Exposure to Coastal Hazards in a Rapidly Expanding Northern Urban Centre, Iqaluit, Nunavut

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ABSTRACT. The City of Iqaluit, Nunavut, is an expanding urban centre with important infrastructure located in the coastal zone. This study investigates the exposure of this infrastructure to coastal hazards (rising mean sea level, extreme water levels, wave run-up, and sea ice). Using a coastal digital elevation model, we evaluate the inundation and flooding that may result from projected sea level rise. Some public and private infrastructure is already subject to flooding during extreme high water events. Using a near upper-limit scenario of 0.7 m for relative sea level rise from 2010 to 2100, we estimate that critical infrastructure will have a remaining freeboard of 0.3–0.8 m above high spring tide, and some subsistence infrastructure will be inundated. The large tidal range, limited over-water fetch, and wide intertidal flats reduce the risk of wave impacts. When present, the shorefast ice foot provides protection for coastal infrastructure. The ice-free season has expanded by 1.0–1.5 days per year since 1979, increasing the opportunity for storm-wave generation and thus exposure to wave run-up. Overtopping of critical infrastructure and displacement by flooding of subsistence infrastructure are potential issues requiring better projections of relative sea level change and extreme high water levels. These results can inform decisions on adaptation, providing measurable limits for safe development.

Key words: Arctic coast; adaptation planning; infrastructure; sea level rise; flooding; sea ice; climate change; coastal management

RÉSUMÉ. La ville d'Iqaluit, au Nunavut, est un centre urbain en plein essor doté d'infrastructures importantes sur la zone côtière. Cette étude se penche sur l'exposition de cette infrastructure aux risques côtiers (niveau de la mer montant, niveaux d'eau extrêmes, vagues et glace de mer). À l'aide d'un modèle numérique de l'élévation côtière, nous évaluons les inondations et les submersions susceptibles de découler de la montée projetée du niveau de la mer. Certaines infrastructures publiques et privées sont déjà la cible d'inondations en présence de très hautes eaux. En nous appuyant sur un scénario dont la limite supérieure est de près de 0,7 m pour la hausse relative du niveau de la mer de 2010 à 2100, nous estimons que les infrastructures critiques auront un franc bord de 0,3 à 0,8 m au-dessus de la marée haute de vives-eaux, et une partie des infrastructures de subsistance sera inondée. La grande amplitude de la marée, le fetch limité sur l'eau et les larges battures intertidales réduisent le risque de l'impact des vagues. Lorsqu'elle est présente, la glace de rive offre une protection aux infrastructures côtières. Depuis 1979, la saison sans glace s'est prolongée de 1,0 à 1,5 jour par année, ce qui augmente la possibilité de la formation de vagues de tempête et, par conséquent, l'exposition aux jets de rive. La submersion des infrastructures critiques et le déplacement des infrastructures de subsistance par les inondations constituent des enjeux potentiels qui doivent faire l'objet de meilleures projections du changement relatif du niveau de la mer et des niveaux d'eau extrêmes. Ces résultats pourront éclairer les décisions en matière d'adaptation, ce qui permettra d'obtenir des limites mesurables en vue d'aménagements sécuritaires.

Mots clés : côte de l'Arctique; planification de l'adaptation; infrastructure; montée du niveau de la mer; inondation; glace de mer; changement climatique; gestion côtière

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INTRODUCTION

Recent rapid changes within the Arctic climate system, such as rising temperatures and increased storm waves during open water, have exacted heavy tolls on the infrastructure of some Arctic coastal communities (Arehart, 2012). The effects of polar climate amplification mean that parts of the Arctic are warming at higher rates than other regions of the globe (Serreze and Barry, 2011). NRTEE (2009) projected significant monetary costs for the replacement and maintenance of aging physical infrastructure at risk from climate change in northern Canada. Billions of dollars will be invested in new infrastructure in the coming decades, highlighting the need for appropriate adaptation strategies.

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Larsen et al. (2008) calculated an additional $5.6–$7.6 billion would be required, in excess of regular maintenance investment, to repair Alaskan infrastructure if projected climate change persists to 2030. Not accounting for climate change, Iqaluit's infrastructure deficit is estimated at $40 million, and there is growing demand for new infrastructure to meet the needs of a rapidly expanding urban centre (Forbes et al., 2012). The environment, isolation, and transportation logistics of the Arctic raise costs, making infrastructure expensive to build and maintain (Forbes, 2011:34). Clearly, an understanding of how projected environmental change will affect infrastructure is needed to improve design, minimize risk, and develop sustainable northern communities.

Since most Canadian Inuit communities are on the coast, so is a large proportion of Arctic infrastructure. Atmospheric warming has already led to coastal changes, such as increased thermal abrasion and coastal erosion (Aré et al., 2008; Forbes, 2011). The threat to coastal infrastructure in the Arctic from changing coastal dynamics is only one among many: others include thaw subsidence, wind, increased intense precipitation, or impeded drainage (e.g., Forbes et al., 2014; Smith, 2014; Smith and Forbes, 2014). In some places, potential impacts have already emerged as hazards, leading to relocation or retreat (Catto and Parewick, 2008). These challenges are exacerbated by sparse data over short time series, which inhibit our ability to predict future hazard conditions (NRTEE, 2009; Strzelecki, 2011). There is pressure to adapt to change and protect key infrastructure. Decisions are made on the basis of available knowledge, including scientific research (Ford et al., 2010; Forbes, 2011). Appropriate responses depend on the nature of the hazard and the infrastructure at risk.

Iqaluit, the capital city of Nunavut, is contending with natural hazards from exposure on many fronts. Thaw subsidence in permafrost has damaged city infrastructure (Nielsen, 2007), food networks of the community are strained by environmental change and an expanding population (Lardeau et al., 2011), and occasional coastal flooding has occurred in the past (Fig. 1). These issues are exacerbated by climate change (Forbes et al., 2012). Adaptation planning is ongoing; it is mandated at both territorial and municipal levels (City of Iqaluit, 2010) and incorporated into the city's Sustainability Plan (City of Iqaluit, 2014). Recent rapid population growth complicates this effort, as the existing infrastructure deficit creates an added burden for investment in solutions. In this context, previous work has identified hazards at the coast, including sea level change, extreme water levels, and changing sea ice patterns, as a topic requiring further investigation to better define the associated exposure and risk (Shirley, 2005; Nielsen, 2007; City of Iqaluit, 2010; Hatcher et al., 2011).

Marine flooding in Iqaluit was reported in 2003 (Fig. 1). Photographs indicate that this flooding happened in calm conditions with no storm influence, leading to questions about its cause. Water-level records indicate that higher flooding occurred during an extreme event in 1964, but
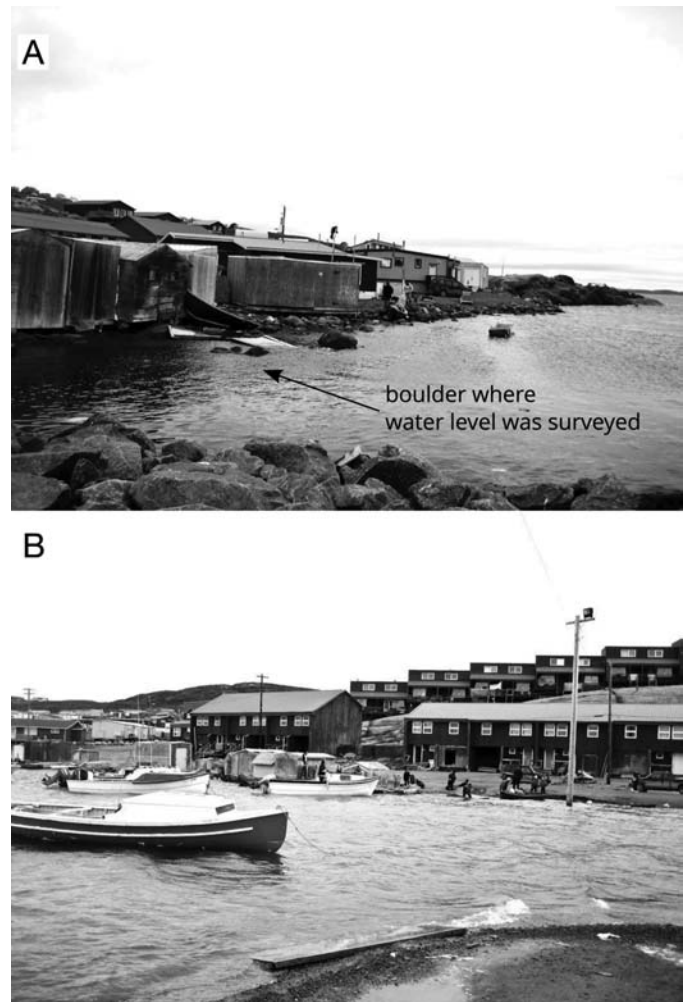

FIG. 1. Flooding that occurred in October 2003. (A) Subsistence infrastructure located near the high water line. Note the half-submerged boulder at the centre of the photo, which provided a survey point to measure the high water level for this event. (B) Small craft basin at the base of the breakwater. Subsistence infrastructure and part of the road are flooded, and residents are moving to secure their boats. These photos were taken roughly 50 m from the base of the breakwater, facing east (A) and west (B). Photos courtesy of Rick Armstrong.

there was little or no damage at that time because the current urban development along the shore did not yet exist (Fig. 2). The public therefore has little awareness of hazard events that could endanger the extensive residential, commercial, public, and subsistence infrastructure put in place over the last three decades. However, archival water-level data provide some insight into the probability of flood recurrence. We may also ask whether the 1964 and 2003 flooding events resulted from unusually high tide and, if so, what the implications would be of coincident storm conditions, or occurrence during freeze-up or breakup of the coastal sea ice.

In this paper, we examine the natural hazards associated with the coastal setting of Iqaluit under present and future conditions. Hazards considered include storm waves, sea ice ride-up and pile-up, and marine flooding associated with storm surges and extreme high tides. We use the latest projections of local sea level rise, incorporating results from
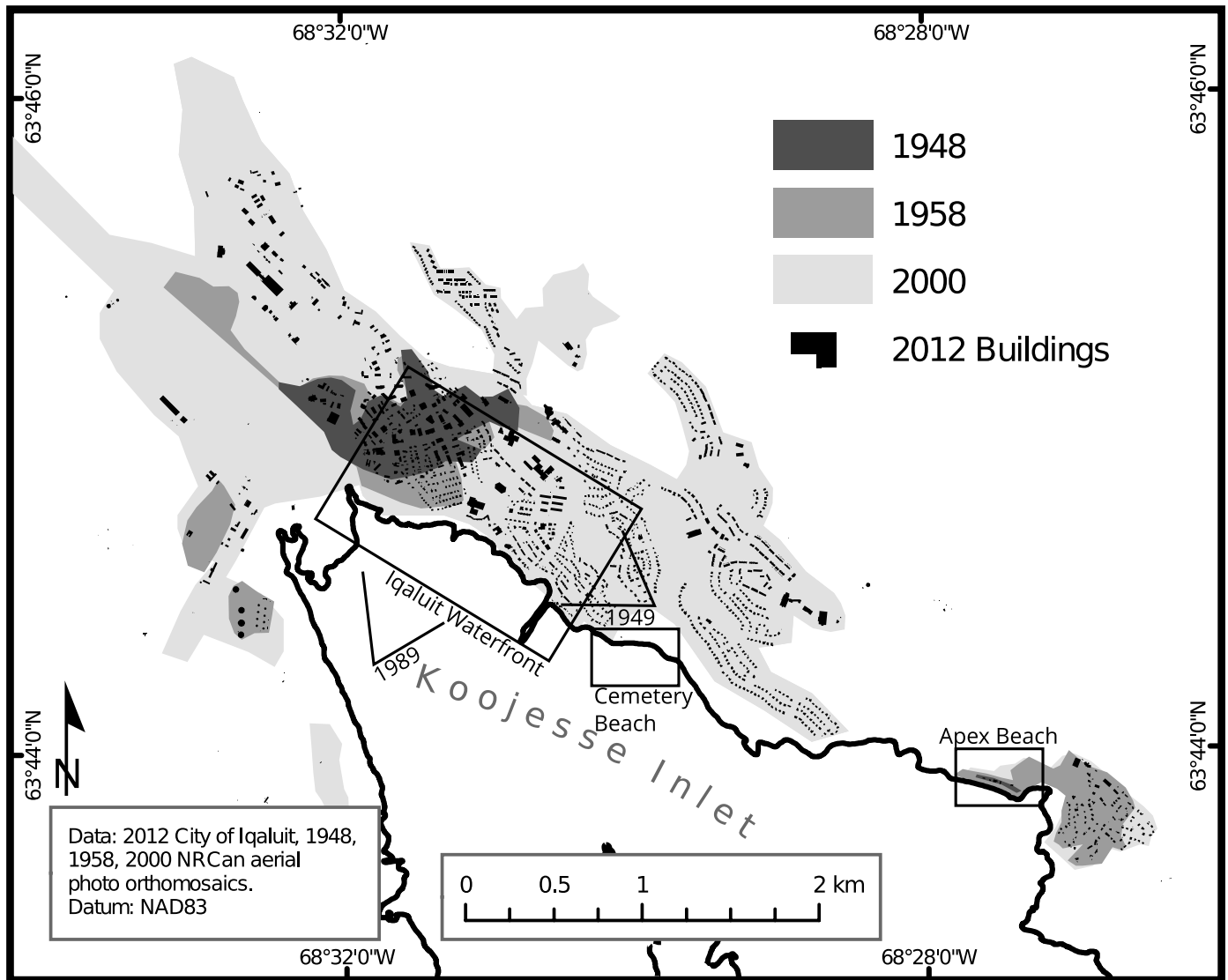
FIG. 2. The development history in Iqaluit shows an expansion from the original airbase site near the head of Koojesse Inlet. The city now occupies the whole northeastern coast of the inlet, with Apex farther east. Triangles show the location of the oblique aerial photos shown in Figure 6, as well as their orientation. Boxes show the three main study areas within Koojesse Inlet.

the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (Church et al., 2013; IPCC, 2013), as well as measured crustal motion at Iqaluit and the gravitational effects on sea level of proximity to the Greenland Ice Sheet and local glaciers and ice caps on Baffin Island (James et al., 2014), to consider infrastructure elevation and exposure to flooding with respect to mean and extreme water levels now and in the future. Local projections of sea ice concentration, storm winds, and waves in Frobisher Bay are beyond the scope of the study, and changes in storm-wave climate are considered only in the context of recent regional trends in the length of the open water season.

As part of an international project on responding to environmental change in coastal communities (Lane et al., 2013), this study was initiated to address the knowledge gap on coastal hazards. The second author had long-term experience in the community, and consultations with local, territorial, and federal agencies preceded the study. These contacts included City of Iqaluit planning staff, the Amarok Hunters and Trappers Association, the Nunavut Research Institute, the Government of Nunavut Department of Environment, the Canada-Nunavut Geoscience Office, and individual residents. Since the study was designed to inform the sustainability planning process and the next revision of the general plan, we collaborated closely with the Director of Engineering and Sustainability and the Sustainability Coordinator (Forbes et al., 2012).

The study objectives were to (1) identify natural hazards that present a risk to coastal infrastructure in Iqaluit, (2) quantify the waterfront exposure in the context of observed trends and sea level projections, and (3) identify coastal infrastructure at risk in Iqaluit. We derived the data needed to address these goals from a number of sources, including archival climate and water-level data, anecdotal information, conversations with city staff and other residents, moored instrument data, and field surveys (Hatcher et al., 2014).
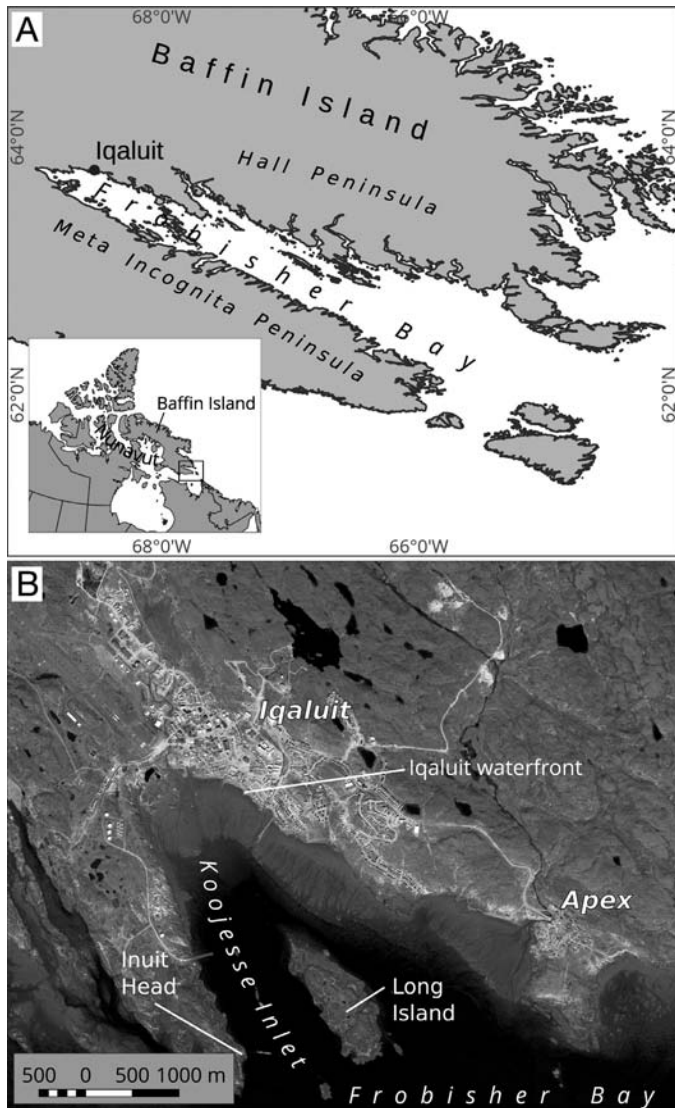
FIG. 3. (A) Iqaluit sits at the head of Frobisher Bay on southeastern Baffin Island. Frobisher Bay is a long, narrow, and deep bay between the highlands of Hall Peninsula and Meta Incognita Peninsula. (B) Koojesse Inlet is oriented NW-SE, with Long Island at its mouth. B contains material © Digital Globe Inc.

STUDY AREA

Environmental Setting

Iqaluit sits at the head of Koojesse Inlet (63.7° N, 68.5°W) in the northwest corner of Frobisher Bay on Baffin Island (Fig. 3). The study area encompasses the full shoreline of the inlet between Inuit Head in the southwest and the old settlement of Apex (now the eastern suburb of Iqaluit) in the east (Fig. 2). The work focused on hazards to coastal infrastructure along three stretches of coastline: the Iqaluit waterfront, the old cemetery, and Apex beach (Fig. 2). The landscape is a product of glacial erosion, which formed a number of rock ridges trending from northwest to southeast with thin till or shallow marine deposits in the interven-ing depressions (Hodgson, 2005; Allard et al., 2012). The rock is granitic and resistant to erosion. There are no trees,

FIG. 4. The coastal setting around Iqaluit. (A) The boulder-strewn tidal flats extend up to 1 km seaward of the beach face, with a very low slope and complex network of shallow tidal drainage channels. Part of the city can be seen in the background. (B) Development on the Iqaluit waterfront; note extensive development in the backshore. (C) Storm swash line on the beach, with boulder groyne in middle distance.

and many of the rock ridges are unvegetated. Permafrost (defined as ground at a temperature < 0°C for two years or more) is ubiquitous above the high-tide line, and excess ground ice is present near the surface in many places, pro-ducing distinctive small-scale landforms and leading to thaw subsidence where the near-surface thermal regime is disturbed by construction or other human activities (Short et al., 2012).

The inlet is macrotidal, with a semi-diurnal tide and spring tidal range of 12.4 m (CHS, 2001). The shore is bare rock in many places, with high-tide beaches of mixed sand and gravel at Apex and along much of the downtown water-front. Very extensive boulder-strewn tidal flats form a wide intertidal zone in most of the study area (Fig. 4A). Simi-lar tidal flats with innumerable boulders on the surface are found along much of the northern coast of Frobisher Bay. At the seaward limit of the flats, the seabed falls off into the deeper waters of the harbour.

Wave action is limited in Koojesse Inlet by a number of factors. The inlet opens to the southeast, and Long Island sits at the entrance, providing some shelter from incident

FIG. 5. Characteristics of sea ice at the coast near Iqaluit. (A) The ice foot develops about halfway down the beach face, and its outer edge is marked by the change from a relatively smooth surface to a chaotic arrangement of ice blocks. (B) Sea ice pile-up at Iqaluit. Light onshore winds with large ice floes in the nearshore produced ice pile-up on the boat ramp near the main breakwater in November 2011. A front-end loader spent the morning clearing the ice, which was piled roughly 2–3 m high on the ramp.

waves (Fig. 3). The islands that separate inner and outer Frobisher Bay lie roughly 54 km (straight line distance) from the mouth of the inlet (Fig. 3) and block all ocean swell. Therefore, the wave field is locally forced and limited by the maximum over-water fetch (less if ice is present). Storms capable of producing waves that can affect the coast are restricted to a narrow south-east fetch exposure. They occur predominantly in fall, when extra-tropical cyclones passing through the Labrador Sea and toward Baffin Bay tend to move westward over southern Baffin Island, bringing warmer air masses north and producing precipitation (Maxwell, 1981; Hatcher, 2014).

Coastal retreat is minimal because much of the shore consists of resistant bedrock, and at least until very recently, the site has been emergent (falling relative sea level) as a result of glacial-isostatic uplift exceeding sea level rise. The rate of downcutting on the tidal flats is unclear. Sediment movement is dominated by sea ice dynamics (McCann et al., 1981; McCann and Dale, 1986; Leech, 1998; Dale et al., 2002). Ice prevails for an average of nine months of the year. During the ice season, thick intertidal ice is repeatedly lifted and dropped onto the flats by the cycle of tides. Sediment is entrained through basal adfreezing, but the ice does not move offshore. This pattern occurs because of preferential thawing of sediment-laden ice in the spring and retention of melting intertidal ice over the tidal flats by the solid landfast ice in deeper water (McCann and Dale, 1986).

We are aware of no previous trend analysis of seasonal sea ice duration in this region. Previous work on sea ice in the area has focused exclusively on the dynamics of breakup, which is a critical annual event for deposition of rafted sediment (McCann and Dale, 1986; Leech,

1998); however, we know less about the process of freeze-up. Community members describe it as a period of change when the sea ice "sets up" on the coast. During this time, access is extremely difficult because the ice is thin and constantly shifting in the intertidal zone over the tidal flats.

Part of the process of freeze-up involves forming the ice foot, an ice accumulation near the high-tide line, where it is frozen to the substrate for the winter. Subsequent inundation during high spring tides builds thickness further and contributes to the development of a flat ice terrace (Forbes and Hansom, 2011). The edge of the ice foot where it meets with mobile intertidal ice acts as a hinge point and is a locus of discontinuous sea ice ride-up and pile-up (Fig. 5A).

Though the coast was formed during a long period of falling relative sea level, the current trend at Iqaluit is unclear. The site has probably been very slowly emergent in recent decades. The crust in this area is still undergoing postglacial rebound, with an uplift rate of 3.97 ± 0.65 mm/yr (about 40 cm per century), as indicated by 4.3 years of continuous GPS measurement (James et al., 2014). This uplift is at least partially offset by local sea level rise, but the rate of rise is moderated by the gravitational effects of proximity to the Greenland Ice Sheet and ice masses on Baffin Island. On the other hand, the effects of ice mass loss in Antarctica will be slightly enhanced in this region (Mitrovica et al., 2001). Relative sea level is known to have risen in recent years in outer Frobisher Bay (farther east), as indicated by flooded habitations of the ancestral Inuit Thule culture (M.E. Thomas, pers. comm. 2009) and geological evidence (Miller et al., 1980).

Urban Development

The present City of Iqaluit began in the mid-20th century as a hybrid settlement around the United States Strategic Air Command base at the head of the inlet (Fig. 6A). Inuit would seasonally occupy the beach in order to take advantage of both employment at the base and good fishing in the inlet (Eno, 2003). Iqaluit is an Inuktitut word that translates to 'place of many fish.' The airbase acted as a nucleus of development, but infrastructure expanded to the shoreline in order to support the landing of supplies arriving by ship (Figs. 2, 6B). As development on the eastern side of Iqaluit grew to the coast, the hamlet of Apex developed 4 km to the east, connected by a road to the core of Iqaluit (Fig. 3). The entire built-up area now falls within the city boundary.

The City of Iqaluit is home to about 7000 people, and the population has been growing for many years, particularly since becoming the capital of Nunavut in 1999. The rate of growth from 2006 to 2011 was 8.3% (Statistics Canada, 2014). The large commercial and institutional buildings along the waterfront have all been built since 1970. Amidst this government and private sector infrastructure in the backshore, traditional activities and a subsistence economy continue, resulting in a proliferation of small wooden sheds and repurposed shipping containers directly adjacent to the high-tide line.

FIG. 6. (A) Oblique aerial photo of the settlement in 1949. Inuit tents can be seen in the foreground (photo: National Air Photo Library, Ottawa). (B) Oblique aerial photograph from 1989 showing the expansion of development toward the coast. Note that boulders have been cleared from a strip of the tidal flats to allow unloading of a ship (photo: S.B. McCann).

The developed waterfront areas in Iqaluit and Apex were divided for planning purposes into two zones according to specifications in the Iqaluit General Plan (City of Iqaluit, 2010). They are defined by horizontal setback distances of 30.5 m and ~75 m from the high-tide line. The first is designated "Open Space" and the second is a rough delineation of the coastal planning zone (designated the Sijjaanga District in the General Plan, *sijjaanga* being Inuktitut for beach area or waterfront). This zone, while intended to restrict commercial and institutional development, includes major commercial and transportation infrastructure. In this study, to quantify the flood hazard, the landward limit of the Sijjaanga District, which is not formally mapped, was set at 75 m inland from the high-tide line. This limit encloses the infrastructure mentioned in the General Plan as belonging within the Sijjaanga District.

The physical character of the coast can be subdivided into two types: beaches and bedrock outcrop. Waterfront development has occurred almost exclusively on the low-slope beaches and emerged relict beaches between rock

headlands (Fig. 4B). The main waterfront of the city is a large bay-head beach. Confined to the north side of the inlet, this waterfront is now fully backed by urban infrastructure. To the east at Apex, the beach is short (less than 500 m) and located adjacent to the outlet of the Apex River. At this site, there is one residence amid a cluster of heritage Hudson's Bay Company buildings, which date from 1949.

Key infrastructure facilities, including municipal utility buildings and residential structures, are located in the backshore of Iqaluit's main beach. The subsistence support structures (the most abundant coastal infrastructure in both number and extent) sit on top of the beach crest along the entire length of the waterfront. Most of these structures are close to the spring high-tide line, between the city and the sea. Subsistence infrastructure is reported to have been flooded in 2003 (Shirley, 2005).

Figure 7 shows the major components of infrastructure within the coastal zone of the three primary study areas: the Iqaluit urban waterfront, cemetery beach, and Apex beach. If we exclude the fuel transfer facility, causeway, and dump across the harbour, the urban waterfront of Iqaluit begins at the head of the inlet, where a river flows onto the tidal flats just east of the sewage lagoon. The latter is retained by two dams. East of this lagoon is the sealift barge-landing facility and the Canadian Coast Guard property. Farther along are a boat yard, housing, and subsistence infrastructure on the west side of Pumping Station 2. From that point, the unpaved coastal access lane runs east along the backshore, with subsistence infrastructure on the seaward side, to the Elders Centre and the North Mart shopping complex. The coastal access lane then continues eastward between the former courthouse and subsistence infrastructure on the beach crest as far as the Visitor Centre. Sinaa Street continues east, landward of the Visitor Centre, the museum, the Amarok building, and two residences, which all have subsistence infrastructure on their seaward side. Immediately beyond this is the small-craft basin at the foot of the main breakwater. Across Sinaa Street is the Grind and Brew café, with Pumping Station 1 behind it. There are several residential properties in this area, including beachfront homes, multi-family structures, and a row of townhouses across from the breakwater and boat launch. The road in this area has been flooded at extreme high tides (Fig. 1B). Moving on to the southeast into the cemetery area, a small pocket beach backed by a single-family home lies between the cemetery and the breakwater. The coast between the cemetery beach and Apex is composed of rock slopes and cliffs, with all structures located on high ground. The Apex River discharges to the flats at the east end of Apex beach. The rest of the Apex coast is a steep bedrock slope or terraced sand and gravel.

METHODS

Documenting coastal hazards in Iqaluit was essentially a mapping exercise enriched by analysis of relevant archival
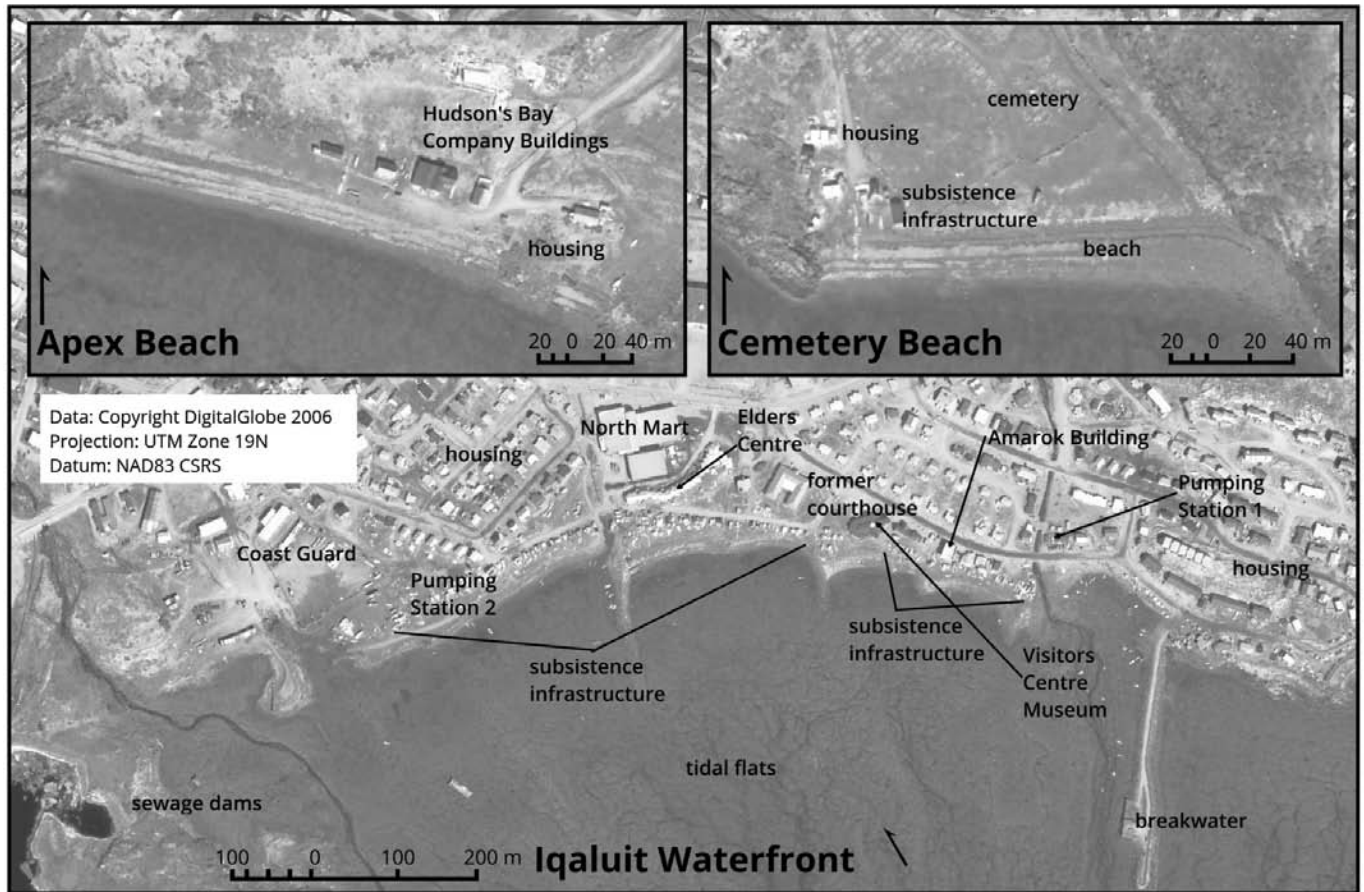
FIG. 7. Key infrastructure layout for the three main sections of the waterfront in Iqaluit and Apex. The location of each area is shown by boxes in Figure 2.

data sets. Fieldwork was conducted between 2009 and 2011. Coastal surveys took place in August of all three years and were augmented by wave and water-level monitoring in 2010 and 2011, with measurement of currents in August 2011. Sea ice observations and surveys were conducted in February and November 2011. For further details on the fieldwork, see Hatcher et al. (2014). The data used in this study can be classified into five categories: topography and bathymetry, infrastructure exposure, climate and weather, waves, and water levels.

Topography and Bathymetry

Topographic elevation points were collected using survey-grade real-time kinematic (RTK) geographic positioning system (GPS) data. The system used was an Ashtech Z-Extreme receiver with an Ashtech dual band carrier-phase antenna. Revisiting various control points established an estimated survey error of ± 0.05 m (Hatcher et al., 2014). The exceptions were indicators of high water levels surveyed on outer Inuit Head and the south side of Long Island, where real-time corrections were not available and the data were post-processed to ± 0.15 m. Bathymetry was determined using GPS-positioned single-beam echosounding (Hatcher et al., 2014) and subsequently augmented by multibeam surveys using the Government of Nunavut

research vessel MV *Nuliajuk* (Hughes Clarke et al., 2015; Mate et al., 2015).

Elevations are always reported with reference to a vertical datum. In this study two were used: the Canadian Geodetic Vertical Datum of 1928 (CGVD28) as orthometric datum (nominally equivalent to mean sea level) and hydrographic Chart Datum. All GPS positions were recorded as ellipsoidal elevations, which were subsequently converted to orthometric elevations using a separation value of 10.166 m. Elevations given in this paper are reported with respect to CGVD28. Chart Datum (the tide gauge zero level) is derived from local tide gauge records and arbitrarily established at a level close to that of the lowest tide. In Iqaluit, mean water level (MWL) is 5.9 m above Chart Datum (CHS, 2001). Lower Low Water Large Tide (LLWLT) is the lowest expected tide at 0.5 m Chart Datum and Higher High Water Large Tide (HHWLT), the highest expected tide, is 11.6 m above Chart Datum (CHS, 2001). Surveys of the tidal benchmark FB1-1968 established that Chart Datum has an elevation of −6.05 m CGVD28. Thus the orthometric elevations of the various tide levels are as follows: −6.28 m (lowest recorded hourly WL), −5.55 m (LLWLT), −0.01 m (MWL), 5.55 m (HHWLT), and 6.04 m (highest recorded hourly WL).

A digital elevation model (DEM) provided by Natural Resources Canada was produced by stereo-pair
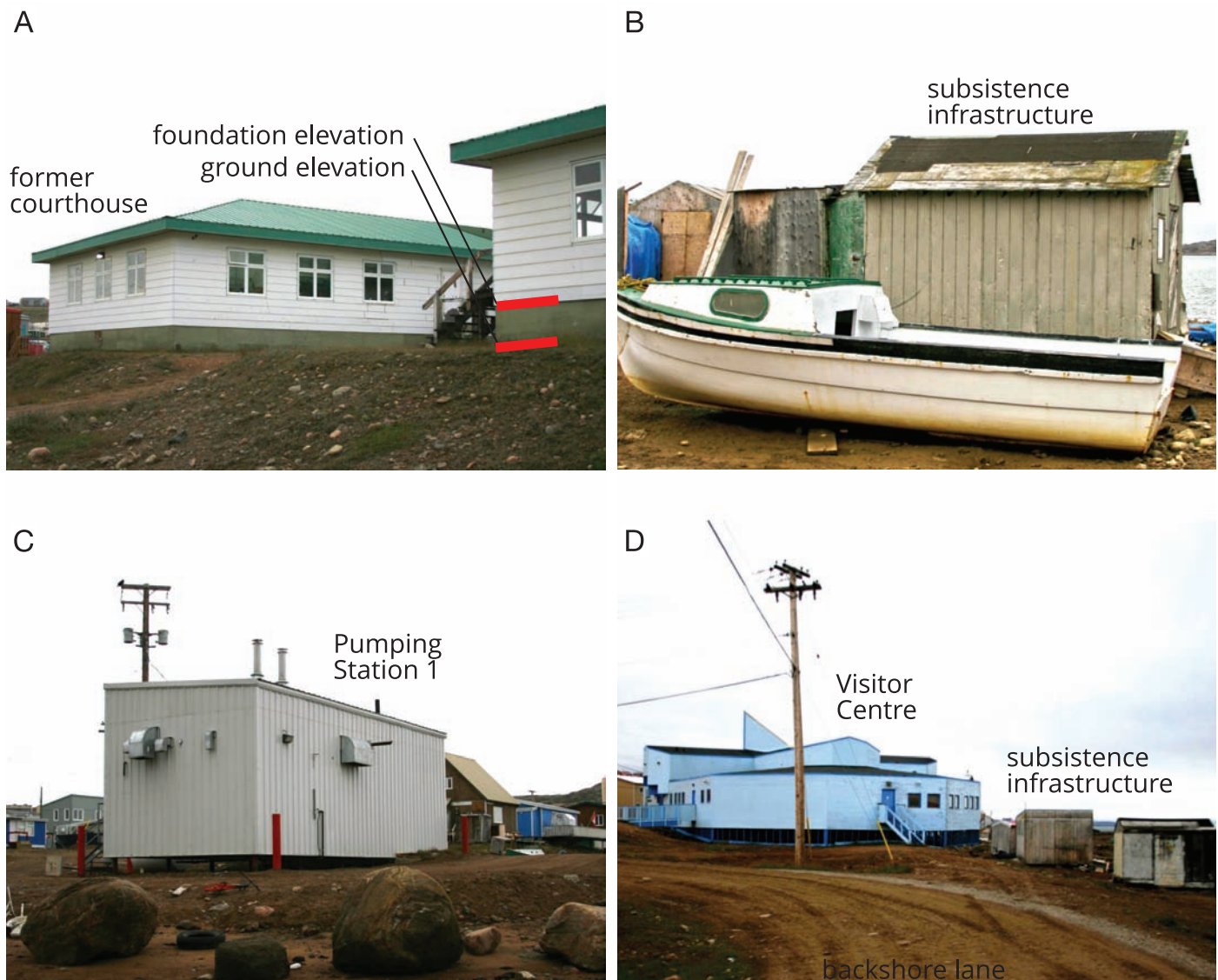
FIG. 8. Examples of the different types of coastal infrastructure on the Iqaluit waterfront. (A) The territorial courthouse building sitting on piles and graded land near the coast. (B) Subsistence infrastructure near the coast varies from makeshift wooden shacks to re-purposed "sea cans" (old shipping containers). (C) The municipal pumping station located at the western end of the city waterfront. (D) The Unikkaarvik Visitor Centre (blue building) sitting on the main waterfront amidst subsistence infrastructure. In the foreground is the lane running along the backshore.

photogrammetry using Worldview 2 satellite imagery. This model excluded much of the intertidal flats because they were partially underwater at the time the imagery was acquired. In this study, coastal survey data were collected to build a seamless digital surface model across the tidal flats and into the nearshore. Elevations in the DEM were defined with respect to CGVD28. Shore-normal transects were surveyed with RTK-GPS at roughly 50 m spacing alongshore. Coincident points (where GPS points overlapped pixels of the DEM) were used to assess the accuracy of the elevations taken from the DEM. Using the GPS points as reference, the standard error was 0.4 m, but with some errors as large as 9 m. Larger errors occurred near the base of buildings as artifacts of the method employed in creating the DEM, but open-area elevations were much

less prone to error. The open-area accuracy of the DEM is assumed to be ± 0.5 m. The resulting horizontal uncertainty in mapping of flood limits is a function of slope (± 5 m at a beach face slope of 6°; ± 8 m at a backshore slope of 3.5°).

Infrastructure Exposure

Coastal infrastructure was classified into six categories: residential, commercial, municipal, cultural, federal, and subsistence. Residential includes housing within 75 m of the high-tide line. Commercial property within the 75 m planning zone includes the North Mart (grocery store) and the Grind and Brew café. Municipal infrastructure includes the two pumping stations, as well as the sewage dams, road and culvert elevations, and the old territorial courthouse

(now owned by the city). Cultural infrastructure refers to municipal buildings that are culturally significant, including the Unikkaarvik Visitor Centre and the Nunatta Sunakkutaangit Museum in downtown Iqaluit and the Hudson's Bay Company buildings on Apex beach. Federal property includes the Coast Guard and other Department of Fisheries and Oceans (DFO) buildings. Finally, subsistence infrastructure describes the sheds and sea cans (re-purposed shipping containers) used by local country-food harvesters, who are organized under the Amarok Hunters & Trappers Association.

Infrastructure elevations were acquired using RTK-GPS on key infrastructure as determined by this classification. Key infrastructure was defined as all municipal, commercial, cultural, and federal buildings found within the 30.5 m coastal planning zone. For residential and subsistence infrastructure, we surveyed the foundation elevations of representative buildings. Where the building was raised above ground elevation on piles driven into permafrost, which is common in Iqaluit, we collected both ground and foundation (off-ground) elevations. Where the two elevations were equivalent, only one value was required (Fig. 8A). For key infrastructure such as the courthouse or the pumping stations, elevations were generally taken on the corner of the building facing the coast, assuming a level foundation. Some categories, such as the subsistence infrastructure or the roadbed elevations, include many points, covering the range of elevations for that type of infrastructure along the length of the study area shoreline.

Climate and Sea Ice

Environment Canada meteorological records of temperature, wind, and precipitation for Iqaluit have been collected since 1946, with quality-controlled hourly measurements at a continuously occupied site since 1953 (Table 1). Additional data have more recently been collected by a climate station located between Iqaluit and Apex. Reliable meteorological information is therefore available in Iqaluit for the last 60 years.

The ice foot along the main Iqaluit waterfront was surveyed in February 2011 using RTK-GPS to obtain elevations on the surface of the ice. These points were directly over transects surveyed in the summer. This survey allowed an estimate of ice foot thickness and elevation for the 2011 ice season. Direct observations of freeze-up by the authors in November 2011 included documentation of ice pile-up along the waterfront.

We used two data sets to evaluate trends in the dates of freeze-up and breakup. These were the Canadian Ice Service Digital Archive (CISDA) (CIS, 2006) and the combined microwave sensor freeze-up/breakup analysis archive from the NASA Goddard Space Flight Center (Markus et al., 2009). The microwave sensor directly measures the onset and completion of freeze-up and breakup by detecting water on the surface. The CISDA records report sea ice concentrations as a fraction of 10 (10 being 100%

TABLE 1. Available climate data for the Iqaluit area. Three of the stations (2402590, 2402591, and 2402594) are at 33.5 m elevation. The other station (2402592) is at 22 m elevation. All stations are located in the same position at 63°45′ N, 68°33′ W, near Iqaluit airport at the head of the inlet.

Station ID	Hourly data	Daily data
2402590	1953−01−01 to 2011−05−11	1946−01−01 to 2008−07−31
2402591	2008−07−03 to 2011−05−11	2008−07−01 to 2011−05−31
2402592	2004−12−16 to 2012−01−01	2004−05−01 to 2011−05−31
2402594	NA	1997−04−01 to 2007−11−30

concentration). We defined the timing of freeze-up and breakup following Gagnon and Gough (2005) as the point at which ice concentration last crosses 7/10 for the season. The presence of a trend was determined using the non-parametric Mann-Kendall test for monotonic trends (Helsel and Hirsch, 1992), as is done in sea ice trend analysis elsewhere (Gagnon and Gough, 2005; Laidler et al., 2009). To add to the two data sets, we also considered ice thickness from a time series initiated by Transport Canada in 1959, but now maintained by the Canadian Ice Service. Weekly thickness surveys are conducted less than 1 km offshore within Koojesse Inlet between January and May of every year.

Waves and Run-Up

Instrument moorings in 2010 and 2011 contributed information on incident waves, currents, and water levels (Hatcher et al., 2014). We collected wave data using seabed-mounted pressure sensors and an acoustic doppler current profiler (ADCP). The pressure sensors were located in the intertidal zone and recorded wave information every 30 minutes. They were deployed from August to October of 2010 and 2011 in various positions in the intertidal zone. A total of six deployments of tide and wave recorder (TWR) pressure sensors (RBR TWR-2050 instruments) and three deployments of a Nortek Aquadopp© 1.0 MHz ADCP provided data on waves and currents. The ADCP recorded surface waves and current velocity profiles at one location on the flats and two in the harbour channels.

The TWRs record simultaneous measurements of wave characteristics and tidal water levels. The water-level measurements have a published precision of ± 0.05% (equivalent to ± 0.005 m in the shallow water configuration used here), whereas the wave measurement uncertainty depends on the dominant wave frequency (Gibbons et al., 2005).

Wave hindcasting to estimate potential run-up heights used a combination of the archived wind records and the simple empirical wind-wave relationships presented in Hurdle and Stive (1989), as revised from the Shore Protection Manual (USACE, 1984). The wind-stress factor was corrected for air-sea interface temperature difference and anemometer elevation according to USACE (1984), using the 10 m anemometer winds reported at the Iqaluit weather station.
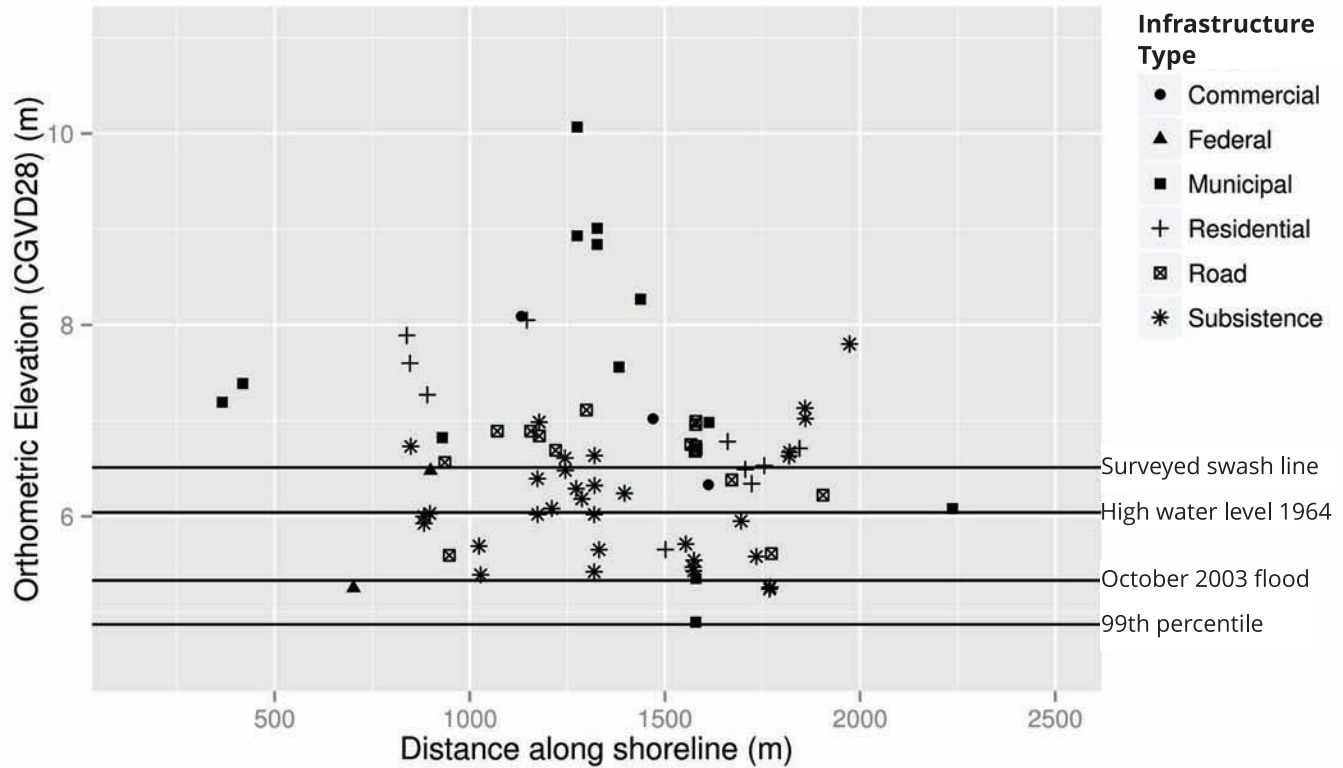
FIG. 9. Elevation values for all surveyed infrastructure points. Noteworthy surveyed and recorded water levels are shown with horizontal lines. The 99th percentile water level is computed from the CHS water-level record.

Water Levels and Sea Level Rise

Water-level records are available in two forms: the historical tide gauge records provided by the Canadian Hydrographic Service (CHS) and the pressure sensor water levels recorded in 2010 and 2011 using the TWR instruments described above. The CHS record is an irregular time series of hourly data with 28 198 hours of data between 1963 and 1977. This means that over the 14-year span for which data exist, there were no observations 77% of the time. The field data include 2670 hours of data in the open water seasons of 2010 and 2011.

To estimate past extreme water levels on the coast within the study area, we used RTK-GPS to survey two types of high water-level proxies: (1) water-level elevation, surveyed retroactively using a photo of a flooding event in 2003 (Fig. 1A, boulder surveyed is at centre of photo directly below red shed), and (2) storm swash limit lines preserved at various places in the vicinity of Iqaluit. These lines were scattered around the outer limits of the inlet on undisturbed beaches (Fig. 4C). Surveying elevations on these swash limits provided undated estimates of extreme high water levels combined with wave run-up.

In this study, a 70 cm rise in relative sea level over 90 years (2010–2100) was adopted as a precautionary estimate, initially based on earlier work by James et al. (2011). The most recent projections for Iqaluit, based on the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) (Church et al., 2013) and

appropriate accounting for crustal motion, gravitational effects, dynamic oceanography, and other factors, indicate a rate of rise for the highest rate of forcing, the so-called "representative concentration profile" 8.5 (RCP 8.5) close to zero, with a 95% confidence interval of about ± 40 cm (James et al., 2014). The use of RCP 8.5 is considered appropriate as a precautionary approach and also recognizes that global CO_2 concentrations are tracking near the upper limits of IPCC projections (Friedlingstein et al., 2014), while observed global sea level rise has been similarly high (Rahmstorf et al., 2007; Church et al., 2013). The IPCC AR5 recognized that additional sea level rise from accelerated drawdown of the West Antarctic Ice Sheet, for which the potential is poorly constrained, would not likely exceed several tenths of a metre during this century (Church et al., 2013). To allow for this scenario, James et al. (2014) provided an enhanced projection of +65 cm based on a number of published estimates of the likely effects of marine ice-sheet instability in West Antarctica. Recent work suggests that increased oceanic melting and hydrofracturing of ice shelves could lead to collapse of the West Antarctic Ice Sheet much sooner than previously thought and to accelerated ice loss from the East Antarctic Ice Sheet (Pollard et al., 2015). The precautionary local sea level rise of 70 cm for 2010–2100 adopted in this paper incorporates an upper 95% estimate of 40 cm for RCP 8.5 enhanced by a smaller 30 cm allowance for instability of the West Antarctic Ice Sheet.

TABLE 2. Trends in two data sets for Frobisher Bay. Significance levels, taken from the Kendall tau rank correlation coefficient, are shown by *** (99%) and ** (95%). Negative values show breakup earlier in the year (negative Julian days), and positive values show freeze-up later in the year (positive Julian days). Positive duration shows the lengthening of the ice-free open water season.

Type	CISDA trend	NSIDC trend
Breakup	−0.95**	−0.55***
Freeze-up	+0.54**	+0.49
Ice-free season	1.58***	1.05***
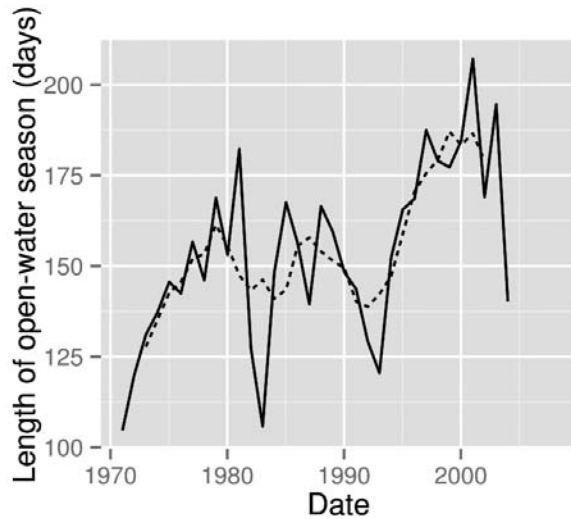
FIG. 10. Time series showing the length of the open water season (measured in days) captured in the CISDA data set. The solid line shows the annual data, while the dashed line shows the five-year running mean.

RESULTS

Iqaluit Topography and Waterfront Exposure

Beach crest elevations throughout the study area vary from beach to beach, largely as a function of exposure. The lowest crest elevations are found on the Iqaluit waterfront (5.1 m), with higher crest levels at the cemetery beach (6.1 m elevation) and Apex beach (6.2 m elevation). Backshore slopes are fairly consistent throughout, except where higher-relief bedrock is exposed. The mean slope of all the backshore transects surveyed (13 in total) is 3.5°. This value translates to a 1:16 slope, where a 1 m rise in water level would flood approximately 16 m horizontally into the backshore, which has implications for flood hazard projections, especially with a strong onshore wind that could drive additional setup and wave run-up.

Measured infrastructure foundation elevations in the waterfront zone range between 4.25 m and 10.13 m elevation (Fig. 9). Subsistence infrastructure is predominantly located at the lowest elevations, closest to the water on the uppermost part of the beach. Residential buildings are, on average, at much higher elevations, although the lowest is a house at 5.6 m (10 cm above HHWLT).

TABLE 3. Description, elevation above mean sea level (CGVD28), and data source for high water levels in Iqaluit. DGPS survey refers to the differential geographic positioning system survey performed in this study.

Description	Elevation (m)	Source
95th quantile	4.00	tide gauge
99th quantile	4.87	tide gauge
max recorded	6.04	tide gauge
Oct 2003 flood	5.33	photograph (DGPS survey)
Cemetery beach	5.31	swash line (DGPS survey)
Inuit Head pipeline	5.66	swash line (DGPS survey)
Inuit Head station	6.06	swash line (DGPS survey)
Inuit Head station	6.19	swash line (DGPS survey)
Long Island	6.48	swash line (DGPS survey)
sewage lagoon	6.51	swash line (DGPS survey)

Sea Ice Hazards

Results of the sea ice freeze-up and breakup timing analysis are shown in Table 2. The ice-free season has lengthened by 1.5 days/year since 1969 (99% confidence). The dates of breakup and freeze-up, as defined in the NASA data, show comparable trends toward earlier breakup (−0.55 days/year) and later freeze-up (+0.48 days/year). Using the definition of breakup and freeze-up for the CISDA data results in trends of −0.95 days/year (breakup) and +0.54 days/year (freeze-up) (Fig. 10). Despite limitations imposed by a lack of satellite coverage prior to 1979, as well as ambiguity in defining the onset of breakup or freeze-up, this analysis suggests that Frobisher Bay is experiencing a decline in the length of the ice season (increase in the length of the open water season). This result is consistent with the trend reported by local observers, including researchers at the Nunavut Research Institute (NRI), who have been monitoring freeze-up and breakup dates since 2002 (R. Armstrong, NRI, pers. comm. 2011).

Examples of minor ice pile-up and ride-up were observed to be widespread throughout the study area in November 2011, but the most substantial occurrences were along a particular segment of shoreline near the base of the breakwater, where a revetment (artificial steepening of the shore) has been built. In this area, there was evidence for both thicker floes and more significant pile-up during spring-tide conditions (Fig. 5B). Along the beaches, the establishment of the ice foot about halfway down the beach face restricted ice pile-up to the lower beach face, well seaward of any infrastructure. The ice foot seems to be established on a depth-dependent basis: in 2011 the seaward edge rested at a consistent seabed elevation of 3.5–4.0 m.

Flooding Hazards and Sea Level Rise

Evidence for extreme water levels is summarized in Table 3. The 95th and 99th quantile water levels from the tide gauge record are 4.00 m and 4.87 m elevation, respectively. The maximum level in the tide gauge record was 6.04 m on November 21, 1964. These values, being from hourly records, may not capture the highest water levels,
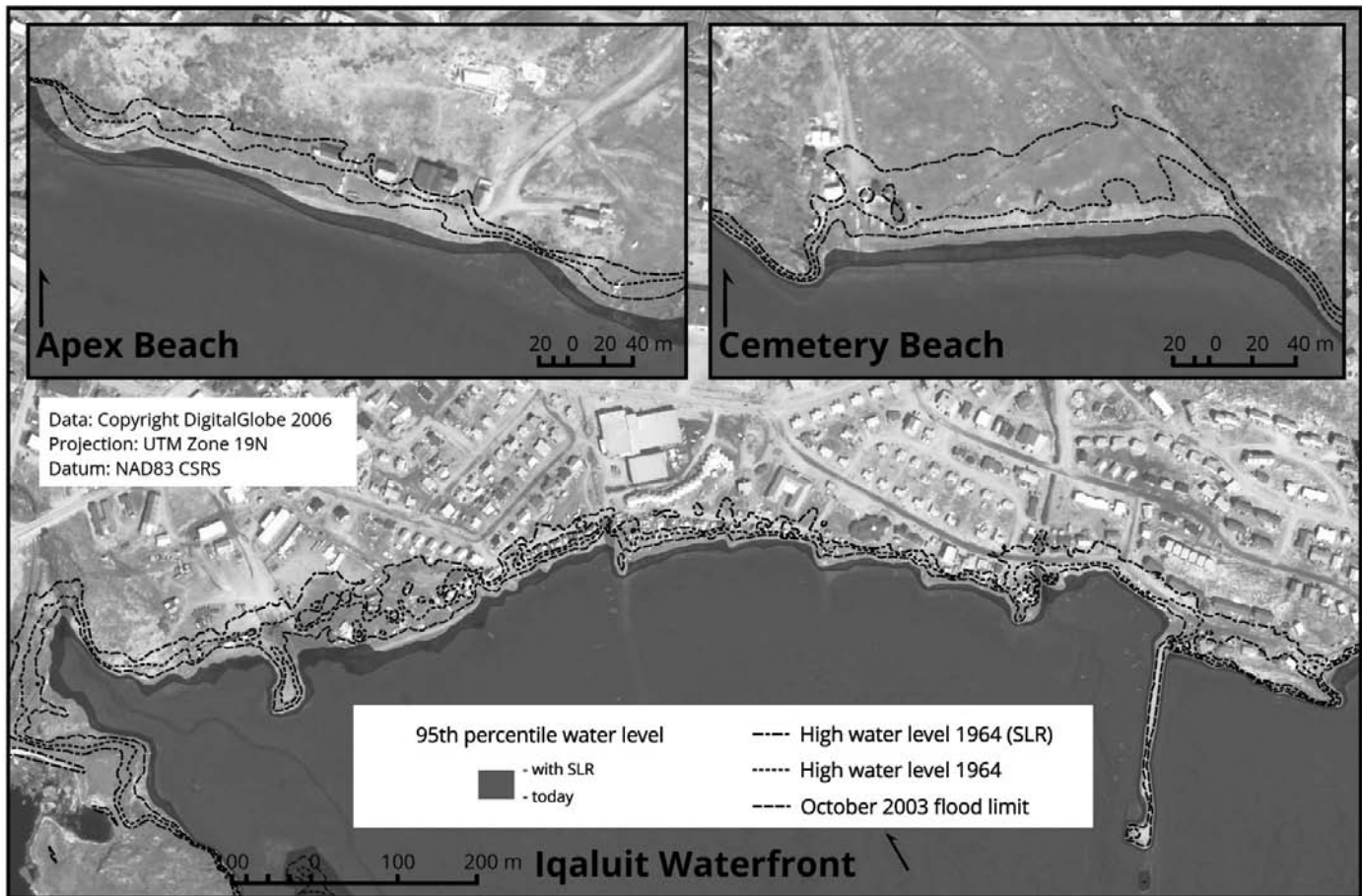
FIG. 11. Flood hazard mapping along the main sections of the waterfront in Iqaluit and Apex. The three areas of the map are the same as the boxes labeled in Figure 2 and shown in Figure 7. The highest inundation flood line shows the scenario of a 0.7 m sea level rise added to the highest recorded water level in November 1964 (6.04 m + 0.70 m).

which may have peaked up to 0.2 m higher, giving a possible extreme instantaneous high water level of 6.25 m (12.3 m Chart Datum; CHS, 2001). Elevations of surveyed storm lines (which do not necessarily record still water levels) ranged from 5.16 m to 6.51 m. The surveyed high water level approximated from the October 2003 flood photograph (Fig. 1A) was 5.33 m. A swash line found at the base of the Inuit Head pipeline had an elevation of 5.66 m, and two other swash lines found farther out Inuit Head were at 6.19 m and 6.06 m (± 0.15 m for these two elevations). The highest swash lines on the outer shores of Long Island were at 6.48 m. The highest elevation swash line in the study area, at 6.51 m, was surrounding the sewage lagoon at the head of the inlet.

The scenario of a 0.7 m rise in mean sea level combined with the historical high water limit was mapped onto the DEM to visualize potential flood limits (Fig. 11). Unlike many coastal beach systems where a defined storm ridge or dune line protects against periodic high water, the fairly even backshore slope in Iqaluit produces incremental landward incursion of floodwater. A rise in sea level of 0.7 m with a high spring tide (0.7 m above HHWLT) would inundate 28% of the 30.5 m coastal ("Open Space") zone and 14% of the coastal Sijjaanga District. The combination of this scenario for sea level rise and a repeat of the highest

recorded water level would flood 46 of the 91 coastal structures (50%), and five of the 61 municipal structures (8%) within the coastal district (Fig. 11).

Waves and Run-Up Hazards

For an open water fetch of 50 km, using meteorological records from Iqaluit and empirical wind-wave relations (Hurdle and Stive, 1989), the greatest wave-producing winds on record (22 Sept 1960, 97 km/h for 3 hours) give a hindcast significant wave height of $H_s = 1.6$ m with peak period $T_p = 5.9$ s. The potential run-up from these waves on a beach slope of 5° typical of Koojesse Inlet is 0.6 m (Hunt, 1959).

Observed H_S reached 0.7 m over the flats and 1 m in deeper water, with peak periods up to about 5 s. At a wave period of 5 s, the waves begin shoaling well out over the tidal flats (in 9.8 m depth, based on the depth-to-wavelength ratio $h/L < 0.25$). Up to 80% energy dissipation between two sensors placed along the path of incident waves was observed in this study. The hindcast 5.9 s waves for the 22 September 1960 event would begin to shoal in a depth of about 14 m and thus would suffer energy dissipation across the full width of the flats even at high spring tide. The wave height at breaking and run-up heights on the beaches
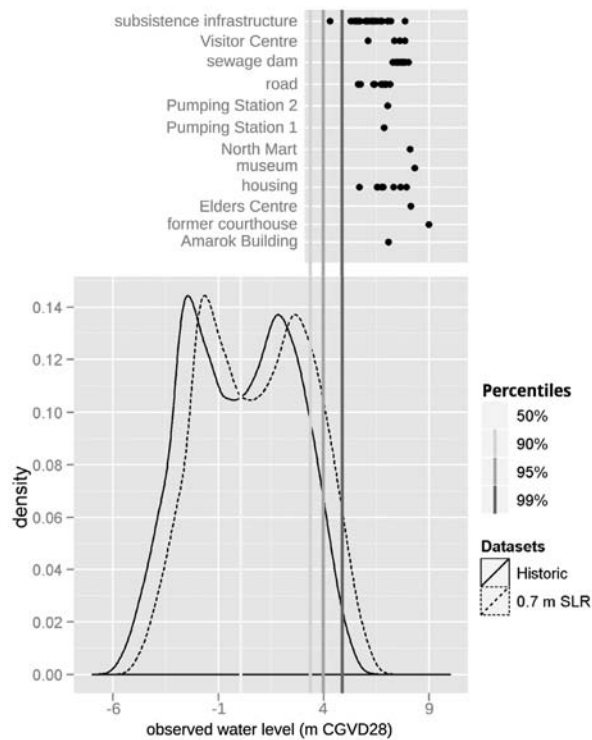
FIG. 12. Elevation ranges for infrastructure groups with water-level statistics plotted. Infrastructure groups follow Figure 7. Sea level parameters are the percentiles of the historical tide gauge record and change in probability with sea level rise of 0.7 m. Note the small elevation buffer between high-tide levels and the subsistence infrastructure.

depend to a large extent on the incoming wavelength and tide level, as well as on the roughness of the shore face, the extent of energy dissipation during shoaling, and the slope of the beach. The largest waves observed during this study coming in at high spring tide would suffer relatively little dissipation and would produce run-up of 1 m or less on beach slopes ranging up to 6° (Hunt, 1959).

Overtopping and Erosion Hazards

Overtopping of one of the sewage lagoon dams could have highly negative impacts on the health of the inlet ecosystem and do damage to the subsistence fishery. Our surveys show crest elevations of 7.7 m on the eastern dam and 7.3 m on the western dam. This is 1.3 m above the highest recorded water level in the tide gauge record. Surveys of storm swash lines near the dams, however, show a run-up limit of 6.5 m, 0.5 m above the highest recorded still water level. With an RMS survey error of 0.05 m, there is 0.08 ± 0.1 m of freeboard (elevation above run-up level) to preserve the integrity of the dam and lagoon (Fig. 12). At the low end of this range, a freeboard of 0.7 m leaves little to no allowance for more extreme events or sea level rise. Apart from downcutting of the tidal flats, erosional retreat of the coast is not a serious concern in Iqaluit. Some parts of the shoreline are resistant bedrock, and in other places the beach sediments have formed at a level consistent with the highest swash run-up levels. However, a rise in relative sea level

would lead to movement of the beach system to adjust to the new mean water level and tidal limits, which would lead to landward and upward movement of the beach sediments.

DISCUSSION

Results of this study investigating the major drivers of coastal hazards and the severity of hazard exposure along the Iqaluit waterfront suggest limited risk for much of the shorefront infrastructure. Nevertheless, some roads, structures, and other key facilities and resources are at risk from flooding, wave run-up, or ice impacts. Detailed mapping of coastal infrastructure shows that development has been concentrated along the beachfront sections of the coast. In these areas some critical infrastructure is found in the backshore, and numerous subsistence-support resources (sheds, sea cans [shipping containers], boats, motors, skidoos, qamutiqs, and other equipment) are concentrated on the uppermost part of the beach. The subsistence infrastructure is found primarily below the elevation of past extreme water levels, implying a tangible risk at the present time (Fig. 11). Much of the other waterfront infrastructure has a freeboard ranging from 1.0 to 1.5 m or more above the highest observed historical water level. At the upper limit of projected local sea level rise over the next century adopted in this study (0.7 m), this freeboard would be reduced to 0.3–0.8 m. Notwithstanding the 2003 flood event, community awareness of the extent of exposure may be limited because the recorded extreme high water level occurred more than 50 years ago, before development at this site.

It is important to acknowledge the remaining uncertainty in the sea level projections, for which the error bars at Iqaluit span a range from falling to rising sea level. This range reflects both the close approximation of the median projections to zero and uncertainties in some of the inputs, such as vertical crustal motion and glacial mass balance, both on Baffin Island and in Greenland (James et al., 2014). The sign of the sea level change at Iqaluit this century is highly sensitive to these variables, one of which (vertical motion) can be resolved by acquiring a longer time series of geodetic monitoring, while the other (ice mass reduction) not only requires more data, but also will be dominated by its response to the global human development trajectory and greenhouse gas emissions (Friedlingstein et al., 2014; Fyke et al., 2014).

The spatial resolution of the two data sets used to determine sea ice trends is somewhat different. The data from Markus et al. (2009) are at a 25 km grid resolution, and the CISDA data are 0.25° resolution (14 km in this area). In this analysis, trends were calculated over the entirety of Frobisher Bay. It is therefore assumed that long-term trends in sea ice breakup and freeze-up for Frobisher Bay as a whole are representative of the trend that would be observed directly off Iqaluit in the upper bay. Obviously, the complexity of sea ice distribution in the bay makes this assumption problematic, but for the purpose of determining the

FIG. 13. High spring-tide water levels during freeze-up build the ice foot to the doorsteps of the coastal subsistence infrastructure (November 2011). These buildings are vulnerable to even slight changes in the dynamics of storms or ice during the freeze-up process.

sign of the trend of freeze-up and breakup (later or earlier in the year), it is considered valid. The CISDA record shows high year-to-year variability in the length of the open water season (Fig. 10), but statistically significant overall trends toward longer open water seasons since 1979 were found in both the CISDA and the NSIDC data sets (Table 2).

Where the beach extends out onto the tidal flat, the ice foot established near the high-tide line extends far enough down the beach face to protect the upper crest area of the beach (and infrastructure located there) from sea ice pile-up (Forbes and Hansom, 2011). The elevation of the ice foot terrace may be lower initially, depending on the phase of the tides, but it rises over time as successively higher tides flood the surface and freeze (Fig. 13). Where the coast has been artificially steepened by construction of revetments for shore protection, a narrower ice foot and deeper water close to shore favour higher ice pile-up under appropriate ice, wind, and spring-tide conditions (Fig. 5B). Severe ice pile-up resulting from onshore winds combined with high tides has been widely documented elsewhere (Forbes and Taylor, 1994). Despite the protection offered by the ice foot, the potential exists for damaging events at Iqaluit. Our field observations documented numerous small pile-up ridges and ridging events (Fig. 5). No accounts of severe ice damage to infrastructure in Iqaluit have been found in discussions with local residents, but this is another phenomenon sensitive to the tide level in a macrotidal setting. As for flooding, the large tidal range reduces the probability of an extreme event, which requires near coincidence with high water, but when that low-probability event occurs, its effects may be unprecedented.

Other research has shown the damaging effects of later freeze-up on the subsistence food harvest (Statham et al., 2015). Discussions with residents suggest that the longer the freeze-up remains dynamic and susceptible to autumn storm effects, the harder it can be to transit the upper foreshore and beach (T. Tremblay, CNGO, pers. comm. 2011). With progressive delay of freeze-up into the fall storm season, there is an increased likelihood of onshore winds acting on mobile ice (Hatcher, 2014).

There is little published information on freeze-up in Frobisher Bay, and its timing can be quite variable (Fox, 2003), with a range of almost 60 days (Hatcher, 2014). In 2011, when our on-site study of freeze-up took place, Koojesse Inlet became largely ice-covered over the course of a week (22–28 November). In the previous year, 2010, open water persisted anomalously into January, and large waves developed during a storm on November 27 (D. Mate, CNGO, Iqaluit, pers. comm. 2011). Another late freeze-up, though not quite so extreme, occurred in 1985. Progressively later freeze-up dates, as observed over the past few decades and expected with climate warming (Table 2), increase the risk of wave run-up events, irrespective of any change in storm climate, by increasing the seasonal window for storms to occur over open water (Forbes and Hansom, 2011; Hatcher, 2014).

Some flooding at Iqaluit has occurred in the absence of storm winds (R. Armstrong, NRI, pers. comm. 2010). This raises the question of whether floods are attributable to high perigean spring tides. Long-term lunar cycles can add an extra 0.2 m on top of high tide levels (Haigh et al., 2011). No flooding occurred during the last two high periods of these long-term lunar cycles in Iqaluit, though a difference of 0.2 m could be substantial here, given the small freeboard. Also, as observed in other large tidal embayments (e.g., Gehrels et al., 1995), a change in sea level (or ice conditions) may alter the tidal dynamics and amplitude at Iqaluit. Modeling of these changes is beyond the scope of this study, and the effects at Iqaluit will likely be minor.

We are unaware of any eyewitness accounts or traditional knowledge of the 1964 flood event. It coincided with a moderate storm with minimum sea level air pressure of 98.6 hPa and easterly winds above 35 km/h, sustained for four hours. In an earlier preliminary report (Hatcher et al., 2011), we erroneously documented a 1.37 m storm surge associated with this event. However, subsequent more rigorous analysis of the tidal data and predictions uncovered timing errors, and the actual offset averaged over that tidal cycle was 0.2 m. This suggests that upper Frobisher Bay, inside the band of islands in the mid-bay region, is somewhat protected from storm surges, although decimetre-scale wind setup, barometric, and ocean dynamic effects occur, as well as wave setup amounting to less than 10% of deepwater wave height (Dean et al., 2005).

Iqaluit's coastline is a complex zone of physical and social interaction with a range of stakeholders and infrastructure types (critical municipal infrastructure, cultural resources, commercial properties and residences, sealift freight handling facilities, and the subsistence infrastructure belonging to hunters and fishers). Risk to the subsistence infrastructure is rooted in the expansion of urban development into the backshore zone, which has left limited space for hunters and fishers, who need to locate on

land with direct access to the sea. Furthermore, the lack of undeveloped space landward of the present subsistence infrastructure prevents retreat in the face of existing and future hazards. This study shows the potential for future higher and more frequent floodwater and sea ice incursion into the subsistence use zone. As visualized in Figure 12, an increase in sea level not only raises the reach of extreme tide and surge events, but also increases the frequency (probability) of flooding to levels rarely flooded today. The potential impacts on subsistence infrastructure, in the context of food security challenges in Iqaluit (Lardeau et al., 2011), represent a source of inequity and non-sustainability. The 2010 General Plan outlines policies for coastal development based on tourism (City of Iqaluit, 2010). It would seem that co-planning of joint use between subsistence activities and tourism may be worth consideration to avoid an increase in coastal vulnerability along the city's spatially constrained waterfront. A more holistic approach to development, exemplified in the Sustainable Community Plan (City of Iqaluit, 2014), may be important to increase resilience on a number of fronts.

Serious limitations are imposed by the scarcity of some key data in this region. In particular, estimates of high water levels are constrained by the short duration, sporadic coverage, and seasonal bias of the tide gauge data. The instrument moorings in 2010 and 2011, deployed as part of this study, provided the first measurements of waves in the vicinity of Iqaluit, but unfortunately did not record a major storm event. The surveyed run-up levels, geomorphology, and local knowledge demonstrate that wave impacts on the coast do occur. This study has shown that the tidal flats play an important role in shore protection, dissipating a large proportion of incoming wave energy, except at the highest tides. The storm of concern is the rare wave event coinciding with the highest tide. The macrotidal regime makes this coincidence more critical than at sites with lower tidal range, reducing the window of opportunity for an extreme water-level event. In the absence of more complete water-level measurements, it is not possible to compute the probability of such an event from empirical records. In addition, remaining ambiguities in the rate of crustal uplift are a major limitation for projections of sea level change in the area. However, ongoing geodetic data collection is expected to provide more reliable rates of uplift, which will help to constrain the projections of local (relative) sea level change.

Sustainable development planning in Iqaluit would benefit from further studies. In particular, it would be valuable to improve our understanding of coastal ice mobility and projections of freeze-up and breakup dates (and length of the open water season) as a function of regional climate projections. The limited importance of coastal erosion removes that issue from the monitoring agenda. Thus coastal monitoring in this area should focus primarily on sea level change, sea ice dynamics, wave climate, wave shoaling, and run-up levels. Detailed surveys of ice pile-up ridges during freeze-up, as well as the conditions that caused them, would help to better define this hazard in the local context. Related monitoring

of ice foot growth and dimensions, including year-to-year variability and trends, would complement this analysis.

Despite the urban context, high number of wage earners, and large proportion of residents originally from elsewhere, the value of traditional knowledge in planning should not be overlooked. A substantial proportion of Iqaluit's residents use the sea ice during the winter for access to country food and have accumulated knowledge on the characteristics of winter ice. During the summer months, residents travel by water throughout the bay and thus are familiar with the patterns of wind and waves and the impacts of storm events. Within the urban centre, hazard events of the past two decades, at least, remain in the memories of long-time residents. This is a knowledge source that can contribute to effective decision making and community resilience. At the same time, instrumental monitoring of key environmental variables, including vertical crustal motion, wind, water levels, waves, and ice, can play an important role in detecting and tracking change, validating and refining projections, and quantifying evolving risks to the people and infrastructure of the city.

CONCLUSIONS

This study has identified three coastal hazards relevant to infrastructure in Iqaluit. (1) Exposure to ride-up or pile-up of sea ice. This hazard involves a variety of factors associated with freeze-up and breakup and an increase in risk associated with climate-induced expansion of the open water season. Ice also plays a protective role in the form of the winter ice foot, which shelters the shore and nearby infrastructure from direct impacts of the mobile ice over the tidal flats. (2) Exposure to flooding of coastal infrastructure. The dominant risk factor is tidal dynamics, combined with relatively minor contributions from steric, barometric, and wind stress events (storm surge). The documented flooding, at least in 2003, seems to have occurred as a result of an extreme tide, perhaps associated with a regional dynamic anomaly. A contribution from a minor storm surge cannot be ruled out. (3) Wave run-up and associated setup. These events have the potential to overtop the sewage-retaining berms and damage other infrastructure along the urban waterfront. A more detailed analysis of this hazard is warranted.

Interacting with all of these, the trend of relative sea level is the dominant control on the vertical extent and landward reach of specific hazard processes. This study has evaluated the change in flooding extent that would result from a 0.7 m rise in local sea level. This scenario is close to the upper limit of plausible change over the 90 years 2010–2100 and appropriate for a precautionary approach with low risk tolerance. It is important to recognize that the statistical uncertainty in the sea level projections includes both rising and falling relative sea level for all representative concentration profiles considered in the IPCC AR5 (James et al., 2014). Nevertheless, analyses of global trends in major climate

variables, including temperature and global mean sea level, have shown that the world is tracking near the upper limits of the range of projections (Rahmstorf et al., 2007; Church et al., 2013). Assuming that relative sea level is rising in Iqaluit, this change will dominate the rise in probability of waterfront flooding and extreme high water events.

This study points to a number of implications for adaptation planning in Iqaluit:

- Steepening of the coastal profile through revetment or armouring may protect against waves, but a steeper profile with a narrow ice foot allows higher ice pile-up, increasing exposure of infrastructure directly landward of the revetment to potential ice impact.
- Accurate surveys of coastal infrastructure have allowed the estimation of waterfront elevations and freeboard under various sea level rise, high water, and wave run-up scenarios. The maximum recorded water level is 6.04 m above mean sea level (1964), and the highest surveyed swash line is 6.51 m (date unknown). This study has shown that for an observed extreme high water event added to a plausible upper limit of the most recent projections of sea level for 2100 (0.7 m above the 2010 mean sea level), 50% of the infrastructure within the coastal "open space" planning zone would be affected, and significant areas of land would be flooded in the developed backshore.
- Some shorefront infrastructure in Iqaluit is already at risk of flooding in extreme high water events, as demonstrated by the tide gauge record for 21 November 1964 and the anecdotal and photographic evidence from October 2003. The expanded flood risk from potential sea level rise within the range of the latest projections warrants attention. This is particularly the case for the coastal subsistence infrastructure, which is an essential contributor to sustainability in Iqaluit, yet its position on the coast means that it is most exposed to any change in hazards arising from sea level rise or changing sea ice and wave regimes.

ACKNOWLEDGEMENTS

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