

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Because the capital city of Charlottetown (see Figure 1) is vulnerable to coastal flooding associated with storm surge events, we selected it as the study area for a mapping project funded by the Climate Change Action Fund of the government of Canada (McCulloch et al. 2002).

Using LIDAR data collected during the summer of 2000, we constructed a digital elevation model (DEM) from which we could predict areas of inundation from storm surge events. Using climatology, oceanography, hydrography, and coastal geology data, we predicted flood levels and used this information for flood simulation modeling on the DEM. Using these models, we generated flood risk maps. We then used GIS to overlay the flood extents with the local infrastructure, including property ownership and building location layers, to assess the economic impact of such events.

Rising waters

Mean sea level has been increasing for the past several thousand years (Parkes et al. 2002). However, changes in local sea level will be different from the global average due to movement of the Earth's crust (Grant 1970).

The tide gauge data from Charlottetown are among the longest, most complete, and most reliable water level records in Canada. They indicate that the relative mean sea level rose at a rate of 32 centimeters in the 20th century since records began in the first decade of the 1900s (see Figure 2) (Parkes et al. 2002).

Crustal subsidence following postglacial adjustments to changing ice and water loads accounts for part of the long-term sea-level rise (perhaps 20 centimeters per century). The remaining 12 centimeters per century is a signal of global and regional sea-level rise. Storm surges and ocean waves are also factors at the coastline and are carried to higher levels on rising mean sea level. Even in the absence of climate change, the present rate of sea-level rise around Prince Edward Island will bring future challenges to human interests and ecological systems in the coastal zone.

Storm surge is generally defined as the algebraic difference between the observed water level and the predicted astronomical level (from tide tables). Scientists predict that many factors may cause increased storminess in the next 100 years (the general scale of this

FIGURE 3 **A pod containing the LIDAR and video system was fitted to the belly of this local helicopter. The GPS antenna is located halfway along the tail of the helicopter. The lower right inset shows the LIDAR operator controls. The inset in the upper left shows the inertial reference system used to measure the attitude.**

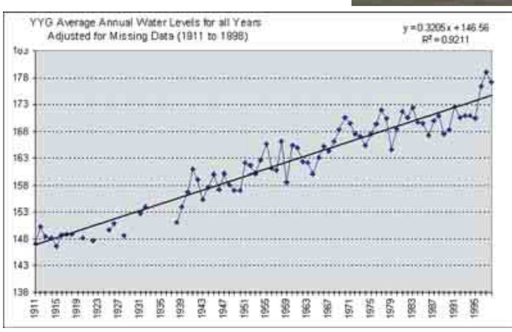


FIGURE 2 **The tide gauge record of Charlottetown from 1911 to 1998 indicates a relative sea-level rise of 32 centimeters in the last century.**

study). The combined effects of sea-level rise and climate change will lead to higher and more frequent flooding of the existing coastal areas and an increase in erosion of coastal features such as dunes.

IPCC estimates that flooding from storm surges threatens the lives and property of approximately 46 million people every year (Houghton et al. 1996, 2001). The coast of Prince Edward Island was initially targeted for this climate-change study in part because it was identified in a recent *Geological Survey of Canada Bulletin* (Shaw et al. 1998) and in previous work from the Canada Country Study on Climate Impacts and Adaptation as one of the regions most sensitive to sea-level rise (Lane & Associates 1986 and Lewis 1997). Factors contributing to this sensitivity include a soft sandstone bedrock, a sandy and dynamic shore zone (but sediment-starved in places), 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.

Geomatics technology

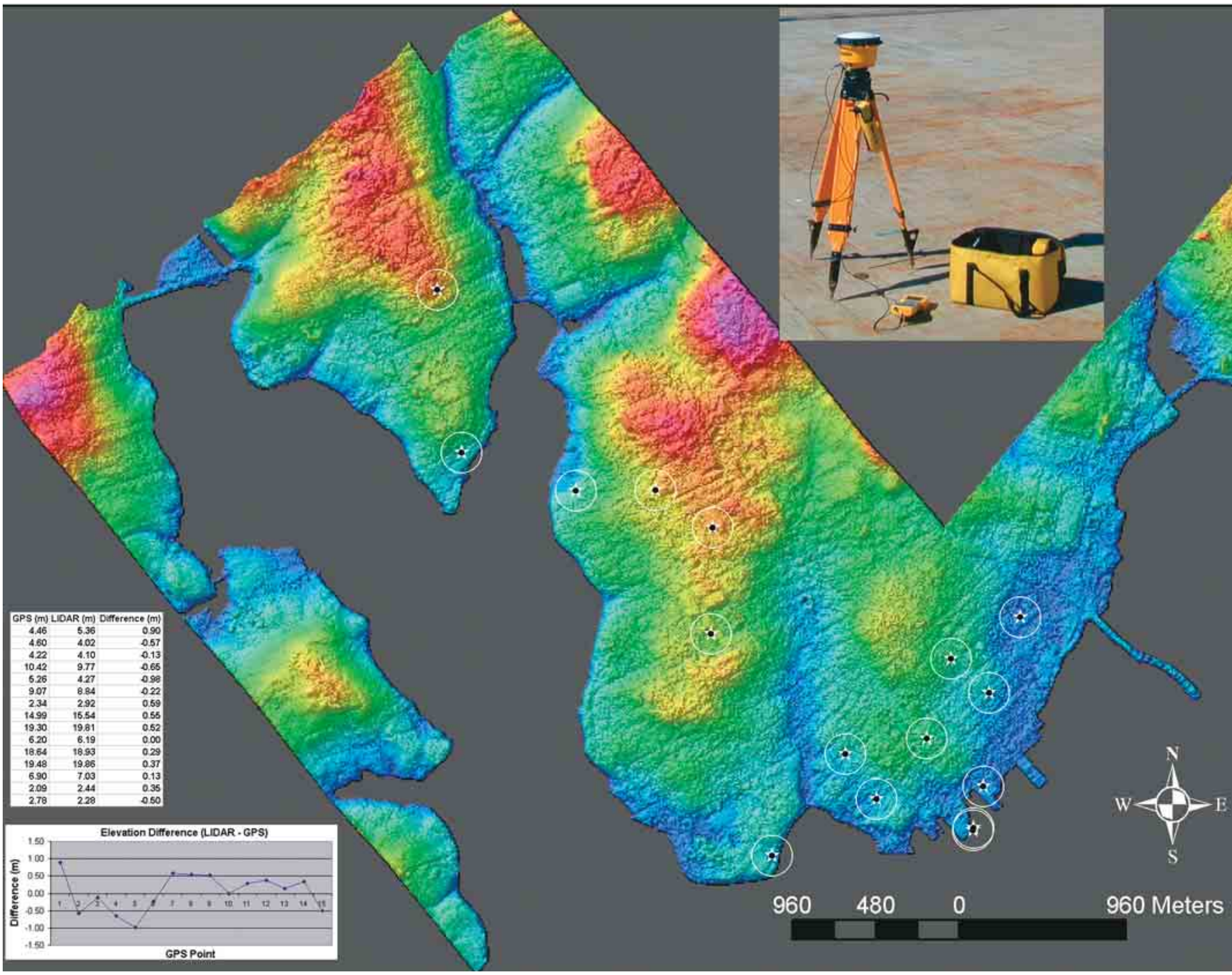
To predict areas at risk to coastal flooding associated with storm surge events we chose LIDAR to obtain a high-resolution, accurate representation of the topography. With LIDAR, an airborne system emits laser pulses toward the ground and measures the return time of the pulses; from this a range is calculated. By using precise GPS technology to determine the location of the aircraft and an inertial reference system (IRS) to measure the attitude (pitch, yaw, and roll) of the aircraft, we can determine the location of individual laser returns.

Terra Remote Sensing of Sidney, British Columbia acquired LIDAR information for part of Charlottetown and the North Shore of Prince Edward Island. They used a helicopter based in Nova Scotia and local GPS control on Prince Edward Island to complete the survey on August 1–2, 2000 (see Figure 3). To assist in interpreting the LIDAR returns, we collected down-looking video simultaneously with the laser data.

The reported accuracy of the overall system is quoted at ±30 centimeters in the horizontal plane and ±20 centimeters in the vertical. Terra RS used a diode-pumped, infrared, yttrium–aluminum–garnet (YAG) solid-state laser pulsed at repetitions up to 10 kHz, scanning at right angles to the aircraft flight path to a maximum scan angle of 57°. We determined laser range distances to a resolution of 0.05 meter and positioned individual shots with a mirror and attitude data from the IRS. The pilot positioned the aircraft using phase kinematic GPS, referenced to a geodetic ground monument north of Charlottetown Airport.

The LIDAR system produces a series of point measurements with associated heights above the ellipsoid. The ellipsoid is a smooth mathematical surface representing the Earth. The height above the ellipsoid is related to the GPS navigation method that uses the WGS 84 (World Geodetic System of 1984) ellipsoid as the reference datum. To relate the height measurements to a geodetic reference (the geoid or approximate mean sea level), an adjustment must be made between the ellipsoid and geoid separation. Elevations on most land-based topographic maps are orthometric heights measured relative to a geodetic datum. For Canada this is known as the CGVD 28 (Canadian Geodetic Vertical Datum of 1928). The separation model between the WGS 84 ellipsoid and the CGVD 28 geoid model is known as HT1_01E, with a reported accuracy of ±5 centimeters produced by the Geodetic Survey Division of Natural Resources Canada.

The firm that acquired the LIDAR data agreed to produce three sets of ASCII files on CD: all laser returns, ground-only returns, and nonground returns representing buildings and vegetation. Each file



GPS (m)	LIDAR (m)	Difference (m)
4.46	5.36	0.90
4.60	4.02	-0.57
4.22	4.10	-0.13
10.42	9.77	-0.65
5.26	4.27	-0.98
9.07	8.84	-0.22
2.34	2.92	0.59
14.99	15.54	0.55
19.30	19.81	0.52
6.20	6.19	0.00
18.64	18.93	0.29
19.48	19.86	0.37
6.90	7.03	0.13
2.09	2.44	0.35
2.78	2.28	-0.50

FIGURE 4 We constructed this bald-Earth DEM from the ground LIDAR hits. GPS validation points (black stars with circles) are overlaid. The table in the lower left (top) shows the differences in orthometric height between the GPS points and the DEM. The graph on the lower left (bottom) indicates an average difference of 4.1 centimeters between GPS points and the LIDAR surface.

contained five columns for each LIDAR point: UTM easting (*x*), UTM northing (*y*), height above the ellipsoid (WGS 84), orthometric height (above the geoid CGVD 28, *z*), and GPS time (seconds from midnight for each day). The GPS time is not usually part of the data delivered by the vendor; however, we needed this information to determine which LIDAR points were flown in specific flight lines. Also, if problems are encountered in the dataset (bad GPS positions, for example), the time tag can be used to extract those points from the dataset.

LIDAR validation

We compared elevations of the wharf and water levels derived from a tide gauge with the LIDAR elevations. We determined that the LIDAR was on average 0.9 meter too low, and made an adjustment of 0.9 meter to the LIDAR elevations. (We also observed a lack of returns from dark targets, such as asphalt on roads and building roofs — a result of a power loss in the LIDAR during the survey and the lower reflectance of the near-infrared laser energy by such targets.) To ensure this vertical adjustment to the LIDAR was appropriate, we carried out a follow-up high-precision GPS data collection in Charlottetown in the summer of 2001.

We collected 15 points throughout the LIDAR coverage area and processed those points using carrier-phase information, providing centimeter-level accuracy. We selected grass-covered flat fields in city parks for the GPS data collection to ensure there would be a sufficient number of LIDAR returns in these areas to provide a detailed ground surface.

We converted the GPS elevations from ellipsoid heights to orthometric heights using the HT1_01E geoid/ellipsoid separation model. We adjusted the LIDAR ground orthometric height values by adding the 0.9-meter offset and built a ground surface DEM. (The details of the DEM construction are discussed in the next section.) We could then compare the GPS orthometric heights with the LIDAR-derived DEM ground surface orthometric heights. We overlaid the GPS points on the DEM surface in a GIS and calculated the orthometric height differences between GPS and the LIDAR surface (see Figure 4). The average difference between the orthometric heights was 4.1 centimeters, indicating that the adjustment of 0.9 meter was appropriate.

Flood simulation modeling

We used the ground LIDAR points to construct a triangular irregular network (TIN) based on the orthometric height. We gridded the TIN to a 2-meter cell resolution and clipped it to the shoreline and data extents, thus removing the erroneous surface values in the water and areas of no data. Visual examination of this image in combination with the ground LIDAR point data revealed that

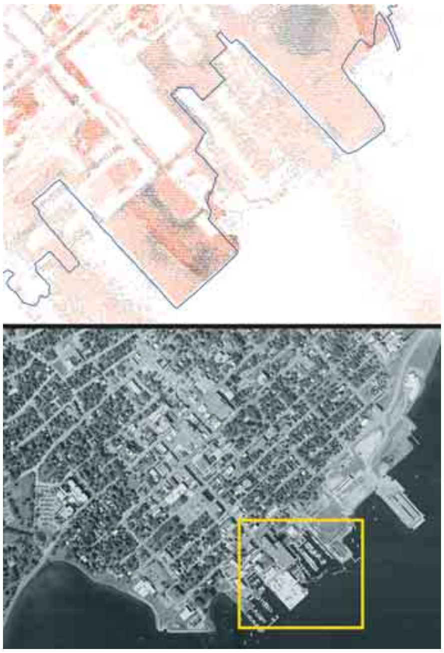


FIGURE 5 This image (top) represents all LIDAR returns, with black coded as ground hits and red as nonground (buildings or vegetation). Notice that most of the points around the edges of the waterfront are coded as nonground. In the aerial photo taken in 2000 (bottom), the yellow box corresponds with the area of LIDAR points in the top image. The lack of points corresponds to areas of asphalt. Aerial photo source: www.gov.pe.ca/mapguide/aerial/mapwindow_new.php3.

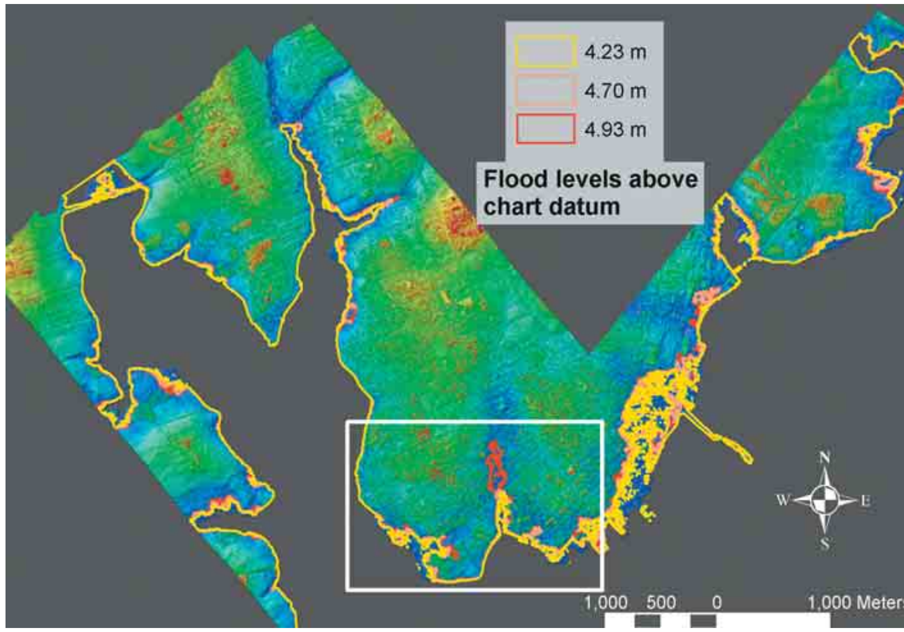


FIGURE 6 The three modeled flood extents are layered over the color shaded relief image of the LIDAR DSM for Charlottetown (yellow=4.23 meters, orange=4.70 meters, and red=4.93 meters above Chart Datum). The flood modeling was done on the modified bald-Earth DEM; however, the DSM is used to visualize the results. The white box corresponds with the area illustrated in Figure 7.

many of the laser returns along the waterfront, specifically on wharves, docks, and seawalls, had been removed. The automated cleaning routines applied by the LIDAR firm's software categorized many of these LIDAR returns as nonground (vegetation or buildings). This resulted in most of the laser hits along the edge of the waterfront being removed from the ground dataset. For example, the laser returns from the water would be coded as ground hits, while the edge of the wharf would be coded as nonground and the central region of the wharf would be coded as ground again (see Figure 5). As a result, the ground surface constructed from hits along the water surface and hits in the central regions of the wharves resulted in the wharves having sloping sides, as opposed to steep vertical sides. Because the gridded surface was intended to simulate a storm surge event and sea-level rise, it was critical to accurately represent the waterfront. To solve this problem, we examined ground and nonground points and extracted those representing hits on the waterfront structures to construct a new TIN and a new gridded surface for the waterfront using linear interpolation. We merged the new waterfront grid with the existing ground grid, producing a more realistic surface representation.

In addition to the ground DEM (to be used for flood simulation), we constructed a digital surface model (DSM) from a combination of all the LIDAR returns to represent the ground, trees, and buildings present. We used this DSM to visualize the flood extents that were determined from the ground DEM.

We defined water levels resulting from storm surge events with respect to height above Chart Datum. Chart Datum is a locally defined vertical reference that represents the lowest water level at lowest tide. We selected three water levels for use in the modeling scenario: 4.23 meters, 4.70 meters, and 4.93 meters above Chart Datum. The first flood level was observed during a January 21, 2000, storm surge event, in which significant coastal flooding was observed. The 4.70-meter level represents the January 21, 2000 storm plus a scenario for 50 years of relative sea-level rise. The 4.93-meter level represents the January 21, 2000 storm plus a scenario for 100 years of relative sea-level rise (see Figures 6 and 7). We converted the flood levels to heights above geodetic datum because the LIDAR surface represents orthometric heights above the geodetic datum. We took the Chart Datum to be 1.69 meters below geodetic datum (CGVD 28) provided by the Canadian Hydrographic Service, Department of Fisheries and Oceans for this area. We also used the flood extents to determine the economic impact of future storm surges.

We integrated the predicted sea-level rise levels with the LIDAR DEM to produce flood risk maps. The extents of the flooded areas were constrained to be connected with the ocean; in other words, low-lying areas inland that may be below the water-level threshold were not flooded if they were not connected to the ocean. In situations where culverts connected low-lying areas, we consulted city engineers to determine if those areas should be included or not. The predicted flood levels for the January 2000 storm agreed well with those that were observed during the event. We then overlaid the flood extents in a GIS on the local infrastructure, property ownership, and building location layers to assess the economic impacts of such events (see Figure 8).

Predicting Charlottetown's future

Charlottetown city planning officials have used this information on flood risk to adapt some of their building permit procedures and long-term adaptation strategy for the city. It coincided with the area's first major sea-level rise due to a storm surge effect from the storm in January 2000. Prince Edward Island has received at least two other major storms since 2000. Charlottetown was fortunate

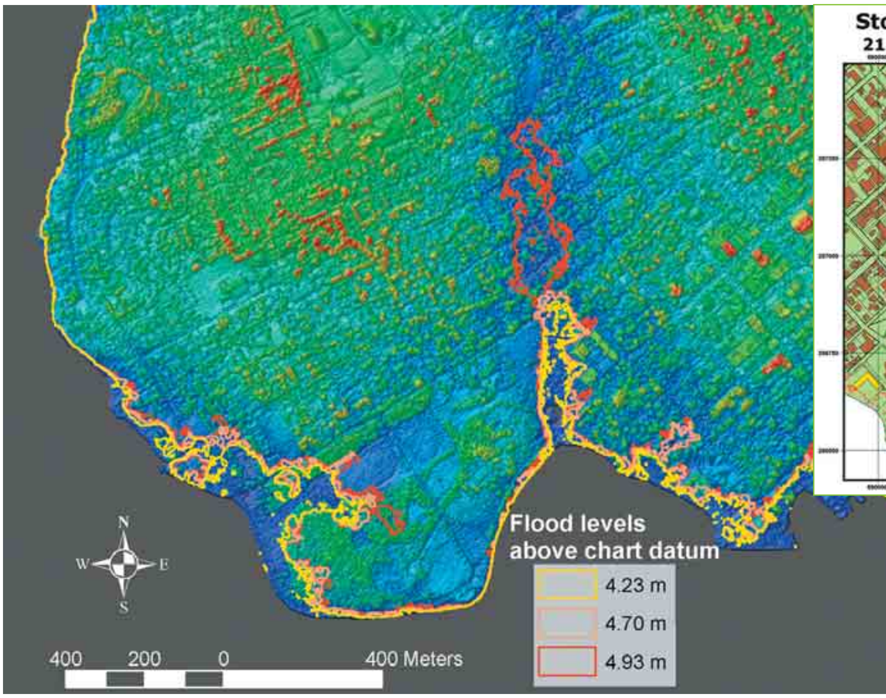


FIGURE 7 **Close-up of the three flood extents for the waterfront area of Charlottetown. The image is a color shaded relief of the DSM.**

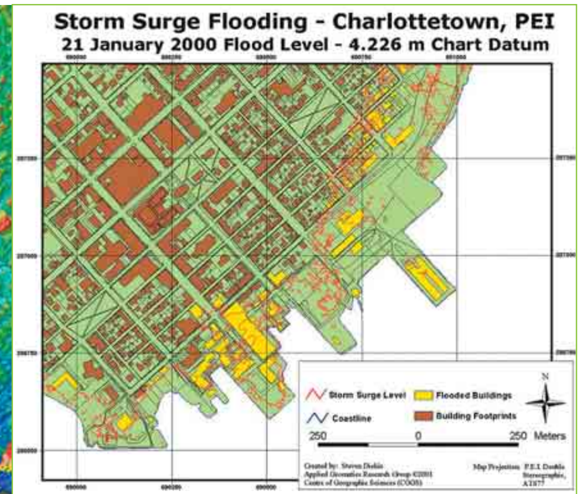


FIGURE 8 **For this GIS overlay of the flood extent with the building footprints, we used assessment values of the buildings to calculate the possible economic impact of such an event.**

to have only minor flooding. The city's past history of development was oriented to the water and many older buildings, street systems, and municipal services run to the water. In recent years the city has developed boardwalks and parks on the waterfront.

Charlottetown has placed the modeling data on its local GIS (ESRI ArcInfo); this has allowed the city's planning department to show developers what the future predictions of sea-level rise will have on any given area over the life of a building. The city has carried out some research on bylaws that are used for flood-prone areas and, in the short term, is looking into adopting some measures to restrict specific development in areas that are prone to sea-level rise. In the long term there is considerable infrastructure (municipal sewer and water, streets, buildings, and so on) in the predicted sea-level rise areas; but the city has yet to decide on what methods or combination of methods to use — protecting, adapting, retreating — from the sea-level rise and future storm surges.

Manufacturers

To create Charlottetown flood-risk maps, the team used LIDAR data collected and processed by **Terra Remote Sensing Inc.** (www.terraremote.com). To validate the data, we conducted ground surveys using **Trimble** (www.trimble.com) GPS receivers (models 4000, 4600, and 4800). For analysis of the LIDAR and building of the flood risk maps, the data was processed using a combination of **ESRI**'s (www.esri.com) ArcInfo GIS and **PCI Geomatics**' (www.pcigeomatics.com) image processing tools on a Unix-based workstation.

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