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ARTICLE

Impacts of past and future coastal changes on the Yukon coast — threats for cultural sites, infrastructure, and travel routes

Anna M. Irrgang, Hugues Lantuit, Richard R. Gordon, Ashley Piskor, and Gavin K. Manson

Abstract: Yukon's Beaufort coast, Canada, is a highly dynamic landscape. Cultural sites, infrastructure, and travel routes used by the local population are particularly vulnerable to coastal erosion. To assess threats to these phenomena, rates of shoreline change for a 210 km length of the coast were analyzed and combined with socioeconomic and cultural information. Rates of shoreline change were derived from aerial and satellite imagery from the 1950s, 1970s, 1990s, and 2011. Using these data, conservative (S1) and dynamic (S2) shoreline projections were constructed to predict shoreline positions for the year 2100. The locations of cultural features in the archives of a Parks Canada database, the Yukon Archaeological Program, and as reported in other literature were combined with projected shoreline position changes. Between 2011 and 2100, approximately 850 ha (S1) and 2660 ha (S2) may erode, resulting in a loss of 45% (S1) to 61% (S2) of all cultural features by 2100. The last large, actively used camp area and two nearshore landing strips will likely be threatened by future coastal processes. Future coastal erosion and sedimentation processes are expected to increasingly threaten cultural sites and influence travelling and living along the Yukon coast.

Key words: Arctic coastal dynamics, permafrost coast, shoreline projection, Inuvialuit cultural features.

Résumé : La côte de Beaufort, au Yukon, Canada, est un paysage très dynamique. Les sites culturels, les infrastructures et les itinéraires de déplacement utilisés par la population locale sont particulièrement vulnérables à l'érosion côtière. Afin d'évaluer les menaces qui pèsent sur ces phénomènes, on a analysé les taux de changement des rives sur une longueur de 210 km de la côte et on les a combinés avec des renseignements socioéconomiques et culturels. Les taux de changement des rives ont été calculés à partir de l'imagerie aérienne et satellitaire des années 1950, 1970, 1990 et 2011. À l'aide de ces données, des projections prudentes (S1) et dynamiques (S2) du littoral ont été établies pour prévoir les positions du littoral pour l'année 2100. Entre 2011 et 2100, environ 850 ha (S1) et 2660 ha (S2) peuvent s'éroder, entraînant une perte de 45 % (S1) à 61 % (S2) de toutes les caractéristiques culturelles d'ici 2100. L'emplacement des caractéristiques culturelles dans les archives d'une base de données de Parcs Canada, du Programme archéologique du Yukon et comme signalé

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dans d'autres documents ont été combinés avec les changements prévus de la position du littoral. Entre 2011 et 2100, environ 850 ha (S1) et 2660 ha (S2) pourraient s'éroder, entraînant une perte de 45 % (S1) à 61 % (S2) de toutes les caractéristiques culturelles d'ici 2100. La dernière grande zone de campement activement utilisée et deux pistes d'atterrissage littorales seront probablement menacées par de futurs processus côtiers. Les futurs processus d'érosion côtière et de sédimentation devraient de plus en plus menacer les sites culturels et influer sur les déplacements et la vie le long de la côte du Yukon. [Traduit par la Rédaction]

Mots-clés : dynamique côtière Arctique, pergélisol de la côte, projection du littoral, caractéristiques culturelles de Inuvialuit.

Introduction

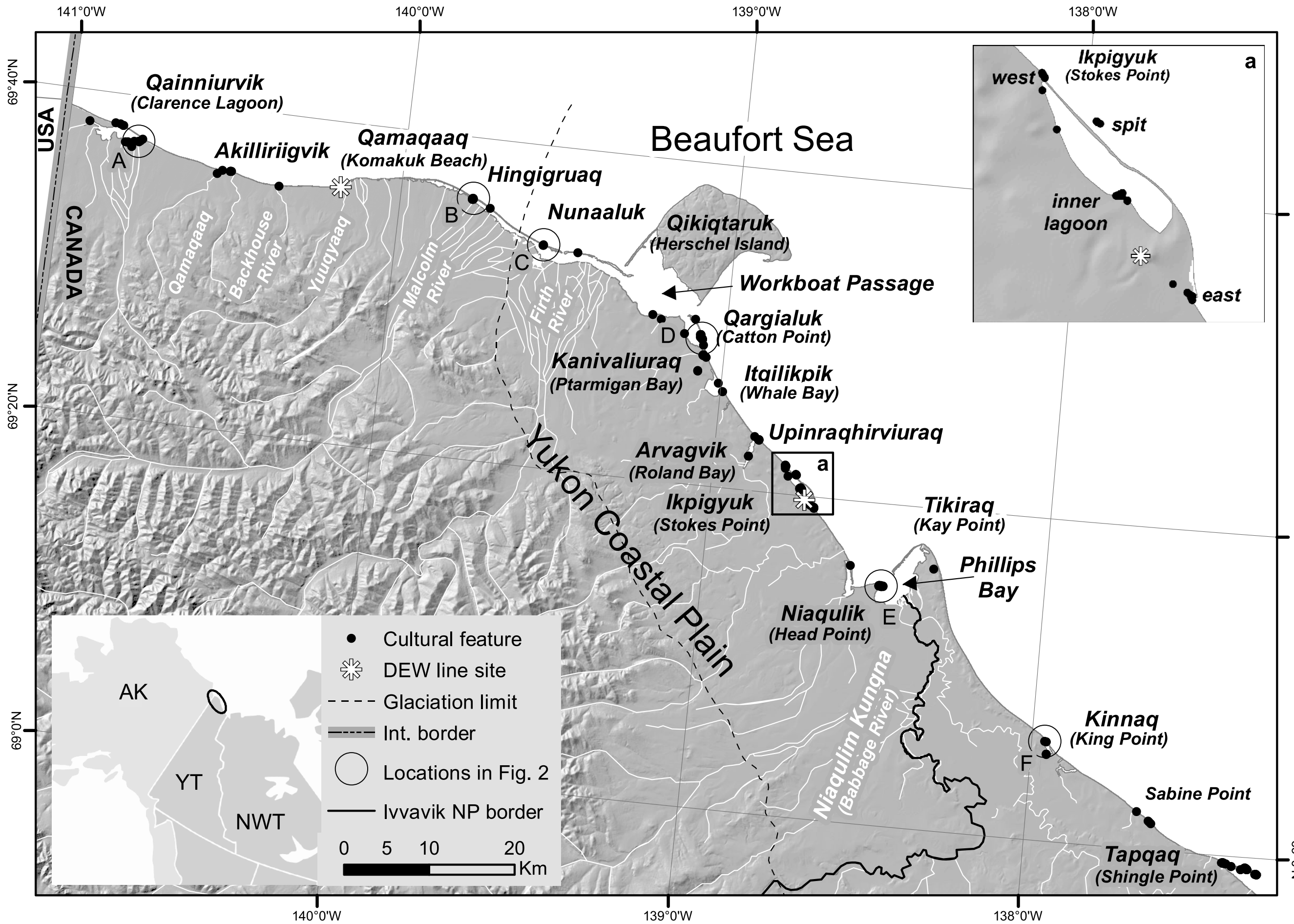
The northern coast of the Yukon, Canada, is extensively used by Inuvialuit and other Indigenous and non-Indigenous peoples. There were settlements along the coast until the middle of the 20th century (Nagy 1994; Thomson 1998) reflecting the important relationship between Inuvialuit and the nearshore Beaufort Sea (Nagy 1994; Alunik et al. 2003). Many cultural sites that give insight into the Inuvialuit way of life prior to contact with Europeans are found along the Beaufort coast. Rare artifacts from the Thule Inuit enrich the archaeological record of this region (Friesen and Arnold 2008; Arnold 2016; Friesen 2016). Numerous artifacts dating from the early 19th century are evidence of contact with early explorers (Franklin 1828; Amundsen 1908), whalers (Bockstoce 1986), and missionaries (Saxberg 1993). More recently, the Yukon coast has been strategically and economically important, as during the Cold War three Distant Early Warning (DEW) line stations were located there (Neufeld 2002; Lackenbauer et al. 2005). Further, since the 1970s, the region has been episodically explored for potentially rich oil and gas resources (INAC 2017).

Roughly two-thirds of the Yukon coast is part of Ivvavik National Park (Fig. 1). The archaeological sites of the park were inventoried systematically in 1996 and 1997 (Thomson 1998). These studies were supplemented by more detailed work at the sites of Qainniurvik (Clarence Lagoon) (Lyons 2004), Nunaaluk Spit (Thomson 2009), and Niaqulik Spit (Head Point) (Adams 2004). These archaeological investigations were accompanied by coastal erosion studies at five main survey sites: Qainniurvik, Nunaaluk Spit, Qargialuk (Catton Point), Ikpigyuk west (Stokes Point west), and Niaqulik (Solomon 1996; Forbes 1997). No systematic analysis of archaeological sites has been conducted along the rest of the coast.

Unlithified and ice-bonded coasts are particularly prone to coastal erosion, as is reflected in their high retreat rates (Mackay 1963; Jones et al. 2009; Lantuit et al. 2012; Günther et al. 2013; Gibbs and Richmond 2015). Erosion rates can reach as high as 9 m/a along the Yukon coast (Irrgang et al. 2018), and coastal erosion and flooding have the potential to put cultural heritage, existing infrastructure, and travel routes at high risk (Jones et al. 2008; Forbes 2011; Radosavljevic et al. 2016). Many cultural sites along the mainland coast, as well as on Qikiqtaruk (Herschel Island), have been or are about to be eroded (Jones et al. 2008; Friesen 2015; Radosavljevic et al. 2016; O'Rourke 2017). Investigations of the DEW line site at Qamaqaaq (Komakuk Beach) show that the landing strip has been eroding, on average, by approximately 1 m/a since the 1950s (Solomon 1998; Konopczak et al. 2014).

The objectives of this study were to assess the impacts of former and future shoreline changes on cultural sites, infrastructure, and travel routes to better understand how coastal

Fig. 1. Study area of the Yukon coast showing the locations of cultural features and infrastructure. Base map: 30 m Yukon digital elevation model, interpolated from the digital 1:50 000 Canadian Topographic Database (Yukon Department of Environment 2016).



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dynamics are influencing living and traveling along the Yukon coast, and threatening evidence of past human activity and habitation.

Study area

The study area spans approximately 210 km of the Yukon coast, from the international border with Alaska, USA, in the west to Tapqaq (Shingle Point) in the east and comprises the 10–40 km wide Yukon Coastal Plain (Fig. 1). Qikiqtaruk is not included in the study area. During the Wisconsinan glaciation, the Laurentide ice sheet extended to the west as far as Firth River and roughly two-thirds of the study area was covered by ice (Mackay 1959; Rampton 1982). Fine-grained lacustrine and alluvial sediments occur west of the Firth River. East of the Firth River, the surficial geology is dominated by fine-grained lacustrine and outwash plains and rolling moraines (Rampton 1982). Qikiqtaruk became separated from the mainland most probably between 650 and 1600 years ago by a narrow and shallow (<3 m) channel, known as Workboat Passage (Burn 2009, 2016; Radosavljevic 2018). Backshore elevations vary from around 6 m near the international border to 2 m within Workboat Passage, and up to 60 m east of Tikiraq (Kay Point). Ground-ice contents are high along the entire coast and reach as high as 74% in the formerly glaciated area where massive ground ice beds are found (Harry et al. 1988; Couture and Pollard 2017). The whole study area is underlain by continuous permafrost (Rampton 1982). Permafrost temperatures have increased by 2.6 °C since 1905 (Burn and Zhang 2009) as a consequence of climate warming (Richter-Menge and Mathis 2016).

The Yukon coast has diverse coastal dynamics. Mean rates of shoreline change are highest in the regions west of Firth River with rates of −0.9 to −1.4 m/a, and lowest in the region of Tapqaq with a rate of −0.1 m/a (Irrgang et al. 2018). However, locally along gravel features, for example, along the barrier islands of Nunaaluk Spit and the spit of Tapqaq, accumulation rates of up to 5 m/a occur (Irrgang et al. 2018). Coastal dynamics are limited to the ice-free period that occurs from the end of June to early October (Galley et al. 2016). Storms, which are very effective in forcing coastal erosion and accumulation, peak in October during ice freeze up (Hudak and Young 2002; Atkinson 2005). The mean maximum wind speed in October averaged over 12 sites along the Beaufort Coast is 12.8 m/s (Atkinson 2005). The most common wind directions are from the southeast and northwest; however, the storms most effective in causing coastal change originate from the northwest (Hill et al. 1991; Hudak and Young 2002; Manson et al. 2005; Manson and Solomon 2007). The astronomical tides are semidiurnal and, with amplitudes of 0.3 to 0.5 m, lie in the micro-tidal range (Harper 1990). Sea level rise in this region amounts to approximately 3.5 ± 1.1 mm/a (Manson and Solomon 2007). However, projections for the year 2100 indicate a sea level rise of 0.52 to 0.98 m (NT Government 2015; Flato and Ananicheva 2017).

There is little infrastructure within the study area. The landing strips at the DEW line stations at Qamaqaaq and Ikpigyuk are the only permanent larger infrastructures (Lackenbauer et al. 2005). The landing strip at Qamaqaaq is built on approximately 6 m high, flat polygonal tundra, whereas the landing strip at Ikpigyuk is built on a set of approximately 1 m high beach ridges. Transportation along the coast during the ice-free season is mainly by boat. Workboat Passage is an important travel route that is taken by local travellers to avoid navigating the potentially rough water north of Qikiqtaruk, and is also used as shelter by barges. The buildings at Pauline Cove represent a former settlement on Qikiqtaruk (Bockstoce 1986) that is part of the Qikiqtaruk–Herschel Island Territorial Park. Along the mainland coast, other than a few widely spread single cabins, the only regularly used remaining camp is at Tapqaq. The last settlements were abandoned in the 1950s (Nagy 1994).

Table 1. Coastal landform classification.

Class number	Coastal landform class	Definition
1	Beach, barrier island, spit	Subaerial sand and gravel beaches that are surrounded by water from both sites, such as spit extensions from the mainland, barrier islands fronting the mainland, lagoons, and river inlets
2	Inundated tundra	Tundra inundated because of thaw subsidence and (or) coastal flooding as an effect of sea level rise. This class includes wetlands and tidal flats.
3	Tundra flats	Low lying tundra with no evident active cliff or inactive cliff
4	Tundra slopes	Inactive cliffs and inactive retrogressive thaw slumps that are flattened and vegetated because of the absence of coastal erosion
5	Active tundra cliff	Cliffs and bluffs that are actively eroding

Methods

Data for shoreline projections

The calculation of shoreline projections is based on shoreline change data from Irrgang et al. (2018). The shoreline position was digitized using orthorectified aerial images from the 1950s, 1970s, 1990s, and for 2011 on GeoEye-1 and WorldView-2 satellite images (Digital Globe 2014, 2016). The Esri ArcGIS extension Digital Shoreline Analysis System (DSAS) version 4.3 (Thieler et al. 2009) was used to calculate shoreline change rates in the study area for three time periods: 1950s–2011, 1970s–1990s, and 1990s–2011. A total of 1967 transects at 100 m alongshore intervals were analyzed to obtain annual mean rates of shoreline change using the method of end point rates (EPRs) (Thieler et al. 2009). The coastal landform classification from Irrgang et al. (2018) was used to associate the change (i.e., acceleration or deceleration) of the EPRs with different coastal landforms. This information was used for a differentiated shoreline projection. The landforms were distinguished in the images from 2011 and were grouped into five classes: (1) beach, barrier island, spit; (2) inundated tundra; (3) tundra flats; (4) tundra slopes; and (5) active tundra cliff (Table 1, after Irrgang et al. 2018).

Shoreline projection for the conservative scenario (S1)

In the conservative scenario (S1), a purely linear shoreline projection was used. S1 is based on the EPRs from the 1950s to 2011. The EPR at each transect was multiplied by the number of years between 2011 and 2100 (89 years) to derive a transect-wise projected shoreline in ArcMap 10.3. As this approach uses rates of shoreline position change which were averaged over 60 years, the effects of severe storm events are smoothed. Thus, we consider the S1 scenario the conservative scenario for future shoreline evolution.

Shoreline projection for the dynamic scenario (S2)

In the dynamic scenario (S2), the transect-wise change in EPRs was calculated by comparing the EPR from the 1970s to 1990s to the EPR from the 1990s to 2011. A change index (Ci) was calculated for each transect as follows:

$$\text{Ci} = (\text{EPR}_{1990\text{s}-2011})/(\text{EPR}_{1970\text{s}-1990\text{s}}) \qquad (1)$$

where $\text{EPR}_{1990\text{s}-2011}$ is the rate of change from the 1990s to 2011 and $\text{EPR}_{1970\text{s}-1990\text{s}}$ is the rate of change from the 1970s to 1990s. The 1990s imagery covers only a fraction of the shoreline in our study area (13%), so the Ci compiled over the area for which imagery was available was extrapolated to the rest of the study area. To do so, a median Ci was calculated for each coastal landform class over the area covered by the 1990s imagery and applied to the same coastal landform class over the entire study area. Change indices >1 imply that shoreline

Table 2. Cultural feature classes.

Cultural feature class	Structures contained
Housing	Sod houses, driftwood log cabins, metal structure warehouses
Burial sites	Inuvialuit and European burial sites
Other features	Tent structures, ice houses, lean-tos, windbreaks, drying racks, stages, refuse areas, and unidentified or not further defined features and wooden structures

changes are expected to accelerate. This applies to the classes 2, 3, and 5 with the indices being 1.86, 1.24, and 1.41, respectively. Change indices <1 imply that shoreline changes are expected to decelerate. This applies to the classes 1 and 4, with the indices being 0.54 and 0.75, respectively.

Because the change indices are based on a comparison of two 20 year time periods (1970s–1990s to 1990s–2011), the EPRs from the 1950s–2011 period were first multiplied by 20 to obtain the linear distance of shoreline change for 20 years. This distance was then multiplied by the respective Ci to account for the estimated acceleration or deceleration of future shoreline change rates for each 20 years. In total, this process was performed 4.5 times (4.5×20 years) to obtain the shoreline position for the year 2100. This approach results in much greater EPRs for all classes with a change index >1, which cover the majority of the study area. Thus, we consider the S2 scenario the dynamic scenario for future shoreline evolution.

Positioning and characterizing of cultural sites

The positions and character of cultural features were provided for Ivvavik National Park between the international border and the Babbage River delta by Parks Canada (Parks Canada Agency 2007) (Fig. 1). The Parks Canada database was expanded by combining it with a database of cultural features from the Yukon Archaeological Program (Yukon Government 2016), which includes features outside Ivvavik National Park. The accuracy of some points within the combined database is considered to be 500 m, which is greater than the projected average net shoreline movement by 2100. As this would influence the calculations of the loss of cultural features, the point positions were improved, where possible. To improve the database, GeoEye-1 and WorldView-2 satellite images from 2011 (Digital Globe 2014, 2016), geo-coded aerial images from the 1950s and 1970s (Irrgang et al. 2018), aerial video collected by the Geological Survey of Canada in 1984 and 1999 (Forbes and Frobel 1986; Solomon and Frobel 1999), location descriptions from Thomson (1998), site visits, and imagery interpretation were used to review the position of each site. We were able to increase the original database by adding detailed information about the nature and quantity of the features. In total, 140 cultural features were either relocated or added to the database, even though not all cultural features described by Thomson (1998) could be positioned on the imagery. Further, we greatly enhanced the position accuracy of about 85% of all cultural features to within 5 m. Cultural features were classified in three groups: (1) housing, (2) burial sites, and (3) other features (Table 2).

Calculation of losses under the S1 and S2 scenarios

Using Esri ArcMap 10.3, two polygon feature classes were created out of the S1 shoreline and the 2011 shoreline, and the S2 shoreline and the 2011 shoreline. The respective polygons were used to identify the cultural features that might be affected by shoreline changes under the S1 and S2 scenarios and to quantify future loss of land along the coast. To provide more detailed information at permanent infrastructure, the landing strips of the DEW line stations at Qamaqaaq and Ikpigyuk were digitized and the landing strip polygons were used to quantify the length of landing strips which would be eroded under both scenarios.

Estimation of future coastal dynamics in very dynamic areas

Workboat Passage and Tapqaq are both areas of high importance for local transportation and recreation. Workboat Passage is enclosed by gravel spits, barrier islands, and sand bars. Tapqaq is also a gravel spit. The S1 and S2 scenarios were not capable of inferring reasonable pathways of future coastal dynamics because the past sediment movements were too dynamic. Instead, a detailed investigation of the shape of these gravel features was conducted for the 1950s, the 1970s, and 2011 to understand their past development. This information was used to draw scenarios for the future development of Workboat Passage and Tapqaq.

Results and discussion

Past and future rates of shoreline change

In the 1950s to 2011 period shoreline retreat was recorded along 85% of all transects (Irrgang et al. 2018). The highest mean negative shoreline change rates (i.e., erosion rates) were measured from Qikiqtaruk towards the west, whereas the lowest mean negative shoreline change rates were measured between Kinnaq (King Point) and Tapqaq (Fig. 1). We attribute this regional pattern to the exposure of the western part of the coast to the most effective storms which originate from the northwest (Solomon 2005; Manson and Solomon 2007) and the comparatively low cliffs. In the eastern part of the study area, the coast is considerably higher and sheltered from northwesterly storms by its orientation towards the east and by Qikiqtaruk (Fig. 1).

For the S1 scenario, the mean EPR for the study area amounted to −0.7 m/a over the 2011–2100 period. The resulting mean land loss amounted to approximately 9.5 ha/a. This could lead to a total loss of land of approximately 850 ha by 2100.

For the S2 projection, the mean EPR for the study area amounted to −2.2 m/a over the 2011–2100 period. The resulting mean land loss amounted to approximately 30 ha/a. This could lead to a total land loss of approximately 2660 ha by 2100. Because the change indices were found to be largest for the coastal landform classes 2 and 5, erosion rates in these areas are expected to be highest by 2100. Thus, cultural features lying in these areas are particularly prone to erosion. The landform classes 1 and 4 were the only ones that had change indices <1. Although cultural features lying in the landform class 4 are considered to be less threatened by coastal erosion, cultural features lying in the landform class 1 are considered to be particularly threatened because of the high natural dynamics of these landforms.

Our method assumes that each transect belongs to the same coastal landform class through time, i.e., that an inactive tundra slope remains an inactive tundra slope from 2011 until the end of 2100. This is obviously not true for each single transect, because the landscape is diverse and coastal geomorphology can change with time. We do anticipate a slight shift from inactive to active shorelines, but the depiction and projection of these changes would require the deployment of complex numerical hydrodynamical models to comprehensively depict the changes in coastal morphology associated with erosion. Because we do not have the input variables for this kind of model, the uncertainty associated with the model outputs would largely outweigh the uncertainties associated with our method. Therefore, we assumed that coastal landforms will not change through time.

The results of the S1 and S2 scenarios show possible lower and upper limits of projections for future shoreline positions, but contain some simplifications. The change indices reflect past shoreline dynamics that occurred during the 1990s to 2011, including the duration of the open water season, the frequency and severity of storms, and sea level rise.

Any future increases in forcing that will exceed the order of magnitude of the past forcing are not considered by either projection. Prominent amplifying forcing factors are, for example, a further acceleration of sea level rise, or a complete loss of summer sea-ice. The rapid reduction of summer sea-ice already has had major effects on the sea state of the Beaufort Sea (Stroeve et al. 2011, 2014; Thomson et al. 2016). Together with the observed trend towards stronger autumn storms (Zhang et al. 2004), the height of the sea state is expected to rise (Vermaire et al. 2013; Thomson and Rogers 2014). We expect these interactions to lead to intensification in coastal erosion. Consequently, shoreline retreat might be more severe than in the S2 projection, which we considered our dynamic case scenario. The application of a spatially averaged Ci can, however, also lead to local overestimation of shoreline change rates for the S2 scenario.

Cultural sites

In total, 168 cultural features along the Yukon coast have been found in 18 separate areas, termed cultural sites (Table 3). Isolated cultural features were found in five locations (the Remaining sites in Table 3). At least 11 of the cultural sites are known to be former small settlements: Qainniurvik, Akilliriigvik, Hingigruaq, Nuunaluk, Qargialuk, Itpiliqpik (Whale Bay), Ikpigyuk west, Niaqulik, Tikiraq, Kinnaq, and Tapqaq (Nagy 1994; Thomson 1998) (Fig. 2). Of the 168 cultural features, 40 were categorized as housing, 29 were burial sites, and 92 were other features, such as tent structures or ice houses (Tables 2 and 3). Ten out of 42 known features at Hingigruaq (Thomson 1998) could be located on satellite images and aerial photographs, but the data, except for the identification of three houses, did not allow a further characterization of these features. No cultural features from the settlements at Tikiraq and Kinnaq could be accurately positioned. No specific information about the quantity and position of cultural features could be obtained for Tapqaq, aside from the identification of 52 roof tops that could be clearly detected on the satellite imagery from 2011. As the majority of roof tops were presumed to be modern and no other information specifying the nature of these roof tops was available, we did not include these features in the statistics regarding losses of cultural features.

In the past, coastal erosion has led to the loss of 44 cultural features, or 26% of the total (Table 3). Under the S1 and S2 scenarios, 32 and 58 additional cultural features will be eroded, respectively, amounting to 19% and 35% of the total inventoried cultural features. Consequently, 45%–61% of all recorded cultural features could be eroded by 2100. As not all sites could be digitized this is a conservative estimate. However, the vulnerability varies between sites. Although, for example, a cemetery at Igpigyuk west and several features at Ikpigyuk spit have been lost to erosion, so far no losses have been recorded at Itpiliqpik and Arvagvik (Roland Bay). The former settlement of Niaqulik is particularly threatened under both scenarios (Fig. 3). In the S1 scenario, nine cultural features are expected to be eroded, whereas under the S2 scenario all cultural features are expected to be eroded by 2100. Figure 3 demonstrates the relative performance of both shoreline projections. The projection algorithms extrapolate the 2011 position of the shoreline based on measured rates of shoreline change, but do not account for the topography of the inland area. On the eastern shore of Niaqulik, the 1950s–2011 EPR is related to the erosion of a low-lying inundating area and is thus comparatively high (Fig. 3). Yet, this section of coast is backed by a much higher hinterland, which will most likely not erode at similar rates. Here, the S2 scenario probably grossly overestimates the erosion of the shoreline. Erosion will most likely decelerate when the shoreline reaches higher topography.

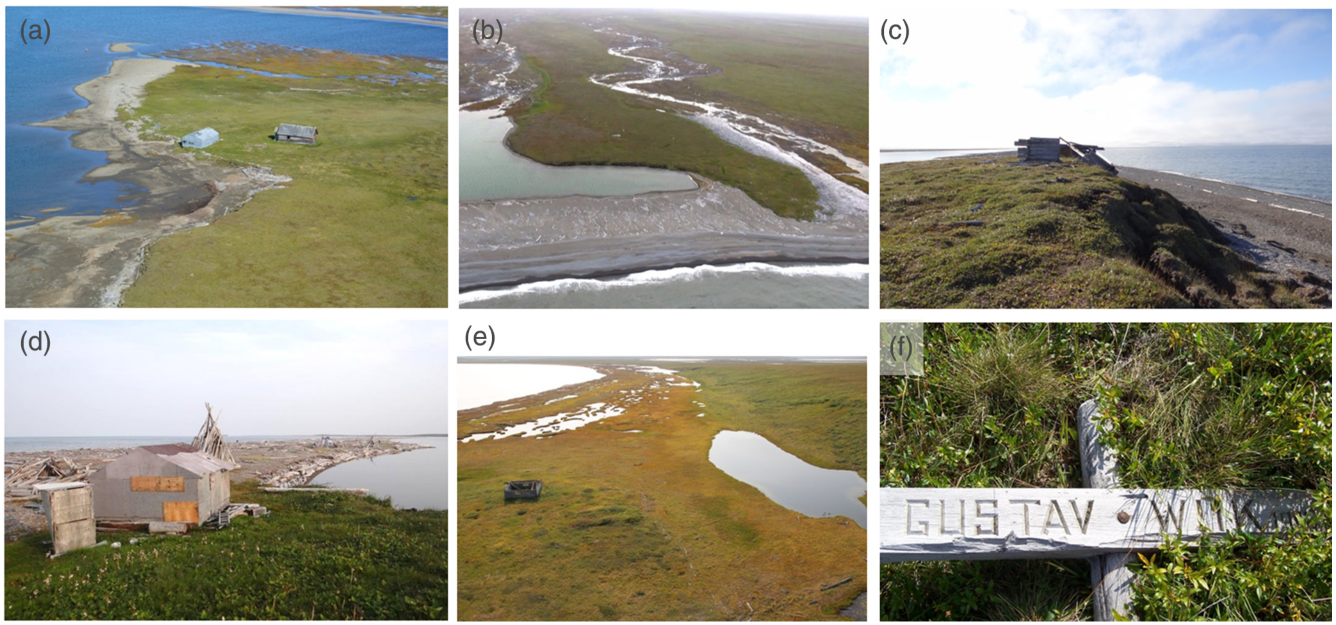
The cultural features of the former settlement of Hingigruaq that could be digitized on the 2011 images are not considered to be threatened in either scenario (Fig. 4). By 2100, the shoreline in the S1 and S2 scenarios is expected to be 17–20 m from the site (Fig. 4).

Table 3. Results of the investigation of cultural features.

Cultural feature class	Total				Housing				Burial sites				Other features			
Cultural site	Total number	Eroded in 2011	Eroded by 2100 (S1)	Eroded by 2100 (S2)	Total number	Eroded in 2011	Eroded by 2100 (S1)	Eroded by 2100 (S2)	Total number	Eroded in 2011	Eroded by 2100 (S1)	Eroded by 2100 (S2)	Total number	Eroded in 2011	Eroded by 2100 (S1)	Eroded by 2100 (S2)
Qainniurvik (Clarence Lagoon)	14	5	6	6	5	1	4	4	0	0	0	0	9	4	3	3
Akilliriigvik	8	3	1	5	3	1	2	2	0	0	0	0	5	2	3	3
Backhouse River	2	0	1	1	1	0	1	1	0	0	0	0	1	0	0	0
Hingigruaq	10	0	0	0	3	0	0	0	N/A	0	0	0	N/A	0	0	0
Nunaaluk	5	2	3	1	2	0	2	1	0	0	0	0	3	2	1	0
Workboat Passage	3	1	0	1	0	0	0	0	1	1	0	0	2	0	0	1
Kanivaliuraq (Ptarmigan Bay)	7	0	1	6	4	0	1	3	0	0	0	0	3	0	0	3
Qargialuk (Catton Point)	30	1	0	0	2	0	0	0	8	0	0	0	20	0	0	0
Itpiliqpik (Whale Bay)	3	0	0	3	3	0	0	3	0	0	0	0	0	0	0	0
Arvagvik (Roland Bay)	2	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
Upinraqhirviuraq (front of Roland Bay)	11	11	0	0	0	0	0	0	0	0	0	0	11	11	0	0
Ikpigyuk west (Stokes Point)	9	9	0	0	0	0	0	0	8	8	0	0	1	1	0	0
Ikpigyuk spit (Stokes Point)	6	6	0	0	2	2	0	0	0	0	0	0	4	4	0	0
Ikpigyuk inner lagoon (Stokes Point)	17	2	7	9	0	0	0	0	6	0	6	6	11	2	1	3
Ikpigyuk east (Stokes Point)	6	0	0	0	4	0	0	0	0	0	0	0	2	0	0	0
Niaqulik	21	2	9	19	6	0	4	6	4	0	0	4	11	2	5	9
Kinnaq (King Point)	5	0	2	3	3	0	1	1	1	0	0	1	1	0	1	1
Sabine Point	4	2	1	2	2	1	1	1	0	0	0	0	2	1	0	1
Remaining sites (isolated finds)	5	0	1	2	0	0	0	0	1	0	0	0	4	0	1	2
Total	168	44	32	58	40	6	11	21	29	9	6	11	92	29	15	26

Note: Results are listed for each cultural site, respectively, going from west to east. Cultural site positions are shown in Fig. 1. For each cultural feature class (housing, burial sites, other features) the total amount, eroded amount in 2011, and expected amount of eroded features by 2100 under the S1 (conservative) and the S2 (dynamic) scenarios for shoreline projections are listed. Cultural class definitions are given in Table 2.

Fig. 2. Photos showing cultural features along the Yukon coast. From west to east: (*a*) Qainniurvik: one wooden store house and one sheet metal structure at a Hudson's Bay Company post, (*b*) Nunaaluk Spit: site of the former Inuvialuit settlement Hingigruaq, (*c*) Nunaaluk Spit: relicts of a cabin built by Alexander Stefansson in 1934 (Forbes 1997), (*d*) Qargialuk: modern cabin together with several traditional Inuvialuit graves (possible pre-contact), (*e*) Niaqulik Spit: relicts of a cabin and the outline of the foundation of a second building — both were part of an Inuvialuit settlement, and (*f*) Kinnaq: replica of the grave marker from Gustav Juel Wiik, who died in 1906 in the Gjøa expedition led by Roald Amundsen. Grave marker was moved inland several times (Mackay 1963). Site locations are indicated in Fig. 1.



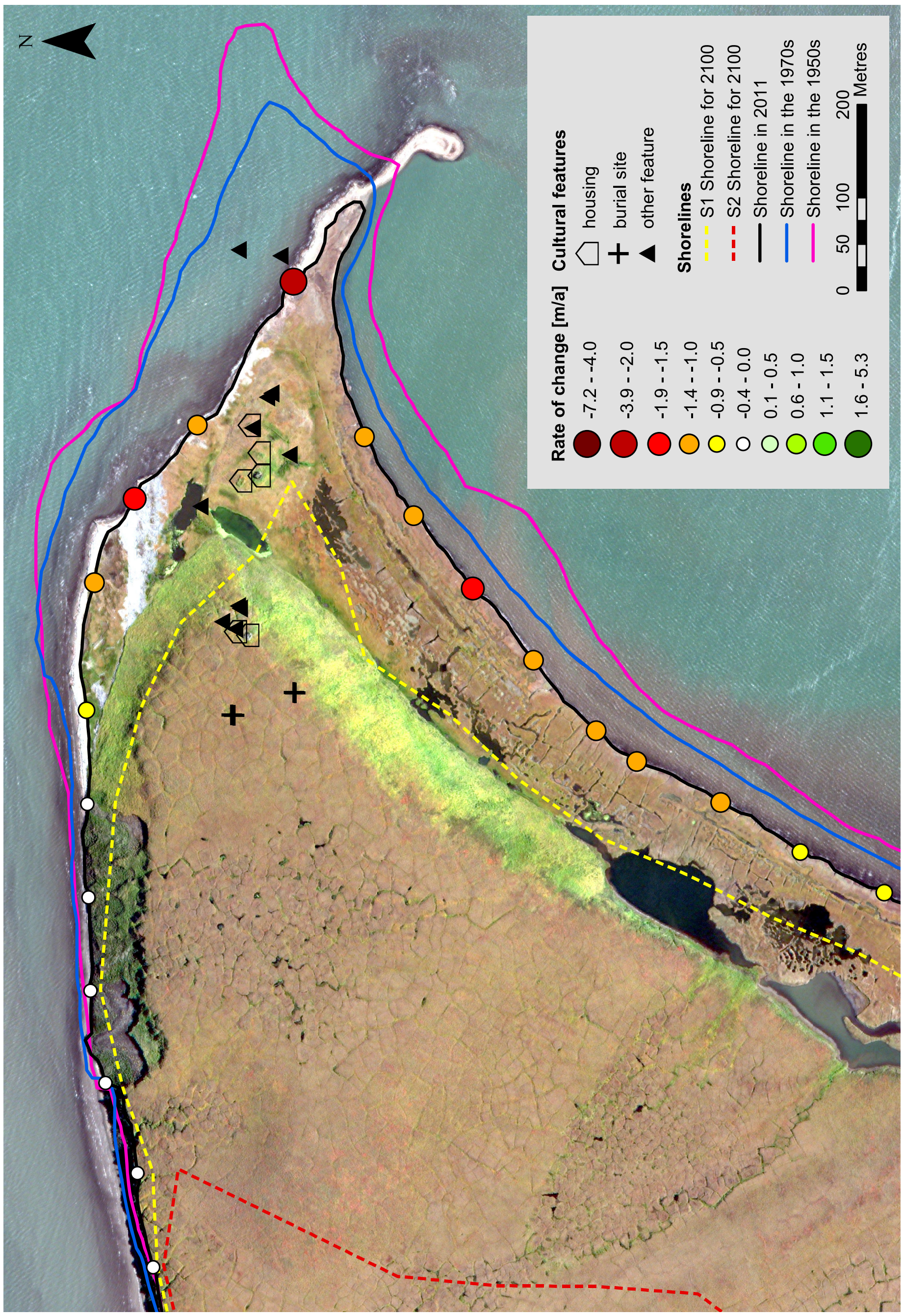
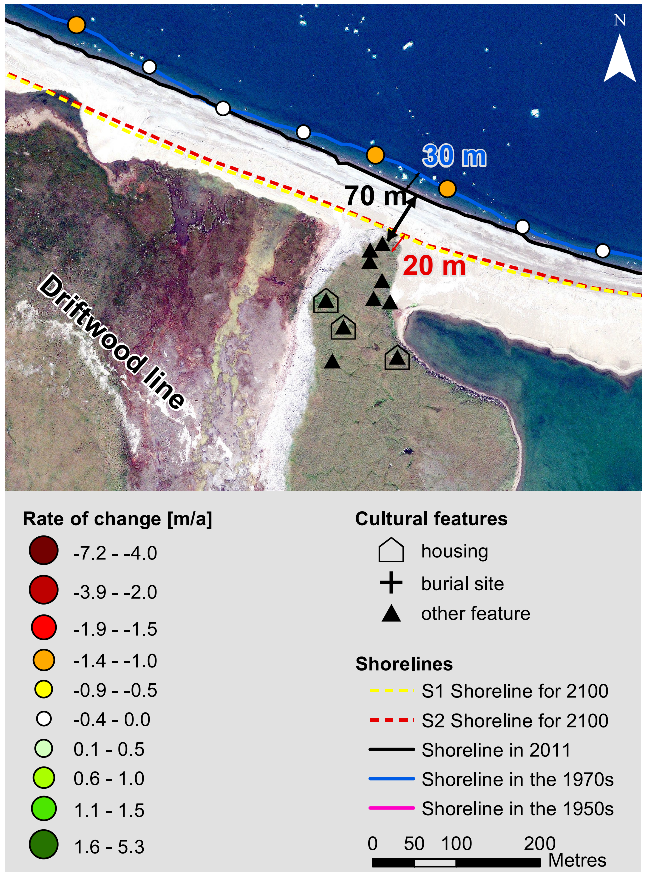


Fig. 3. Former settlement of Niaqulik. Base image: WorldView-2 scene from August 2011.

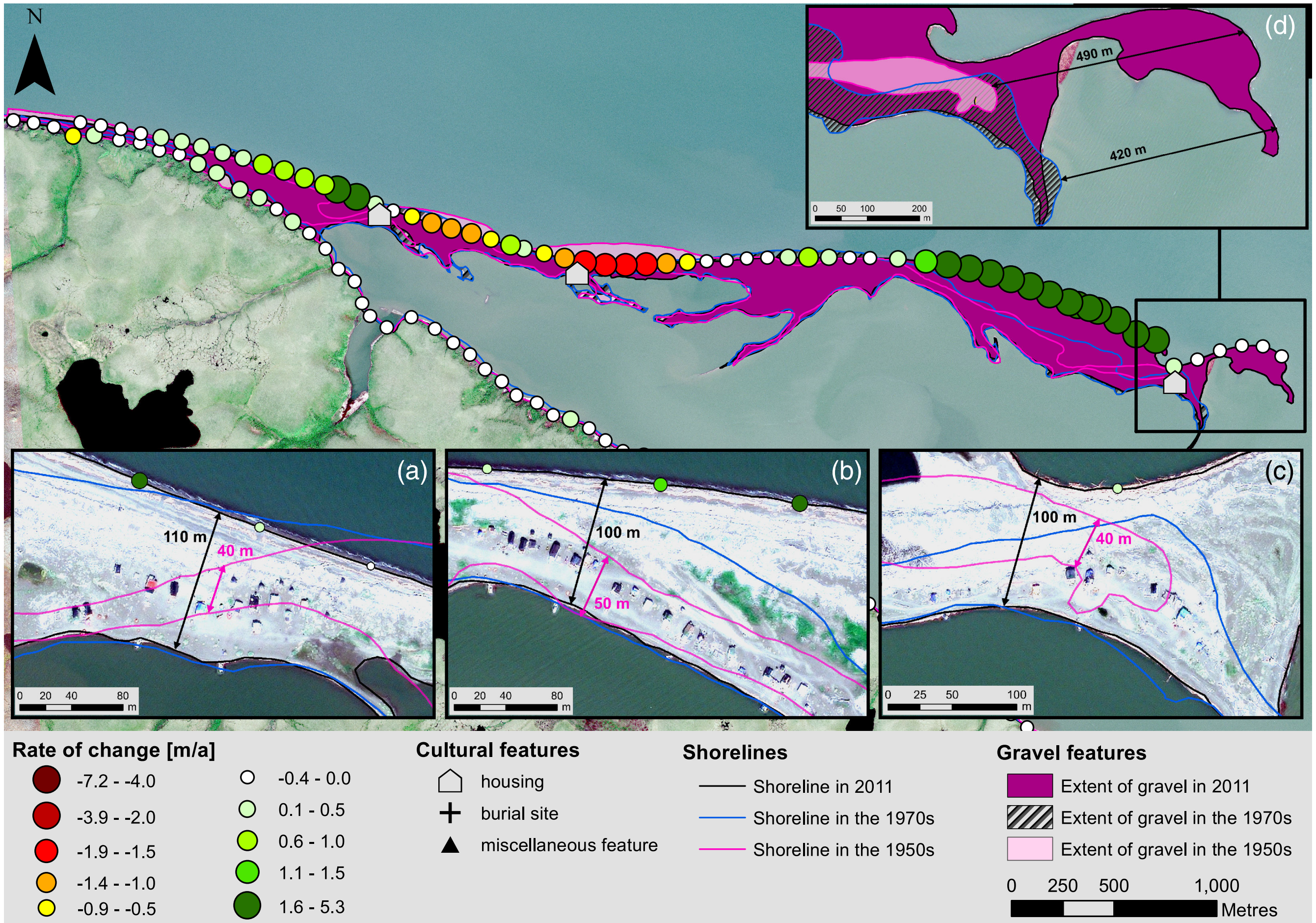
Fig. 4. Former settlement area of Hingigruaq. Ten out of 42 known cultural features could be located on the satellite image. Some of the features that could not be located on the images may have been eroded by 2011 (Thomson 1998). Base image: GeoEye-1 scene from July 2011.



Even though the shoreline was 70 m away from the site in 2011, driftwood lines present at 1.8 m elevation relative to sea level and visible on the 2011 satellite images suggest that the surrounding lower-lying area is subject to large-scale flooding. Observations from Tuktoyaktuk, east of the Mackenzie River, and the Alaskan Beaufort coast to the west show that large scale flooding can inundate areas up to 2.4 and 3.4 m a.s.l., respectively (Reimnitz and Maurer 1979; Harper et al. 1988). With an elevation of 2.8 m relative to sea level, Hingigruaq is low enough to be at risk for storm surge flooding. Continued erosion together with projected rise in sea level up to 1 m by 2100 (NT Government 2015; Flato and Ananicheva 2017) and the trend to stronger autumn storms (Zhang et al. 2004) will make Hingigruaq more vulnerable to flooding. Hingigruaq shows that the distance of the cultural site from the coast is not a systematic protection against coastal processes, and specifically not against episodic flooding during storms.

Tapqaq is the last remaining periodically occupied camp along the Yukon mainland coast (Fig. 5). There are three areas of occupation on the spit: Down the Hill Camp, Middle Camp, and Point Camp. As already stated in the section on coastal dynamics, most gravel features are too dynamic to develop reasonable shoreline projections. Thus, the past development of the spit was taken as a foundation for the estimation of future dynamics.

Fig. 5. Tapqaq with its three camps. From west to east: (*a*) Down the Hill Camp, (*b*) Middle Camp, and (*c*) Point Camp. The upper right inset (*d*) is a zoom on the distal end of the spit. Base image: GeoEye-1 scene from July 2011.



A comparison of the area in the 1950s, the 1970s, and 2011 revealed that the spit was largest in 2011. The length of the spit was approximately 6000 m in the 1950s, and lengthened approximately 500 m by 2011 (Fig. 5). The spit widened considerably between the 1950s and 2011 in the area of Down the Hill Camp, where in 2011 it was 110 m wide (Fig. 5, inset *a*). In the area between Down the Hill Camp and Middle Camp, the spit migrated 100 m to the south and narrowed from approximately 100 to 60 m between the 1950s and 2011. In the area of Middle Camp, the spit widened from approximately 50 m in the 1950s to 100 m in 2011 (Fig. 5, inset *b*). The greatest changes are in the area of Point Camp where the spit extended by approximately 500 m to the east between the 1950s and 2011 (Fig. 5, inset *d*). Some of the structures are therefore built on sediments that were deposited after the 1950s. Where the distal end of the spit was located in the 1950s with a width of 40 m, it is now as wide as 100 m (Fig. 5, inset *c*). In summary, all camps lie in areas where the spit has widened since the 1950s.

The shoreline north of Down the Hill Camp has been retreating since the 1950s and erosion has accelerated since the 1970s. If this process continues in the future, Down the Hill Camp could be threatened by shoreline erosion. Towards the north of Middle Camp is an area that has been accumulating sediment since the 1950s, and thus Middle Camp is not considered immediately threatened by shoreline erosion. Point Camp is also not considered immediately threatened.

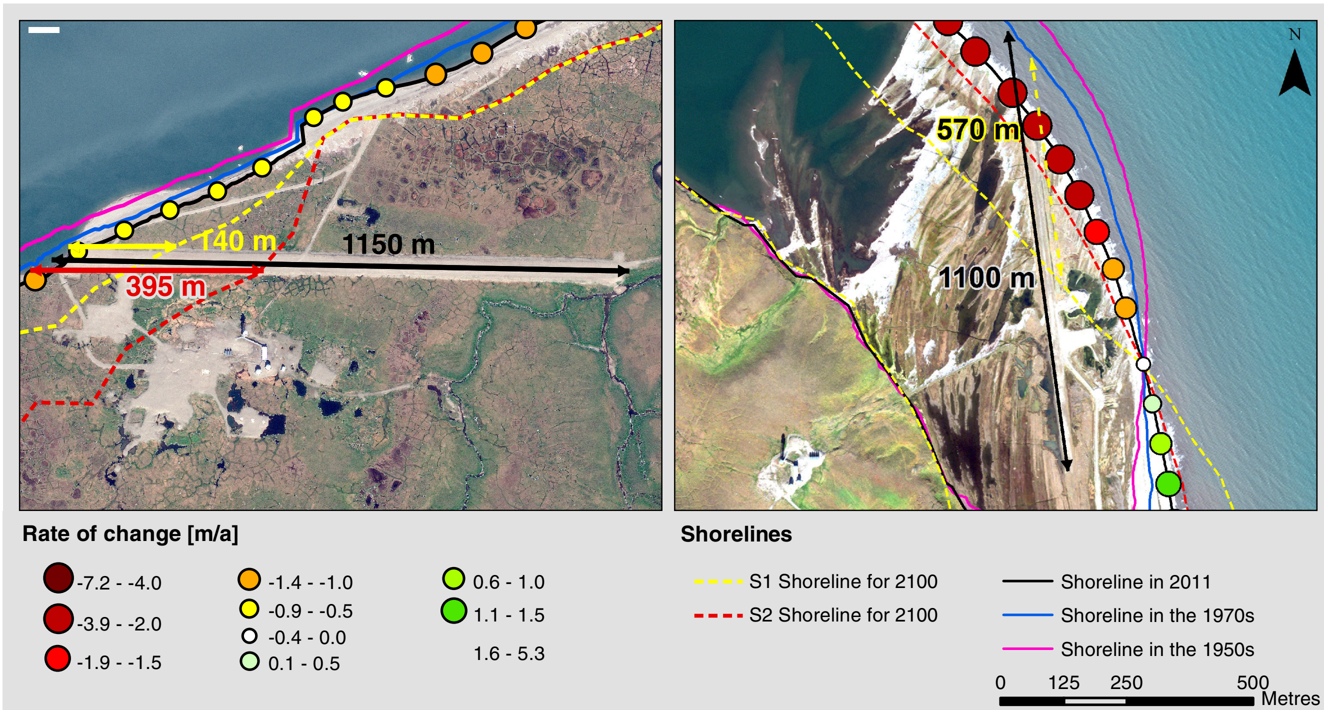
With projected relative sea level rise of up to 1 m by 2100 (NT Government 2015; Flato and Ananicheva 2017), all three camps will become more prone to the risk of periodic flooding during storms, and eventually to permanent flooding because of sea level rise. As storms have been observed to increase in frequency and intensity with ongoing climate change (Zhang et al. 2004; Vermaire et al. 2013), the risk of spit breaching is likely to increase (Héquette and Ruz 1991; Morton and Sallenger 2003). The most vulnerable area was found to be between Down the Hill Camp and Middle Camp because it has been decreasing in width since the 1950s. With the predicted rise in sea level (NT Government 2015; Flato and Ananicheva 2017), extension of the open water season (Wang and Overland 2009; Stroeve et al. 2011, 2014; Barnhart et al. 2016), and increase in storminess (Vermaire et al. 2013), coastal erosion to the west of Tapqaq is expected to increase potentially providing more sediment to Tapqaq through longshore drift processes.

Whether sediment supply to Tapqaq from longshore drift will be sufficient to effectively counteract inundation caused by sea level rise remains an important question of interest, both scientifically and for the longevity of Tapqaq. A subsequent study incorporating topographic (e.g., LiDAR) and bathymetric data combined with hydrodynamic modelling would be necessary to estimate the flood risk and breaching risk for Tapqaq more accurately.

Infrastructure and travel routes

The DEW line stations of Qamaqaaq and Ikpigyuk each have one landing strip which is occasionally used for landing of fixed-wing aircraft (Figs. 6*a* and 6*b*). At Qamaqaaq, 46 m of the landing strip has been eroded since the 1970s. In the S1 scenario, a further 140 m may be eroded, shortening the landing strip to 980 m. In the S2 scenario 395 m are expected to be eroded, which will shorten the landing strip to 725 m. At Ikpigyuk, the length of the landing strip was approximately 1100 m in the 1970s. Between the 1970s and 2011, 180 m was eroded. Both scenarios project a substantial shortening of the landing strip to approximately 500 m. The elevation of the landing strip is on an average 1.2 m a.s.l. With further rise of sea level, the risk of flooding and permanent inundation will threaten the landing strip. Consequently, the shoreline projections and interpretation suggest that by 2100 both landing strips along the Yukon coast may become unsafe for loaded fixed-wing aircraft.

Fig. 6. (*a*) Distant Early Warning (DEW) line station at Qamaqaaq. The landing strip is built on polygonal tundra approximately 6 m a.s.l. Base image: GeoEye-1 scene from July 2011. (*b*) Stokes Point DEW line station. The landing strip is built on a set of approximately 1.2 m high beach ridges. Base image: WordView-2 scene from August 2011.



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Workboat Passage is an important travel route used to avoid exposed waters north of Qikiqtaruk. Both entrances to Workboat Passage are defined by gravel spits and are highly dynamic (Fig. 7). In the 1950s, the western entrance was approximately 690 m wide, and it widened by 20 m in 2011. During the same time, the Nunaaluk barrier island system migrated east and north, increasing the risk to boats and barges of running aground while entering the passage. The eastern entrance narrowed from 1800 m in the 1970s to 690 m in 2011. The average water depth within the passage is around 2 m with wide areas of shallow banks <0.5 m deep on the southern side of the passage (Radosavljevic 2018). As coastal erosion, and hence the amount of sediment in nearshore waters, is expected to increase in the future, we expect the sediment supply for all spits to remain stable or increase, even though further sea level rise may also lead to increased erosion of these spits.

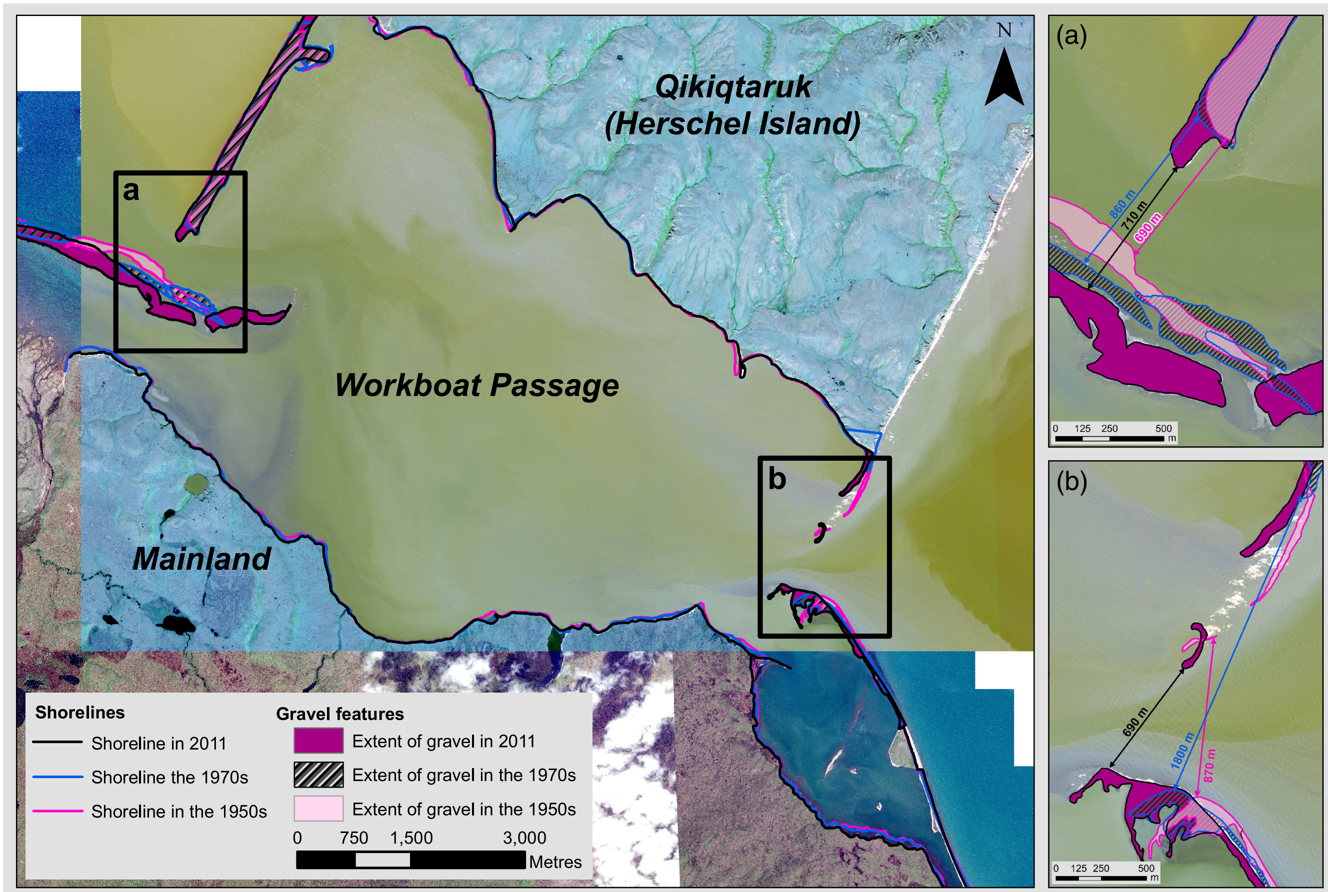
The tidal and wind-driven currents at both entrances to Workboat Passage are strong and the depths are up to 10 m (Radosavljevic 2018), so closure of either entrance is unlikely. Occasional strong storms from the west and from the east will help to maintain the entrances. Independent of the prevailing wind direction, the water is in constant movement through the passage and does not pool.

Conclusions

Shoreline change rates derived from air- and satellite-borne imagery from the 1950s, 1970s, 1990s, and 2011 were used to assess the impact of shoreline changes on cultural features, infrastructure, and travel routes along a 210 km length of the Yukon coast. These data were used to create conservative (S1) and dynamic (S2) scenarios to project two shoreline positions for the year 2100 to estimate how future shoreline changes may affect cultural sites, infrastructure, and travel routes. The main results are as follows:

- Under the S1 scenario, the mean rate of shoreline change is −0.7 m/a, resulting in a mean future land loss of 9.5 ha/a and total loss of approximately 850 ha between 2011 and 2100. Under the S2 scenario, the mean rate of shoreline change is −2.2 m/a, resulting in future land loss of 30 ha/a and a total loss of approximately 2660 ha between 2011 and 2100.
- Past shoreline changes have led to the erosion of 26% of all inventoried cultural features. An additional 19%–35% are expected to be eroded under the S1 and S2 scenarios, leading to a loss of 45% (S1) to 61% (S2) of the inventoried cultural features along the Yukon coast by 2100. As not all extant cultural features could be mapped, this might be still a conservative estimate. Neither of the shoreline projections include ground elevation data, so some cultural features that are not considered threatened may be inundated. In the future, coastal processes are expected to further reduce the number of cultural features along the Yukon coast.
- All three camps at Tapqaq are built in areas in which the spit has been widening since the 1950s and are not directly threatened by erosion. However, future sea level rise and more intense storms have the potential to seriously threaten all camps. Highly resolved topography and bathymetry data would allow for more accurate analyses and better prediction of the future risk of shoreline erosion, spit breaching, and floodings at Tapqaq.
- The landing strips of the two DEW line stations of Ikpigyuk and Qamaqaaq are expected to be substantially shortened by 2100 to 530 and 755 m, respectively. Additionally, because of its low elevation, the landing strip at Ikpigyuk is in danger of becoming periodically or permanently flooded. The projections suggest that both landing strips near the Yukon mainland coast will be directly impacted by erosion and (or) flooding by 2100.
- The travel route through Workboat Passage between the mainland and Qikiqtaruk is likely to remain open at both entrances.

Fig. 7. Workboat Passage. Inset (*a*) zoom to its western entrance. Inset (*b*) zoom to its eastern entrance. Lower base image: GeoEye-1 scene from July 2011. Upper base image: GeoEye-1 scene from August 2011.



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