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Beaufort Sea coastal mapping and the development of an erosion hazard index

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ABSTRACT: As a first step towards a comprehensive treatment of the influences of climate change on coastal erosion along the Canadian Sector of the Beaufort Sea, we have mapped important attributes of the coastal geology of the Beaufort coast and developed an index (Beaufort Sea Erosion Hazard Index – BEHI) that describes the relative erosion hazard. By concentrating on the geological and morphological attributes, we can separate the potential erosion hazard which is more or less constant through time from those aspects which is likely to change as a result of climate change. In general, high BEHI scores were strongly associated with high retreat rate (RR), but as the BEHI decreases the relation becomes noisier. While the index will never be a substitute for site-specific engineering design studies, it can provide a means for identifying coastal reaches with the most potential for high erosion rates.

1 INTRODUCTION

The low, ice-rich, Beaufort Sea coast of Canada has been identified as highly vulnerable to the effects of sea level rise and climate warming (Shaw et al. 1998, Solomon et al. 1994). Projected changes in sea level associated with greenhouse warming, along with possible increases in the length of the open-water season and in storm frequency and intensity, will likely increase the rate of coastal change along the Beaufort Sea. Erosion and other coastal changes are forced by storm-driven waves, superimposed on storm surges that develop over the shallow continental shelf during the 3–4 month open-water season. These storms rapidly erode the unlithified but frozen low bluffs, wetlands and deltas that characterise much of Beaufort coast. Erosion currently threatens archaeological remains and waterfowl habitat at many locations along the coast (Solomon 1996, Forbes 1997) and has been a perennial problem at Tuktoyaktuk since its inception (Solomon & Covill 1995). In addition, safe and efficient hydrocarbon development in the region is dependent on an understanding of the spatial and temporal distribution of coastal change.

As a first step towards an improved understanding of coastal erosion along the Beaufort Sea, we have mapped the morphologic and textural attributes of the Beaufort coast using oblique, low-elevation aerial videography. The mapped data was incorporated into a Geographical Information System (GIS) that was used to develop an index that describes the relative erosion hazard.

2 COASTAL MAPPING AND THE CIS

The Beaufort Sea Coastal Information System (CIS) is a database of coastal morphology and materials which is based on mapping from aerial video. The database structure utilizes a tripartite cross-shore designation of backshore, foreshore and nearshore zones each of which are mapped onto a single linear route. The database is implemented using ArcInfo's dynamic segmentation function. Sherin & Edwardson (1997) provide a more complete discussion of the database design and the use of dynamic segmentation for coastal mapping is discussed in Sherin (2000).

For the purpose of this study as well as other applications, new aerial oblique video was acquired in 1999 and the coast of the Canadian Beaufort Sea was mapped into the CIS. The video was also compared with video acquired in 1984 and areas of coastal change were identified. In all, 1637 km of coastline were mapped (Figure 1). The database can be queried in order to extract a range of information about coastal morphology and material properties. For instance, in the backshore, cliffs comprise 1024 km or 62% of the coastline and more than 80% of those are less than 5 m in elevation. Very low cliffs (less than 2 m elevation) are found along the backshore of 445 km (more than 25%) of the coast. Ice indicators such as retrogressive thaw failures (51 km) are common west of the Mackenzie Delta, whereas ice-wedge polygons (156 km) are the predominant ice-indicator east of the delta.

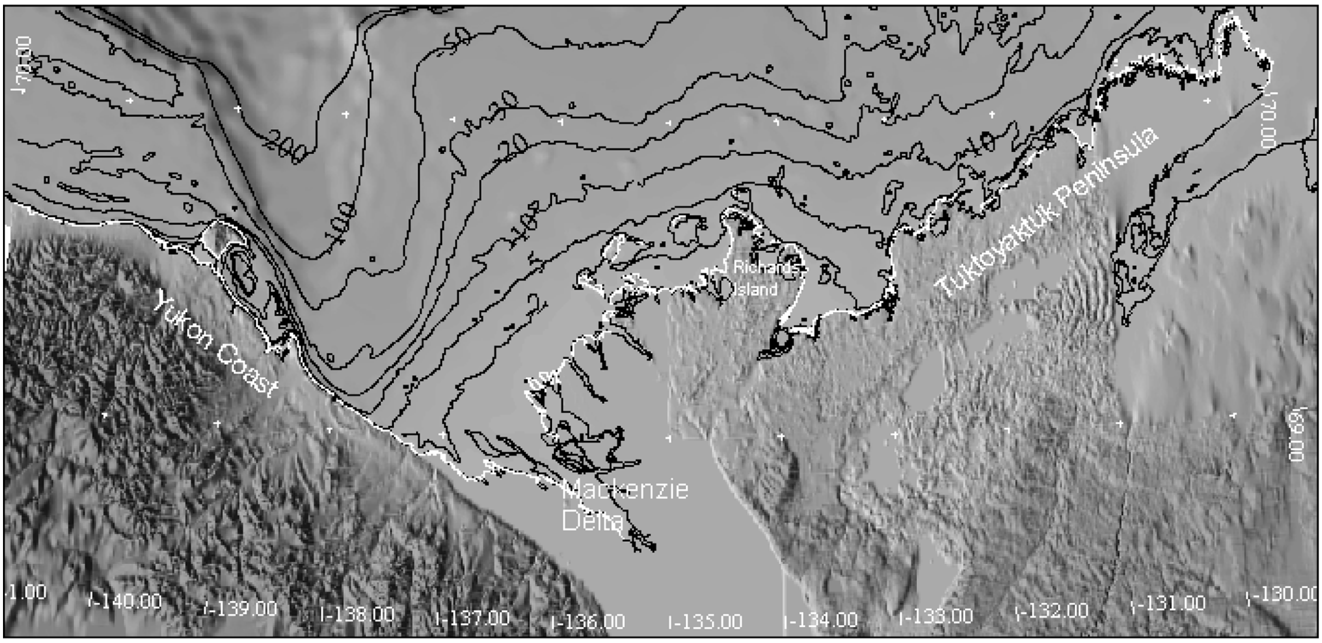

Figure 1. The Canadian sector of the Beaufort Sea is consists of a wide low relief coastal plain east of the Mackenzie Delta and a narrow, mountain backed plain to the west, along the Yukon coast. The white coastline illustrates the extent of coastal mapping coverage. Data for the land digital elevation model comes from the GLOBE dataset. The bathymetry is based on Canadian Hydrographic Charts.

In the foreshore, beaches are the dominant landform comprising 1257 km of coastline. Coarse beaches composed of mixtures of sand, pebbles and cobbles are slightly less common than beaches composed mostly of sand and finer sediments or organics. The coarser beaches dominate the Yukon coast and most of Kugmallit Bay, whereas finer materials are found on the delta front and along the northern sections of the Tuktoyaktuk Peninsula. The ability to query the database for various coastal attributes was used extensively in the construction of the Erosion Hazard Index.

3 DEVELOPMENT OF A BEAUFORT SEA EROSION HAZARD INDEX

Erosion in any environment is a function of coastal geology, morphology and oceanographic forcing. The geological attributes of the coast control the strength (or resistance) of coastal materials and the availability of sediments for transport. Oceanographic forcing includes the wave, current, and water level regimes that supply the energy for abrading, entraining and transporting sedimentary materials. Coastal morphology (or form) controls the transformation of energy at the interface between the water, seabed and subaerial coast as well as the volume of material available for transport (through coastal elevation). In high latitudes, ice plays a role in both protecting the coast during the portion of the year when the sea is ice covered and in entraining and transporting materials by frazil ice development and ice scour (see Forbes & Taylor 1994). In addition, water temperature influences the rate of ice-bonded permafrost thawing in the nearshore and coastal environments which in turn controls the rate of sediment release during storms (e.g. Are 1988). Air temperature may also be an important influence on the rate of thermokarst development.

As part of the assessment of coastal stability and climate sensitivity along the Beaufort Sea coast, we have identified relevant attributes of the coastal geology of the Beaufort coast as mapped into the CIS database and developed an index that describes the relative erosion hazard. By concentrating primarily on the geological and morphological attributes, we can separate the potential erosion hazard which is more or less constant through time from that aspect which is likely to change as a result of climate change (e.g. oceanographic and meteorological forcing). The Beaufort Sea Erosion Hazard Index (BEHI) is based on coastal geological attributes compiled in the CIS database. Table 1 presents the scoring used for the various attributes in the development of the BEHI.

The index is calculated by summation of all of the scores for each segment of coast with a unique set of form and material attributes. Backshore and foreshore were calculated independently before being combined in order to evaluate the relative contributions of the 2 zones. In general, there was insufficient information about the nearshore features to include them in the calculation.

Table 1. Coastal attributes and scores for calculating the BEHI.

Backshore form	**Backshore score**
Cliff height	
High	1
Moderate	2
Low	3
Very low	4
Slope height	
High	1
Moderate	2
Low	3
Stability	
Unstable	1
Partially stable	2
Stable	3
Ice content	
Wedge/massive/pingo ice	3
Polygons	3
Retrogressive Thaw Failure (RTF) (active)	3
RTF (stable or partially stable)	2
No ice indicators	1
Wetlands	3
Backshore material	
Organic	3
Clastic	0
Foreshore form	**Foreshore score**
Detached barrier	5
Barrier with washover	4
Inlet or ebb tidal delta	4
Attached spit or barrier without washover	3
Wetlands	3
Fringing or pocket beach	2
Intertidal or supratidal flats	2
Wide-fringing beach	1
Drowned tundra	1
Flood delta	1
Transverse bars	1
Tombolo	1
Foreshore material	
Silt/peat/mud	3
Sand	2
Pebbles and cobbles with sand	1

Additional morphological attributes not in the original CIS were added to the score to account for differences in exposure to erosion-inducing NW storms (a function of the 2-dimensional shape of the coastline), variations in the potential storm surge elevations due to morphological factors and nearshore slope (which controls maximum storm wave height) (Table 2). Exposure was evaluated subjectively, and scored from −2 to 1 for the range from well-sheltered to very exposed (specifically to the northwest). Storm surge elevation potential was scored by appending the maximum surge predicted for a modelled extreme storm to each coastal segment. The surge height potential was scored from −1 to 2 according to the predicted water level elevation for that storm based on the assumption that generally water levels will be proportional to that maximum height and the spatial distribution of maximum surges will be similar for the surge-producing NW storms. Nearshore slope was mapped by developing a digital elevation model of the coastal Beaufort Sea using a combination of Canadian Hydrographic Survey charts and field sheets. This was done using a triangulated irregular network algorithm as implemented by the Vertical Mapper add-in to MapInfo GIS software. The slope was then calculated using the same software and the slope angle for the grid cell immediately adjacent to the CIS coastline was assigned to each coastal segment. Slope angle was scored from 0 to 2 with the lowest slopes assigned a score of zero.

Table 2. Additional morphological attributes and scores for development of the BEHI.

Exposure	Score
Well-sheltered	−2
Sheltered	−1
Exposed	0
Well-exposed	1
Storm water level elevations	
0.0–0.5 m	−1
0.5–1.0 m	0
1.0–1.5 m	1
1.5–2.5 m	2
Nearshore slope	
0.00–0.01°	0
0.01–0.10°	1
0.10–1.06°	2

Table 3. The distribution of scores and class rank show that about half of the coastline is characterized by high to very high erosion hazard.

Score	Rank	Length of coast (km)
⩾1 to <9	Very low	161
⩾9 to <11	Low	270
⩾11 to <13	Moderate	344
⩾13 to <16	High	393
⩾16 to 24	Very high	470

Raw erosion hazard scores range from 1 to 24 with a mean of 11.7 and a median of 11. These scores represent a total of 1637 km of coastline. The raw scores were aggregated to reduce the number of classes to five by using the "natural break" algorithm in MapInfo. This algorithm minimizes the differences between the in-class values of the average for each range. Table 3 shows

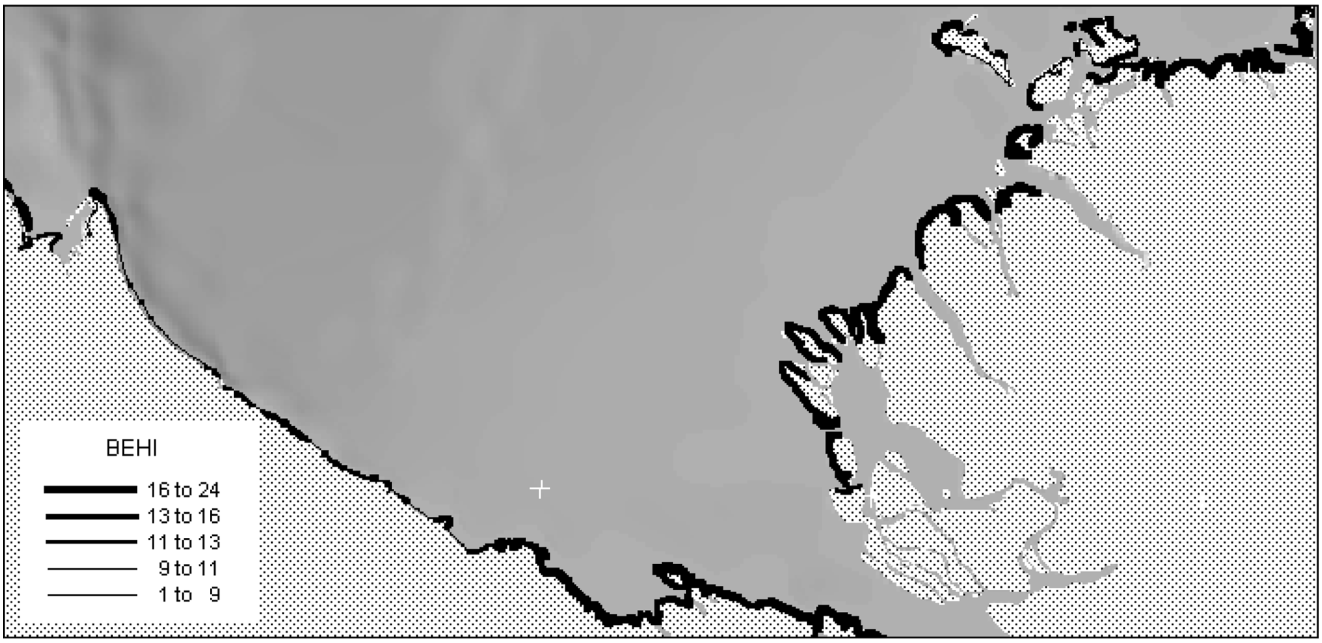

Figure 2. A detailed subset of the BEHI along the eastern Yukon coast and the Mackenzie Delta front show the variability of erosion potential in the study area. It is not possible to show this level of detail over the entire study area in a single figure.

the breakdown of classes and the amounts of coastline (in km) represented by each class. The classes were assigned relative qualitative erosion hazard rankings from ranging from very low to very high.

The length of coast increases with rank with the lowest ranking representing only 160 km of coastline. This is consistent with our knowledge that, in general, the coast is retreating. The coast with the highest erosion hazard ranking is concentrated along the modern Mackenzie delta front where very low peat and silt bluffs erode rapidly (Figure 2).

4 DISCUSSION

In general the rankings agree with our perception of the relative stability of the coastal regions. Harper et al. (1985) mapped the coastline of the Beaufort Sea using oblique aerial video (flown in 1984) and performed measurements of erosion rate based on the comparison of air photos from the late 1940s and early 1950s to the early 1970s. The technique involved the measurement of distance from a coastal feature (cliff-top, cliff-base or waterline) to a recognizable feature identifiable on 1:50000 or smaller scale air photos and on 1:50000 topographic maps. His summary of retreat rates identified high rates (greater than $2\,\mathrm{m\,a^{-1}}$) associated with the Mackenzie Delta, moderate rates (1–$2\,\mathrm{m\,a^{-1}}$) along the most of the Tuktoyaktuk Peninsula coast and somewhat lower rates (0–$1\,\mathrm{m\,a^{-1}}$) on the Yukon coast. A small segment of prograding coastline (at rates of 0–$1\,\mathrm{m\,a^{-1}}$) was identified on the west side of Richards Island. It should be noted that these rates represent only a snapshot in time and depend on the climatic conditions which prevailed during that time period. Meteorological records only extend back to 1962, so we are unsure as to how the decade of the 1950s compared with more recent decades.

With this caveat in mind, we compared the rates of cliff retreat described above with the raw erosion hazard scores. The erosion rate point data were joined to their proximate coastal segments to which the coastal attributes had already been assigned. The resulting GIS database table contained information on the coastal attributes, the hazard index scores and the erosion rate data for each coastal segment for which all of the data were available. This database was analysed in order to investigate the relations between the retreat rate (RR) for the line segments and the associated index values. In general, for coastal segments where RR was low, the BEHI may be either high or low, but where the RR is high, BEHI is invariably high (Figure 3). This behaviour is not surprising because the BEHI is essentially an indicator of erosion potential, not erosion rate.

More detailed analysis was performed to examine the spatial distribution of coastal segments which were essentially misclassified (i.e. high BEHI associated with low RR). The distribution suggests that exposure was not given sufficient weight, and that the temporal aspect of change, which is not captured by the single RR value, is important. The former observation is based on the BEHI of coastal segments in the lee of islands in the Delta region. These segments are very well protected from waves in all directions so that the exposure is quite limited. The use of a fetch calculation instead of the subjective exposure ranking would be a better

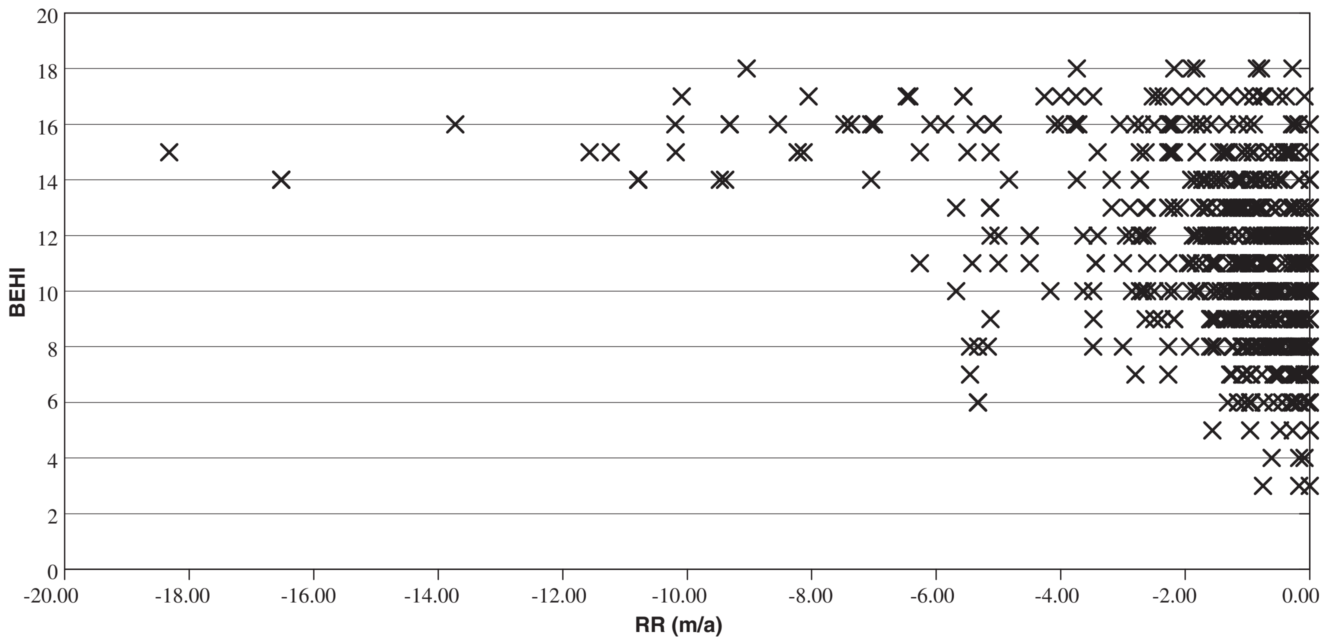

Figure 3. High BEHI is associated with high RR, but at low RR, BEHI ranges widely.

method of describing exposure in this context. Other coastal segments were identified with areas which had undergone a significant change in morphology between 1984 and 1999 including an increase in retrogressive thaw failure activity or major realignment of a coastal reach due to breaching of a lake or barrier. At the present time, we do not have any information about the temporal variability of the RR on a regional basis, however, we do know that there is considerable variability annually and decadally from several site specific studies (Dallimore et al. 1996, Mackay 1986, Solomon & Covill 1995). In this sense the BEHI provides a more conservative (from an engineering perspective) evaluation of erosion potential than a single long-term erosion rate measurement.

Other factors that influence RR include waves, currents, air and water temperature and sea ice processes. In a study of bluff retreat at 17 locations along the Beaufort coast, Héquette & Barnes (1991) noted that RR was poorly correlated with coastal morphology and ice content. They included wave energy in their study and concluded ice gouging of the seabed plays a significant role in determining RR.

5 CONCLUSIONS

A hazard index was developed for a portion of the Canadian Beaufort Sea coast based on coastal mapping using aerial videography and a conceptual understanding of high latitude coastal processes specific to the region. It was implemented using a GIS. While the BEHI is not a proxy for erosion rate measurements, it can serve as a guide to those locations which exhibit geological conditions which make them susceptible (to varying degrees) to coastal erosion. Incorporation of wave and current energy and more extensive coastal change measurements may improve the correlation between BEHI and RR, however, the index will never be a substitute for site specific engineering design studies. The BEHI can provide a means for identifying coastal reaches with the most potential for high erosion rates.

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