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Abstract

A Halifax Harbour Plan is being developed within the context of the 25-year Regional Municipal Planning Strategy in the Halifax region of Nova Scotia. This strategy recognizes the importance of climate change and the need for a precautionary approach to minimize negative impacts of rising sea level. Airborne LiDAR data were acquired in 2007 to produce a high-resolution digital elevation model (DEM) as a basis for mapping flood limits. The selection of flood levels for adaptation planning required an understanding of present and future sea-level rise (SLR), vertical land motion, extreme water levels (combined tide and surge), harbour seiche and wave runup. Relative sea level in Halifax Harbour has risen at 3.2±0.13 mm/a since 1920 through a combination of regional subsidence (1.6±0.3 mm/a) and local SLR (~1.6 mm/a). Scenarios of future extreme water levels were developed using (1) current local SLR, (2) the upper limit of the 2007 IPCC projections, and (3) a higher projection based on a growing scientific consensus that the IPCC upper limit may have been overly conservative. These projections of SLR (0.16, 0.59, and 1.3 m over ~100 years) were combined with regional subsidence and extreme water levels for 2-, 10-, and 50-year events derived from a generalized extreme values distribution of annual extreme water levels in Halifax Harbour. The resulting water levels were applied to the LiDAR DEM to visualise the extent and depth of flooding for each event. A plausible upper limit with very low probability was developed by superimposing the record storm surge on the highest tide with a sea-level rise of 1.3 m. A buffer ranging from 1 to 2 m was considered to account for observed values of seiche and wave runup in various parts of the harbour. This study provides the scientific basis for a set of plausible scenarios for a 100-year planning horizon, but the choice of water level for planning purposes is a policy decision.

Introduction

After more than 90 years of ongoing tide-gauge measurements in Halifax Harbour (and more than 110 years since the tide gauge was installed in 1895), it is clear that mean sea level as measured at the gauge has been rising continuously over that time (Grant, 1970; Forbes et al., 2008). Furthermore, there is now wide consensus that the global climate is warming and that this warming will result in accelerated sea-level rise and other consequences such as changes in storm intensity and possibly frequency, with serious implications for coastal residents and stakeholders (IPCC, 2007a, 2007b).

The Halifax Regional Municipality (HRM) has been a leader among Canadian municipalities in climate-change planning (Mehdi et al., 2006). The HRM Regional Municipal Planning Strategy (RMPS), adopted by Council in August 2006, included policies to address climate change. The RMPS recognized the effects of climate change, including sea-level rise and storm surges, on Halifax Harbour and other coastal areas in HRM and endorsed the precautionary principle as an important policy consideration. The harbour (Fig. 1) is a globally competitive seaport with billions of dollars in existing infrastructure and ongoing commercial, residential, and recreational development. A need was recognized to gather appropriate scientific data on the harbour shoreline, future sea levels, flooding hazards and vulnerability to incorporate climate-change issues and adaptation measures into the new Halifax Harbour Plan.

This discussion paper arose from a September 2008 meeting of the informal science advisory panel for development of the Halifax Harbour Plan. Under the direction of Roger Wells, the lead planner for the harbour plan, the objective of that meeting was to decide on an approach for selecting extreme water-level scenarios to be used in presentations to major stakeholders, HRM Council and the general public. The intent was to select appropriate levels to provide policy guidance within the new harbour plan and to reduce the vulnerability of future development around the harbour.

Objectives

The objectives of this report are four-fold:

- to describe the process used to simulate flooding hazards by virtual flooding of a digital elevation model (DEM) derived from LiDAR (airborne laser altimetry) surveys (Figs 2 and 3);

- to summarize information on current rates of relative sea-level rise and land subsidence in the Halifax region;

- to describe the approach used to develop scenarios for future sea-level rise and associated extreme water levels under a warming climate; and

- to present the scenarios and resulting levels used to derive the flood limits by virtual flooding of the DEM.

Limitations

This paper is based on the best available evidence at the time of writing. Estimates of sea-level rise and crustal motion will improve over time, as will our understanding of future climate trends and their implications. We cite the results of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) as the best published scientific consensus (IPCC, 2007a). However, new insights developed and published since 2006 suggest that the AR4 projections of sea-level rise were conservative and that the global mean sea level is likely to rise more rapidly than the upper limit projection in the AR4. We present some of the evidence for this conclusion in a later section.

Any number of scenarios for future sea-level rise and extreme water levels could be developed. Scientific data can inform the policy discussion, but in the end the choice of scenarios to be used for planning purposes is not a scientific result but a policy and community decision. Best practice suggests that it

should follow a precautionary approach in the face of evidence pointing to potentially significant impacts without adaptation. This paper presents the scientific basis for computation of water levels corresponding to three policy options selected for discussion purposes.
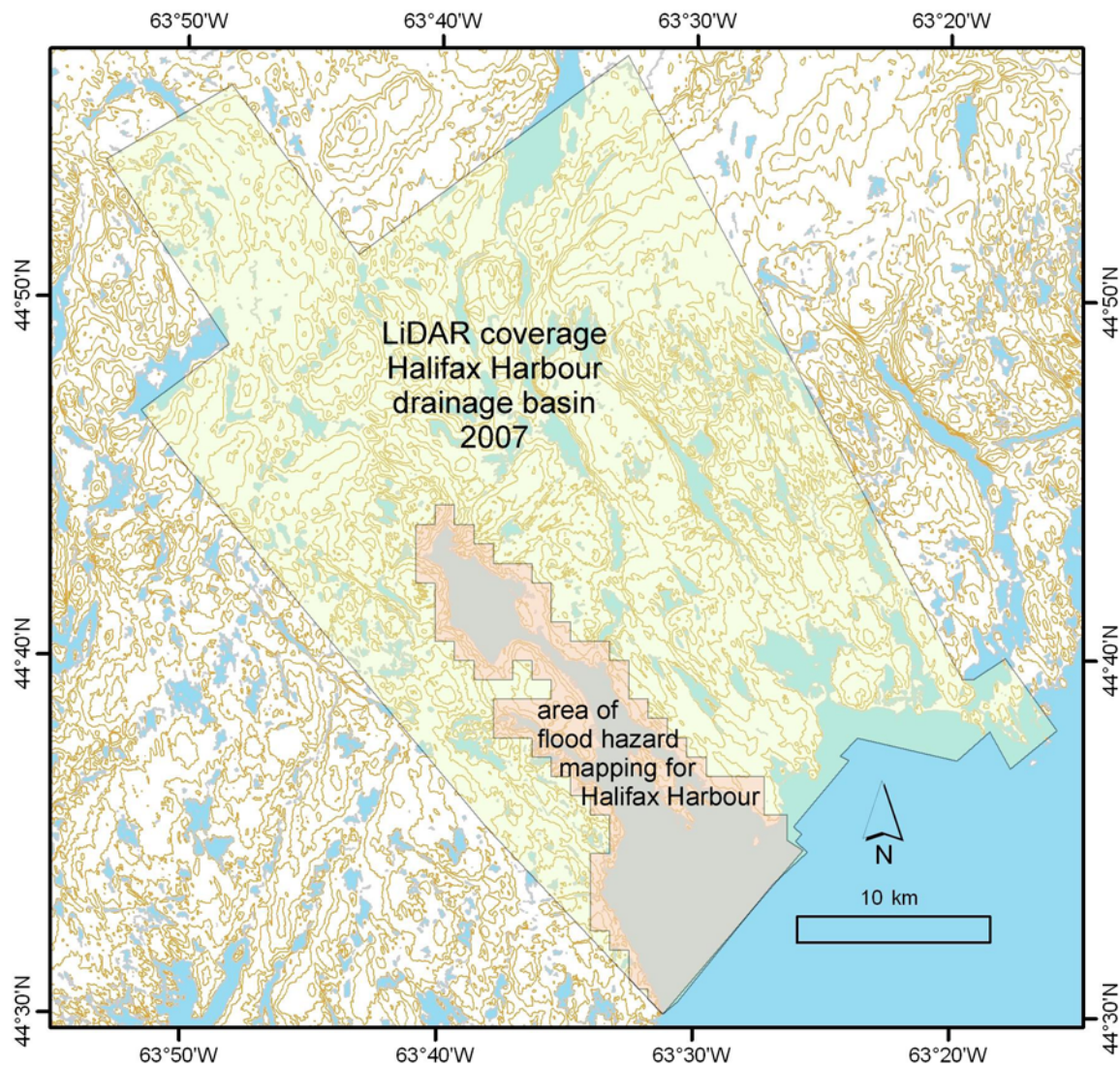
Fig. 1. Halifax Harbour, showing extent of 2007 LiDAR coverage for harbour drainage basin and subset used for flood hazard mapping in the harbour (see Fig. 2).
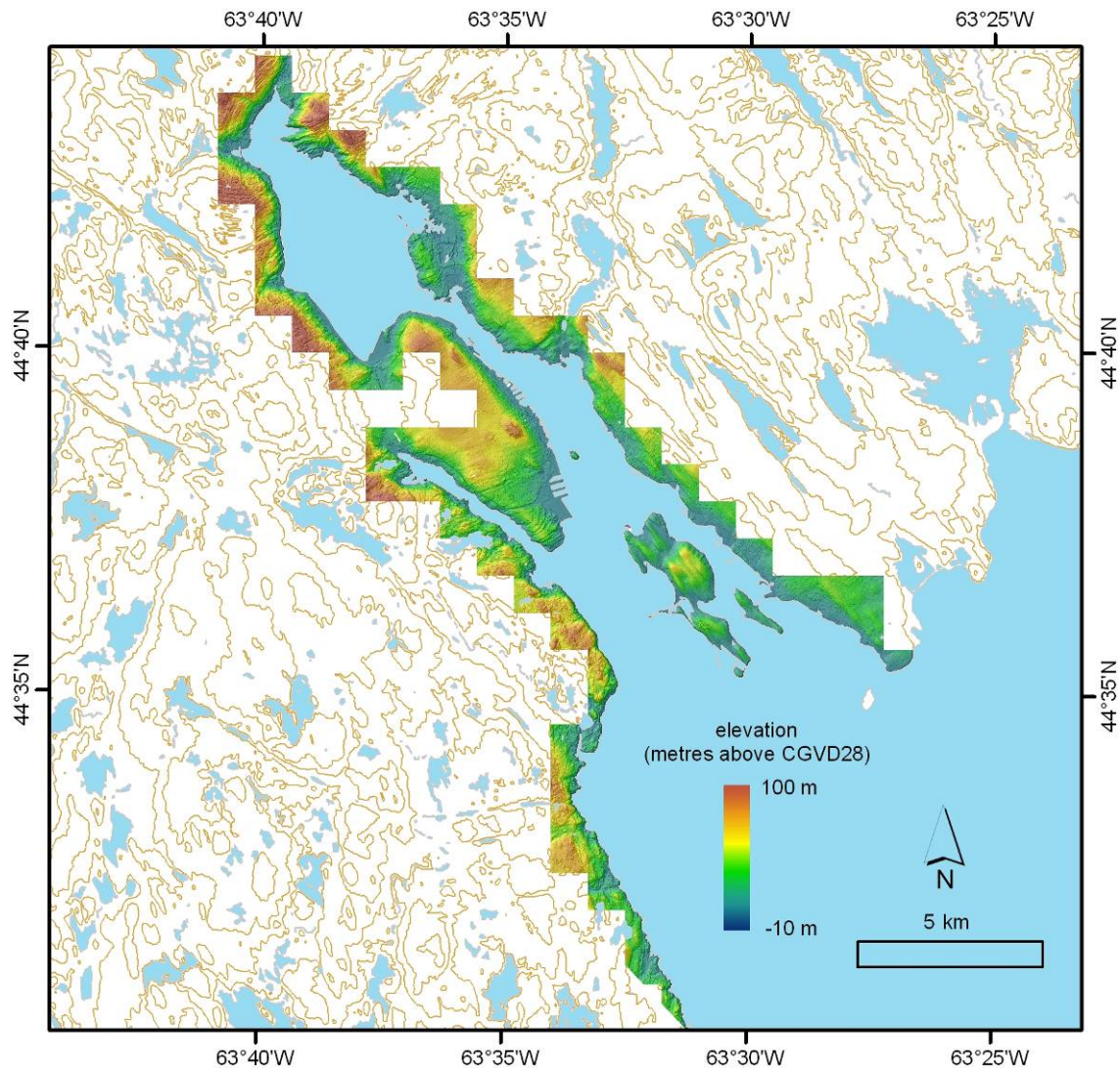
Fig. 2. Subset of 1 km^2 tiles forming digital elevation model
created for flood hazard mapping in Halifax Harbour.
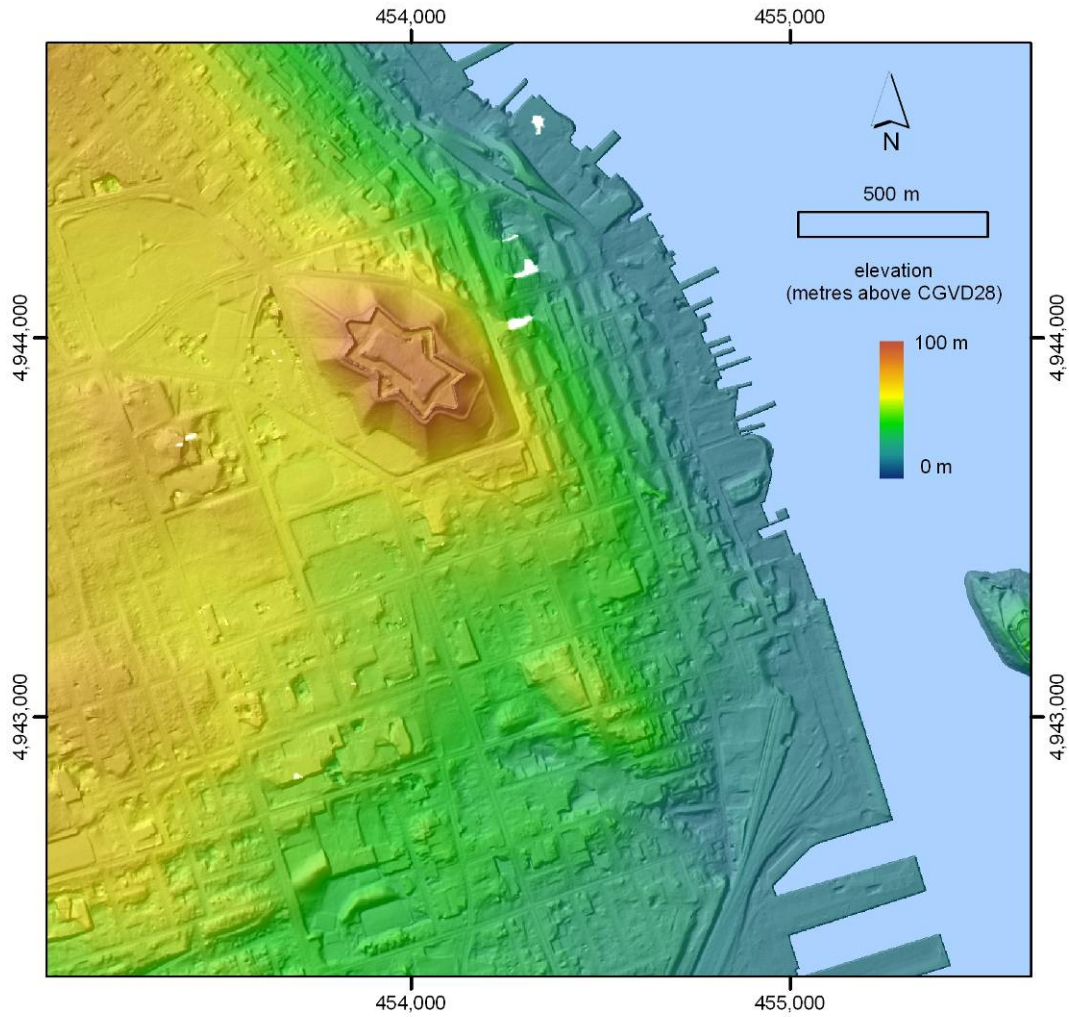
Fig. 3. Part of the 'bare-earth' digital elevation model for downtown Halifax with part of Halifax Harbour, derived from the LiDAR survey data. This is a colour-coded shaded-relief image, where the colours denote elevation, from dark blue (sea level) to green, yellow, and orange (higher elevation). The water mask is pale blue. Coordinates represent UTM zone 20 easting and northing in metres (NAD83 [CSRS]). Vertical datum is CGVD28.

Policy options

We have selected three scenarios for high water levels as a basis for discussion and adaptation planning. These are:

> 1 – a relatively low level (highly conservative projection with very high probability of exceedance: low adaptation cost, high risk of negative impacts with adaptation to this level);

> 2 – a medium level (high probability projection: moderate adaptation cost, moderate risk of negative impacts with adaptation to this level);

> 3 – a high level (plausible high projection with low probability of exceedance: higher adaptation cost, lower risk of negative impacts with adaptation to this level).

Scenarios 1, 2, and 3 correspond to three different projections of sea-level rise. The extreme water levels associated with each of these scenarios involve storm surges (meteorological increases in water level over and above the tide level) defined in various ways. For the first two scenarios, three sub-options were selected to represent high water levels superimposed on higher sea level. These correspond to storm-surge events associated with annual extreme hourly water levels with return intervals of 2, 10, and 50 years. For the third scenario, two sub-options were selected: a 50-year event and a realistic 'upper bound', the latter combining the record storm surge (Hurricane Juan) with higher high water level at large tides, a combination with a very low joint probability.

Mapping future flood levels

Digital Elevation Model

The flood extents associated with each of the water-level options were determined by flood simulation in a GIS, using a high-resolution digital elevation model derived from airborne topographic LiDAR (Light Detection and Ranging)[a] data (Fig. 3). This involves an infrared laser beam which scans back and forth beneath the aircraft, providing a swath of laser hits for which the horizontal and vertical coordinates (position and elevation) can be determined. The position and attitude of the aircraft are determined using differential GPS and an inertial motion sensor. These provide the location and orientation of each laser pulse. The distance to any point of light reflection is determined by the two-way time of travel combined with the speed of light. Together these data provide the position of each laser hit with a horizontal precision of about ±0.3 m and vertical precision of ±0.15 m or better. Similar surveys have been undertaken elsewhere in the Maritimes over the past decade for the purpose of modelling coastal inundation under storm surges superimposed on rising sea levels (e.g. Webster and Forbes, 2006; Webster et al., 2006; Bernier et al., 2007)

A LiDAR survey was undertaken in the spring of 2007 after snowmelt and prior to full leaf-on to develop a bare-earth digital elevation model as a basis for flood-hazard mapping around Halifax Harbour. The data acquisition was handled under contract by PHB Lasermap (HRM Tender 07-033, http://www.halifax.ca/council/agendasc/documents/070320ca1112.pdf) and funded by HRM with contributions from the Nova Scotia Department of Energy and the Halifax Port Authority and in-kind contributions from other partners, including Natural Resources Canada. The bare-earth model was developed from the initial surface elevation model (which includes vegetation and buildings) by classifying individual laser hits as on-ground or off-ground and removing the latter from the model. The combined models have numerous potential uses, including modelling of surface water drainage, mapping of surficial geology, quantification of urban tree canopy, determination of cut and fill for development

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[a] Also known as 'scanning laser altimetry'.

projects, or view-plane analysis, to name but a few that have been applied in HRM. The survey coverage acquired in 2007 included the entire drainage basin of Halifax Harbour (including a portion of Hants County) and additional coverage along the Eastern Shore, including a large block from Chezzetcook to Jeddore extending inland to Musquoidoboit Harbour. The total area amounted to about 1393 km^2.

Validation surveys using differential GPS tied to geodetic monuments were undertaken in 2007 and 2008, providing numerous check points surrounding the harbour to validate the positions and elevations in the DEM. Validation analysis completed to date indicates excellent quality almost entirely within the ±0.15 m vertical specification in the contract and in many cases much better.

The validity of the flood simulations can be assessed by modelling historical events for which flood extents are known. This was done for Hurricane Juan, but the simulated flooding was less extensive than observed (Fig. 4). The peak storm surge in Hurricane Juan did not coincide with high tide and the maximum water level could have been 0.8 m higher if it had coincided with higher-high water at large tides (HHWLT). We simulated flooding at this level and found that the flood limits were closer in some areas to what was observed, due to seiche, runup, and overtopping that ranged from <0.4 m to more than 1.7 m above the peak stillwater level (see later sections).

Fig. 4. Debris deposited on and beneath undercut CN rail line at Dartmouth Point on the morning after Hurricane Juan. Runup here was 1.64 m above the highest water level recorded at the Halifax tide gauge across the harbour. Note that water level remains unusually high at the time of photography. Photo: DLF/GSC, 2003-09-29.

Vertical datum and water levels

The definition of vertical datum is critical to any discussion of tides and flood levels. Navigation charts use a local datum defined to be close to lower low-water at large tides (i.e. rarely uncovered). The water levels recorded at the Halifax tide gauge and the tidal predictions in the published tide tables are all

referred to this local Chart Datum (CD). Mean sea level (MSL) lies above Chart Datum. The Canadian Geodetic Vertical Datum 1928 (CGVD28) was originally defined as mean sea level measured in 1928 at two tide gauges on the Pacific coast and three on the Atlantic coast, one of which was Halifax. The mean sea level at Halifax in 1928 was 0.79 m above present Chart Datum, effectively the same as the 0.8 m separation between CD and CGVD28 (Fig. 5). Mean sea level is now above CGVD28 (Fig. 5) with a mean of 1.02 m CD and standard deviation of 0.02 m over the 5 years 1999-2003. A value of +0.20 m CGVD28 for 2001 is adopted in the development of scenarios below. MSL in 2001 was in fact 1.04 m CD or 0.24 m CGVD28, so we may have introduced a slight (2-4 cm) low bias in the flood estimates. Because, as these data show, mean sea level has been rising against the coast in the Halifax region, Chart Datum was redefined in 1987 to be 0.29 m higher than before (Fig. 5). Higher high water at large tides (HHWLT) is 2.1 m CD (1.3 m above CGVD28) and the record water level in Halifax Harbour (during Hurricane Juan in 2003) was 2.91 m CD (2.11 m above CGVD28).
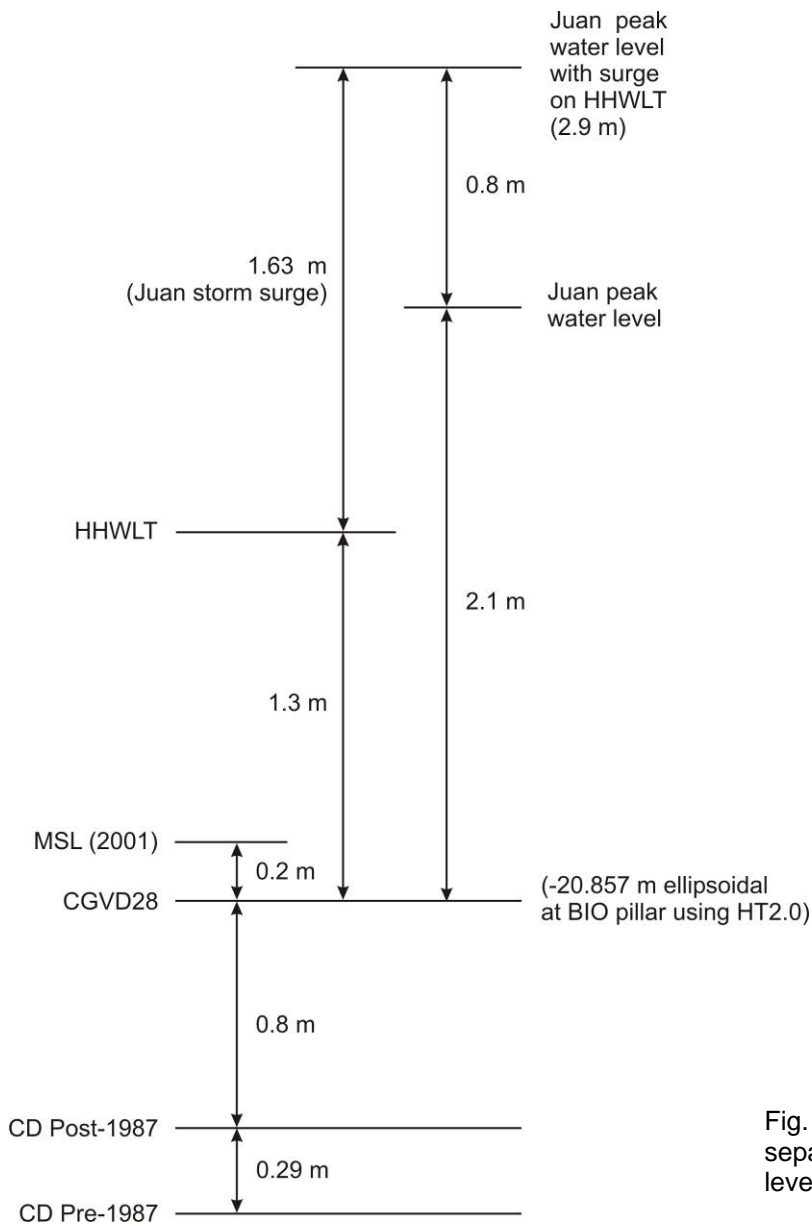

Fig. 5. Vertical datums and separations with key water levels in Halifax Harbour.

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All water-level data in this report are referenced to the present (post-1987) Chart Datum or to CGVD28 (which is unchanged). The data were obtained from the on-line data base maintained by the Canada Department of Fisheries and Oceans (http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/index-eng.html, most recently accessed 2009-10-09).

Projecting extreme water levels

Components of extreme water level are:
- rising mean sea level,
- land subsidence,
- storm surge (including tide-surge interaction),
- wave setup and runup, and
- harbour seiche.

Each of these components is considered below.

Extreme water levels during storms

We have two ways of estimating extreme water levels during storms. The first is to look at the storm surge (difference between observed water level and tidal prediction). The maximum surge observed in Halifax Harbour occurred during Hurricane Juan in 2003. It reached 1.63 m at 00:00 AST 29 Sep 2003 (from 15-minute tide-gauge data), 15 minutes after the maximum 15-min water level of 2.91 m CD (2.11 m CGVD28) at 23:45 AST 28 Sep 2003. In the hourly water-level record, the maximum water level was 2.84 m CD (2.04 m CGVD28) at 00:00 AST 29 Sep 2003.

The next highest surge in the 1919-2007 Halifax hourly tide-gauge record was 1.23 m during an event in December 1934. Had either of these surges coincided with a high spring tide, the total water level would have greatly exceeded anything in the existing record dating back to 1920 and earlier. Adding the record Juan storm surge to the highest astronomical tide level provides an extreme storm scenario.

The other strategy for estimating extreme storm levels is a probabilistic approach using an annual extreme values analysis. The extreme values are detrended by subtracting the annual mean water level from the annual extreme level (hourly data) and a plot is produced showing the water levels associated with varying probabilities or return periods (Fig. 6). From the record of observed water levels (1920-2007), we can select a water level corresponding to any chosen return period from 2 to 88 years (the water level in Hurricane Juan was the highest in this time interval and by extrapolation of a best-fit curve was approximately a 100-year event). In the scenarios below, we take a level for a typical strong nor'easter (2 year return period), a less frequent large storm (10-year return period), and a rare but not exceptional event (50-year return period).

In additon to the components of water level discussed above, harbour seiche and wave setup and runup can increase the elevation reached by water during a storm. Seiche effects (longitudinal and transverse oscillations determined by the basin dimensions) have been observed in Halifax Harbour with amplitudes of 0.3 m or more (P. MacAulay, Canadian Hydrographic Service, pers. comm., 2009). Differences in the maximum water level observed during Hurricane Juan between the Halifax tide gauge in HMC Dockyard and another gauge at the Bedford Institute of Oceanography (BIO) may be attributable to seiche effects induced by the storm surge. The peak (15 minute) water level in Hurricane Juan at BIO was 0.21 m higher and 15 ± 7.5 minutes later than the peak at the Halifax gauge. Extreme water levels at the Halifax gauge incorporate seiche but levels elsewhere in the harbour may differ due to basin oscillation. Wave runup is a function of wave conditions, exposure, and shore slope and roughness. The elevations of wave

wash limits around the harbour were surveyed after Hurricane Juan and levels were measured up to 1.7 m higher than the peak water level at the gauge (see section on wave runup below).
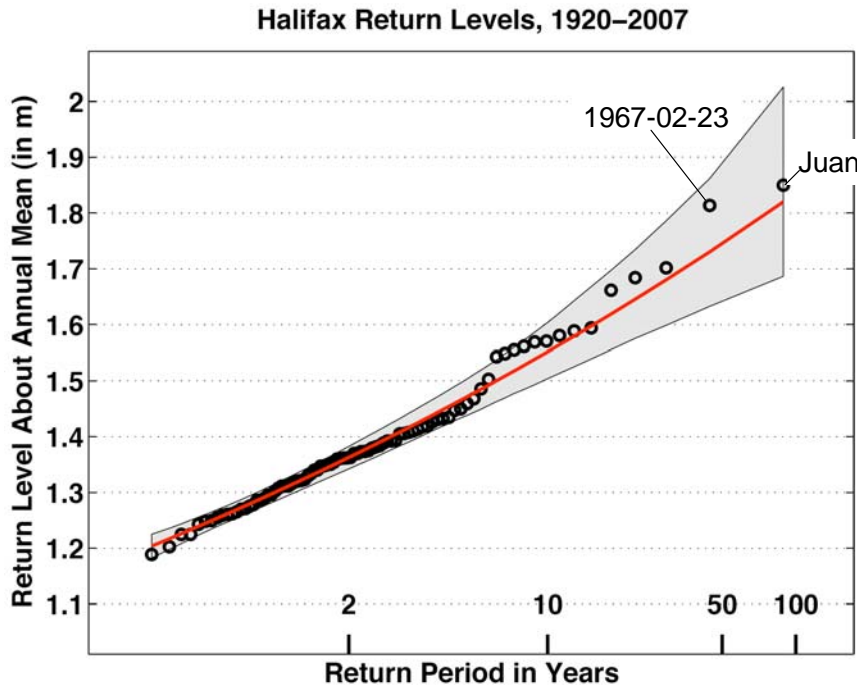

Fig. 6. Annual extreme water levels (hourly) at the Halifax tide gauge, 1920-2007 (values relative to annual mean), with generalized extreme values distribution and 95% confidence limits. Note record water level in hurricane Juan and previous record in February 1967.

Mean sea level and subsidence

Global mean sea level is not flat. The geographic variation in mean sea level (also called the mean dynamic topography of the ocean) has a relief of about 1.8 m around the globe (http://www.aviso.oceanobs.com/en/home/index.html, accessed 2009-01-28). Regional and local mean sea level may therefore deviate from the global mean sea level (equipotential surface or geoid). The regional or local rate of sea-level rise may also differ from the rate of global mean sea-level rise. This will result from differential steric effects (see below) and also from gravitational and other geodynamic effects associated with water contributions from melting of land-based ice (e.g. Mitrovica et al., 2001, 2009). The latter may reduce the rate of sea-level rise in the Halifax area by about 78% for contributions from the Greenland Ice Sheet and 10% for global contributions from glaciers and ice caps, while it will increase local sea-level rise by 8% for contributions from the Antarctic Ice Sheet. The combined effect depends on the relative proportions of meltwater contributions from the three sources. The scenarios presented in this report exclude these adjustments.

Rising global mean sea level consists of two components, a *eustatic* component related to the total mass of water in the ocean basins (e.g. additions from melting glaciers, ice caps, and ice sheets; losses from storage in reservoirs), and a *steric* component related to the water volume (resulting from changes in temperature and salinity). An analysis of monthly mean water level at Halifax from 1919 to 2006 shows a rising trend of 3.20 ± 0.13 mm/a (Forbes et al., 2008). This is the so-called 'relative' sea-level rise because it is the change in water level relative to the land surface. In other words, it is a combination of local sea-level rise and land subsidence.

The rate of crustal subsidence in the Halifax area has been measured since 2002 at a continuously operating GPS site maintained by the Geodetic Survey Division of Natural Resources Canada at the Bedford Institute of Oceanography in Dartmouth, NS (Forbes et al., 2008). The latest ITRF2005 solution for vertical motion at this site from the International Earth Rotation and Reference Systems Service is -1.7 ± 1.5 mm/a (i.e. downward, adding to relative sea-level rise at the coast). A published rate for the Halifax GPS site computed by Wöppelmann et al. (2007) is -1.57 ± 0.26 mm/a. Subtracting this value from the relative sea-level trend, we obtain an estimate of 1.63 ± 0.39 mm/a for the local sea-level rise, very close to the latest re-evaluations of global mean sea-level rise (Church et al., 2004; Church and White, 2006; Domingues et al., 2008). This suggests that global-mean projections may be reasonably applied in Halifax without correction for a regional bias. It is important to note, however, that should future increases in the rate of sea-level rise be derived primarily from melting of the Greenland or Antarctic ice sheets, the observed sea-level rise in Halifax would be reduced or increased respectively relative to the eustatic volume change or the response could be mixed in proportion to the ratio of contributions from the two sources (Mitrovica et al., 2001).

The global mean sea-level rise (SLR) projections from the IPCC Fourth Assessment Report (IPCC, 2007a) are shown in Table 1. These projections (in metres) represent the difference between the projected global mean sea level for 2090-2099 and the observed mean sea level for 1980-1999. This presents a slight challenge in developing estimates for SLR over 100 years. If we assign a time interval from the mid-point of 1980-1999 (1990) to the mid-point of the last decade of the 21st century (2095), the duration is 105 years. Normalising the AR4 values to 100 years and adjusting upward to account for the non-linear trend, we obtain a maximum value of 0.57 m for the A1FI scenario. Combining this rate of sea-level rise with the ongoing crustal subsidence measured in the Halifax area, we obtain a relative sea-level rise for Halifax of 0.57+0.16 m or a total of 0.73 m over 100 years, with an error estimate on the crustal subsidence of about 0.03 m (or possibly more).

Table 1. Projections of global mean sea-level rise from
the IPCC Fourth Assessment Report (AR4).

SRES emission scenario	(1980-1999)-(2090-2099) sea-level rise (m)
B1	0.18 – 0.38
A1T	0.20 – 0.45
B2	0.20 – 0.43
A1B	0.21 – 0.48
A2	0.23 – 0.51
A1FI	0.26 – 0.59

Rahmstorf et al. (2007) have shown, using observations since 1990 (base year of the IPCC projections), that air temperature and SLR are tracking close to the upper limit of the projections from the IPCC Third Assessment Report (IPCC, 2001) and above the upper limit of the AR4 projections. The AR4 projections

excluded contributions from acceleration of outflow glaciers draining the Greenland and Antarctic ice sheets, an acceleration observed over the past few years (e.g. Alley et al., 2005, 2008; Velicogna and Wahr, 2006; Rignot et al., 2008). Therefore, in developing a precautionary upper limit of flooding, we believe it is reasonable to adopt (as a minimum) the upper limit estimate from the AR4 (0.57 m over 100 years).
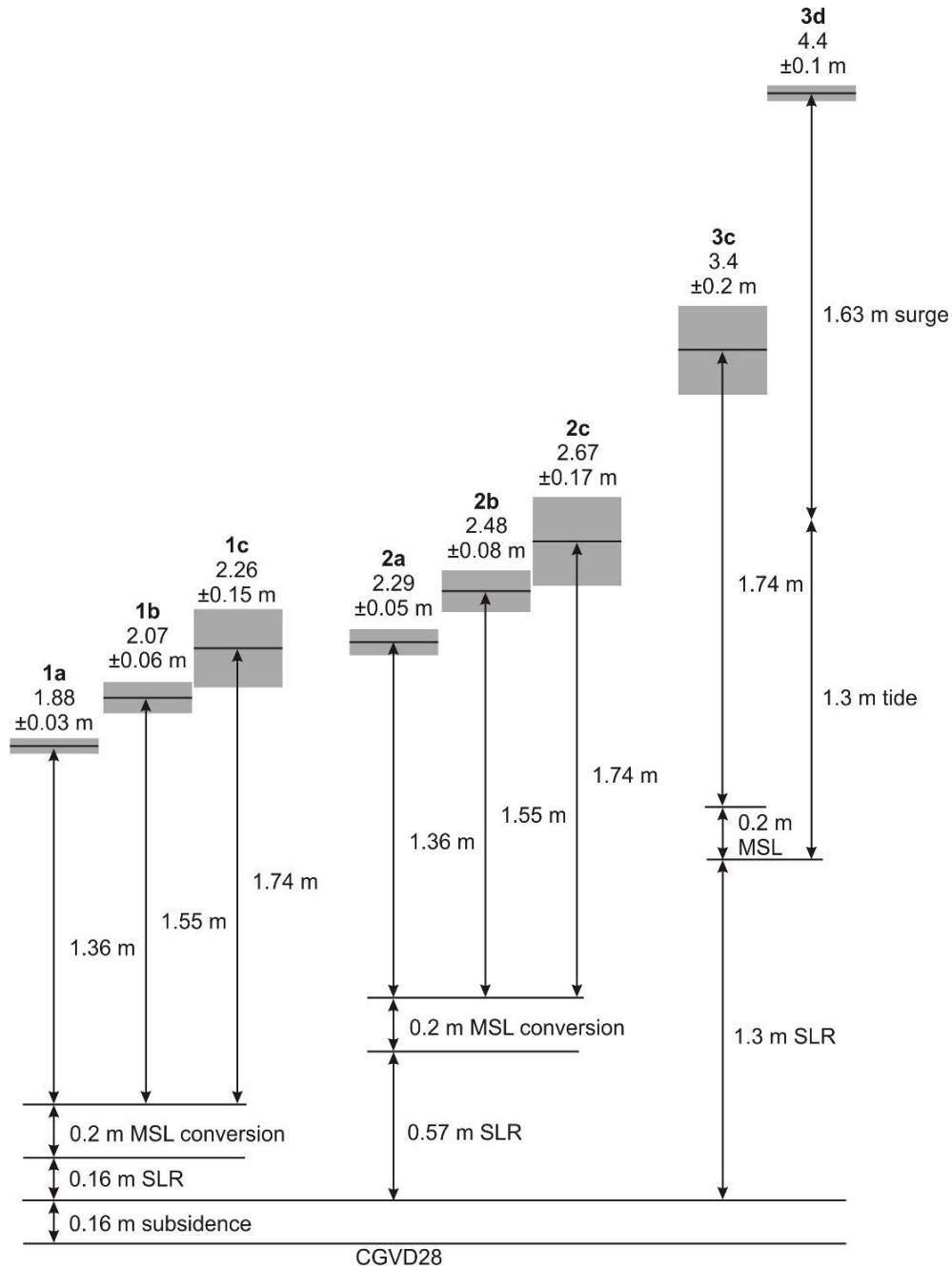

Fig. 7. Graphical representation of the three extreme water-level scenarios adopted for Halifax Harbour, showing component contributions under the various assumptions outlined in the text.

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In an alternative analysis using a linear model for the response of SLR to global mean temperature, Rahmstorf (2007a, b) has suggested a rise in global mean sea level between 0.5 and 1.4 m from 1990 to 2100 (upper limit approximately 1.3 m over 100 years). Using a more complex but conceptually similar approach, Grinsted et al. (2009) obtained projections of 0.91 to 1.32 m for mean sea level in 2090-2099 using the A1B scenario (1.10-1.60 m for A1FI) and argue that there is low probability of the rise being within the IPCC confidence limits (Table 1). We adopt a value of 1.3 m below in postulating an extreme high water level (Scenario 3).

High water-level scenarios for Halifax Harbour in 2100

We have developed three high-water scenarios for modelling and presentation purposes. These are based on various assumptions about the trend of mean sea level at Halifax over the coming century, combined with land subsidence and storm surge. As noted earlier, the first two scenarios are presented with three alternative storm levels, related to annual extremes with return intervals of 2 years (50% probability in any one year), 10 years (10% probability in any one year), and 50 years (2% probability in any one year). A 50-year event is also included in scenario 3.

Based on the annual extremes analysis of water levels for Halifax Harbour (1920-2007) (Fig. 6):
- the 2-year return level (annual maximum hourly water level) is 1.36 ± 0.02 m,
- the 10-year return level (annual maximum hourly water level) is 1.55 ± 0.05 m,
- the 50-year return level (annual maximum hourly water level) is $1.74 \, ^{+0.14}/_{-0.11}$ m.

These extreme water levels for the various storm conditions (return intervals) are expressed as deviations from the annual mean water level and then added to the estimates of future mean water level under climate change. The future increase in sea level is determined from the projections outlined above and added to the vertical ground motion using the rate of -1.57 ± 0.26 mm/a (-0.16 ± 0.03 m/century) quoted above. The water levels relative to CGVD28 resulting from the three SLR scenarios combined with the various storm conditions are shown below (Fig. 7).

Scenario 1

No acceleration of sea-level rise. Relative sea level continues rising at the historic rate in Halifax Harbour (0.32 ± 0.01 m per century). Storm climate (frequency and intensity) is assumed to remain unchanged. The 100-year water levels (including seiche at the gauge and excluding wave runup) are:
   a. *2-yr return level:* $0.20+0.32+1.36 = 1.88 \pm 0.03$ m
   b. *10-yr return level:* $0.20+0.32+1.55 = 2.07 \pm 0.06$ m
   c. *50-yr return level:* $0.20+0.32+1.74 = 2.26 \pm 0.15$ m

Scenario 2

The IPCC AR4 upper-limit projection of SLR for the A1FI emission scenario, adjusted to 100 years, is +0.57 m. Subsidence is assumed to remain constant at 0.16 ± 0.03 m over the century. Storm climate (frequency and intensity) is assumed to remain unchanged. The 100-year water levels (including seiche at the gauge and excluding wave runup) are:

   a. *2-yr return level:* $0.20+0.57+0.16+1.36 = 2.29 \pm 0.05 \pm e$ m
   b. *10-yr return level:* $0.20+0.57+0.16+1.55 = 2.48 \pm 0.08 \pm e$ m (Fig. 8)
   c. *50-yr return level:* $0.20+0.57+0.16+1.74 = 2.67 \pm 0.17 \pm e$ m (Fig. 9)
where *e* is unquantified error associated with the estimate of SLR.

Scenario 3

The upper-limit estimate of SLR from Rahmstorf (2007a) is +1.3 m for 100 years. This is considered first with a 50-year extreme water level (3c). Second, we take the record storm surge in Hurricane Juan (1.63 m) and assume it coincides with higher high water at large tides (HHWLT), which is 1.30 m (CGVD28) assuming no change in tidal amplitudes. This provides a realistic upper bound with very low probability. Subsidence is assumed to remain constant at 0.16 ± 0.03 m. Storm climate (frequency and intensity) is assumed to remain unchanged. The resulting extreme water levels (excluding effects of seiche and wave runup) are (Fig. 7):

    c. *50-yr return level:* $0.20+1.3+0.16+1.74 = 3.4 \pm 0.2 \pm e$ m (Fig. 10)

    d. *Upper bound:* $1.3+0.16+1.3+1.63 = 4.4 \pm 0.03 \pm e$ m

where *e* is unquantified error associated with the estimate of SLR.

The present record water level in Halifax Harbour (2.11 m CGVD28 in Hurricane Juan) is exceeded by Scenario 1c, Scenarios 2a, 2b, 2c, and Scenarios 3c and 3d.
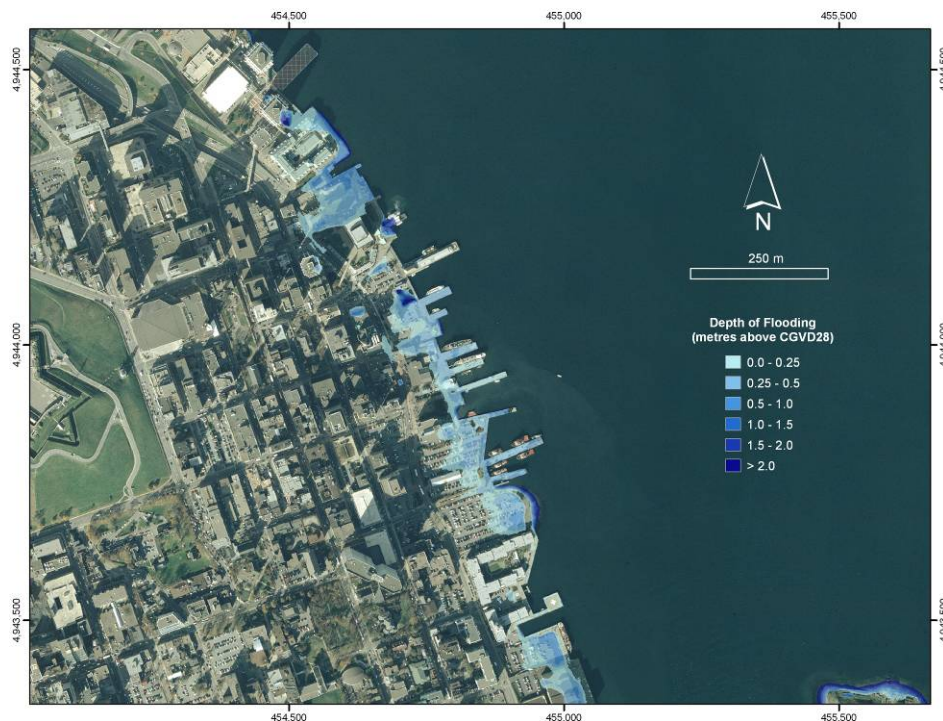
Fig. 8. Flooding extent and depths (still-water level) for Scenario 2b (a highly plausible event) in downtown Halifax. This represents a 10-year high-water event superimposed on the AR4 upper-limit sea-level rise in the year 2100. Flooding was carried out on the bare-earth LiDAR DEM (Figs 2 and 3) with results displayed here on the post-Juan aerial photography (courtesy Nova Scotia Department of Natural Resources).

Fig. 9. Flooding extent and depths (still-water) for Scenario 2c (as 2b but for 50-year extreme water-level event) in downtown Halifax. Backdrop is the same post-Juan aerial photography (courtesy Nova Scotia Department of Natural Resources).
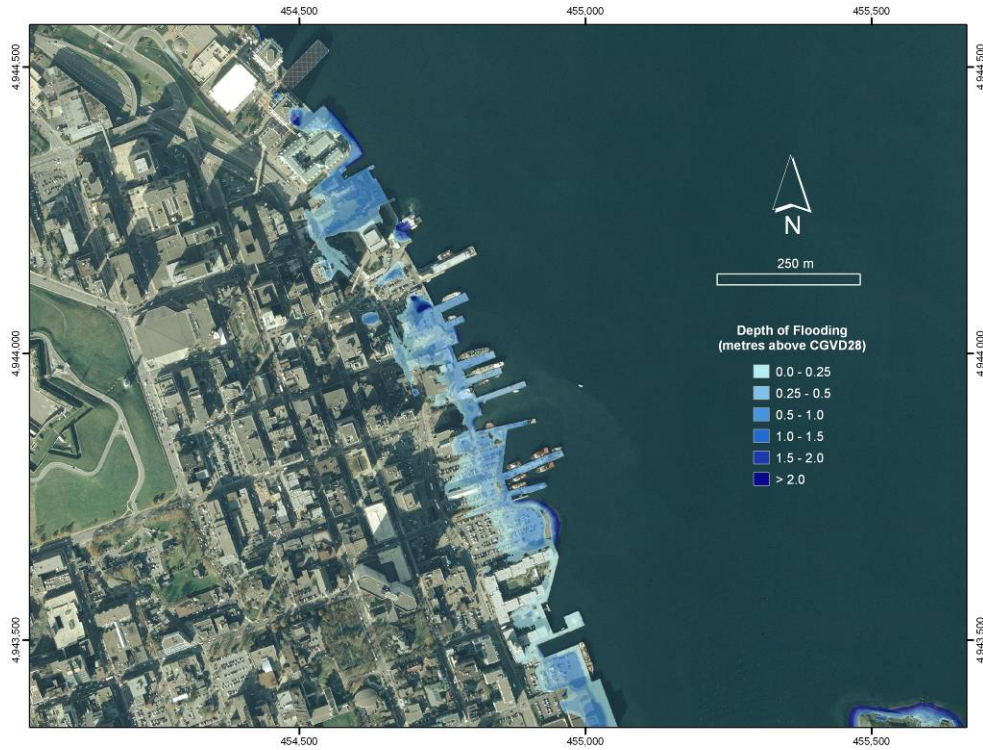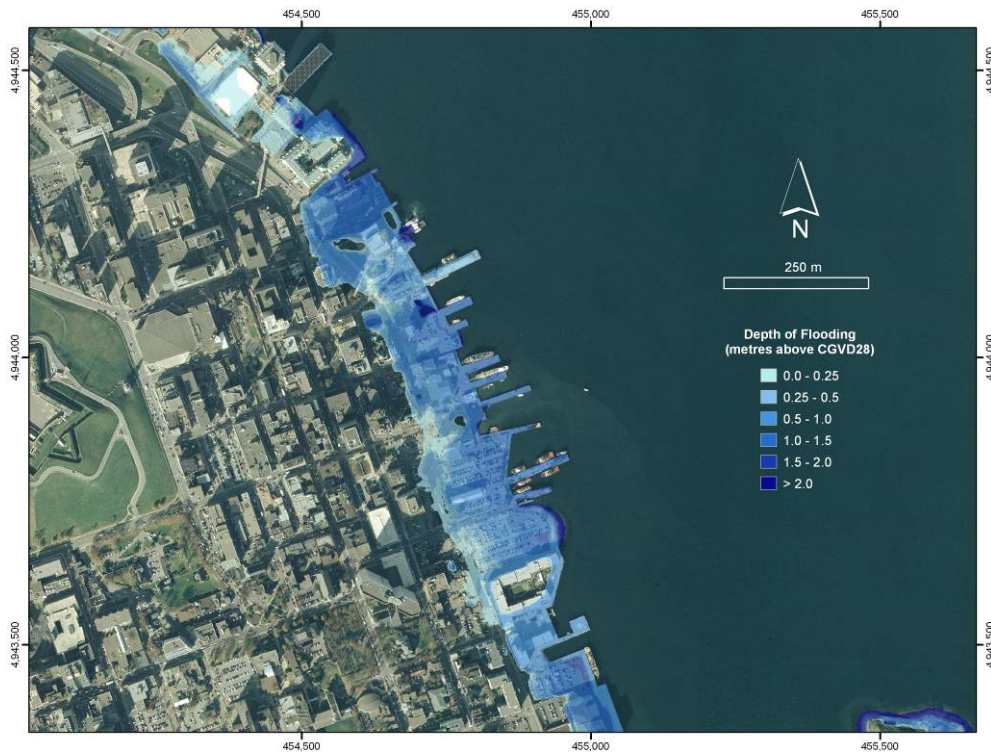

Fig. 10. Flooding extent and depths (still-water) for Scenario 3c in downtown Halifax. Backdrop is the same post-Juan aerial photography (courtesy Nova Scotia Department of Natural Resources).

Simulations of flooding extent and depth in the year 2100 along the Halifax downtown waterfront are shown in Figures 8 to 10. This analysis was carried out on the bare-earth LiDAR DEM and has been completed for the entire harbour. Scenarios 2b and 2c represent 10-year and 50-year high-water events superimposed on the upper-limit projection from the IPCC AR4. These may represent a strong nor'easter and a rare major storm, respectively. It is clear from Figure 8 that extensive flooding will occur in the downtown core during 10-year events. This degree of flooding is highly probable at 2100 and can be expected with lower but growing probability through the coming century. A more extreme event (50-year high-water) shown in Figure 9 will cause more extensive downtown flooding, including two sections of Lower Water Street.

The flooding extent and depths for Scenario 3c are shown in Figure 10. This represents the same major storm as Scenario 2c – an event with a 50-year return interval in 2100 – superimposed on a sea-level rise of 1.3 m. Note the very extensive flooding of Lower Water Street and adjoining properties.

Wave runup in Halifax Harbour

The foregoing analysis does not account for wave setup, runup, breaking, splash, and overtopping. These effects (collectively grouped here as runup) combined with seiche were assessed by marking or photographing high-water limits and debris lines for two major storm events – Hurricane Juan in 2003 and Post-Tropical Storm Noel in 2007. Here we present results for Hurricane Juan. Off the mouth of Halifax Harbour, deepwater significant wave height (average of highest third of the waves) in Hurricane Juan was measured at 9.0 m and the maximum measured wave height was 19.9 m. Due to some instrument wander, it is believed that the significant wave height may have been as high as 11 m (P. Boywer, Canadian Hurricane Centre, Meteorological Service of Canada, pers. comm., 14 January 2009). These large waves propagated directly up the axis of the harbour parallel to the track of the eastern eyewall, riding on record high water levels near the peak of the storm. Shoreline sites facing south and projecting out into the harbour, such as Point Pleasant and Dartmouth Point (Fig. 4), recorded consistently high combined seiche and wave runup (>1 m) with a maximum observed value of 1.7 m (Fig. 11). Runup as high as 1.1 m was measured along the Halifax waterfront at Bishop's Landing. Due to the potential for flooding and infrastructure damage from wave forces and floating debris, it is obviously important to account for this factor in the planning process. It would be possible to model these effects. An alternative approach may be to add a buffer ranging from 1 to 2 m (depending on exposure) on top of the high-water scenarios outlined above.

Discussion

The levels developed for Scenario 2 in the previous section made use of the maximum projection in the IPCC AR4. It is important to note, however, that even the AR4 acknowledged the possibility that this projection might be too low by 0.1-0.2 m (IPCC, 2007a). This is the additional amount estimated to account for accelerated glacier outflow from large ice sheets should this exceed the rates observed over the decade 1993-2003 and grow linearly with global average temperature. Adding this component would raise the upper limit projection for the A1FI scenario from 0.59 m to 0.76 m. The IPCC authors noted that higher values cannot be excluded but that "understanding of these effects is too limited to assess their likelihood or provide a best estimate or an upper bound for sea level rise" (IPCC, 2007a, Section 10.6).
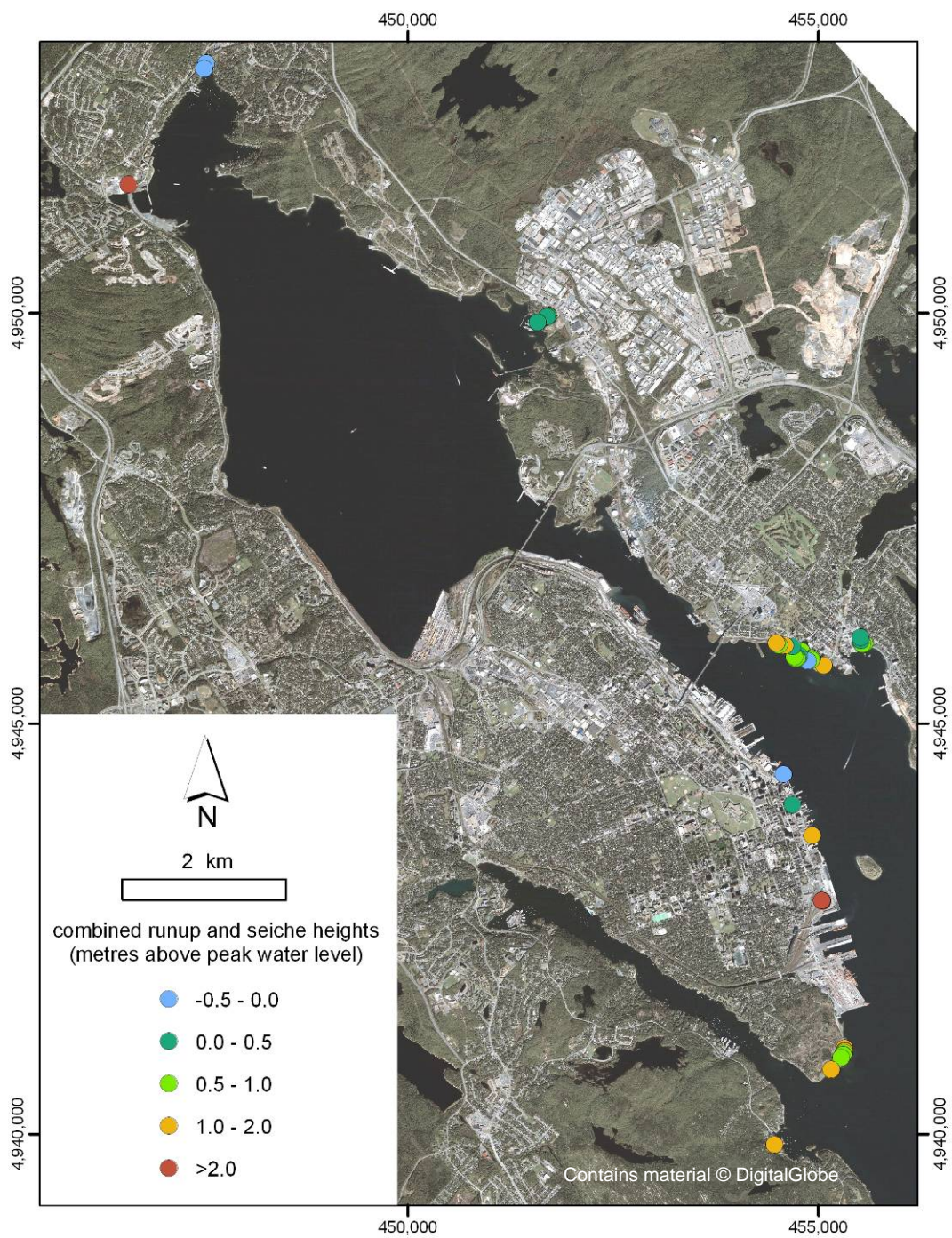
Fig. 11. Combined runup and seiche levels (metres) above maximum recorded water level in Hurricane Juan, from real-time kinematic (RTK) differential GPS surveys of observed runup levels or debris lines. Background image is QuickBird satellite imagery acquired August 2004.

Subsequent studies cited above (e.g. Rahmstorf et al., 2007) have suggested that observed SLR is tracking above the upper limit of the AR4 estimates and close to the (higher) upper limit of projections from the Third Assessment Report (IPCC, 2001). Observations of accelerated ice loss from both Greenland and Antarctica, in large part through accelerated flow velocities in outlet glaciers, have triggered concern that the AR4 projections may seriously underestimate the upper range of SLR. Projections of SLR ranging up to 1.4 m (Rahmstorf, 2007a) and 1.6 m (Grinsted et al., 2009) for the 1990-2100 time frame are not inconsistent with glaciological constraints presented by Pfeffer et al. (2008). These latter authors consider physically plausible glaciological conditions required to produce various rates of ice loss and sea-level rise. They conclude that a sea-level rise greater than 2 m by 2100 is highly unlikely and a much more plausible scenario in the context of known glaciological processes is an increase of about 0.8 m over the same time interval. Siddall et al. (2009), using a simple empirical model of integrated sea-level response to global temperature change (similar to the approach of Ramstorf, 2007a) obtain an estimate of 0.82 m for the global mean sea-level rise during the 21st century. Horton et al. (2008), applying a similar semi-empirical approach applied to latest-generation coupled global climate models, obtain estimates of 0.62-0.88 m for IPCC scenario A1B (2001-2005 to 2100) but do not provide estimates for A1FI.

The post-AR4 expansion of scientific attention to global SLR suggests that Scenario 2 presented in this study has a high probability and may well underestimate sea-level rise in Halifax Harbour during the coming century. Use of this scenario for planning purposes would be consistent with the global consensus as of 2007 represented by the IPCC AR4. On the other hand, a sea-level rise of 1.3 m plus subsidence (e.g. Scenario 3c) cannot be discounted and may provide a reasonable alternative option for precautionary planning.

During the past century, the rate of sea-level rise in Halifax Harbour, excluding land motion, has been reasonably comparable to the global mean rates obtained by Church et al. (2004) and Church and White (2006). On this basis, the scenarios discussed in this study have adopted projections of global mean sea-level rise. Two additional effects may result in departures of Halifax water levels from the global mean. Mitrovica et al. (2001) pointed out that gravitational effects are important in determining the distribution of sea-level rise from melting land ice. Large ice sheets, particularly those in Greenland and Antarctica, exert a gravitational pull that raises mean sea level in the vicinity. As the ice sheets melt, water is added to the ocean but the gravitational pull on sea level is reduced. In the Halifax area, this results in a reduced sea-level rise relative to the global mean for contributions from Greenland and smaller ice caps and glaciers, but an increase for contributions from Antarctica. We are therefore more sensitive in the Halifax region to ice losses from the Antarctic Ice Sheet. The combined effect depends on the source of contributions, but can be estimated for specific scenarios. For the A1FI scenario (IPCC, 2007a), the upper-limit projection (0.59 m, or 0.57 m over 100 years) is reduced to 0.47 m. Overall, this effect is likely to reduce maximum water levels by up to 2 cm for our Scenario 1, 10 cm for Scenario 2, and perhaps as much as 25 cm for Scenario 3 (T.S. James, pers. comm., 2009). As of yet, we have not built these adjustments into the flood hazard mapping.

In addition to gravitational effects on the distribution of sea-level rise, spatial variability may also occur in response to ocean dynamics, which may have the potential to offset the gravitational effects described above. The spatial distribution of sea-level rise under various emission scenarios has been poorly constrained by the model sets employed in the IPCC Third and Fourth Assessments. Recent analyses have provided better information on the spatial distribution of sea-level rise over the past 15 to 50 years (Church et al., 2004; Domingues et al., 2008). In a recent review article, Milne et al. (2009) concluded that "most studies constrain global mean sea-level rise to less than one metre over the twenty-first century, but departures from this global mean could reach several decimetres in many areas." Recent work has identified dynamic effects associated with weakening of the Atlantic meridional overturning circulation (through reduction of deep-water production). This may result in higher mean sea levels in the northeastern USA and Atlantic Canada (Yin et al., 2009; Hu et al., 2009). Specifically they compute an additional sea-level rise of up to 0.2 m for A1B and A2 emissions scenarios in our region.

The water-level departures from the mean presented in Scenarios 1, 2, and 3c were derived using the annual extremes analysis presented in Figure 6. This is based on historical data and assumes a stationary storm climatology. Although debate continues over the evidence for increased tropical cyclone activity in recent decades, there is a theoretical basis for assuming that a warmer global climate may lead to more intense hurricanes. In Canadian waters, higher sea-surface temperatures over the Gulf of Maine and Scotian Shelf may be expected to favour maintenance of hurricane conditions more often for tropical storms reaching our latitude. This is particularly relevant for the Halifax region because many of the most severe storms are tropical or post-tropical. Other high-water events are caused by extra-tropical winter cyclones – for example, the previous record water level in February 1967 (Fig. 6) – and there is some evidence to suggest that the most intense winter cyclones may become more frequent (Lambert, 2004). Bernier et al. (2007) explored the potential for modelling the impacts of changing storm intensity through adjustments to the shape of the extreme values distribution. Their analysis for a sea-level rise of 0.7 m over 100 years concludes that changes in flood risk at Halifax are dominated by the sea-level rise but that modest increases in storm intensity could raise water levels by several decimeters. In this study, we have made no adjustments for changing storm characteristics. As pointed out by Bernier et al. (2007), the impact of rising sea level is not restricted to raising the maximum level of flooding, but also includes changes in the frequency of exceeding lower flood levels. Events with a return period of 100 years today (the present record water level in the harbour) may become frequent events occurring every few years with a sea-level rise of the order we anticipate in the coming century.

Additional factors that may raise water levels above the still-water projections in Scenarios 1 to 3 include harbour seiche effects and wave runup. As noted earlier, the seiche amplitude could amount to 0.3 m or more and wave runup as high as 1.7 m has been measured in the harbour. This suggests the need for an additional elevation buffer of as much as 2 m in the most exposed locations, with much less required elsewhere in the harbour. Proposed wave modelling in the harbour would help to refine the buffer requirement.

Summary

This report provides a brief overview of the scientific basis for flood-risk modelling under rising sea level in Halifax Harbour. A high-resolution digital elevation model has been created using the results of an airborne topographic LiDAR survey. The 90-year record of hourly water level at the Halifax tide gauge has been analyzed to determine the long-term trend of rising relative sea level (3.2 ± 0.13 mm/a) and to build an annual extremes model for estimating future high-water events. The current rate of crustal subsidence in the Halifax region (vertical motion approximately -1.6 ± 0.3 mm/a) has been estimated from continuous GPS data collected since 2002.

Using the upper limit of projections for accelerated global mean sea-level rise published in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC, 2007a), we estimate relative sea level rise in Halifax Harbour amounting to $0.57+0.16 = 0.73$ m over the 100 years from 2000 to 2100. The AR4 noted the possibility that the upper range of the projections should be increased by 0.1-0.2 m to account for accelerated outflow and loss of ice from the major ice sheets in Greenland and Antarctica. Evidence emerging since the release of the AR4 suggests that the range of SLR may have been underestimated by the IPCC and that a global mean SLR of 1.3 m over the coming century may be plausible.

Based on this analysis and a policy approach using three scenarios ranging from low to high projections of SLR (from high probability with low adaptation cost and high risk to lower probability with higher adaptation cost and lower risk), the following SLR models were adopted for development of high-water and flooding scenarios:
- Scenario 1: continued 20th century rate of relative SLR (0.32 m/century including subsidence),

- Scenario 2: IPCC maximum projection (A1FI) normalized to 100 years (0.57 m/century SLR)
- ';Scenario 3: a higher estimate derived from post-AR4 published sources (1.3 m/century SLR).

Combining these values with probabilities of extreme water levels from the annual extremes analysis, we adopt the following water levels for 2-, 10-, and 50-year events in 100 years under Scenarios 1, 2, and 3c (relative to CGVD28):

- *Scenario 1*
    - a - 2-year event – 1.88 ± 0.03 m
    - b - 10-year event – 2.07 ± 0.06 m
    - c - 50-year event – 2.26 ± 0.15 m
- *Scenario 2*
    - a - 2-year event – 2.29 ± 0.05 m
    - b - 10-year event – 2.48 ± 0.08 m
    - c - 50-year event – 2.67 ± 0.17 m
- *Scenario 3*
    - c - 50-year event – 3.4 ± 0.2 m

Scenario 3d was developed using a different approach, combining the record Hurricane Juan storm surge superimposed on HHWLT with the higher post-AR4 projection of 1.3 m SLR over 100 years. This gives a water level of

- *Scenario 3d* – 4.4 ± 0.1 m $\pm$ additional unquantified error.

This level could be exceeded but the probability is extremely low. Thus it is presented as a plausible upper bound. It is noteworthy that the present record water level in Halifax Harbour is exceeded by Scenarios 1c, 2a, 2b, 2c, 3c and 3d.

These scenarios do not account for gravitational effects related to meltwater contributions from various sources, which may reduce projections by about 0.02 m for Scenario 1, 0.10 m for Scenario 2, and possibly as much as 0.25 m for Scenario 3. Nor do they include increases in sea level related to ocean circulation changes, which could be in the vicinity of 0.2 m. Our scenarios also exclude seiche and wave effects, which may cause flooding and damage up to 1.7 m or more above the projected levels we have computed. Seiche may produce water levels up to 0.3 m higher or more in parts of the harbour some distance from the tide gauge. For this reason, a vertical buffer of up to 2 m above the scenario levels may be required in some places for planning purposes.

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