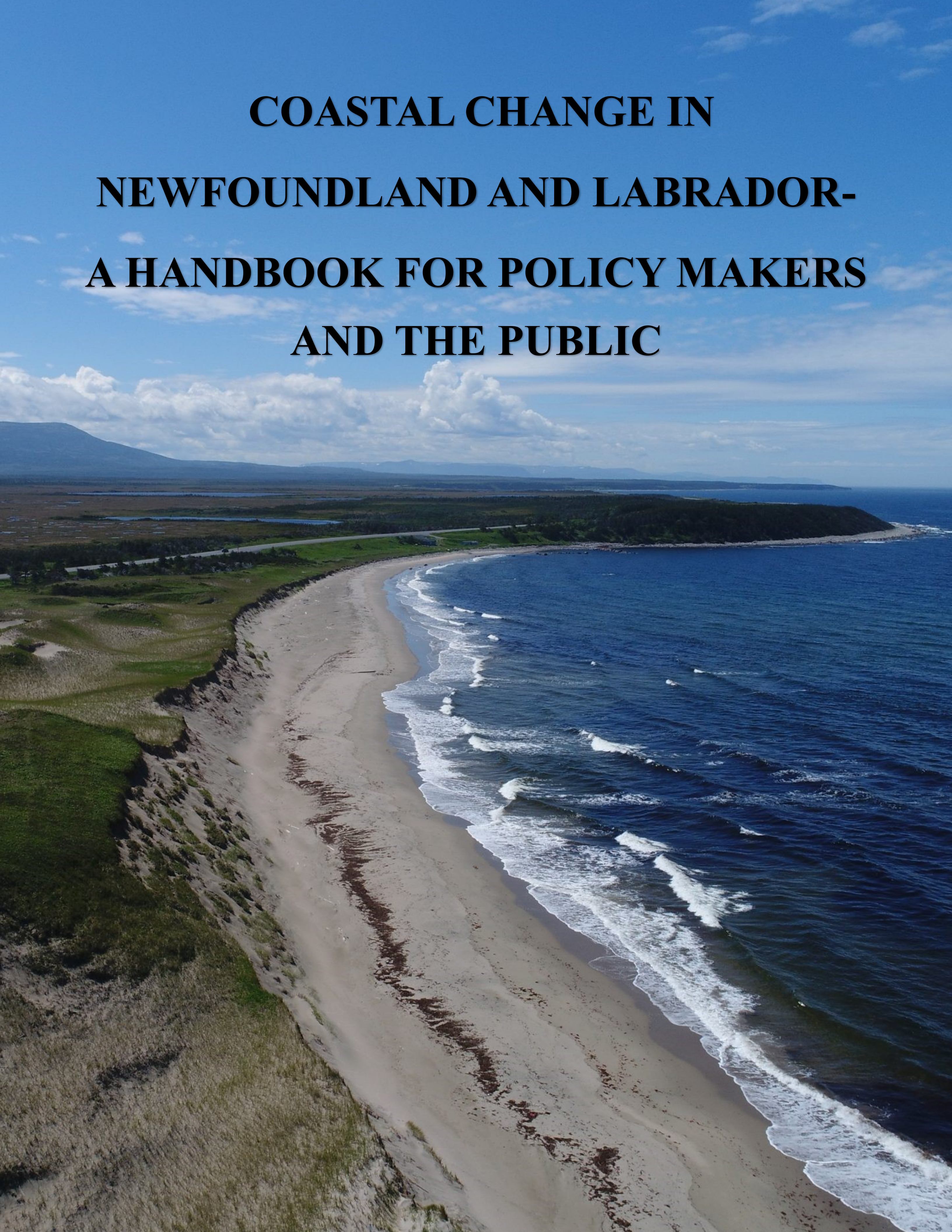
COASTAL CHANGE IN NEWFOUNDLAND AND LABRADOR- A HANDBOOK FOR POLICY MAKERS AND THE PUBLIC



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Through this handbook, users should get an improved understanding of issues relating to erosion, flooding, and slope movement in our coastal environment. For decision makers, the site aims to empower users to make more informed decisions on coastal issues in Newfoundland and Labrador.

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Executive Summary

The coast is constantly changing. These changes occur daily due to the interaction of tides, waves, and weather. Longer term changes occur as a result of changes in climate and sea level. The coast was considerably different 10,000 years ago, just after the last ice age. Relative sea level was higher in some places than it is today, and lower in others. Even in the last 100 years the coast has changed, and there is no doubt it will look different 100 years from now. Why? What are the processes that cause the coast to change? How, if at all, will these processes be affected by climate change?

This handbook focusses on the processes that shape our coast, the current rates of coastal erosion and how these rates are measured, and how these rates may be affected by the changes in both climate and sea level predicted for the province.

Each coastal area of the province has individual characteristics (cliff height and sediment composition, beach width and composition, near-shore environment, direction in which slopes are facing, vegetation types and coverage etc.) which makes providing an average erosion rate challenging. Measured cliff top erosion rates around the province vary from 0 cm/year on bedrock-dominated cliffs and completely vegetated sediment cliffs, to over 100 cm per year on sand-dominated coasts (*e.g.*, Cheeseman Provincial Park) or on exposed coasts with narrow beaches (*e.g.*, Crabbes River in St. George's Bay). A nominal average coastal erosion rate for the Province is about 20 cm/year. It is almost certain this nominal rate will increase because of climate change and rising sea level.

There are four main strategies to consider in response to coastal change:

1. Protection. These measures including sea walls, revetments (*e.g.*, rock wall), beach replenishment or dune stabilisation. Protection measures are expensive (commonly tens to hundreds of thousands of dollars) and consideration has to be given on the value of what is being protected versus the cost of the protection measures

2. Accommodation. This may consist of engineering solutions for buildings and other structures to withstand potential impacts, such as improved flood protection and the raising of structures, and municipal set-back limits for development.

3. Retreat. If the first two strategies are not viable retreat from the coast may be required.

4. Do nothing. Let nature takes it course. No mitigation or adaptation is required in areas where development has yet to occur.

There are numerous potential responses to mitigate and adapt to the effects of increasing coastal erosion and flooding because of sea level rise and climate change. Data on the type of hazard, the risk (high versus low), rates of change (fast versus slow) are critical in this process.

There are consequences for coastal change based on expected changes in climate and rising sea level in much of the province.

Expected change	Consequence	Implication for Coastal Change
Increase in mean daily precipitation, particularly in the winter Intensification of precipitation Increase in frequency of precipitation events Increase in the maximum precipitation falling over 3, 5 and 10 consecutive days	Increase in soil saturation Increase in snowmelt Increase in surface water Increase in ground water	Increase in clifftop and cliff face erosion Increase in slope movement
Rise in sea level	Increase the height of extreme water levels Increase in waves height Increase in level of high tide	Increase in the extent and frequency of coastal flooding Increase in the erosion of the cliff base Landward migration of beaches and dunes
Decrease in the duration and extent of sea ice	During the winter, an increase in the potential for large waves to form and for erosion from waves	Increase in the extent and frequency of coastal flooding Increase in the erosion of the cliff base Landward migration of beaches and dunes
Increase in severity and number of hurricanes over the Atlantic Ocean and in the severity of other storms	Increase in movement of beach sediment and material from the base of cliffs	Increase in the potential for new beaches to form, and for beach accumulation downdrift of areas of erosion
Increase in severity and number of hurricanes over the Atlantic Ocean and in the severity of other storms	Increase in wave height. During winter, an increase in the potential for large waves to form and erosion from waves; an increase in storm surge	Increase in coastal flooding potential Increase in the erosion of the cliff base Landward migration of beaches and dunes
Increase in growing degree days	Increase in vegetation growth	Increase in dune and slope stability

This handbook is subdivided into 5 sections.

Section 1: Current rates of coastal change and responses – a discussion of the current rates of coastal erosion measured in the province, and the potential responses to coastal erosion.

Section 2: Future trends – a discussion of the predicted changes in sea level and climate in Newfoundland and Labrador.

Section 3: Sources of information - why and how to use coastal data – a discussion of information available on the coast from numerous sources. This section explains why this data is useful, where to find it, and how to use it for infrastructure and community planning.

Section 4. Coastal processes – a description of the natural processes which occur in the ocean and along the coast.

Section 5: Measuring rates of coastal erosion in Newfoundland and Labrador – a discussion on how coastal change data is collected, primarily by Government of Newfoundland and Labrador through the Coastal Monitoring program.

Users wishing to access data and regional case studies can visit the Coastal Change in Newfoundland and Labrador website.

The aim of this handbook is not to make policy makers into climate-change geoscientists. Rather it is to provide policy makers with the information they need to make sound science-based decisions regarding planning around our coast. This will help ensure appropriate and sustainable development of our coastal regions.

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Introduction and Guide Outline

For those who live, work, or play around the coast of Newfoundland and Labrador it will come as no surprise to learn that the coast is constantly changing. These changes occur daily due to the interaction of tides, waves, and weather, however in considering how to develop our communities along the coast we need to understand longer-term trends.

The coast was considerably different 10,000 years ago, just after the last ice age. Relative sea level was higher in some places than it is today, and lower in others. Even in the last 100 years the coast has changed, and there is no doubt it will look different 100 years from now. Why? What are the processes that cause the coast to change? How, if at all, will these processes be affected by climate change?

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The guide provides numerous illustrations, and the image can be viewed by clicking on the link found below each illustration, or on the illustration itself. Links to external website are found throughout the text, and can be viewed by clicking on any text which is blue and underlined.

The aim of this guide is not to make policy makers into climate-change geoscientists. Rather it is to provide policy makers with the information they need to make sound science-based decisions regarding planning around our coast, and to be adequately informed to be able to ask the right questions. This will help ensure appropriate and sustainable development of our coastal regions. This guide relies on readily available sources of information (mostly websites of Government and non-governmental organizations) rather than the academic literature, which may be difficult for most readers to access. This information is provided below. You are encouraged to consult these websites for further information.

Current Rates of Coastal Change and Responses

Section 1

Each coastal area of the province has individual characteristics (cliff height and sediment composition, beach width and composition, near-shore environment, direction in which slopes are facing (called 'aspect'), vegetation types and coverage etc.) which makes providing an average erosion rate challenging. Measured cliff top erosion rates around the province vary from 0 cm/year on cliffs composed of bedrock or those completely vegetated, to over 100 cm per year on sand-dominated coasts (*e.g.*, Cheeseman Provincial Park in southwest Newfoundland) or on exposed coasts with narrow beaches (*e.g.*, Crabbes River in St. George's Bay). A nominal average coastal erosion rate for the Province is about 20 cm/year. It is almost certain this nominal rate will increase as a result of climate change and rising sea level.

Bedrock cliffs, such as these at Pouch Cove, erode more slowly than those composed of surficial sediment.

These rates assume continuous erosion and precludes those areas where catastrophic failure of the coast has occurred (*e.g.,* at Daniel's Harbour), where tens of metres of coast were eroded in a single event. Similarly, cliffs which had been previously stable for decades can be modified by a single storm where waves have eroded the base of the cliff. Such events are difficult to incorporate into a coastal change prediction.

Landslide at Daniel's Harbour, 2007. This was a catastrophic failure, where 10's of metres of coast were eroded in a single event.

The photographs were taken in 1999, 2005 and 2011 at Point Verde. The cliffs are composed mostly of sand and gravel, with few boulders on the narrow beach to protect the base of the slope from waves. This explains the fast erosion rates (up to 1 m per year) compared to other sites where average erosion rates are about 20 cm per year.

Responses

There are numerous potential responses to mitigate and adapt to the effects of increasing coastal erosion and flooding because of sea level rise and climate change. The final decision on which approach to take must weigh numerous factors, both social and economic. Data on the type of hazard, the risk (high versus low), rates of change (fast versus slow) are critical in this process.

There are four main strategies:

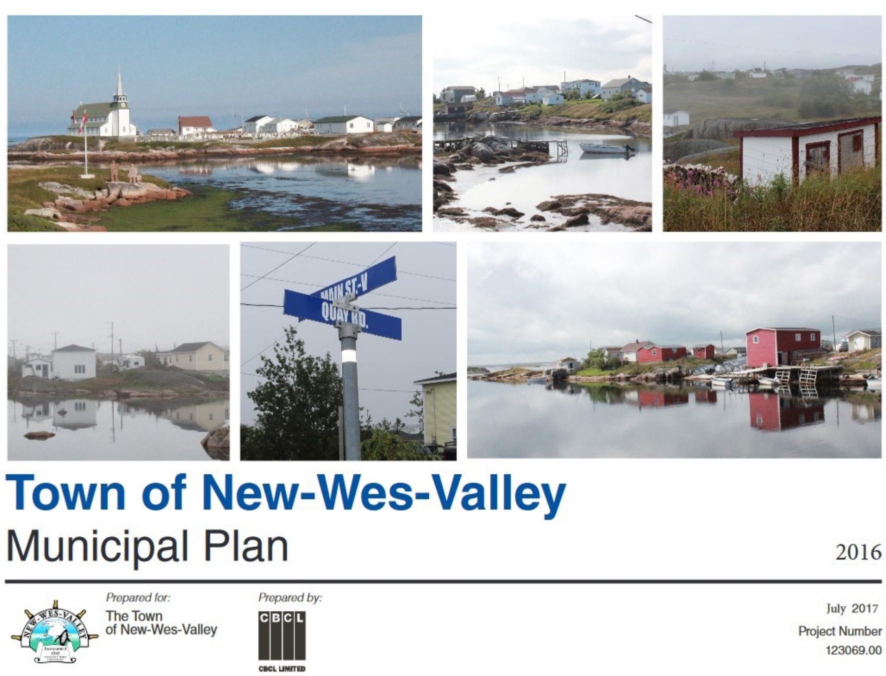
1. <u>Protection measures</u>

These could be hard (sea wall, or revetments (*e.g.*, rock wall)) or soft (beach replenishment, or dune stabilisation) engineering measures. Protection measures are expensive (commonly tens to hundreds of thousands of dollars) and consideration has to given on the value of what is being protected versus the cost of the protection measures.

Examples of 'hard' coastal protection: Left- revetment at Fortune; centre left- boulder retaining wall, CBS .
Examples of 'soft' coastal protection: Centre right-dune stabilisation, Gros Morne National Part, right – beach replenishment, CBS.

2. <u>Accommodation</u>

This could consist of engineering solutions for buildings and other structures to withstand potential impacts – such as improved flood protection, and the raising of structures. Municipalities could establish set-back limits for development. Set-back limits define, for instance, the distance from a cliff edge within which development is restricted. Such set-back limits should aim for 100 years of sustainability of residential/ commercial use and take into consideration current and predicted erosion rates. Of course, these set back limits are only valid for the time of implementation and should be reviewed at least every decade, in the light of new coastal change data, to ensure that set-back limits are maintained.



The New-Wes-Valley municipal plan includes a policy which ensures that new developments are set back an appropriate distance from the coast to ensure that the risks associated with a changing climate are reduced.

3. Retreat

If the first two options are not viable, then retreat from the coast may be required. This has already been implemented in Newfoundland and Labrador following the landslide in Daniel's Harbour in 2007.

View of the landslide area at Daniel's Harbour shortly after the 2007 landslide (left and centre) and in 2017 (right). Several structures and the road were relocated inland after the landslide. The foundations of the three houses circled in the left and centre photos are circled in the right photo.

4. Do nothing

However unlikely, a municipality may opt to do nothing and simply let nature take its course, while hoping for the best.

Mitigation costs for areas eroding but with no current development = $0!

Closed trail in Conception Bay South, Avalon Peninsula because of coastal erosion.

The first three responses imply there is something along the coast which requires mitigation or adaptation. In areas where development has yet to occur, science-based planning should limit the need for mitigation or adaptation.

Future Trends

Section 2

“*There is nothing permanent except change”* (Heraclitus, Greek Philosopher).

The coast we see today will almost certainly look different 100 years from now. The processes acting on the coast are the same as in the past, but their strength will be influenced by two main factors: changes in sea level and climate change.

Changes in sea level

Defining sea level

What is meant by ‘sea level’ and how is it defined? Sea level changes constantly because of tides and climatic factors, including wind, hurricanes, and tropical storms, all of which can produce water levels far above the normal tidal range. Other factors, such as coastal geology (including changes in the Earth’s crust) and the near-shore bathymetry, all influence water levels. There is considerable variability in sea level over time and space.

Mean sea level (i.e., the location of the 0 m contour on topographic maps) is defined as halfway between the average high tide and average low tide measured from tide gauges. In Canada, the Canadian Hydrographic Service is responsible for determining the position of mean sea level, which they accomplish by smoothing variations into local tidal base levels (termed tidal datums). In eastern Canada, mean sea level is based on observations made over a 19-year period at Father Point, Rimouski, Québec. Mean sea level for other parts of the world are based on observations from similar local sites

Relative sea-level change

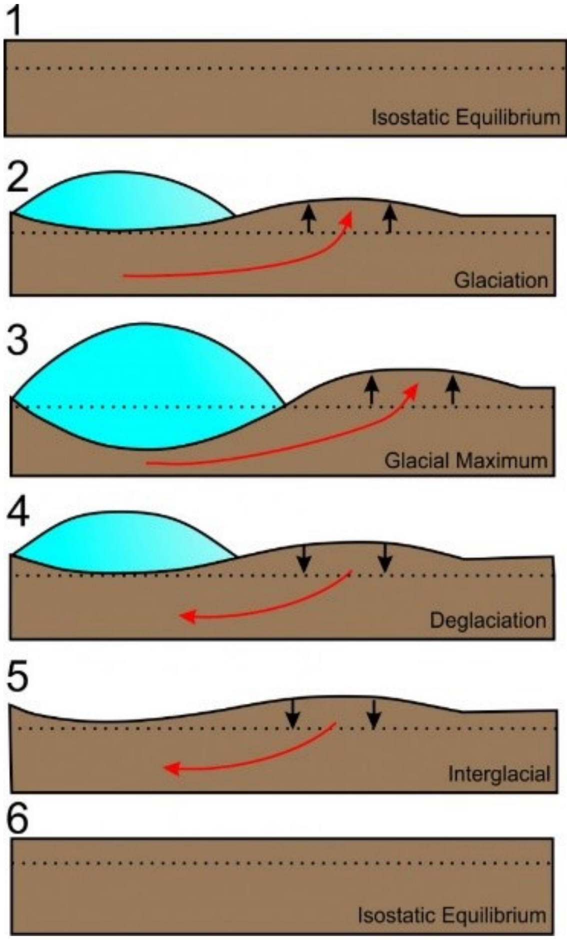
It is hard to believe that if we were in St. Anthony 10,000 years ago the ocean surface would be 145 m above what it is today. The evidence for changing sea level is in features such as beaches or deltas, which are formed at sea level, being found at current elevations well above modern sea level. Since the last ice age, sea level in many parts of the province has changed drastically – from being much higher than present (particularly on the west coast and in southern Labrador), and falling below present sea level (mostly on the west coast), to gradually rising over the past several thousand years. An understanding of the patterns of sea level change is an important consideration for planning in coastal communities.

During the last glacial period, water previously held in the oceans was taken up by the ice sheets. This resulted in a significant lowering of ocean levels, such that parts of the Grand Banks were exposed. Similarly, the weight of the ice sheets pushed the Earth’s crust downward in areas beneath and around the edges of the ice sheet, with the amount of depression increasing toward the centre of the ice sheet. As the ice sheets melted, water flowed back into the ocean. This resulted in a rapid rise of sea level, and a more gradual rebounding of the crust as the weight of the ice sheets was removed. This latter process continues today. The individual components of land (termed ‘isostatic’) and ocean (termed ‘eustatic’) adjustment are difficult to separate, and thus changes in sea level are expressed as relative changes.

Past sea level changes

Evidence of sea-level change in the province consists of the preservation of features found above, or even below, modern sea level which originally formed along the coast (*e.g.,* beaches, deltas, terraces, or sea stacks). In some areas, sediments which were originally deposited below sea level are now found above sea level. Some of these sediments contain marine shells, which scientists can use to estimate when the shells were deposited.

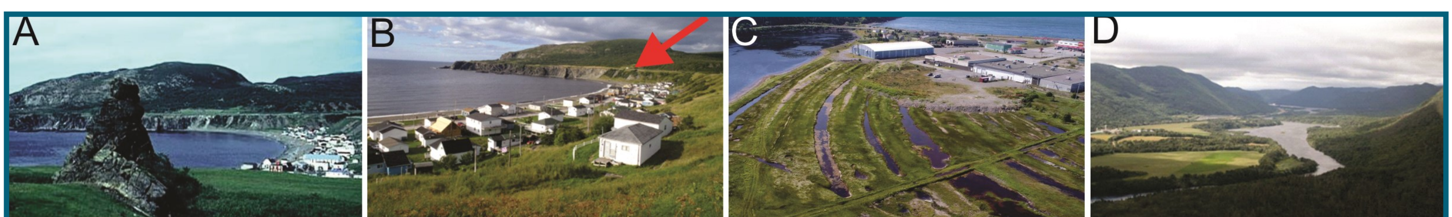
Most areas of Labrador record a pattern of gradual relative sea-level fall from the maximum current elevation at which evidence of higher sea levels is found (termed the marine limit). The marine limit in Labrador ranges from about 150 m above modern sea level in southern Labrador to 16 - 57 m at Cape Chidley at the tip of northern Labrador.



On the Island of Newfoundland, the highest marine limit is at the tip of the Great Northern Peninsula (about 145 m). From the marine limit, sea level fell rapidly in most places around the Island, falling below modern sea level to a lowstand (the lowest level recorded) from which sea level has been gradually rising. Recent sea-level rise has been documented from inundation of forests and peat bogs adjacent to the coast, the development of salt marshes and the erosion of coastal cliffs.

The only area from which no raised marine features have been identified is the east coast of the Avalon Peninsula north of Cape Broyle. In the St. John's area, for instance, sediment cores taken from the harbour show that a freshwater lake existed shortly after deglaciation. Relative sea level in St. John's Harbour has risen continuously over the last 10,000 years.

The effect of glaciation on the Earth's crust. The weight of ice pushes down the Earth's crust forcing the material comprising the mantle out towards the edges of the ice sheet (Diagrams 2 and 3). A 'bulge' in the crust is noted beyond the edges of the ice sheet. As the ice sheets melted, the crusts rebounds as the weight is removed. The 'bulge' also moves back towards the centre (Diagrams 4 and 5). Diagrams 1 and 6 show isostatic equilibrium before and after glaciation.



Features and landscapes formed at higher sea level.

A. Sea stack at Trout River; B. Raised delta at Trout River; C. Raised beaches at Placentia. These ridges are being slowly drowned by rising sea level; D. The lower reaches of the Humber River were below sea level at the end of the last glacial period. The Humber River valley was flooded by the sea all the way up to Cormack.

The rate of sea-level rise over the last 50 years can be determined from the examination of tide gauge data. Given the short period involved and the accuracy of dating control, the precise rate of sea-level rise can be approximated at between 1 and 4 mm per year. In much of Labrador, relative sea level is still falling. This is indicated by raised beaches, ranging in elevation from the marine limit to modern sea level.

Evidence of sea-level rise in the province.
Right. A salt marsh on the west coast. These require rising sea level to develop.
Left. Spruce stump dated at about 2300 years old found below high tide at Big Seal Cove, Avalon Peninsula.

<u>Future changes in sea level</u>

In addition to the rise in sea level as a result of crustal adjustment following the last ice age, future changes in sea level in Newfoundland and Labrador will be impacted by global sea-level rise as a result three factors: warming ocean water (as it is less dense, warm water takes up more space than cold water), glacier melting, and disintegration of the Greenland and Antarctic ice sheets.

Evidence of recent sea level rise. Left: Tide gauge record from Port aux Basques. A tide gauge continuously measures sea level relative to a fixed point. Multiple daily measurements record the height of the surrounding water, and include the daily tides. The graph shows elevation (side) and years (bottom). The red line shows the overall upward trend in sea level at Port aux Basques. Right: Coastal erosion at O'Donnels.

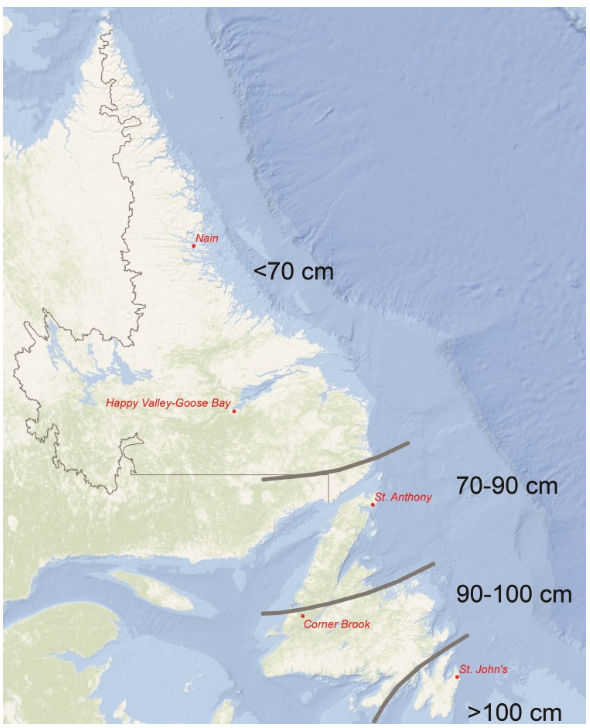
The Intergovernmental Panel on Climate Change (IPCC) is an intergovernmental body of the United Nations dedicated to providing objective, science-based information on climate change. The IPCC suggests a rise in global sea level of up to 98 cm by 2100, depending on what future climate scenario is used. Due to the uncertainty around how climate will change, the IPCC releases a range of possible scenarios based on various assumptions about how we are impacting climate, primarily the concentration of greenhouse gases in the atmosphere and what we are doing to restrict them. Based on the currently high concentrations of greenhouse gases in the atmosphere, sea-level rise is trending on the high end of the projections. Click for the IPCC report on global sea level change.

Most of the potential sea-level rise is produced by the melting of the West Antarctic and Greenland ice sheets. The two ice sheets differ in many respects not least of which is that the West Antarctic ice sheet is largely ocean-based, whereas the Greenland ice sheet is land-based. The West Antarctic ice sheet contains enough ice to raise sea level by 5-6 m should it all melt, and instabilities in the ice sheet could allow large pieces, some as big as Prince Edward Island, to break off and float away after a period of sustained warming, or if other factors raised sea level. The Greenland ice sheet contains enough ice to raise sea level about 7 m, and although it is already contributing to sea-level rise (from melting), it does not contain the same instabilities as Antarctica that could result in a rapid ice collapse.

Community	Sea Level Rise Potential (cm)
St. John’s	113.0
Long Harbour	115.6
Corner Brook	108.7
Goose Bay	49.4
Nain	48

Potential sea level rise from a Geological Survey of Canada report . Projections are presented for the upper end of future climate scenarios (i.e., business as usual, with continued greenhouse gas emissions and limited government intervention).

Regardless, the total amount of global sea level rise by 2100 is uncertain, beyond the fact that sea level is rising. Similarly, the impacts of this global sea-level rise on Newfoundland and Labrador is equally uncertain in terms of the absolute amount of sea-level rise. Nevertheless, global trends, plus evidence for local isostatic adjustment of the crust suggest that a relative sea-level rise of over 110 cm is expected for eastern parts of the Island by 2100, with somewhat lesser rise predicted on the west coast and into Labrador. This rising trend could be exacerbated by partial disintegration of the West Antarctic ice sheet which could contribute an additional 5 cm of sea-level rise by 2100.



What data to use really comes down to a question of risk. The high end of the various projections is the most reflective of current trends of greenhouse gas emissions and global sea level rise. For management and planning in coastal areas, where there is commonly significant municipal infrastructure to consider, it seems prudent to err on the side of caution and go with the upper end of the likely range of values

Where the tolerance of risk to sea level rise is very low (*e.g.*, building a significant piece of municipal infrastructure with a long-projected life span) consideration of the additional 65 cm of sea level rise from West Antarctica may be appropriate.

Predicted rise in sea level in the province by 2099. Modified from Batterson and Liverman, 2010, click here for the report.

Changes in climate

Predictions of the future trend in climate are derived from climate modelling. There are numerous climate models, and most indicate a warming climate for eastern North America.

In 2013, the Government of Newfoundland and Labrador commissioned a detailed, accessible summary of expected climate change impacts within the province, which was updated in 2018. Click here for the 2018 report. The 2018 report provided projections for 29 communities in Newfoundland (22 communities) and Labrador (7 communities, including Schefferville) for a wide range of climate parameters. The projections are based on a ‘business as usual’ climate change scenario, which assumes continuing growth of carbon dioxide emissions with few government restrictions. At present, this scenario most closely reflects recent observations and carbon emissions anticipated in the near future under current international controls.

The reports provide an insight into what is projected to be a warmer and wetter climate for the province. Some predictions are positive, depending on your viewpoint, *e.g.,* warmer overall climate, and longer growing season. However, the projections have negative implications for coastal erosion and coastal flooding. For the purpose of this discussion focus will be on 2 parameters – mean temperature and 3-day precipitation.

Mean temperature is shown for St. John's, Corner Brook and Nain, as representative of three diverse parts of the coast. Values from the last century (20th Century) are the baseline (*i.e.,* what we know to be correct). Predicted values for the middle of this century (2041-2070) and the end of the century (2070-2100) are also shown. In all areas, mean temperature (*i.e.,* the average air temperature for each season over a given period of time, in this case 3 months) is predicted to rise by 4-6°C (compared to 20th Century climate), with the exception of Nain. Winter temperatures there are predicted to rise by over 10°C by 2100.

Community	Period	Winter	Spring	Summer	Fall
St. John's	20th Century	-3.2	1.8	14.1	7.6
	2041-2070	0.2 ± 1.5	3.4 ± 0.9	16.5 ± 1.2	10.9 ± 1.3
	2071-2100	2.1 ± 1.8	5.3 ± 1.5	18.3 ± 1.8	13.0 ± 1.7
Corner Brook	20th Century	-4.9	2.3	15.7	7.5
	2041-2070	-0.5 ± 1.5	5.4 ± 1.3	18.7 ± 1.3	10.5 ± 1.3
	2071-2100	1.9 ± 2.0	7.4 ± 1.5	20.7 ± 1.9	12.6 ± 1.8
Nain	20th Century	-15.5	-5.1	9.3	1.6
	2041-2070	-8.2± 2.1	-2.5 ± 1.8	11.9 ± 1.4	5.2 ± 1.7
	2071-2100	-4.6 ± 2.9	0.2 ± 2.4	14.1 ± 2.0	7.2 ± 2.2

The table to the left shows predicted values for St. John's, Corner Brook and Nain - Mean air temperature data for the period 2041-70 and 2070-2100 compared to 20th Century data, for Winter (December-February), Spring (March-May), Summer (June-August) and Fall (September-November). Standard deviation (±) is a measure of how spread out the numbers are and is included as a measure of uncertainty. More details on standard deviation can be found here.

Maximum 3-day precipitation is important because hazardous precipitation events often occur over several days, during which reservoirs, soil-moisture capacity, and water bodies may gradually become overwhelmed, leading to flooding and slope-stability issues, even if the intensity of precipitation (the amount of precipitation per hour) remains low. Many of the landslides experienced in the province have occurred following prolonged periods of precipitation (commonly rainfall) when the soil cover became saturated. Maximum precipitation falling over three consecutive days is predicted to increase by 1-12 mm. The greatest increases are predicted to occur on the island in winter. Predicted increases are generally smaller in Labrador.

Community	Period	Winter	Spring	Summer	Fall
St. John's	20th Century	84.4	81.8	62.6	79.2
	2041-2070	85.0 ± 7.8	76.3 ± 5.5	77.9 ± 10.3	94.5 ± 4.4
	2071-2100	90.8 ± 8.8	82.4 ± 5.8	80.2 ± 11.2	97.5 ± 4.9
Corner Brook	20th Century	56.9	43.2	50.3	56.1
	2041-2070	55.1 ± 4.4	49.5 ± 3.1	65.4 ± 8.8	68.7 ± 8.4
	2071-2100	61.7 ± 4.4	55.1 ± 4.1	71.1 ± 12.7	74.4 ± 10.5
Nain	20th Century	74.7	63.8	53.8	52.7
	2041-2070	68.3± 10.3	55.7 ± 7.8	71.8 ± 5.2	69.3 ± 5.6
	2071-2100	69.3 ± 14.4	61.9 ± 8.9	77.6 ± 8.5	70.7 ± 5.8

Table showing maximum 3-day precipitation (mm) and projected change for St. John's, Corner Brook and Nain for the period 2041-70 and 2070-2100 compared to 20th Century data, for Winter (December-February), Spring (March-May), Summer (June-August) and Fall (September-November). Standard deviation (±) is included as a measure of uncertainty.

In combination, the potential implications for the coast of a warmer and wetter climate are:

- Less snow cover in winter, and an increased frequency of rainfall or rain-on-snow events.
- Increased surface runoff may produce increased gullying in winter.
- Increased absorption of water into the ground, increasing groundwater flow.
- Increased thaw depth in permafrost areas or other areas of frozen ground, mostly in northern Labrador. This will lead to ground instability in some places, as well as the release of methane gas to the atmosphere thereby exacerbating warming trends.
- Less sea ice offshore of Labrador and on the north coast of the Island. This will impact transportation on the Labrador coast, both negatively through the disruption of traditional winter access along the coast and positively by extending shipping seasons. A reduction in sea ice will likely have negative impacts on coasts because sea ice protects the coast from winter storm waves and storm surge.
- Less ice build-up along the shore (termed shorefast ice). This ice protects the coast from storm damage in the winter.
- An increased frequency of landslides and avalanches.
- An increase in coastal flooding
- An overall increase in the rate of coastal erosion.

Changes in storm surge

If the frequency and intensity of severe storms is predicted to increase, then it is reasonable to assume that storm surges are also likely to become more frequent and of greater intensity. The impact of increased frequency and intensity of storm surge will be exacerbated by rising sea level, which will result in the narrowing of many of our beaches, particularly those backed by cliffs. This will result in more frequent wave impacts on our coastal cliffs, as well as increased coastal flooding.

Storm-surge modelling has been undertaken by Environment Canada. The storm-surge models predict a 0.5 to 1.0 m increase in storm surge for the province. This is in addition to the increased height of waves experienced at the coast.

The Environment and Climate Change Meteorological Service (MSC) of Environment Canada issues storm surge warnings. These are issued for abnormally high-water levels and high waves (storm surge or storm tide) caused by storms, which have the potential to cause coastal flooding. This usually occurs when tides are at their maximum. An increased frequency of such warnings is to be anticipated.

Large wave, Cape Spear, Avalon Peninsula

Consequences and implications

There are consequences for the expected changes in climate and rising sea level in much of the province, which will have implications for coastal change. A summary table is presented below.

Expected change	Consequence	Implication for Coastal Change
Increase in mean daily precipitation, particularly in the winter Intensification of precipitation Increase in frequency of precipitation events Increase in the maximum precipitation falling over 3, 5 and 10 consecutive days	Increase in soil saturation Increase in snowmelt Increase in surface water Increase in ground water	Increase in clifftop and cliff face erosion Increase in slope movement
Rise in sea level	Increase the height of extreme water levels Increase in waves height Increase in level of high tide	Increase in the extent and frequency of coastal flooding Increase in the erosion of the cliff base Landward migration of beaches and dunes
Decrease in the duration and extent of sea ice	During the winter, an increase in the potential for large waves to form and for erosion from waves	Increase in the extent and frequency of coastal flooding Increase in the erosion of the cliff base Landward migration of beaches and dunes
Increase in severity and number of hurricanes over the Atlantic Ocean and in the severity of other storms	Increase in movement of beach sediment and material from the base of cliffs	Increase in the potential for new beaches to form, and for beach accumulation downdrift of areas of erosion
Increase in severity and number of hurricanes over the Atlantic Ocean and in the severity of other storms	Increase in wave height. During winter, an increase in the potential for large waves to form and erosion from waves; an increase in storm surge	Increase in coastal flooding potential Increase in the erosion of the cliff base Landward migration of beaches and dunes
Increase in growing degree days	Increase in vegetation growth	Increase in dune and slope stability

Gullying along the cliff at Holyrood Pond, Avalon Peninsula. With changes in the climate, gullying will become more common.

Sources of Information-Why and How to Use Coastal Data

Section 3

There is plenty of information available on our coastal environment, which can assist when making planning decisions or to improve understanding of your local area. Why are these data useful, what do they mean and where are they? In this section we will address these important questions. The list of websites provided is not exhaustive but will be enough to get you started. Using all these data when making decisions in coastal environments can help decrease the vulnerability of planned infrastructure to climate change and sea level rise, and reduce negative impacts on the environment.

Climate data

Are climate and weather the same thing? No. Weather is what you see when you look outside – it could be raining, snowing, windy, dry, warm, or cold. We check the weather forecast to plan our day. Weather can change from minute to minute and hour to hour, as we all know. Climate is the average weather we experience, or expect to experience over a period of time – if you are in Corner Brook in January you can expect it to be cold (mean temperature -4.9° C) and precipitation will likely be as snow. If you are in Corner Brook in August, you can expect it to be warm (mean temperature 15.7° C) and any precipitation will be as rain. That is the climate. It does not mean it cannot occasionally be raining and 10° C in Corner Brook in January, or that snow is impossible in Corner Brook in July. Climate is what you expect, weather is what you get.

When we are planning for future developments near the coast (or anywhere for that matter), we need to consider our local climate and how that climate is likely to change in the future. Will our winters become warmer? What about our summers? Will there be less snow and more rain in the winter? How much precipitation do we get, and will the climate become wetter? Will our area become stormier? Will the climate become windier? Many of these factors are important in determining what coastal erosion will take place. We may not be able to answer all these questions with assurance (wind is difficult to predict, for instance), but they need to be asked, to reduce the risk of costly mistakes.

Climate data is useful for a range of applications. For example, wind direction and speed can tell us about the wave directions and wave heights to be expected; rainfall data provides information on surface runoff and groundwater; storm information may point to triggers for coastal erosion.

Weather is what we experience at the moment, in this case, a sunny day in Terrenceville, Burin Peninsula.

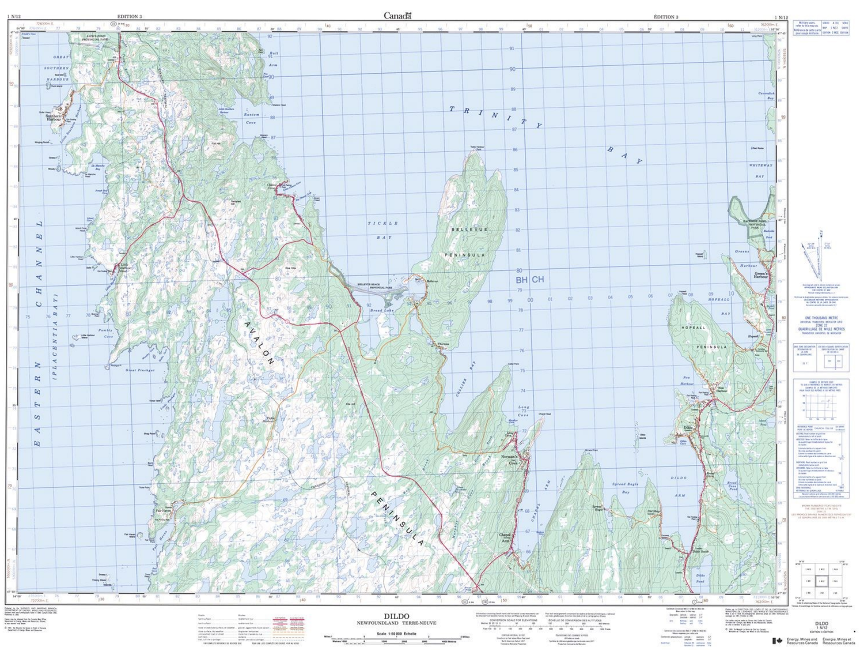
Climate and climate change data are available from Environment Canada, and from the Provincial Government:

- This site provides historical climate data for 337 sites in Newfoundland and Labrador.
- This site provides data on a wide range of climate variables for Newfoundland and Labrador, in an easy-to-view format. The province is divided into 10x10 km cells, any of which can be selected, and the data viewed. The site also includes climate change projections for each of the communities included.
- This is a report commissioned by the Provincial Government on climate-change projections for 29 communities in Newfoundland and Labrador. A wide range of climate variables is included. It is an excellent resource and highly recommended.
- This site provides summaries of data, primarily from the report noted above.

Topographic maps

These maps show the surface features of an area. They are useful for visualising the layout of a community or region, how high the land surface and structures built upon it are above sea level or how far they are located from the coast, the relative steepness of slopes within an area, and the location of roads and other infrastructure.

Published topographic maps are available at various scales, a common one being 1:50,000 – in other words one centimetre(or one inch or one of any unit) on the map equals, respectively, 50,000 centimetres (inches or any unit) on the ground. Maps of communities are commonly at 1:2,500. The larger the scale number the larger the area the map shows, and the smaller the features displayed on the map. A 1:2,500-scale map is used to show communities, and this would be considered large-scale. Maps showing entire provinces could be at a scale of 1:1,000,000; these are small-scale maps. A scale bar is commonly found on a map; this enables the user to see at once the distance on the ground represented by its equivalent distance on the map. This is particularly useful if the map has been photo-enlarged or reduced.

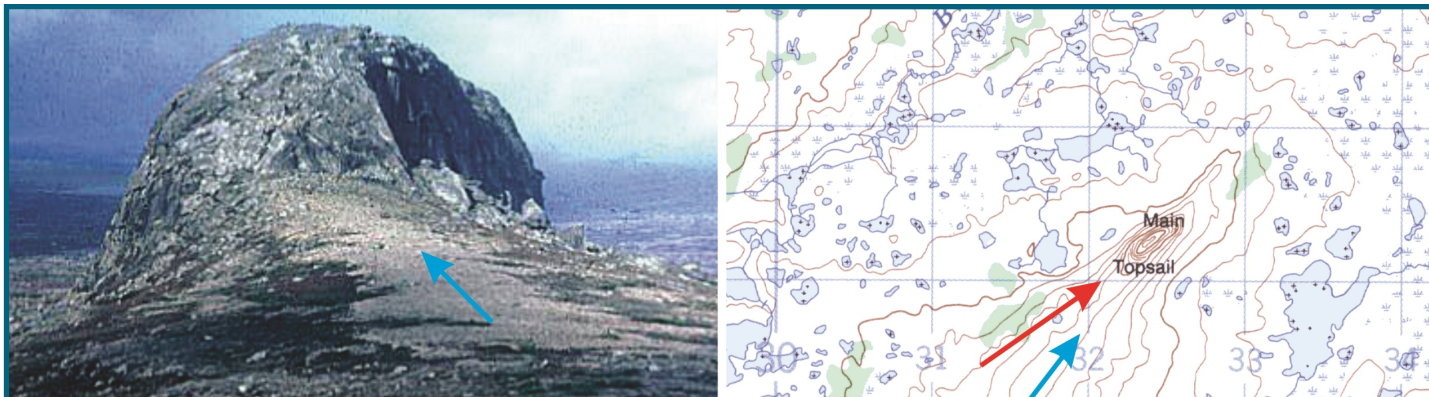


Example of a topographic map. The scale and scale bar are shown on the bottom centre of the map, under the name of the map region (open link below). The contour interval and other information are on the right side of the map.

Most large-scale maps contain contour lines. Contours are lines of equal elevation above sea level and are therefore very useful when discussing sea level rise. Topographic maps show lines for only certain elevations – on a 1:50,000 scale map they are commonly 10 m apart (only 10, 20, 30 m etc. are shown), whereas on a 1:2,500 scale map contours are commonly 2 m apart (2, 4, 6 m contour lines). This ‘contour interval’ is always found on the margin of the map. Only every fifth contour is labelled – this contour is thicker and/or darker than the rest.

Contours also help us visualise the shape and steepness of the terrain. If the contours are close together, you are looking at a steep slope. If the contours are widely spaced the terrain is relatively flat. Here is an example using a photo for comparison:

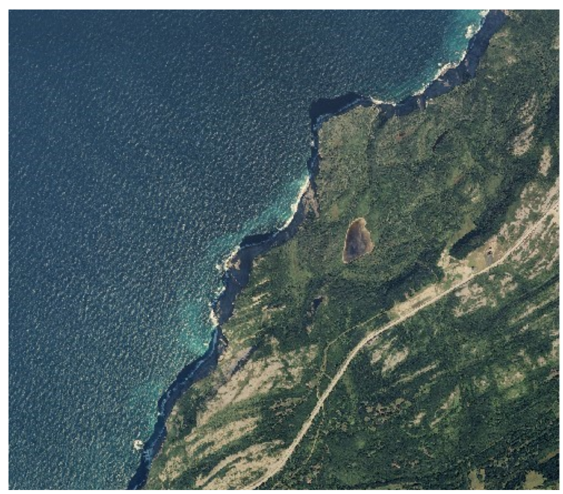
Topographic maps for Newfoundland and Labrador, at various scales, can be found here.



Photograph of the Main Topsail (on left) and the topographic map of the same feature (on right). The east-west and north-south grid lines on the topographic map are 1 km apart. The red arrow shows the approximate direction of view. The contours (10 m contour interval) around the Main Topsail are close together indicating a steep slope, whereas those on the ramp (blue arrow) are stretched out. The contours in the larger area surrounding the Main Topsail are far apart indicating relatively flat ground.

Aerial photographs

Aerial photographs are any photograph taken from the air. Normally, aerial photographs are taken from a plane with the camera pointing down (vertical photographs), but can be taken from an angle (oblique photographs). Aerial photographs are available for most areas for different years (from which comparisons can be made), and at different scales (showing greater or lesser amounts of detail). From aerial photographs cultural (buildings, infrastructure etc.) and natural (hills, valleys, lakes, forests etc.) features can be identified.

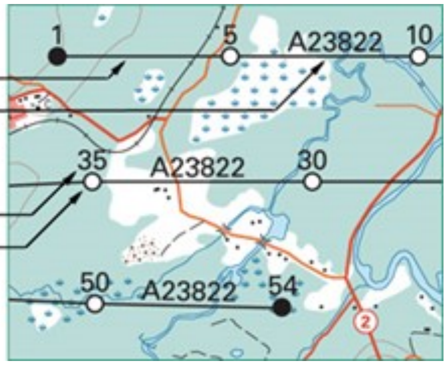


Example of a vertical aerial photograph.

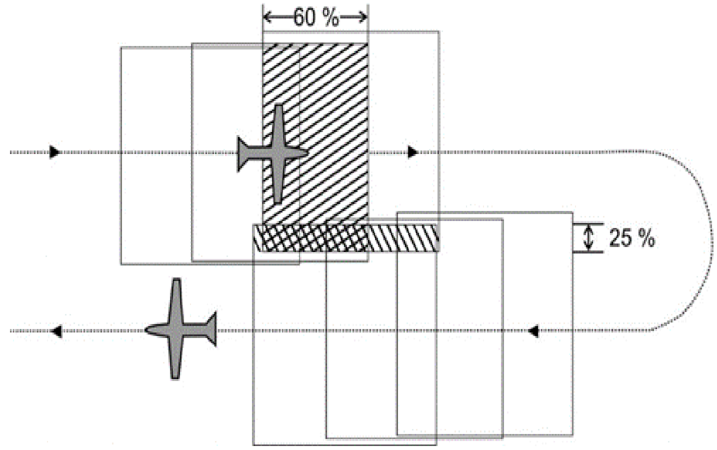
Vertical (left) and oblique (right) photographs of the same area of cliffs near Holyrood Pond on the Avalon Peninsula. These images were taken from the DJI Inspire 2 drone.

When an area is covered by an aerial survey, the plane flies a path, termed a flight line, back and forth across the area taking photographs at regular intervals. There is always an overlap on the photographs to ensure complete coverage and to allow stereoscopic viewing (more detail on this topic below). Aerial photographs are designed to have a 60% overlap on the same line, and a 25% or 30% overlap between adjacent lines.

Flight Line
Roll Number
Photo Number
Photo Centre



A sample index map for aerial photographs. The index map shows the Roll Number and the Photo Number. The centre of the photo is shown by a dot. In this way the appropriate photograph for the area of interest can be selected.



Sequence of aerial photographs required to cover an area.

Aerial photographs are catalogued by flight line (the Roll Number), and the photo number, with the centre of the photograph being shown on the Index Map. Click here for Index Maps.

One of the many attributes of aerial photographs is that they can be viewed stereoscopically – in other words the photographs can be viewed in 3D. This is where the overlapping comes in. Stereo photos take advantage of the way our brain works – our eyes see two similar views of the world and our brain converts the information into a 3D image. Try looking at an object and closing one eye. Open that eye and close the other. You see two slightly different views of the same thing – the brain processes this information to give us a 3D image. We cannot see in 3D without it. Try catching a ball with one eye closed!

Aerial photographs for different years (consult the aerial photograph indexes to see what is available for your area) can be useful when seeing how things have changed in an area in a general way *e.g.*, showing longshore drift as sediment builds up behind coastal structures, past slope movement shown by landslide scars, and how coastal protection has changed. Older aerial photographs are in black and white, but recent photographs are in colour. Much of our recent aerial photography is also available digitally on-line.

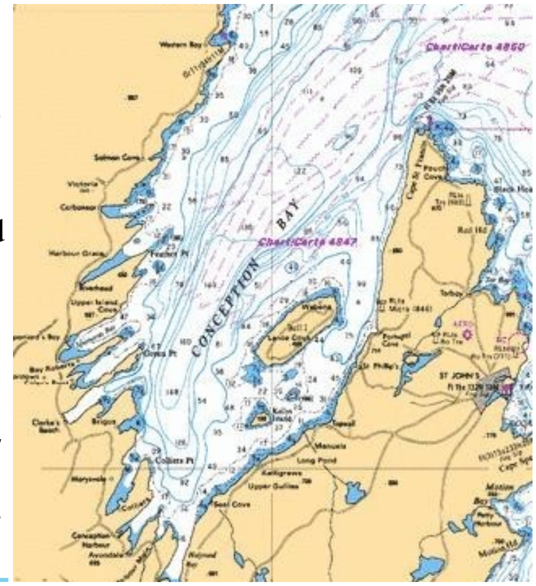
Aerial photographs can also be ‘stitched’ together to produce a single photograph or ‘photo mosaic’. These are known as ‘orthophotographs’ – they have been corrected or 'ortho-rectified' such that the scale of the combined photograph is uniform. An aircraft’s altitude is never perfect, so changes in scale occur. An orthophotograph can be used to measure true distances. Some of these orthophotographs, complied from UAV (drone) photographs, have been produced by the Government of Newfoundland and Labrador (GNL) as part of the Coastal Monitoring program.

Aerial photographs for the province can be found at by clicking here or through the Land Use Details Atlas**.**

Nautical charts

In the same way that topographic maps show land features, nautical charts show bathymetry (water depths) and features of the ocean floor. These maps are useful because they show the shape of the ocean floor, and the presence of shoals and other sub-surface features which may influence wave development and their impact on the coast.

Hydrographic charts (maps of the ocean floor) are produced by the Canadian Hydrographic Service and are distributed on their website, or via authorised dealers in Newfoundland and Labrador. These charts have lines of equal depth (like contours but called 'depth contours' or 'isobaths'). They also contain information on the nature of the seabed (including the sediment type). Nautical chart information can be found here.



This chart for Conception Bay shows a deep channel west of Bell Island (maximum depth 290 m) extending north-northwest between Brigus and Cape St. Francis. Like topographic maps, the closer the isobath lines are, the steeper the undersea terrain.

Tidal data

We are all aware of the rhythmic rise and fall of water along our ocean coast. Knowledge of tides is critical in navigation and in harbour construction.

Tides and the associated coastal currents are also important in transporting sediment along the coast and are therefore an important component of coastal erosion. Areas with a high tidal range (the height between the lowest of low tides and the highest of high tides) are likely to have more coastal erosion than those areas with a low tidal range. The tidal range in Newfoundland and Labrador is 1-2 metres for the northeast and southwest coasts, and 2.1-4 metres for the rest of the province. This is low compared to much of Atlantic Canada, particularly the Bay of Fundy region which has a tidal range of over 10 metres.

Tides are also important when considering storm surge – a storm surge arriving on a high tide has considerably greater potential for damage than one arriving on a low tide. Areas with a low tidal range are therefore more at risk from storm surge than those areas with a high tidal range, because the height of the storm surge could exceed the tidal range.

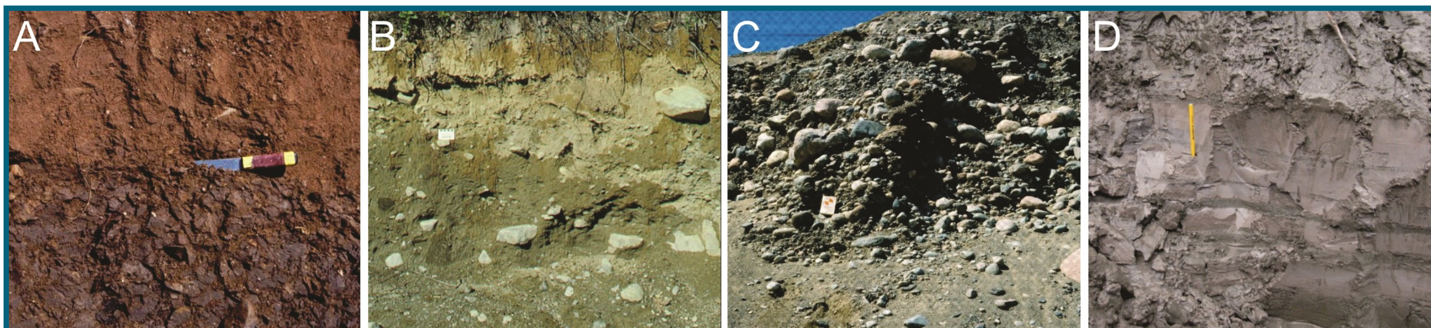
Tide-gauge data, including historical information, is available from Fisheries and Oceans Canada for 122 stations in Newfoundland and Labrador. Five of these sites, at St. John's, Argentia, Bonavista, Port aux Basques and Nain, are reference sites and have records of longer duration than the others.

Surficial geology

Surficial geology describes the unconsolidated sediments on the surface of the Earth and the processes which formed them. This branch of geology is focused on the last 3 million years of Earth's history – in our part of the world this period was dominated by glaciations and, most recently, by the activities of humans. Knowledge of the surficial geology is important because it increases our understanding of the sediments found along the coast, as each sediment type has different characteristics and erode at different rates. For example, a sand-dominated cliff will erode faster than one comprised of boulder-rich till. Sand has little internal strength, whereas till is a more cohesive sediment. Additionally, boulders eroded from till will collect at the base of the slope providing protection from waves.

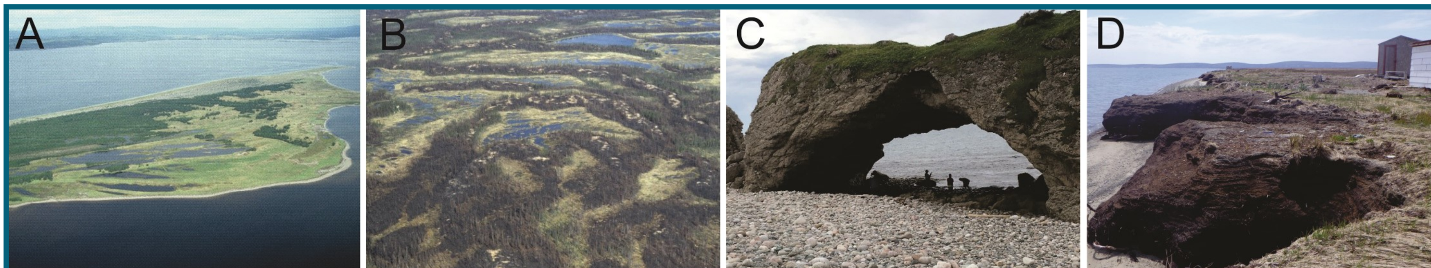
We have all seen the various sediment types found in our province, although we may not have known what they were. Till is essentially bedrock ground up by glaciers. Till commonly has a wide range of grain-sizes – from clay to boulders. Till is common across the province but looks different in different areas. This is because till is a product of the various bedrock types the glaciers moved over. A red sandstone bedrock will produce a red sandy till. A grey shale bedrock will produce a grey clayey till. If the glacier passed over each bedrock types the resulting sediment may be a pinkish sand-clay till. The more types of bedrock the glacier travels over the more variable the composition of the till.

Sediment washed out of a glacier is similar to what we find in many modern stream- and river-beds – a mixture of sand and gravel. Most of the fine-grained material is washed away to be eventually deposited in ocean or ponds as muds (a mixture of silt and clay). During glacier melting huge volumes of sediment were released, resulting in thick (metres to tens of metres) deposits of sand and gravel.



Surficial sediment:
A) Two tills – the lower till (below the knife) was derived from red shale bedrock – it is a clay-rich till. The upper till was derived from a red sandstone – it is a sandy till. There are many different rock types because rivers are efficient at moving sediment long distances.
B) A stony till. This sediment has a wide range of grain sizes, from clay to boulders.
C) Sand and gravel washed out of a glacier. There is very little silt and clay in this sediment – the silt and clay have been washed away. The gravel is well rounded because the rock fragments have been rolled around in a river. There are many different rock types because rivers do a good job of moving sediment long distances. These sediments are found in all parts of the province, but typically in river valleys.
D) Muds (mostly silt and clay) washed out of melting glaciers and deposited in the ocean and exposed when the sea level dropped. There is some layering in this sediment because of settling to the ocean floor – coarser grains settle quicker than finer ones. These sediments are found in many parts of the province, but especially on the west coast.

Some sediments and features were deposited after the glaciers melted. These include peat (organic matter formed in bogs or fens), beaches, sand dunes, and beach ridges.



Sediments and features formed since the glaciers melted:

A) Beach ridges (crescent-shaped features) formed during changes in sea level (Flat Bay spit).

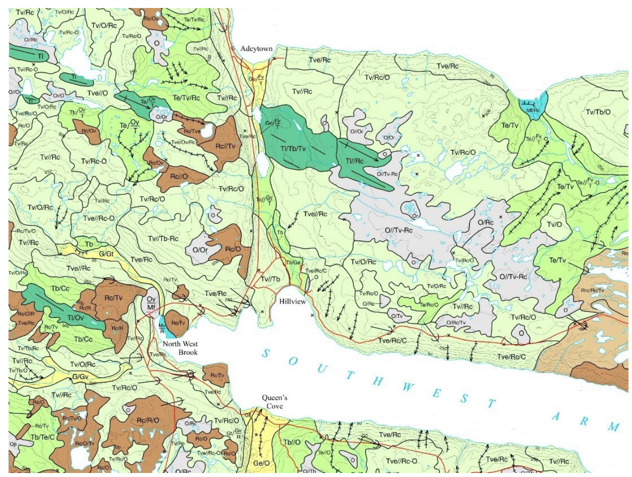
B) Sand dunes in Labrador.

C) Beaches – this one is gravelly although others are sandy.

D) A thick layer of peat. These deposits originally formed in bogs, but some are now exposed along the coast such as this one at Shoal Point, Port au Port Peninsula.

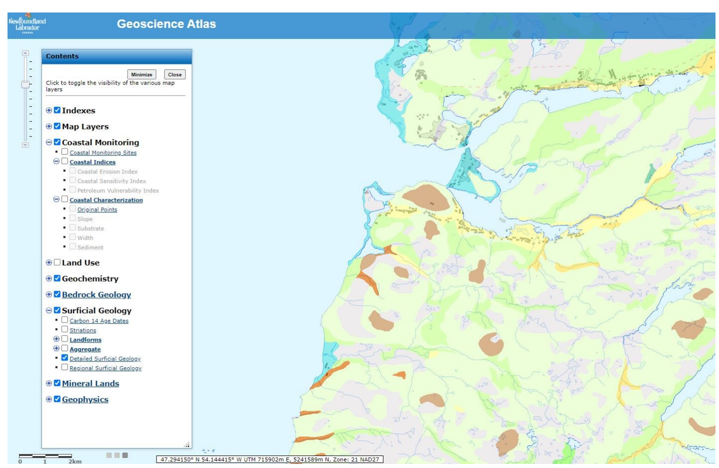
Surficial geology maps show the types of sediment found in an area. On the surficial geology map below, produced by the Geological Survey of Newfoundland and Labrador (GSNL), areas of rock are shown in brown, various types of till are shown in green, sand and gravel deposits are shown in yellow, marine sediments are shown in blue, and organic deposits (bogs) are shown in grey. A legend explaining the sediments in more detail accompanies the map.

Information on the surficial geology of the province can be found here. This site is optimised for Internet Explorer.



An extract from a surficial geology map produced by the GSNL.

Still from a video showing surficial sediment in coastal cliffs at Point Verde, Avalon Peninsula.

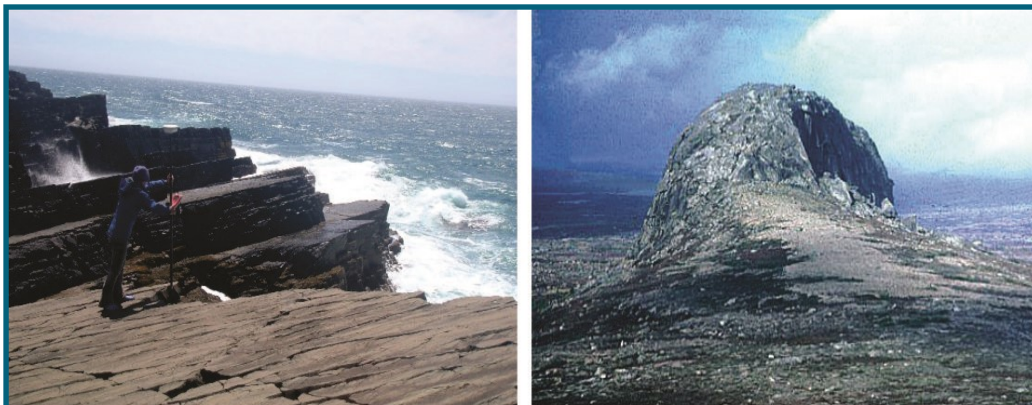


Part of the Surficial Geology layer on the Geoscience on-line site. The area shown is Placentia.

Bedrock geology

Bedrock geology describes the solid rock and the processes which formed it. This branch of geology focuses on those periods prior to the last 3 million years. In our province the youngest rocks are about 300 million years old (Carboniferous rocks on the west coast) and the oldest about 4 billion years old (found near Saglek, Labrador). The geology of our province is diverse and complex.

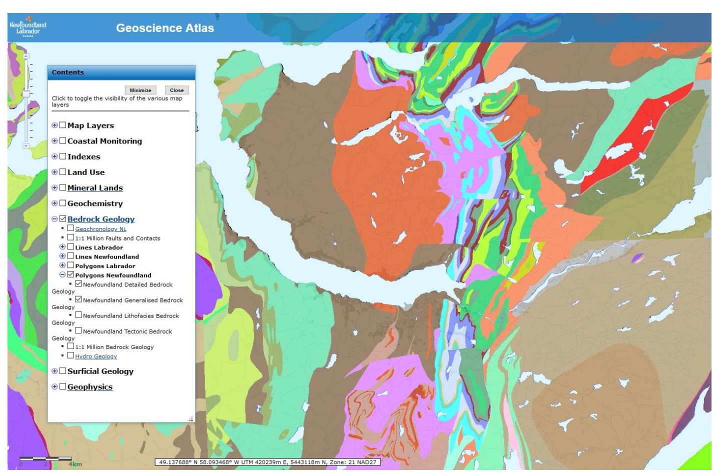
Bedrock coasts erode much more slowly than those composed of sediment. That is not to say that bedrock coasts cannot erode quickly under the right circumstances. The rate of erosion is dependent on many factors. Those rocks with distinct layers or cracks (*e.g.*, shale, argillite) erode faster than those with none. The most common type of weathering in bedrock in the province is frost wedging (discussed in more detail in the Coastal Processes section). Fine-grained bedrock with no joints, bedding planes, or fractures (*e.g.*, quartzite, fine-grained granite, gneiss) is the most resistant to erosion. Some rocks dissolve slowly over time (*e.g.*, limestone and dolostone).



Rocks with distinct layers (or cracks) such as to the left will erode faster than rocks with few layers or cracks, such as the one to the right. This is mainly the result of their susceptibility to frost wedging.

Information on the bedrock geology of the province can be found here. A list of reports and maps produced by the GSNL can be found here.

Video of bedrock-dominated coast at Pouch Cove.



Screenshot of part of the Bedrock Geology layer on the GSNL Geoscience on-line site. The area shown is Corner Brook-Deer Lake- Grand Lake.

Coastal classifications

These attempt to allow comparisons between different parts of the coast and to provide a foundation for climate-change adaptation measures. There are a number of these coastal classifications, but the CanCoast project of the Geological Survey of Canada provides a national overview.

In classifying Canada's coast CanCoast considers the following factors:

1. Sea-level change. Is sea-level projected to rise or fall, and how much? Sea level is projected to rise in all of Newfoundland and Labrador.
2. Wave heights, including the effects of sea-ice. The removal of sea ice will result in an increase in wave height. This is particularly important in the Arctic regions, and our province is not projected to experience a significant change in wave height.
3. Ground ice content. These are areas of permafrost (i.e., ground below 0o C for more than 2 consecutive years). Areas with significant permafrost will likely experience significant erosion if the permafrost thaws.
4. Coastal materials. What the coast is composed of has a significant impact on susceptibility to erosion. Bedrock is generally resistant to erosion, whereas sand (for example) is eroded easily. Much of our coast is bedrock, although significant areas (*e.g.*, St. George's Bay, Bonavista North) have large areas of easily erodible surficial sediments along the coast.
5. Tidal range. Areas with a high tidal range are likely to have more coastal erosion than areas with a low tidal range. Conversely, areas with a low tidal range are more at risk from storm surge than areas with a high tidal range.
6. Backshore slope. Coasts with steep beaches are less likely to be impacted by storm waves than gently sloping beaches. Many of our beaches are steep.

These factors are considered for early and late 21st century climates, to illustrate the potential impacts of climate change. The CanCoast report can be found here and a data download here.

Maps are shown for each of the factors noted above, allowing a visual comparison with other provinces. Much of the coast of Newfoundland and Labrador has a moderate- to high-sensitivity to a changing climate. In other words, our coast is likely to be increasingly impacted by climate change.

In the absence of data from a specific monitoring site, this index provides a useful general guide to coastal sensitivity to climate change.

Other coastal classifications for Newfoundland and Labrador can be found here.

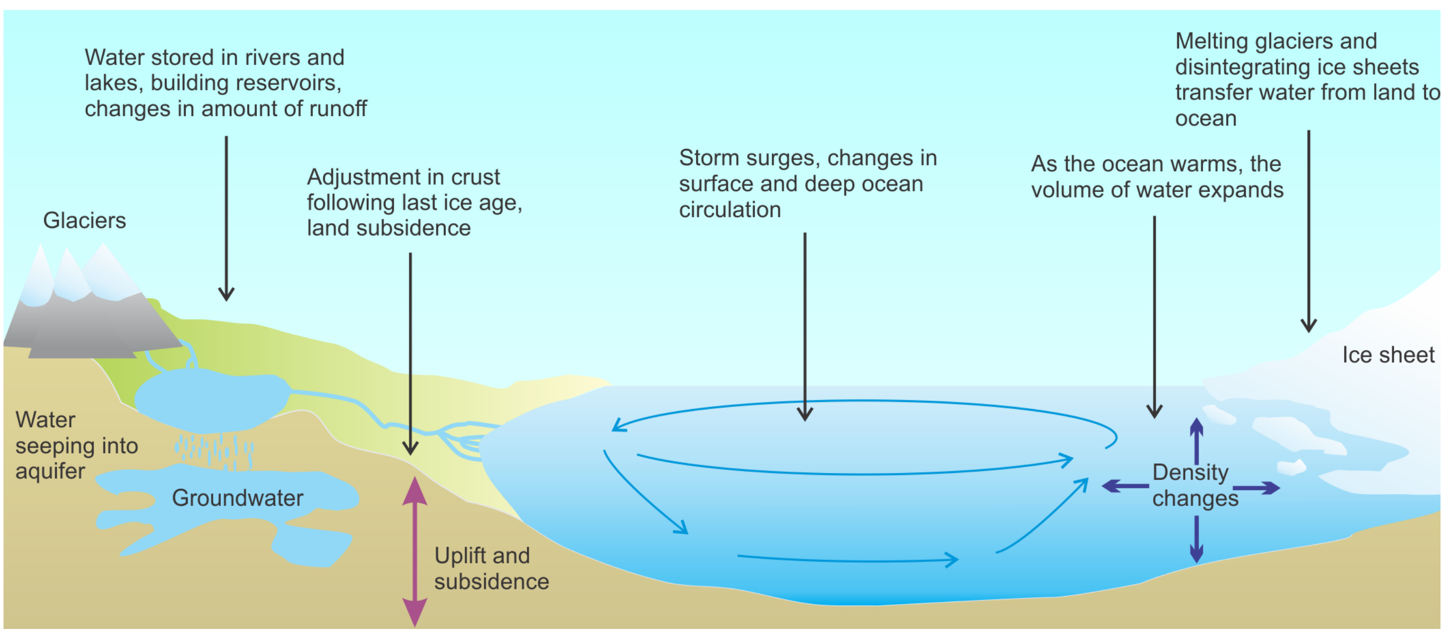
Sea-level change

Incorporating potential changes in sea level into any decision on development adjacent to the coast is critical. The risk of not doing so may be costly remedial measures or a shorter than expected lifespan of the development.

Sea-level has been changing throughout geological time, and there is no reason to believe it will not continue to change in the future. Sea-level change is discussed in more detail below. Sea-level is rising globally as a result three factors: thermal expansion of warming ocean water, glacier melting, and disintegration of the Greenland and Antarctic ice sheets. Future changes in sea level in Newfoundland and Labrador will be largely controlled these global factors, and the continuing effects of crustal movement related to the last glacial period.

The total amount of sea-level rise in our Province by 2100 is not known with 100% certainty, but over 110 cm of rise is expected for eastern parts of the Island, with 90-100 cm of rise predicted on the west coast and less than 70 cm of rise in Labrador. This rising trend could be exacerbated by partial disintegration of the West Antarctic ice sheet which could contribute an additional 65 cm of sea-level rise.

Due to the various uncertainties (particularly climate modelling) involved in predicting future changes in sea level, a range of values are commonly presented. What data to use comes down to a question of risk. For management and planning in coastal areas, where there is significant municipal infrastructure to consider, it seems prudent to err on the side of caution and go with the upper end of the likely range of sea-level rise. Where the tolerance of risk to sea level rise is very low (*e.g.*, building a significant piece of municipal infrastructure with a long-projected life span) consideration of the additional 65 cm of sea level rise from West Antarctica may be appropriate. Data on sea level rise projections by the Geological Survey of Canada can be found here and a report by the Geological Survey of Newfoundland and Labrador here.

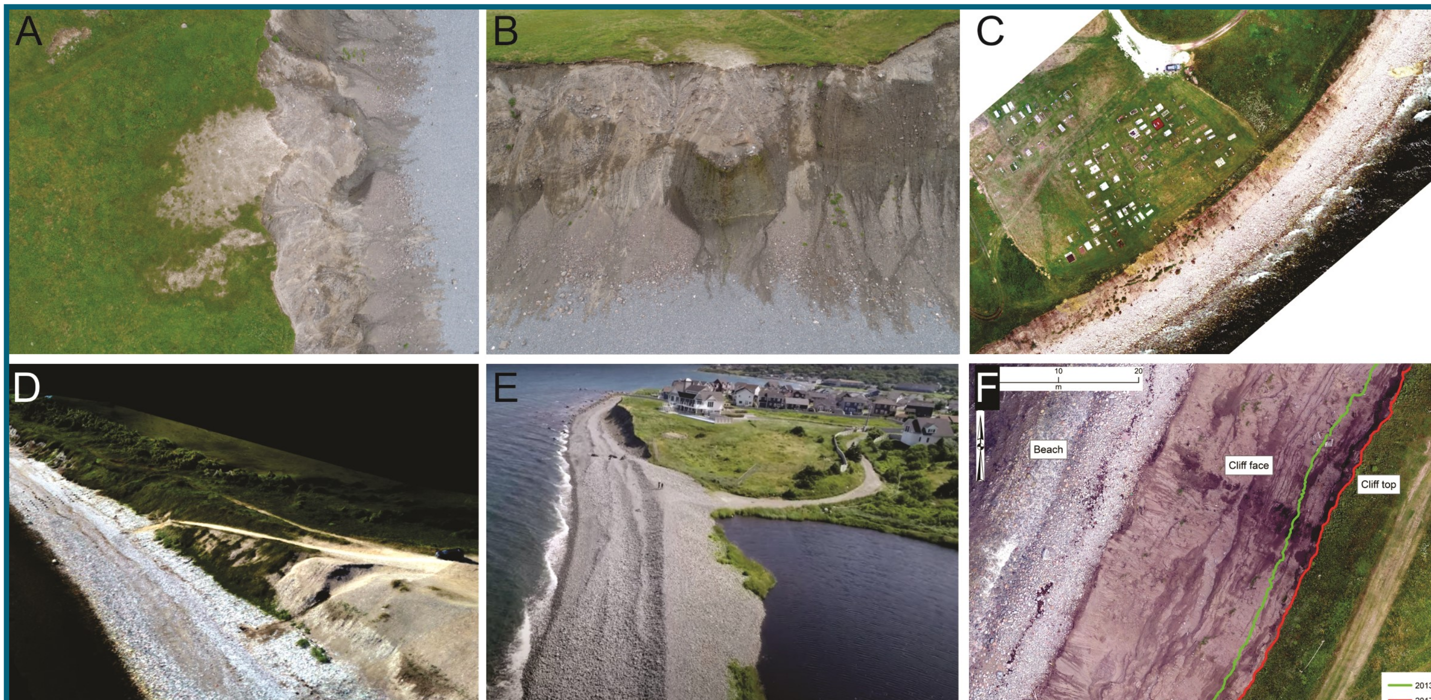


Relative sea level is the height of the water, relative to the land. It depends on both volume of water in the ocean, which varies due to processes including ice melting and thermal expansion of water, and the vertical motion of the land itself. In Canada the land is either falling or rising due to the deformation of the Earth's crust due to the last glaciation.

Observations

Projections, coastal classifications, and models of future change are important in planning for any development along the coast. However, they are no substitute for data on the rates of coastal erosion, measured in the field. The Government of Newfoundland and Labrador, in cooperation with the Geological Survey of Canada, has been conducting field research on the rates of coastal erosion for over 30 years. Currently, over 110 sites in Newfoundland and Labrador are being monitored. In recent years, surveys have used Unmanned Aerial Vehicles (UAVs) or 'drones' which have enhanced the program's effectiveness. A wide range of products are freely available from the GNL, including:

1. Photographs.Vertical and oblique images collected using the UAV or from the ground.
2. Orthophotograph. Aerial photographs 'stitched' together to produce a single photograph.
3. Models. 3D representations produced from imagery collected by UAVs.
4. Videos. Produced from the UAV flying along the coast.
5. Cliff-line positions and rates of erosion. Comparisons between ground and aerial surveys from different years to quantify the rate of coastal erosion using specialised computer software.
6. Field observations: Descriptions of coastal features.



GNL products:
A) Vertical photograph of Holyrood Pond, Avalon Peninsula.
B) Oblique photograph of the same area as A). These images were taken from the Inspire 2 drone.
C) Orthophotograph of Marches Point East, Port au Port Peninsula, from images taken in 2017.
D) 3D model of part of a cliff at Kippens, Western Newfoundland.
E) Still from a video of Conception Bay South, Avalon Peninsula.
F) View looking vertically down on the cliff at Crabbes River South, showing erosion between 2013 and 2017.

A compilation of information and data in an easy to view format from the GNL Coastal Monitoring program is linked here and data from the Geoscience Atlas can be found here. These sites are highly recommended.

Google Earth

Google Earth (click here) is a computer application that shows a 3D representation of Earth based primarily on satellite imagery. As with aerial photographs, Google Earth provides a way to visualise communities or regions, and cultural (buildings, infrastructure etc.) and natural (hills, valleys, lakes, forests, coastal etc.) features. The advantage of Google Earth is that all the images are available in one place.

In Google Earth you can zoom to your community (or anywhere else in the world) and take a look around – put Newfoundland in the middle of the map by holding down left mouse button and rotating the globe, then use the wheel on the mouse to zoom in (or out).

Google Earth has numerous tools, including:

- Elevation. The elevation of a point (wherever the mouse is) is shown on the bottom right side of the Google Earth screen. This is useful for identifying areas potentially at risk from rising sea level.
- Street View. A ground view along roads can be seen by dragging the person icon (bottom right side of Google Earth screen – select and hold icon with left mouse button) to any road coloured blue and releasing the mouse button. Move locations by clicking on the arrows. The view can be rotated by holding down the left mouse key and using the mouse. Click 'Exit Street View' to return to aerial view.
- Measurements. Measuring between points can be achieved by using the measuring tool – an icon that looks like a ruler. This is useful for calculating the 'fetch' (the distance over which waves can develop) at a site, amongst other things.

There are many other applications of Google Earth which can be explored using their tutorials.

Additional sources

Sources of information contained within this guide, and not referred to previously are:

- An overview of storm surge
- The 2018 Intergovernmental Panel on Climate Change report on Sea Level Change
- United States Geological Survey report on landslides
- Government of Newfoundland and Labrador Climate Change website

Coastal processes

Section 4

Our coast is a dynamic environment. The natural processes of deposition and erosion that form the coast have been active for thousands of years and will be for the foreseeable future. Understanding these processes is important because they impact human-related activity. Decision makers need to understand them so that communities and municipalities can maintain current infrastructure and plan for future development and growth.

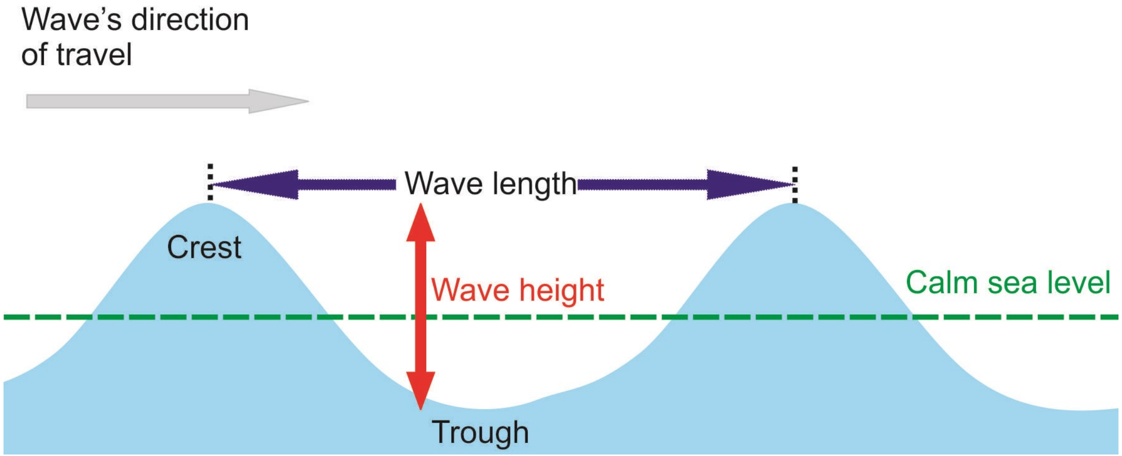
Coastal change

Coastal erosion is the movement of material from the coast by wave action, wind, surface water, groundwater, ice, gravity, human activity and other processes. Sediment eroded from the coast is deposited offshore, further along the coast or inland of the coast. Rates of coastal change have been calculated by the Government of Newfoundland and Labrador (GNL) for over 30 years, based on data from repeated surveys of the same site. Erosion rates vary from close to 0 cm per year in areas dominated by bedrock to over 100 cm per year in sand-dominated areas, with an average of about 20 cm per year. This may not seem like much, but over a 10-year period even the average rate of erosion could result in the coast moving 2 metres (m) (7 feet) landward. This might be an inconvenience to the owner of a garden or temporary structure near the cliff edge but would be a major concern if the area contained a house, road, or other critical infrastructure.

The rate of coastal change is commonly gradual, and can be driven by waves, surface water, groundwater, melting of ground ice, freeze-thaw, wind, mass movement and/or human influences. These factors are discussed in greater detail below. However, metres of coast can also be removed in a single event, due to processes including mass movement (*e.g.*, a landslide) or a storm surge.

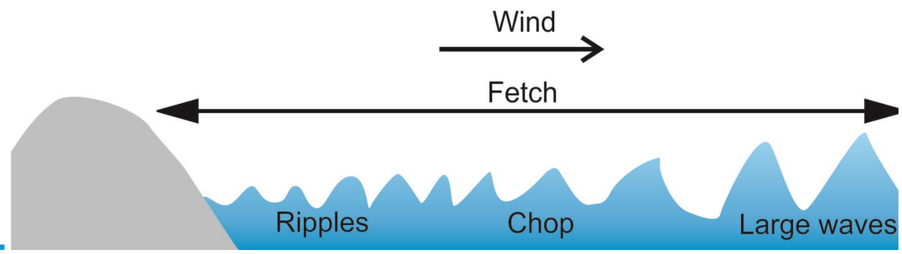
1. <u>Waves</u>

Despite appearances, waves do not move water across the ocean. Waves are created by energy passing through water, causing it to roll in a circular motion. Imagine a buoy floating on the ocean – it appears to bob forward and upward when hit by a wave, but then settles down and back in an orbital rotation as the wave continues by. Waves transmit energy, not water.



Features of a wave.

During winter months, the presence of sea ice reduces (or eliminates) the potential for surface wave development in some parts of the province. Ice can also form at the base of cliffs in the winter from a combination of groundwater seeping onto the cliff face and freezing, and from freezing sea spray. 'Shore-fast ice' (ice 'fastened' to the coast) can protect the cliffs from erosion during the winter months.



The effect of fetch on wave development.

During winter months, the presence of sea ice reduces (or eliminates) the potential for surface wave development in some parts of the province. Ice can also form at the base of cliffs in the winter from a combination of groundwater seeping onto the cliff face and freezing, and from freezing sea spray. 'Shore-fast ice' (ice 'fastened' to the coast) can protect the cliffs from erosion during the winter months.

Shore-fast ice can protect cliffs from potentially damaging waves.

The gravitational pull of the sun and moon on the earth also generates waves, known as tides. Even tidal action can be a contributing factor to coastal erosion.

Potentially dangerous waves can be produced by severe weather, such as a hurricane or other major storm – not uncommon occurrences in Newfoundland and Labrador. Strong winds and pressure from this type of severe storm produce a 'storm surge'. Globally, storm surges have led to most of the fatalities and destruction experienced during hurricanes, claiming 90% of victims, and are the primary reason residents in coastal areas are evacuated as storms approach.

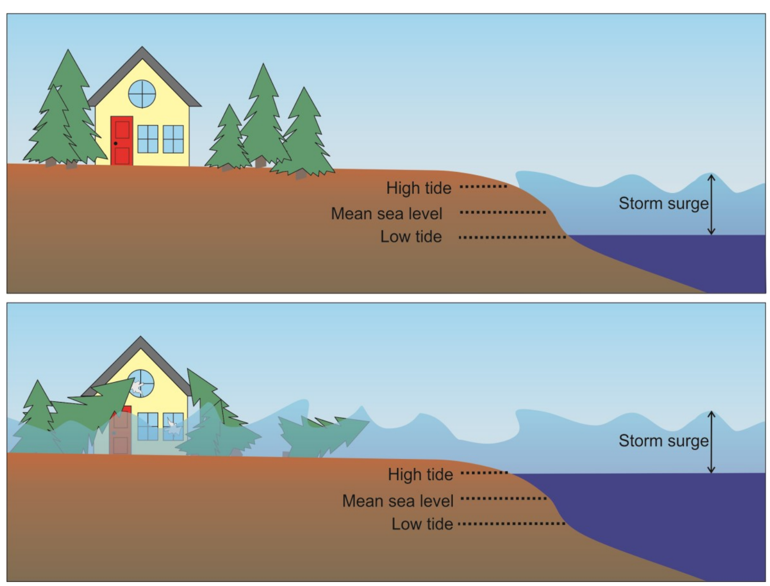


Diagram illustrating the impact of storm surge on the coast. A storm surge of the same magnitude will produce more damage on a high tide than if the same storm surge arrives on a low tide.

Some facts about storm surge:

- Storm surge is an increase in water level produced by a combination of water pushed ashore by wind around the eye of a hurricane or major storm (the biggest contribution), and the increase in surface water elevation in areas of low pressure – the water is literally lifted upwards (small contribution). Storms are typically low-pressure events.
- Storm surge generally occurs where winds are blowing onshore.
- Maximum storm surge occurs to the right of the storm track, and where the strongest winds of the hurricane or storm occur.
- Generally, the higher the hurricane's category or the stronger the wind, the higher the storm surge; and the larger the size of the hurricane, the greater area of the storm surge.
- On an open coast faster-moving hurricanes cause higher storm surges than do slower moving hurricanes, while in bays or other enclosed bodies of water higher storm surge is associated with a slower moving hurricane or storm.
- The severity of damage associated with a storm surge is commonly dependent on the tidal phase at which the surge occurs, with storm surges on a high tide, particularly a 'spring tide' being the most likely to be damaging. 'Spring tides' are higher than normal tides, which occur approximately every 14 days in conjunction with the moon's orbit around the Earth – they have nothing to do with the Spring season.
- The nearshore bathymetry (the measurement of the depth of water) is important. As the hurricane or storm reaches shallower water near the coast, the consequent vertical movement of water encounters the sea floor. The water can no longer move downwards and so can only move upwards and inland. For areas with gentle slopes offshore, storm surge may be large, but waves are small. On the other hand, areas with deep water just offshore may experience large waves, but little storm surge.
- Flooding at the coast during storm surge is often exacerbated by heavy rainfall immediately inland causing river levels to rise.
- The total change in water level during a storm surge is a combination of Storm surge, Tides, Waves and Freshwater input.

Still from a video of a storm surge in Flat Rock, Avalon Peninsula.

Other hazardous waves can be generated when underwater disturbances displace large amounts of water quickly, such as earthquakes, landslides, or volcanic eruptions. These very long-wavelength waves are called tsunamis. They are rare in Newfoundland and Labrador, but not unknown. In 1929, a tsunami hit the Burin Peninsula resulting in 28 fatalities. Storm surges and tsunamis can produce waves and local sea-level rise, which can reach far inland depending on the local topography.

As waves approach the coast their circular motion meets the seabed causing the wave height to increase and the wavelength to decrease. Because the sea floor is rough, it acts as a source of friction, causing the base of the wave to slow down and for the wave to steepen, and break. Eventually the wave height exceeds about 1.3 times the wavelength, and the wave becomes unstable forming a 'breaker'. Often breakers curl forwards as they break. This is because the bottom of the wave slows down before the top of the wave, as it is the first part to encounter the seafloor. The top of the wave gets "ahead" of the rest of the wave but has no water underneath it to support it.

Energy is released as the wave breaks producing turbulence (the surf). This turbulence churns up the material on the ocean floor. The noise of water and sediment being moved up and down a beach as even gentle waves break is evidence of this release of energy.

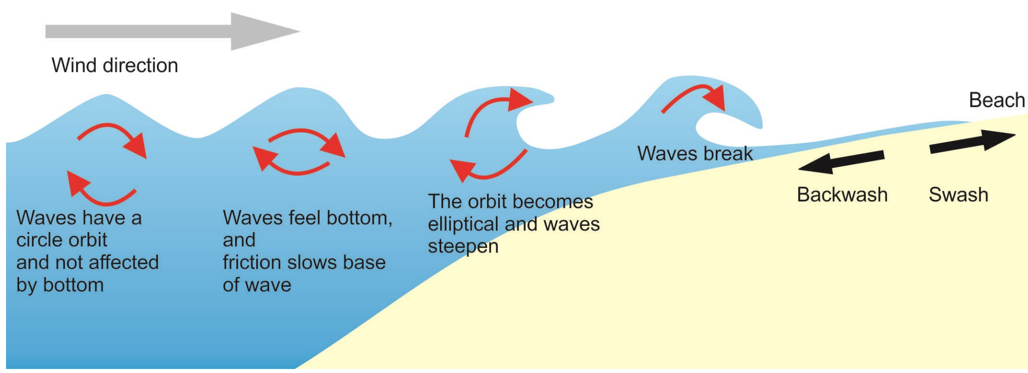
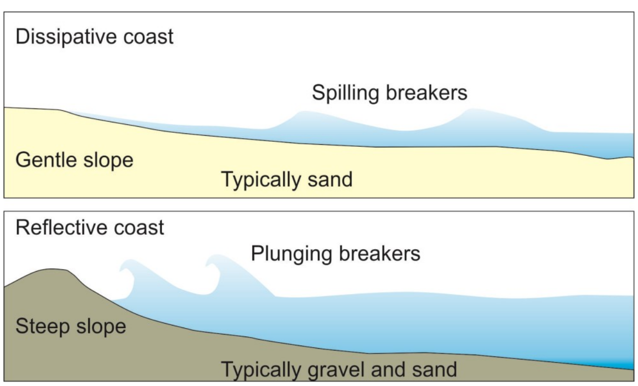


Diagram showing why waves break. The water that washes up the beach after the wave breaks is called 'swash', whereas the water that returns to the ocean is 'backwash'.

The bathymetry close to the shoreline is important. If water is shallow offshore, with a gently sloping sea bottom, waves will break further offshore and are unlikely to cause much sediment to move. Coasts with this type of bathymetry are referred to as 'dissipative' because the wave energy dissipates further offshore. Coasts in which the water is deep offshore, with a steeply sloping bottom, will cause waves to break closer to shore and more erosion is to be expected. These are referred to as 'reflective' coasts.



Coastal types common in Newfoundland and Labrador.

Coastal erosion can also occur when the energy released by a wave directly impacts a cliff face. Erosion may be from the water, under pressure, getting between grains on the cliff face (if composed of surficial sediment), forcing water into fractures or cracks in bedrock, or from the material (such as sand and cobbles) the wave picks up as it is breaking and hurls at the cliff face. However, the biggest factor in erosion of a cliff is the pressure of air trapped beneath breaking waves. When waves break against a cliff air is forced between particles or cracks in bedrock, causing erosion. The water itself exerts a pressure only slightly greater than atmospheric, but the air pressure beneath the breaker may be as much as four times that of atmospheric pressure.

2. Surface water

Rainfall and surface runoff can contribute significantly to cliff erosion. Raindrops falling onto exposed parts of the cliff can dislodge particles, and flowing water can transport them to the base of the cliff, where the particles may be subsequently removed by waves. Running water flowing onto the cliff can produce channels (rills and gullies), which subsequently become the focus for further water flow, increasing rates of erosion at these points.

Gullies on a cliff at Flat Bay, St. George's Bay. Gullies are formed by surface water flowing over the cliff.

3. Groundwater

Groundwater is water that exists underground in saturated zones beneath the land surface. The upper surface of the saturated zone is called the water table. Like surface water, groundwater will flow naturally towards the ocean. Groundwater discharge along the coast is visible as seeps, either through fractures in bedrock or at the boundary between permeable material (*e.g.*, sand) and impermeable material, such as clay or bedrock. Groundwater seeps may contribute to coastal erosion, most dramatically during winter, when groundwater seeps freeze, and physically alters the cliff face.

Groundwater seeping from a cliff at Kippens, St. George's Bay. Groundwater seepage often occurs at the contact between permeable, loose sediment above (in this case, sand and gravel) and impermeable sediment below (in this case, silt and clay).

4. Permafrost/ground ice

Permafrost is defined as ground with a temperature that remains at or below 0°C (32°F) for two or more years. In coastal areas frozen ground is resistant to erosion if ice within the ground stays frozen. When the ground warms and thaws, ice that was held within the ground can melt, resulting in erosion which can include landslides. Thawing of permafrost is a major factor in Arctic regions, and in parts of northern Labrador.

Melting permafrost on Herschel Island, Arctic Canada. Photograph by Boris Radosavljevic.

5. Freeze-thaw

Freeze-thaw erosion is a process where water percolates into cracks in rock, subsequently freezes, with the consequent expansion wedging rock fractures apart (ice takes up more space than the equivalent amount of water. This can be demonstrated by putting a bottle of water in the freezer overnight and looking at it the next morning). Rock type is critical in determining the susceptibility to erosion of bedrock slopes. Fine-grained bedrock with no joints, bedding planes, or fractures (*e.g.*, quartzite, fine-grained granite) are the most resistant to erosion, whereas bedrock with well-developed joint or fracture patterns or bedding planes (*e.g.*, shale) are the least resistant to erosion.

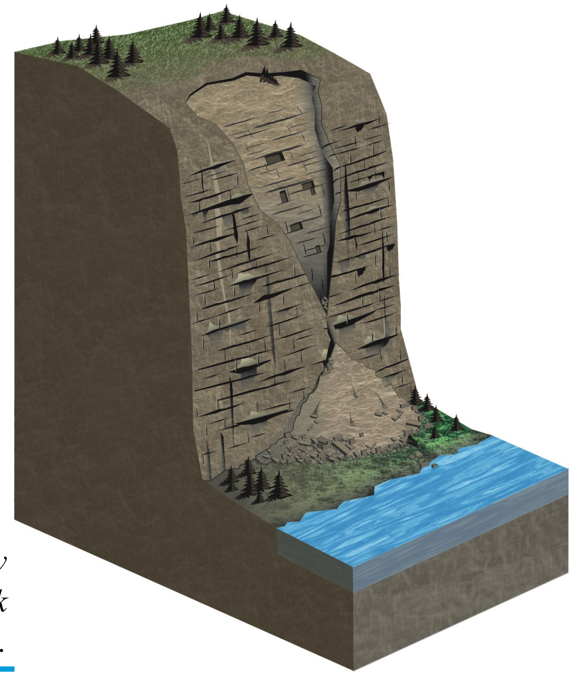


Diagram illustrating rockfall and the effect of freeze–thaw weathering on bedrock surfaces. Rock weathered from the bedrock collects at the base of the slope as talus.

6. Wind

Wind is a common process, and one which can remove material from a slope. Wind can remove small particles from beneath larger ones causing them to separate and fall. Wind erosion is especially significant in dry areas, in coastal sand dunes, and on sandy beaches. Wind can also deposit sediment when there is a drop in wind speed, which can occur as air moves over rough surfaces, such as driftwood, or when wind-blown sediment reaches the top of a slope. Wind erosion is substantially reduced if the sediment is moist or if the area is vegetated.

7. Mass movement

Weathering is the physical disintegration or chemical breakdown of soil, sediment, and rock by the processes outlined above. Mass movement is the downslope movement of weathered material, primarily by gravity.

There are a variety of terms for types of mass movement, including landslide, rockfall, debris flow, soil creep, and avalanche. All of these can occur at the coast.

Mass movements range from very slow (*e.g.*, soil creep) to rapid (*e.g.*, rockfall, debris flow). Rapid mass movements are potentially dangerous and frequently result in property damage and/or loss of life. These commonly occur on steep slopes (greater than 20°) and involve rock, soil, and/or snow. Water is commonly a critical factor, and many of these rapid mass movements occur during or immediately following heavy precipitation.

Types of mass movement may be subdivided into 3 broad categories – falls, slides, and flows. Some mass movements have components of more than one category, *e.g.*, avalanches, where a fall of either rock or snow may trigger a slide farther down the slope. Avalanches are described separately.

i. *Falls*

Falls are a rapid mass movement in which rocks of any size fall through the air or down a steep (>30°) slope. Rockfalls result from erosion along fractures (joints or bedding planes) in bedrock, commonly as a result of freeze-thaw. Rockfall may also occur because of undercutting of slopes.

Weathering of bedrock in the province is commonly by freeze-thaw, where water penetrates cracks in rock, freezes and wedges rock apart. Material commonly collects as talus (loose material) on slopes below cliff faces (arrow), such as this one in the Humber River gorge near Corner Brook.

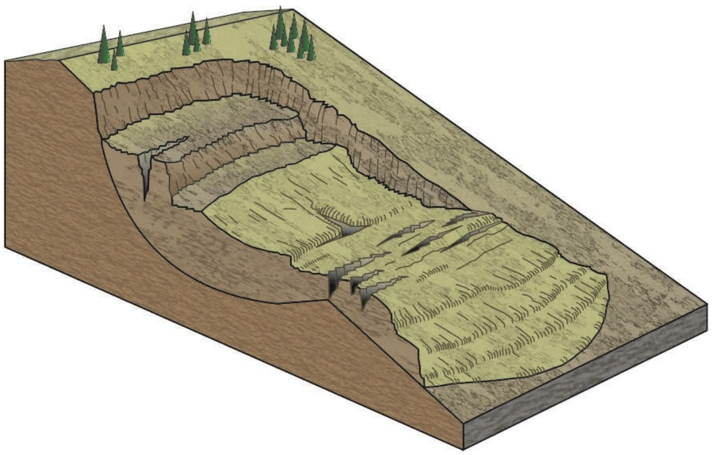
Rockfalls are common in the province, and the debris range in size from small rocks falling from a cliff, to larger falls that damage property or infrastructure. Boulders will commonly roll well beyond the base of the cliff, a factor which needs to be considered in planning infrastructure near the base of steep hills.

Rockfalls:
Left) Rockfall on the Pitts Memorial Drive, St. John's. Fractures in this area are oriented towards the road increasing the risk of rockfall (red arrow).
Right) In February 1999, a boulder detached from a slope in Upper Island Cove, bounced down the slope, through the side of a house and landed on a car causing significant damage. Fortunately, there were no injuries.

ii. *Slide*

A slide involves movement of material along a failure surface(s) and may involve bedrock or surficial sediment. This type of mass movement can be slow (over a period of weeks or years) or fast (over a period of seconds). Common types of landslide in our province are rotational slides or slumps, in which movement occurs along a curved surface.

In a rotational slide movement is characterized by the backward rotation of the slump block (away from the direction of sliding). Slides occur most often in unconsolidated material, although they can occur in bedrock. Slides are commonly caused by stream or wave erosion at the base of a slope, which removes support for the overlying material. Slope oversteepening also can be caused by human activity, such as the construction of highways and land development.



Rotational slide. Note the curved failure surface.

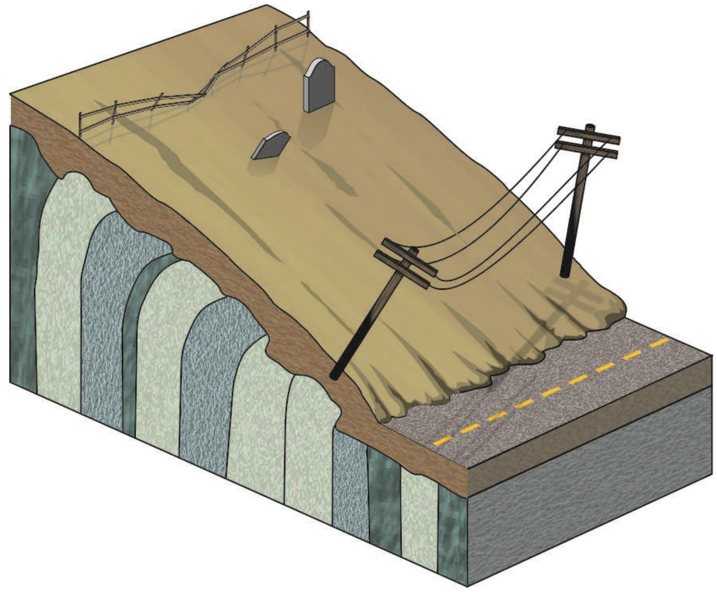
Small rotational landslide at Daniel's Harbour. The landslide resulted from coastal erosion at the base of the slope. Note that many of the trees point in towards the slope. This is the result of the rotational failure of the slope material.

iii. Flows

Flows are mass movements in which material flows as a viscous fluid. This type of movement can be slow moving (*e.g.*, soil creep) to rapid (*e.g.*, debris flows).

Soil creep is controlled by gravity and is the extremely slow (a few centimetres of movement per year) downhill movement of soil or rock. Soil creep produces the greatest effect on the landscape, both in terms of the volumes of sediment moved and the monetary cost of damage in areas where infrastructure is affected. Soil creep can result in tilted trees and poles, cracked retaining walls and foundations, and damaged streets and sidewalks.

Trees bending downslope are good evidence of soil creep on a slope.



Soil creep can have dramatic effects on structures found on or at the base of slopes.

Debris flows occur on steep slopes dominated by a thin layer of sediment overlying bedrock – a situation which describes many coastal areas in Newfoundland and Labrador. Debris flows can be extremely damaging, and develop rapidly, so there is commonly little warning of their occurrence. These flows contain up to 30% water, which allows them to travel long distances beyond their source areas. They generally occur on slopes greater than 20°, although flows on very low-angle slopes may occur, especially in areas underlain by marine clays.

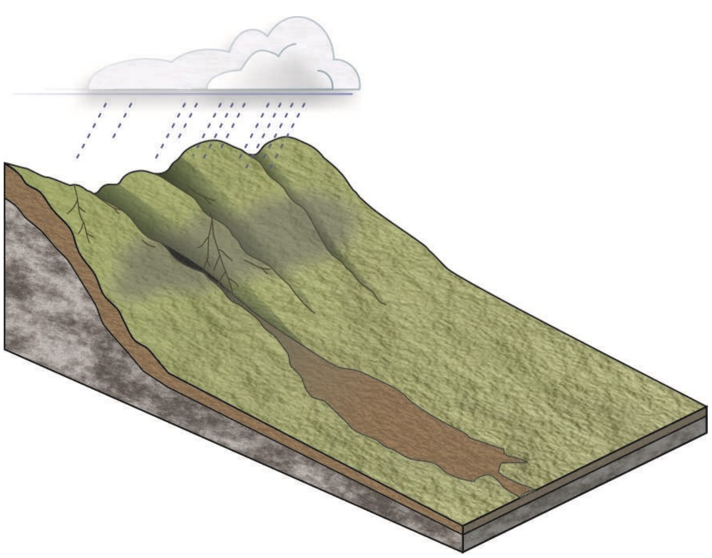


Diagram illustrating a debris flow.

Result of a debris flow at Harbour Breton in 1973 which caused the deaths of 4 children and destroyed four homes. The flow occurred at 1 a.m. with no warning. The debris flow followed a period of heavy rain saturating the thin layer of sediment overlying bedrock on the slope.

Avalanches are a rapid mass movement and consist of a combination of snow and ice, which may include sediment, rock, and vegetation. As with other mass movements, avalanches can be extremely destructive. Avalanches occur on steep slopes (30° to 50°), although they may cover gentler slopes below the start zone of the avalanche. The trigger for an avalanche is commonly heavy snowfall, deposited either by wind or direct precipitation, over a smooth surface, which may have been created by a rapid fall in temperature in the days preceding the snowfall, a period of freezing rain, or burial of a weak layer (*e.g.*, light, fluffy snow) by denser, wetter snow. Alternatively, high winds blowing over a slope may create a cornice (an overhanging edge of snow), which breaks off, falling to the slope below and triggering an avalanche. There have been 75 recorded deaths from avalanches in the province, many of which have been in coastal communities.

Damage to houses in the Battery, St. John's caused by an avalanche in 1959. The avalanche destroyed several houses and killed 5 people. Despite construction of snow fencing, an avalanche in 2020 damaged homes in the same area.

8. Human (anthropogenic) influences

Coastal erosion processes are natural and in themselves are not an issue of concern. It is when they impact people that issues occur. We also impact the rates of erosion through our activities including digging into the base of slopes, quarrying close to the coast, building on the edge of slopes, and removing vegetation from slopes.

Triggers for coastal change

1. Changes in slope angle

Generally, steeper slopes are less stable than gentler slopes. Increases in slope angle because of undercutting by wave action, stream flow, or from construction activities, increases the gravitational stress on slopes.

Waves at Sandy Cove removed sand from the base of the slope. As a result, failure of the slope above is likely .

2. Increased water content

Water may enter the slope from heavy rainfall, rain-on-snow events or from snow melt. In all instances, there is an increase in the weight of the surface sediment, and of the lubricating effect of water (water reduces the frictional forces between individual grains in sediment), both of which contribute to mass movement. Thin soils on steep slopes are particularly susceptible to mass movement, and where failure occurs in such circumstances it is commonly rapid and potentially destructive.

A debris flow down the channel in the background inundated homes in Gambo during flooding associated with Hurricane Igor in 2010. The houses were subsequently condemned, and residents relocated.

3. Loading or overloading

Loading or overloading a slope can occur not only from introducing water to the slope, but also from structures either built on the slope or near the top of the slope, or from dumping, filling, or piling up of material at the top of the slope. The additional weight created by overloading increases the water pressure within the slope material, which consequently decreases its strength. If sufficient weight is added, the slope will eventually fail

Cracking in the foundation of a shed in Gambo. The cracking has resulted from construction too close to the edge of a cliff composed of sand and gravel, leading to overloading of the slope.

4. Changes in vegetation

Vegetation is important to maintaining slope stability because of its ability to absorb or intercept water, and because roots bind soil particles together and anchor vegetation to bedrock or sediment. If vegetation is removed there is an increased risk of mass movement. On the contrary, planting vegetation may help to reduce the risk.

A landslide on a deforested steep slope in British Columbia. Similar processes occur on deforested slopes in Newfoundland and Labrador.

Planting vegetation, such as marram grass, on sand dunes reduces rates of erosion, such as at Western Brook in Gros Morne National Park .

5. Earthquakes and other factors

Earthquakes may cause a slope to fail – generally, the more unstable the slope the less the amount of shaking required. Similarly, ground shaking may be produced by volcanic eruptions, explosions or even thunder. In this Province, the frequency of earthquakes is low, there are no active volcanoes, and there is currently no triggering of avalanches using explosives.

Factors that impact susceptibility to erosion

1. Sediment type

The composition of a cliff may affect the potential rate of erosion. Different types of surficial sediment are eroded at different rates, *e.g.*, a sand-dominated cliff will erode faster than one comprising boulder-rich till. This is because sand has little internal strength and crumbles easily, whereas till is more cohesive. Also, till commonly contains boulders which, when eroded from the cliff, collect at the base of the slope providing protection for the cliff from waves. Sediment type also affects the movement of water through the cliff. If groundwater encounters an impermeable layer it will flow along its upper surface until it finds an exit. This may be on a cliff face where the exit is characterised by a seepage line. These impermeable layers are important in a cliff face because they define zones of weakness. Sediments above the impermeable layer can become saturated with water and subject to failure. This brings us to another important point:

2. Slope stability (shear strength versus shear stress)

The steepest angle that a slope can maintain without collapsing is its ‘angle of repose’. At this angle, the shear strength (the ability of a slope to resist downward movement) of the slope's material exactly counterbalances the force of gravity. For unconsolidated material (sand, gravel, till and other surficial material overlying bedrock), the angle of repose normally ranges from 25° to 40° depending on the type of sediment, moisture content, grain shape and grain angularity. Slopes are constantly adjusting to forces acting on the slope (*e.g.*, rainfall, seasonal changes in vegetation, snowmelt, and drought) and the resulting changes in the stability of the material of which the slope is composed.

Sand and gravel slope, near Kippens, western Newfoundland.

The ability of a slope to resist downward movement is defined as the 'shear strength'. The shear strength is a combination of the strength and cohesion of the material, and the amount of internal friction between sediment grains. Shear strength is controlled primarily by particle shape, voids between sediment grains, fluid content and the grain-size of the material. Water is important in contributing to shear strength. For example, dry sand poured from a bucket forms a cone and has a maximum slope angle at the angle of repose; saturated sand flows to cover a large area; but moist sand can construct structures that have vertical walls; this is because the surface tension of a film of water holds the grains together. Shear strength is increased by any external support on the slope (*e.g.*, vegetation). This is why newly constructed slopes adjacent to highways are hydroseeded or sand dunes planted with grasses; in both cases to reduce erosion.

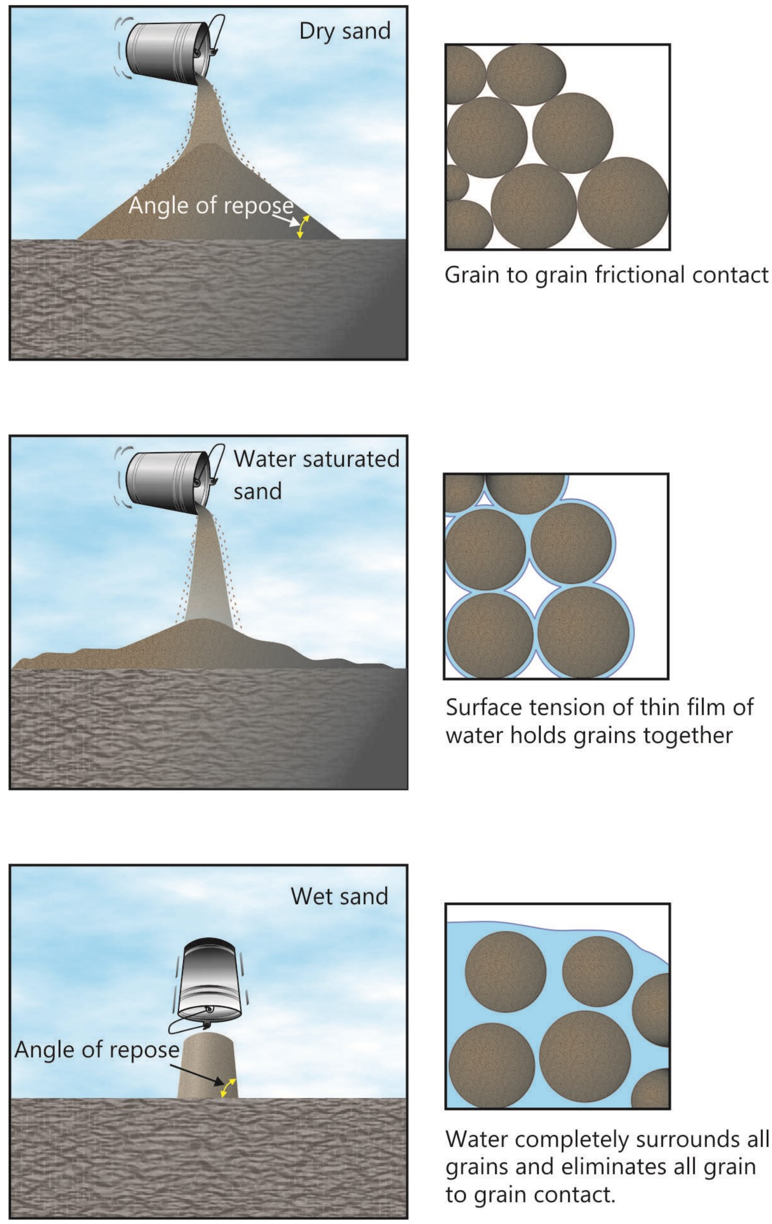


Diagram showing the effect of water on the angle of repose of sand.

Shear stress (caused by gravity) opposes a slope's shear strength and is the major force behind slope erosion. Gravity operates vertically but also influences movement parallel to slope, which causes instability. Generally, the greater a slope's angle, the greater is the chance for slope erosion. However, erosion can occur at very low slope angles, *e.g.*, within marine clay.

Sediment transport

Beaches are composed of sediment (sand, gravel, boulders) with the nature of the material being determined by wave energy (high energy coasts with pounding surf tend to produce more gravel beaches, whereas low-energy coasts with gentler waves produce more sandy beaches), and the nature of eroding cliffs (gravel-rich cliffs tend to produce gravel beaches). Seasonal variations are important, and many beaches change their characteristics during the year – steeper, more gravelly in the winter as a result of more intense storm activity and less steep, and less gravelly in the summer months.

Sediment moves along the coast through a process termed longshore drift. Wind-generated waves are controlled by the direction of the prevailing winds and by ocean currents. Waves commonly strike the coast at an angle. As the waves break, they churn up sediment which is moved onto the beach (swash). On the other hand, the backwash moves sediment back down the beach as a result of gravity, always at an angle perpendicular to the coast. The next wave moves sediment up onto the beach, and the backwash brings it down. Thus, sediment moves along the coast in a zig-zag pattern.

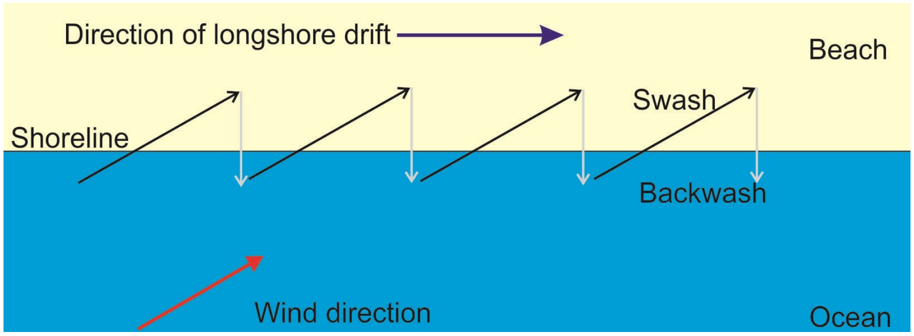
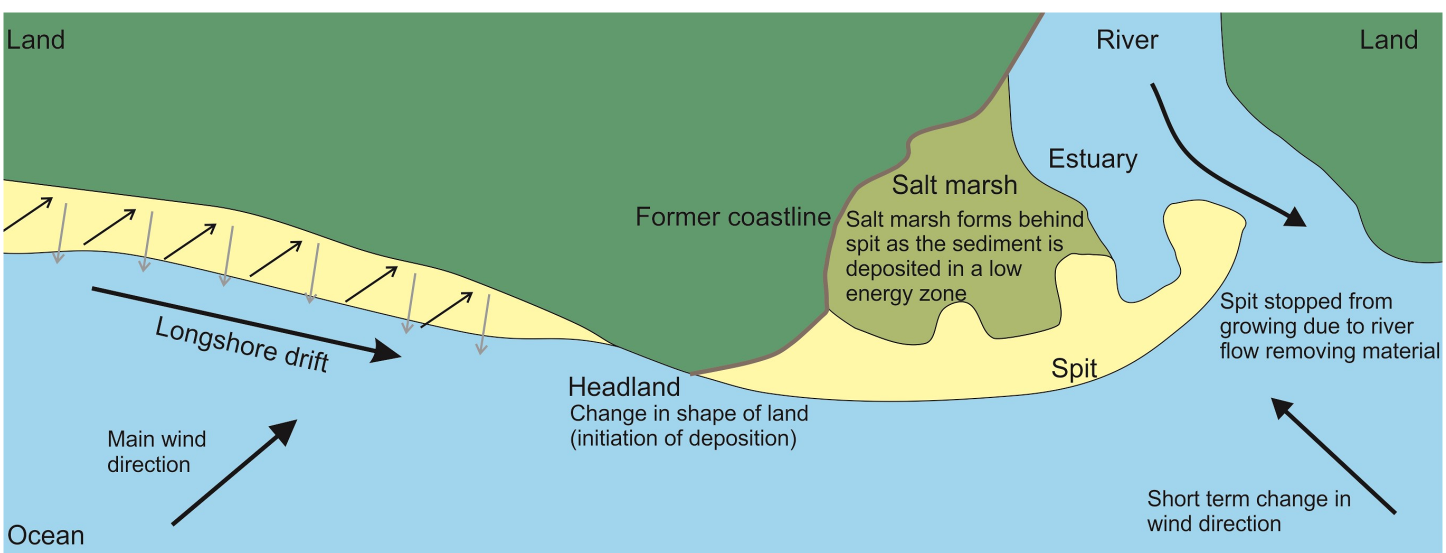


Diagram showing process of longshore drift. Waves move sediment up the beach (swash) at an angle. Water and sediment move back down the beach at an angle perpendicular to the coast (backwash). By repeating this process, sediment moves down the coast in a zig -zag pattern.

There is plenty of evidence of longshore drift , as sediment builds up behind obstructions (either man-made or natural) or from the development of spits or tombolos (a spit that connects an island to the mainland).

An example of a tombolo – a spit connecting an island to the mainland. This one is at Ferryland. Photo credit: Eric Watton.

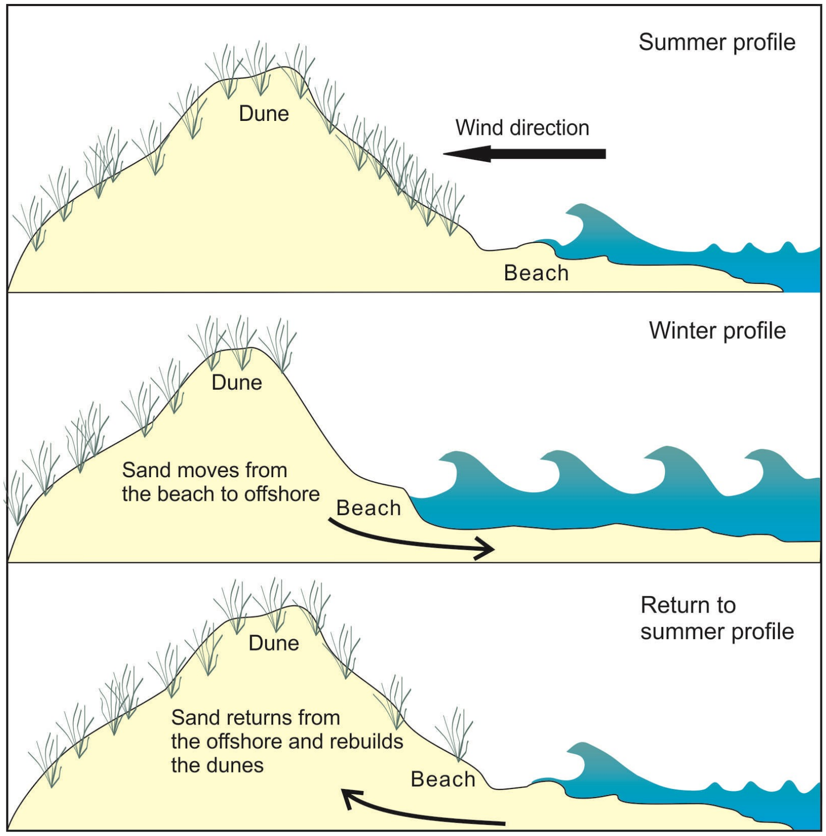
The build-up of sediment behind the wharf in Forteau is evidence of longshore drift. In this example, drift is from the top of the photograph to the bottom.



A diagram illustrating the development of a spit, produced by longshore drift.

Seasonal changes

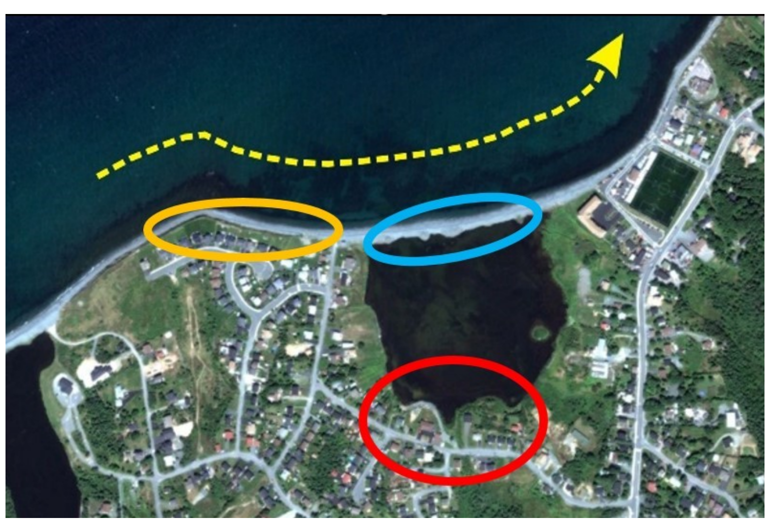
Seasonal changes to the rate at which the coast is eroded are common and are the result of changes in wave energy reaching the coast. Summer waves typically have lower energy and transport sediment onto the beach forming a gentler slope. Winter storm waves are typically higher energy, and transport sand offshore, creating a generally steeper slope and a more gravelly beach.



Seasonal changes on a coast. Over time sand dunes or beaches may migrate either landward or seaward because of coastal processes.

Coastal systems

Our coast is a product of the inter-relationship of the various processes we have already discussed. The processes of erosion, sediment transport, and sediment deposition which produce the features we find along the coast cannot be viewed in isolation. A change in one process will likely result in changes elsewhere along the coast. For example, a municipality gives permission to a resident to build a retaining wall to protect part of the cliff. This results in less sediment being eroded off the cliff at that point – and would likely be considered a success. However, the consequences are less sediment being supplied to the adjacent beach, and subsequently moved along the coast to replenish other beaches. These beaches may have protected their adjacent cliffs from wave impact, or low-lying ground from flooding. Without the beach, cliff erosion and/or coastal flooding increases. This not only damages property but could affect coastal ecosystems such as salt marshes or sand dunes. Similarly, the retaining wall now causes wave energy to be focused on the edges of the wall, enhancing erosion in these areas – and so solving one problem has produced numerous others. This is somewhat oversimplified but serves to illustrate that actions along the coast cannot be viewed in isolation, and careful consideration is required before enacting any changes.



An example of a coastal system. Material removed by erosion from the cliff (orange circle) is transported (yellow line) to the beach (blue circle). The beach protects the houses (red circle) from flooding. Changes in one part of the system could affect other parts of the same system.

Measuring Rates of Coastal Erosion in NL

Section 5

We have discussed in some detail the processes of coastal erosion and coastal change in Newfoundland and Labrador. Our coast is certainly changing, and we need to adapt to these changes, but we also need firm data on which to base decisions. The Government of Newfoundland and Labrador has been conducting research on our coast for over 30 years, initially in collaboration with the Geological Survey of Canada (GSC). Data on rates of coastal erosion, as well as photographs, videos, graphics illustrating coastal change, digital elevation models and other digital products for most parts of the province are freely available on the Government of Newfoundland and Labrador's website.

The following section will describe how data are collected, analysed, and presented. A list of sites housing coastal data is also provided.

Methods of measurement

There are several ways of measuring physical changes along the coast, particularly rates of erosion.

1. Ground photographs

Historical photos of coastal areas, when compared to the present-day, commonly show significant changes in vegetation, sediment type, land use and surface features; however, rates of erosion, if any, cannot be quantified with any accuracy.

Two photographs of Ferryland looking toward the Head, from 1954 (left) and 2013 (right). Although there are differences between the photographs it would be difficult to quantify any changes.

2. Digital aerial photogrammetry

This is a method whereby aerial photographs (photographs taken from a plane or other flying object, such as a drone) from different years of the same area are compared to calculate erosion rates. This method was used in St. George's Bay, based on aerial photographs from 1974 and 1986. This method had an error of plus or minus 2.2m, and therefore was only useful in areas with a high erosion rate.

3. Low-tech field surveys

For cliff-top erosion sites, survey pins were established 10-25 m from the cliff edge. Distances from the survey pin to the cliff edge were measured using a measuring tape along a bearing measured by a compass. Where possible other features (*e.g.*, fence posts, transmission towers, boulders, or other prominent features) were used to supplement the benchmark. At most sites at least four measurements to the cliff edge were obtained. In the case of beach sites, survey pins were placed back from the beach and profiles were measured using a simple paired-surveying (Emory) pole and tape method, along a bearing perpendicular to the beach. Profiles incorporated any features on the beach (*e.g.*, beach cusps, ridges, changes in sediment type, changes in vegetation), and extended into the water where possible. This was the common survey method at the Government of Newfoundland and Labrador prior to 2010.

Beach survey using an Emory pole.

4. High-tech field surveys

Real Time Kinematic (RTK) surveying equipment collects precise (centimetre-scale) location data. The RTK equipment comprises a stationary base receiver (the 'base station'), one or more roving receivers, and a radio link. The base station is set up over a site of known location, such as a permanent Geodetic survey benchmark. The base station is in the line-of-sight of the roving receivers. The base station continually collects satellite signals and any positional errors (*e.g.*, satellite orbit errors) are transmitted to the roving receivers allowing for the coordinates of the roving receivers to be corrected in real time. This results in precise relative and absolute location data. Depending on the site, beach profiles (surveys perpendicular to the shore), sand dunes, the cliff base and cliff top are all surveyed. Surveys using RTK equipment have been used since 2011 by the Government of Newfoundland Labrador, and since the early 1990s by the GSC.

Using an RTK roving receiver at Cheeseman Provincial Park.

Setting up RTK base station (yellow tripod) at L'Anse Amour.

5. Unmanned Aerial Vehicle

In 2015, the Government of Newfoundland and Labrador started using an unmanned aerial vehicle (UAV, also known as a drone) to collect land surface (topographic) data. The UAV allows access to many sites previously challenging to reach safely. The UAV is equipped with a digital camera and controlled by an operator on the ground; while in flight, the camera takes overlapping aerial photographs, either vertically down or at oblique angles. Ground-control points, which are markers distributed evenly throughout the study site, are surveyed using the RTK. These data are used to increase the horizontal and vertical accuracy of the drone imagery.

UAV (drone) taking photo of cliff face at oblique angle.

After completion of the flight, the data are processed to produce a digital 3D surface model as well as orthophotographs (basically, a mosaic of overlapping aerial photographs 'stitched' together to produce one large photo) and digital elevation models. The vertical and horizontal error of the surveys is plus or minus 5 cm or less.

Video of flying the UAV.

Sources of error and data inaccuracy

Nothing's perfect. Three main sources of error decrease data accuracy:

1. Instrument accuracy

Instrument accuracy for the RTK is related to errors in the satellite orbit, and atmospheric interference. These errors are generally plus or minus 1 cm. For images collected from the UAV, data accuracy is plus or minus 2 cm.

Image of a satellite. Similar ones are used in RTK surveys.

2. Measurement error

The estimated human error of the survey data collected by RTK surveys is +/- 10 cm. Inaccuracy is due to the RTK rover pole not being consistently vertical in strong winds, and to uncertain definition and measurement of the cliff edge in areas where the edge is not well defined.

Holding the Rover pole vertical in strong winds can be a challenge. The photograph also illustrates the difficulty in accurately defining the cliff edge.

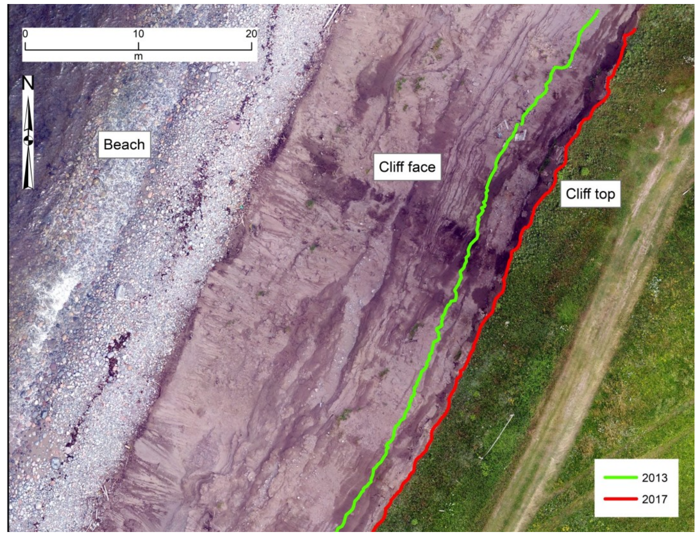
3. Short-term noise

Using short-term data (less than 5 years) can result in the over- or under-estimation of long-term rates of erosion (*e.g.*, it is quite possible that during a five-year period there were fewer (or more) storms than normal). In general, the longer the time the better, but preferably at least ten years of data are required for reliable estimates of coastal change. The effect of these sources of error will decrease over time when the amount of coastal change exceeds the amount of error associated with the surveys, highlighting the importance of long-term data.

Long-term records are important for determining erosion rates. A single event, such as a severe storm, can change the coast for years. Two photos of the CBS coast, from 2014 (left) and 2020 (right). In early 2020, waves from a storm removed a large quantity of sediment from the base of the cliff, resulting in significant coastal change. Note the boulder on the beach in 2020, which was in the cliff in 2014.

Quantifying erosion rates

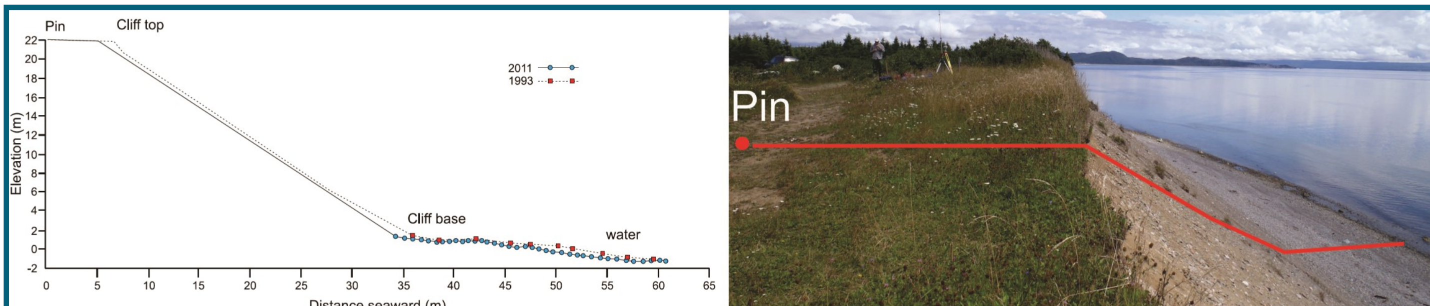
Comparisons between ground or aerial surveys from different years are used to quantify the rate of coastal erosion. These comparisons require the use of specialised computer software. Details of this process can be found [here.]



View looking vertically down on the cliff at Crabbes River South. The top of the cliff was surveyed by RTK and drone methods multiple times, including in 2013 (shown by the green line on the photo) and in 2017 (shown by the red line). By measuring the distance between the location of the clifftop in 2013 and 2017 and dividing this distance by four (years between surveys), we can calculate the average yearly rate of erosion along the clifftop.

Changes in beach profiles

Profile graphs (plotting elevation change against distance perpendicular to the beach) between the survey benchmark and the ocean are generated. To show changes in beach profiles, profiles for different years are overlain on each other. In this way, migration of beach crests or changes in sediment accumulation (or loss) can be determined.



Cliff and beach profiles from Kippens. Data from different years are overlain on each other to show changes in the profile. In this example, the clifftop (green dots) and cliff base (continuous line) are both moving landwards.

Final thoughts

Does all this mean we should not develop along the coast and all head inland? Obviously not, but we need to be prepared for a future along our coast which will be impacted by rising sea level and a changing climate. We need to develop with these factors in mind.

Hopefully, this guide has provided some additional resources and enhanced your personal knowledge of the physical processes acting along our coast. The future sustainability of our coast and our coastal communities is up to us.