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Impacts of Four Storms in December 2010 on the Eastern Shore of Nova Scotia

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Abstract

A series of intense low pressure systems struck the Atlantic Maritime Provinces during each week in December 2010. Record storm surges during December 21 and 27 most impacted the shores of Cape Breton Island and southern Gulf of St. Lawrence. Impacts along the coastal highlands of Cape Breton Island were compounded by high river discharge and slope instability caused by heavy rainfall during the December 14 and 21 events.

Detailed observations and repetitive surveys of physical impacts to specific shore types from the December 2010 storms were limited to shores east of Halifax, Nova Scotia. The rapid succession of storms prohibited shoreline recovery and resulted in net shoreline retreat. Cumulative impacts of the storms included: an upper beach and backshore dune retreat of 7 to 9 m along sand and mixed-sediment barrier beaches; a beach crest retreat of 2 to 4 m across high and low gravel barriers respectively; and a cliff top erosion of 1 to 1.8 m (between September 2010 and March 6, 2011) which was 4 to 7 times the average annual rate compiled between 1986 and 2009. Despite accelerated shore erosion caused by these storms, longer term evolutionary trends observed at select shores were only slightly altered.

Longshore variations of storm impacts on specific beaches were a function of antecedent shore conditions. (a) At Miseners-Long Beach, representative of a high gravel barrier, increased changes across the upper beach and backshore signal future increased beach mobility, instability and a shift toward a low gravel barrier beach. (b) At Cow Bay Beach, representative of a low gravel barrier, the loss of small segments of high, narrow barrier, and the initiation of a new tidal channel signal continued rapid beach migration into Cow Bay Lake. (c) At Lawrencetown Beach, representative of a mixed sediment barrier, variable changes along the backshore revealed different longer term responses. To the east sediment deposition into backshore craters is depleting shoreface sand reserves and accelerating the breakdown of adjoining foredunes. To the west the movement of large quantities of coarse clasts to the upper beach imply it is evolving toward a high gravel barrier similar to Miseners-Long Beach. (d) At Conrads Beach, representative of a sand barrier, contrasting beach responses were recorded east and west of Fox Point. To the east, a maximum foredune retreat of 9.1 m was caused by repeated wave attack. To the west the foredune was cut back, however the change only represented a temporary interruption in a recent phase of foredune progradation since a tidal inlet was closed in the late 1980s.

Front Cover: Repetitive surveys of Lawrencetown Beach N.S revealed the sequence of changes caused by the four storms. In the first storm, upper beach and dune erosion of 1.7 m was followed during the next storms by localized dune scouring and the final storm transported coarse sediment upslope infilling much of the dune cut or infilling the adjoining low backshore areas dug during past commercial sediment excavation activities (photo January 20, 2011- P1209213).

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Introduction

A series of four intense low pressure systems struck the maritime provinces during December 2010. Variations in climatic and marine conditions during the four storms confirmed storm surges are the primary marine hazard in the Gulf of St Lawrence. Along coastal areas fringing the highlands of Cape Breton Island the impacts of storm surges are compounded by high river discharge and slope instability caused by heavy rainfall. Total rainfall for the month of December 2010 at Sydney NS was 429.9mm. (Daily Observation Data, Environment Canada).

Detailed observations of the physical impacts of the four storms are limited to shores east of Halifax, Nova Scotia. Attention is focused on the magnitude of physical responses along five shore types to the varying storm conditions and how antecedent shore conditions influenced the immediate and longer term response along and between each shore type from this quick succession of storms.

December 6-7 was a wind and high water event; 40,000 customers lost power in Nova Scotia and New Brunswick; the Halifax -Dartmouth Ferry was cancelled and waves damaged shores along northern New Brunswick. Maximum wind gusts of 126 km/hr were recorded at McNabs Island, Halifax Harbour, NS, 109 km/hr at North Point, PEI and 83 km/hr at Miscou Island, NB.

December 6th

Dalhousie NB. Winds, waves and high water levels impacted northern New Brunswick. Parts of Route 134 were closed and more than 20 homes were evacuated. Shown are waves breaking against a seawall at Inch Park. Telegraph Journal, 7 Dec. 2010.

Dec. 6, 2010, Bill Clarke/ Canadaeast News Service.

December 13-15 was an intense wind and rain event especially on Cape Breton Island. 173 mm of rain fell in Sydney NS and wind gusts reached 124 km/hr at Grand Etang NS and 106 km/hr at McNabs Island, Halifax Harbour, NS

December 14th

Margaree Valley, N. S. Les Suetes winds of up to 100 km/hr and heavy rainfall (173 mm in Sydney, 194 mm at North Highlands Museum, Cape North) on Dec. 14 and 15 closed many roads in northern Cape Breton Island because of mud slides, flooding and washed out bridges such as the Margaree bridge shown.

Dec. 15, 2010, The Cape Breton Post; Deidre Fraser (Cape North) Bill Danielson (Smelt Brook).

December 21-23, a major storm surge along Gulf of St. Lawrence shores resulted in significant shoreline erosion, road and bridge closures and damage to coastal infrastructure e.g. Gabarus, Louisbourg and Dominion Beach, NS. At Malpeque, PEI the fish plant was flooded by 1 m (first time since opened in 1934). Strong winds and heavy rain washed out roads and bridges on northern Cape Breton Island: 120 mm of rain fell at Ingonish Beach and North Mt. NS. The wave rider buoy off Halifax Harbour stopped transmitting data mid day on Dec.21. as significant wave heights were decreasing from 5.1 m to 4 m.

December 21st

West Point PEI, Much of the PEI coastline was impacted by the Dec. 21 storm surge. Dunes that sheltered West Light from the ocean were swept away and offices were water damaged. Along the north shore Parks Canada reported 10 feet of dune erosion along Brackley Beach and the lighthouse at Beach Point on southeast PEI was knocked off its foundation.

23 Dec. 2010 CBC News

December 21st Con't

Irving Eco-Centre, Bouctouche, NB, After two days of high winds and water levels large sections of the boardwalk, on Bouctouche spit were ripped out and strewn along highway Route 475.
23 Dec. 2010, Moncton Times & Transcript (Photo D. Bérubé , NB DNR)

Pointe-du-Chene, southeast N.B., Example of coastal flooding at a residence. The wharf at Shediac NB was also severely damaged by waves during the Dec 21 storm.
23 Dec. 2010 CBC News , Moncton, NB (photo Denis, Pointe-du-Chene)

Big Island N.S.,
Road crews were busy trying to repair a section of highway that was washed out in the Dec. 21 storm surge. The road links Big Island to the mainland along Northumberland Strait, NS. Roads to Sinclair and Caribou Islands were also closed during the storm.
22 Dec. 2010, Ray Burns ,
The News, New Glasgow NS.

December 21st Con't

Louisbourg, N.S.
Wave slamming against the quay wall at Fortress Louisbourg caused localized flooding within the fortress.

22 Dec. 2010 Rebecca Duggan, Parks Canada

Cole Harbour/ Rainbow Haven N. S.
Low areas along Eastern Shore NS were flooded multiple times in December 2010. Flood level at a residence on Dec. 21 (shown) was not as high as on Dec. 6 (red line) when water levels 0.73 m higher were recorded in Halifax.

21 Dec. 2010 Bob Taylor, GSCA

December 27-28, created severe blizzard conditions in New England; strong winds 152 km/hr in CBI highlands and record water level conditions occurred along the Gulf of St Lawrence (surge of 1.47 m at Escuminac NB). Notable snow or rain fell in the three Maritime Provinces and 45,500 customers lost electricity.

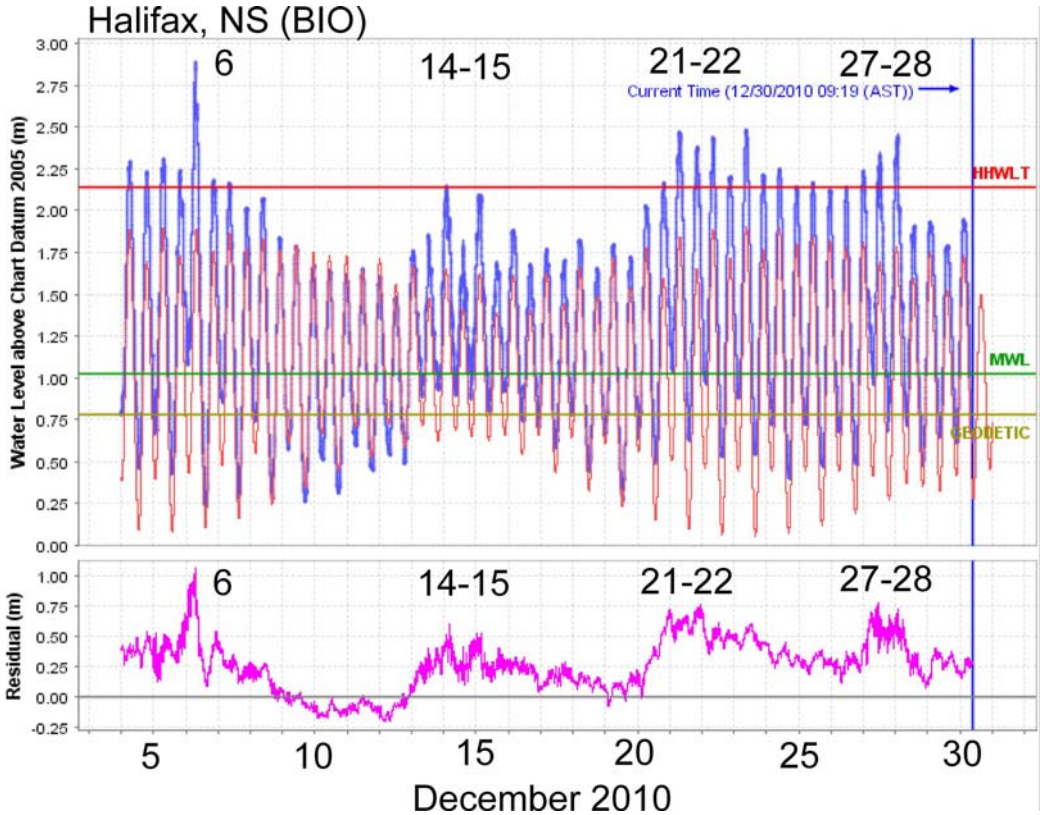
Gabarus N. S., The seawall protecting the town was severely twisted as parts of the wall collapsed seaward because of wave scouring and other parts were pushed landward as the beach built higher against it. By March 2011 when this photo was taken the beach had partially rebuilt against the seawall.

Acknowledgements

We thank many local residents for continued support and observations that contribute to our understanding of the impact of storms to our coastlines. Photographs for this report were contributed by Henk and Elizabeth Kwindt, Deidre Fraser, Bill Danielson and Rebecca Duggan (Parks Canada) while photos from the Gulf of St Lawrence shores were obtained from webpages of several local newspapers and Dominique Bérubé, New Brunswick Department of Natural Resources. Tide gauge records were courtesy of the Canadian Hydrographic Service, Department of Fisheries and Oceans and wave records were from buoy 44258 maintained by the weather office, Environment Canada. We thank Daniele St Louis for her assistance with field surveys and John Shaw (Geological Survey of Canada) for his review and comments on an earlier draft of this manuscript.

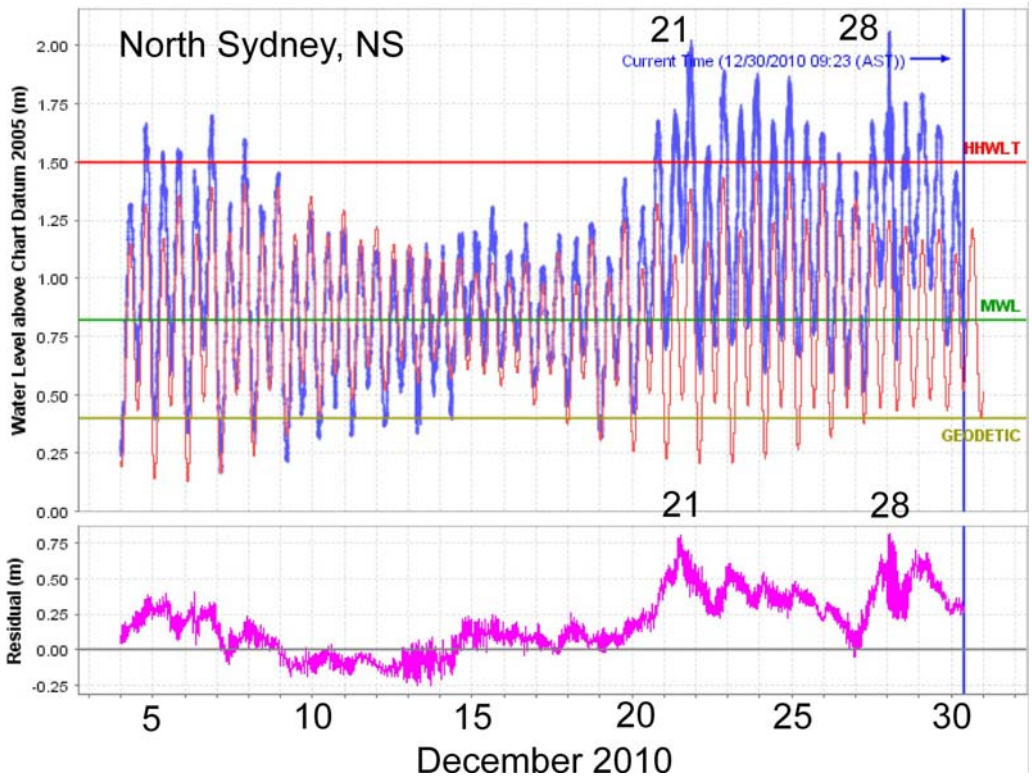
Oceanographic and Meteorological Conditions

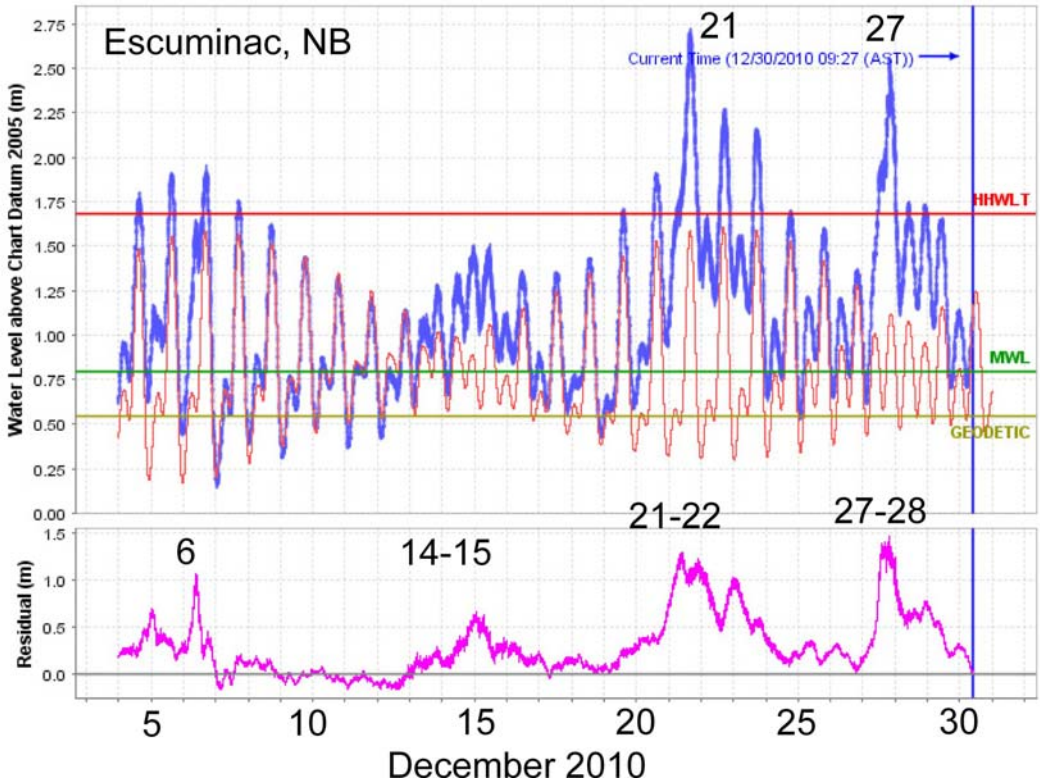
Tide gauge records from Halifax, North Sydney, NS and Escuminac, NB, 2010 illustrate variations in the magnitude of storm surges (residuals) and total water levels (chart datum) observed in the region December 4-30, 2010. Storms on the 6th, and 21st and 27th occurred closer to spring tides while the December 14th storm was at neap tide. In Halifax highest water levels on December 6 caused the greatest flooding whereas on December 27 low water levels combined with higher waves caused the greatest physical coastal impacts. Higher water level (Escuminac) and waves impacted NE New Brunswick on December 6 but it was the large storm surges during December 21 and 27 that most impacted the shores of Cape Breton Island (North Sydney) and the southern Gulf of St Lawrence (Charts courtesy of Canadian Hydrographic Service).



Halifax (BIO) N.S.: Maximum storm surge corresponded closely with the predicted highest daily high tide on December 6th but on the 21st and 27th it was closer to the lower predicted daily high tide. The longest duration (7.5 hrs) of surge conditions (>0.6 m predicted) was associated with the December 21 event. The largest storm surge, the fourth highest on record, was 1.04 m on December 6 which produced a maximum water level of 2.86 m (chart datum). For comparison, the maximum storm surge recorded at Halifax was 1.5 m producing a water level of 2.90 m (chart datum) during Hurricane Juan on 28 September 2003.

North Sydney N.S.: Maximum water level recorded in December was 2.04 m at 01:30 AST, December 28, 2010 (surge=0.80 m). Higher than normal water levels were recorded from December 21-24. Fortunately, during the storm of December 21 the maximum surge of 0.77 m occurred close to low tide. Maximum water level ever recorded at North Sydney was 2.3 m on 5 Feb. 1974 (CHS, 2011).



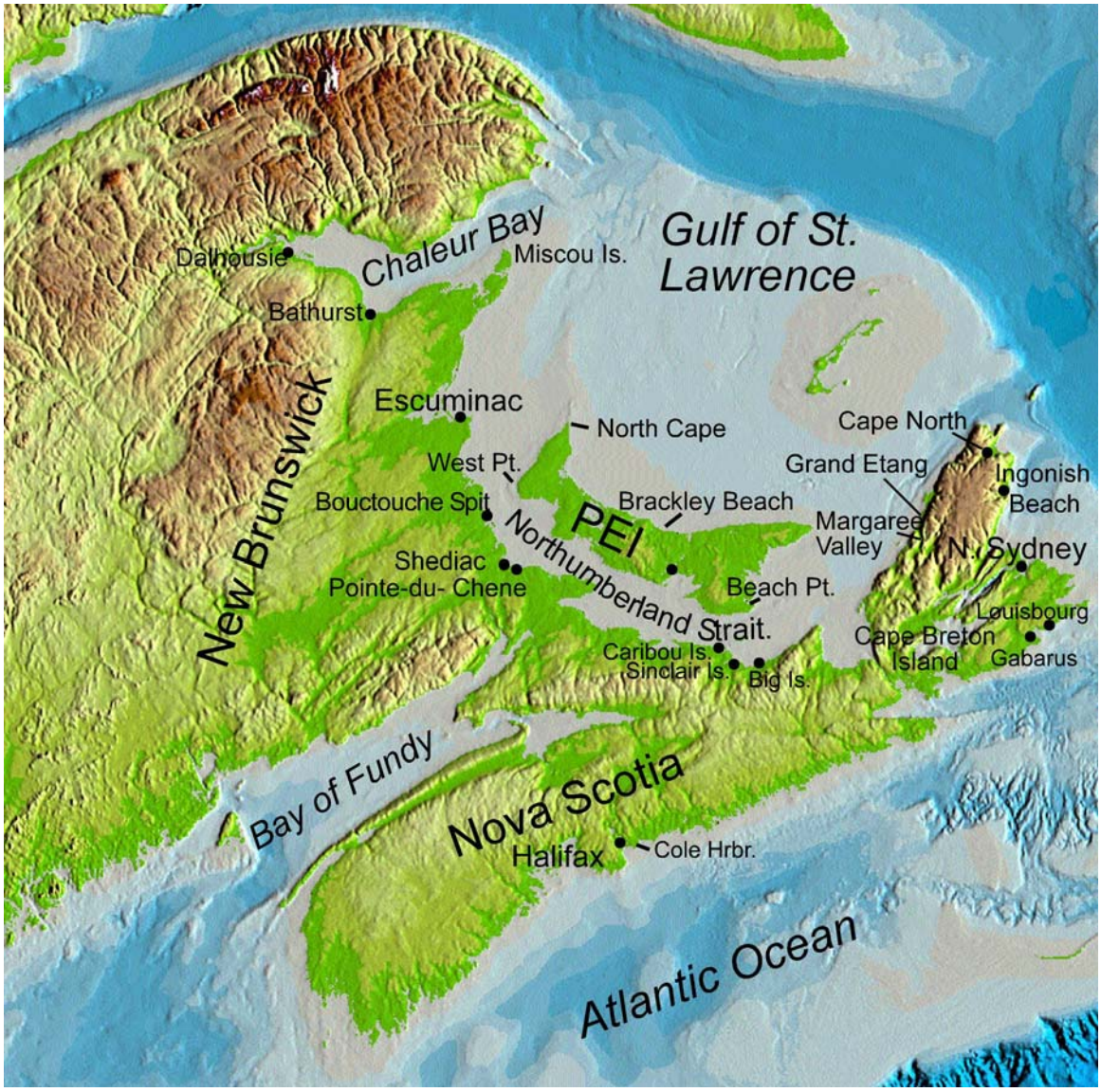


Escuminac, N.B., Record water levels of 2.72 m and 2.56 m were recorded on December 21 and 27, respectively. Maximum storm surge was 1.47 m on December 27th. Storm surges on December 21 and 27 caused the greatest coastal impacts because they occurred close to high tide, whereas the surge (1.05 m) on December 6th occurred closer to low tide. Maximum water level recorded at Escuminac before 2010 was 2.4 m (CHS, 2011).

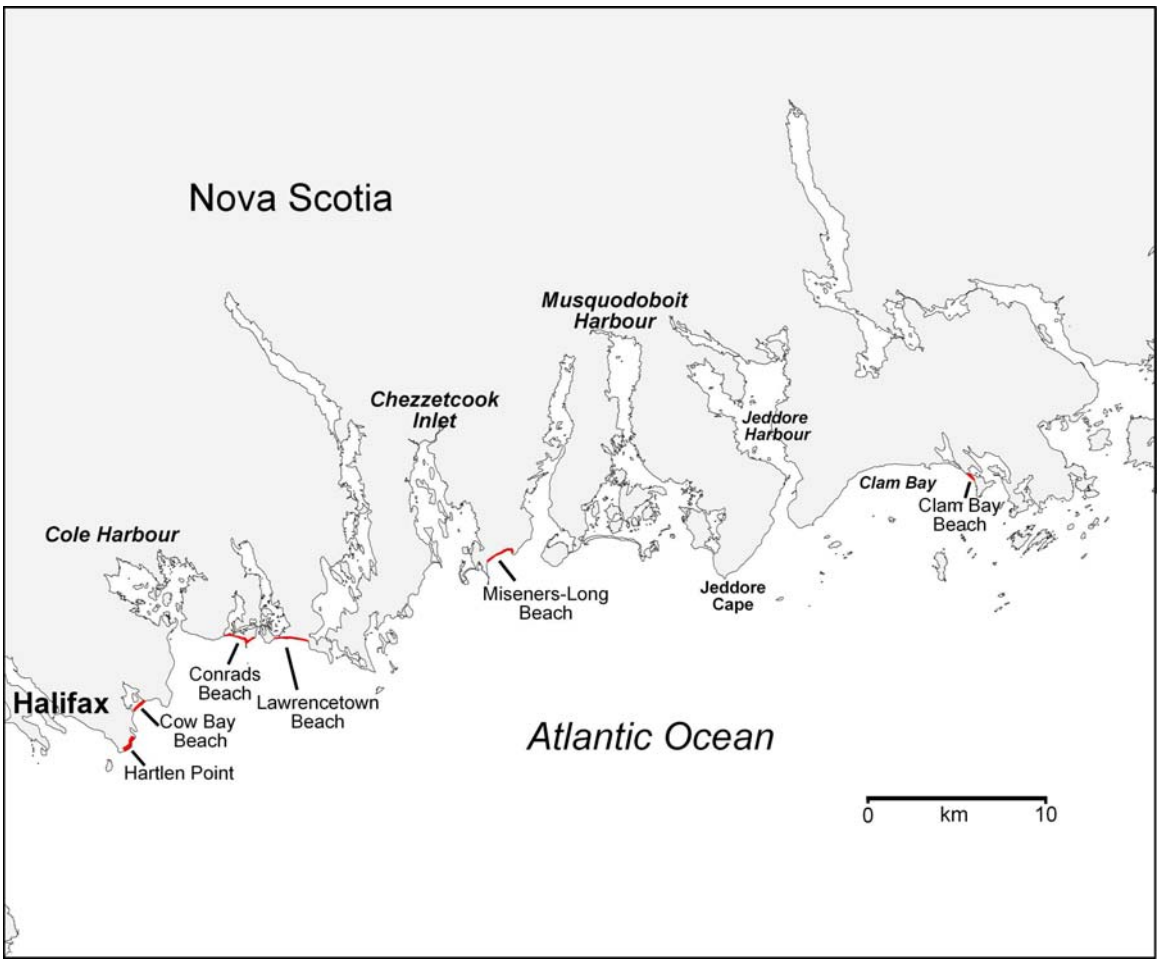
Table 1. Water level and wave conditions recorded near Halifax NS during the four December storms. Sea level was from tide gauge at BIO, Dartmouth (Courtesy of CHS-DFO Canada); waves spectrum from buoy CC44258 located in 58 m water depth off Halifax Harbour (Courtesy DFO and EC Canada); and barometric pressure and wind data from Halifax (Stanfield) International airport.

Date December 2010	***Max. Sea Level (CD)***	***Max. Sig. Wave Ht (m)***	***Peak Wave Height (m)***	***Peak Wave Period (Sec)***	***Barometric Pressure (kPa)***	***Max. Wind Speed (km/h)***	***Wind Dir. (deg)***
5-6	2.86	7.9	16.6	11.6	95.02	69	150
13-14	2.13	8.5	14.9	15.1	96.99	70	140
21-23	2.47	5.1	10.2	12.8	96.82	52	10
27-28	2.42	no data			94.83	46	310

Place Names


Gulf of St. Lawrence
Chaleur Bay
Dalhousie
Miscou Is.
Bathurst
New Brunswick
Escuminac
North Cape
West Pt.
Bouctouche Spit
Brackley Beach
PEI
Northumberland Strait.
Shediac
Pointe-du- Chene
Beach Pt.
Cape North
Grand Etang
Ingonish Beach
Margaree Valley
N. Sydney
Louisbourg
Cape Breton Island
Gabarus
Caribou Is.
Sinclair Is.
Big Is.
Bay of Fundy
Nova Scotia
Halifax
Cole Hrbr.
Atlantic Ocean

Study Sites on Eastern Shore, Nova Scotia



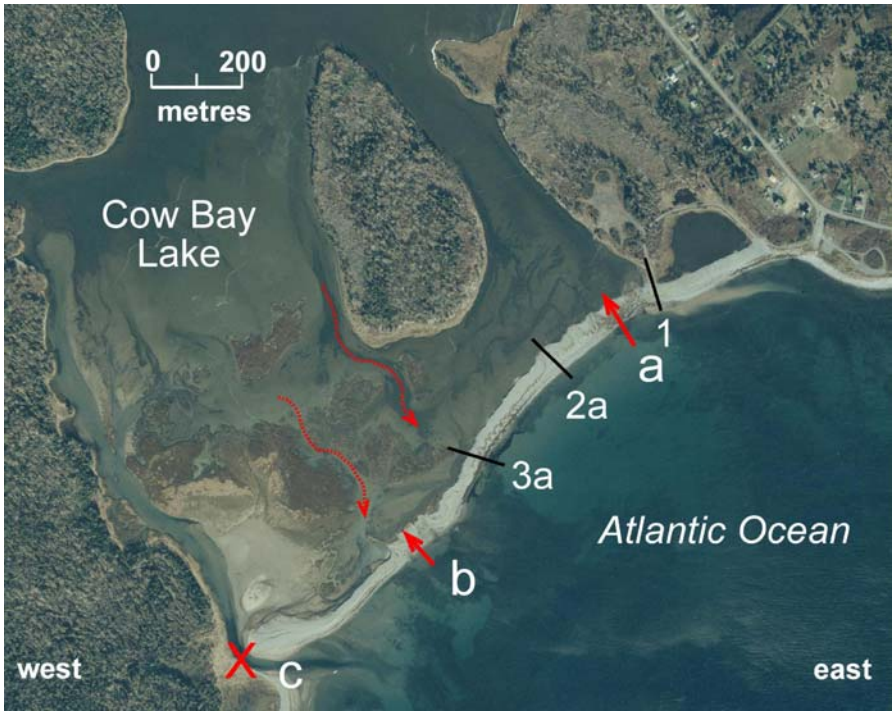
Eastern Shore Nova Scotia: Repetitive shore surveys were completed to assess the impacts of the December 2010 storms at the five western sites marked in red. At Clam Bay Beach, the most eastern site, only repetitive photographs were taken of changes.

Eastern Shore, Nova Scotia

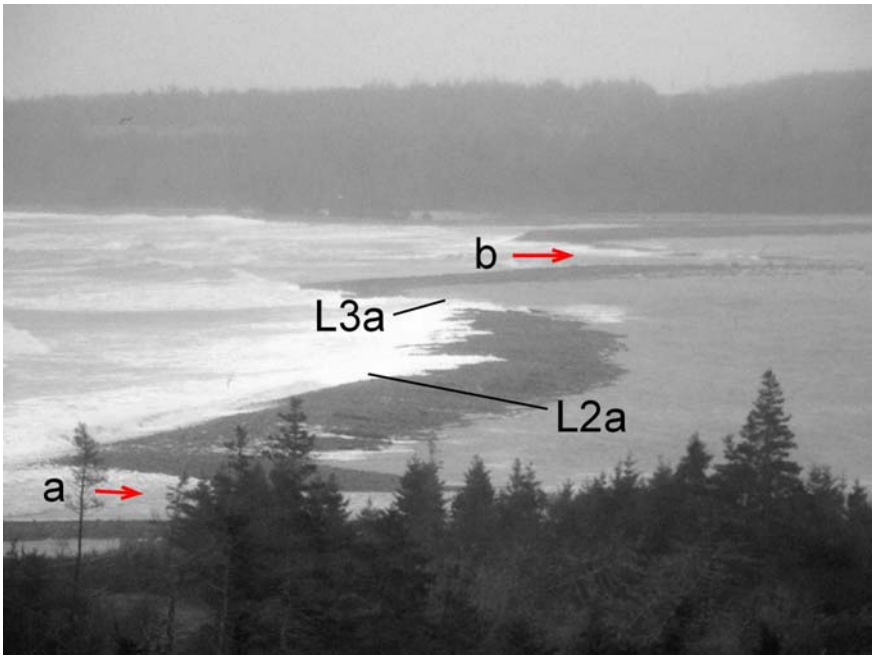
Hartlen Point Shore Cliff

Hartlen Point south: Increased exposure to waves during the December 2010 storms resulted in erosion rates of 4 to 7 times the average annual rate compiled over 23 years from 1986-2009. Cliff top retreat at Hartlen Point south was 1 to 1.8 m between September 2010 and March 6, 2011. Actual retreat is anticipated to be greater in many places because frozen sod drapes (shown in photo) extended as much as a 1.5 m seaward along the cliff top edge in March 2011. (photo P3069320, 6 March 2011).

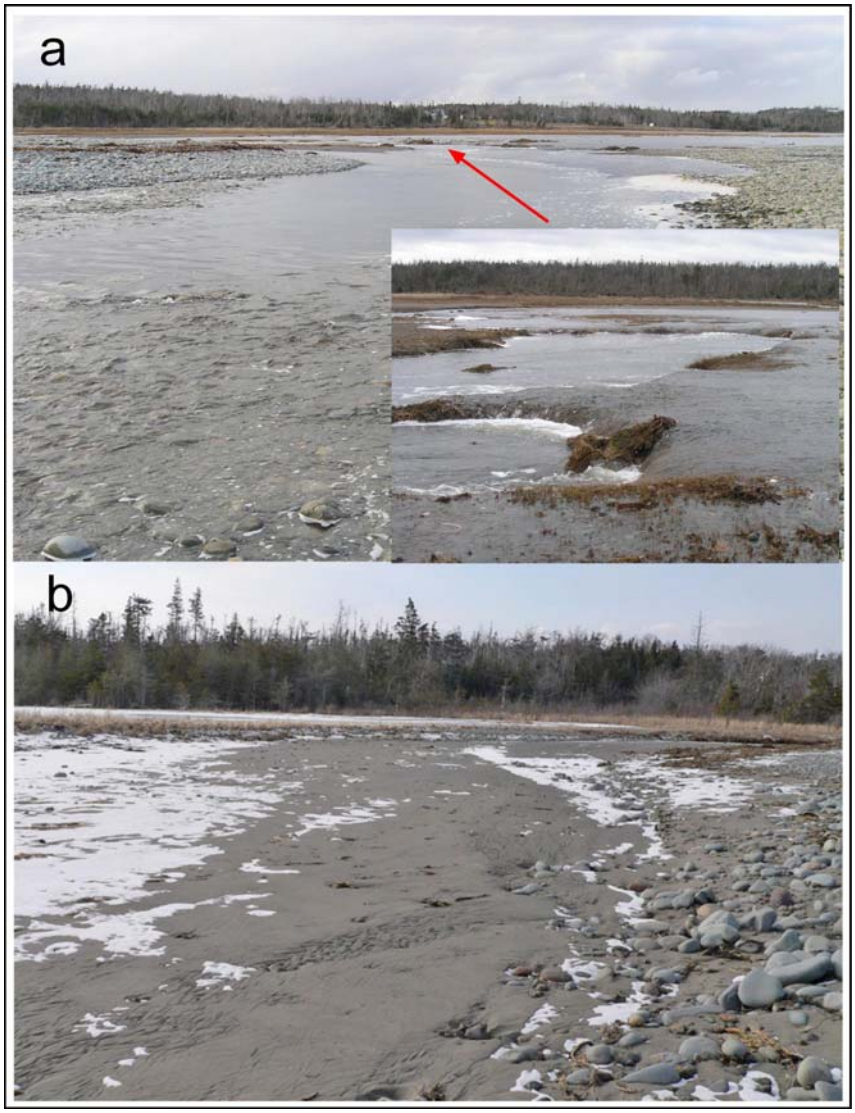
Cow Bay Beach Low Gravel barrier beach



Cow Bay Beach, location of cross-shore survey lines 1, 2a and 3a, two major washover channels "a and b" (red arrows) and the outlet from Cow Bay Lake at "c" locally known as "the run". Impacts of the December 2010 storms included outlet switching from "c" to "b", landward barrier beach migration near L3a and beach crest building at and east of Line 1. Dotted lines show active lake outlet flow channels leading to channel "b".



Cow Bay Beach, view just after high tide on the morning of December 21 showing the extent of wave overwash. Waves were pushing the beach landward near L3a and flowing through channels a and b. Water level on December 21 was 0.4 m less than on December 6 but higher than on December 14 and 27 (photo H. Kwindt, local resident).

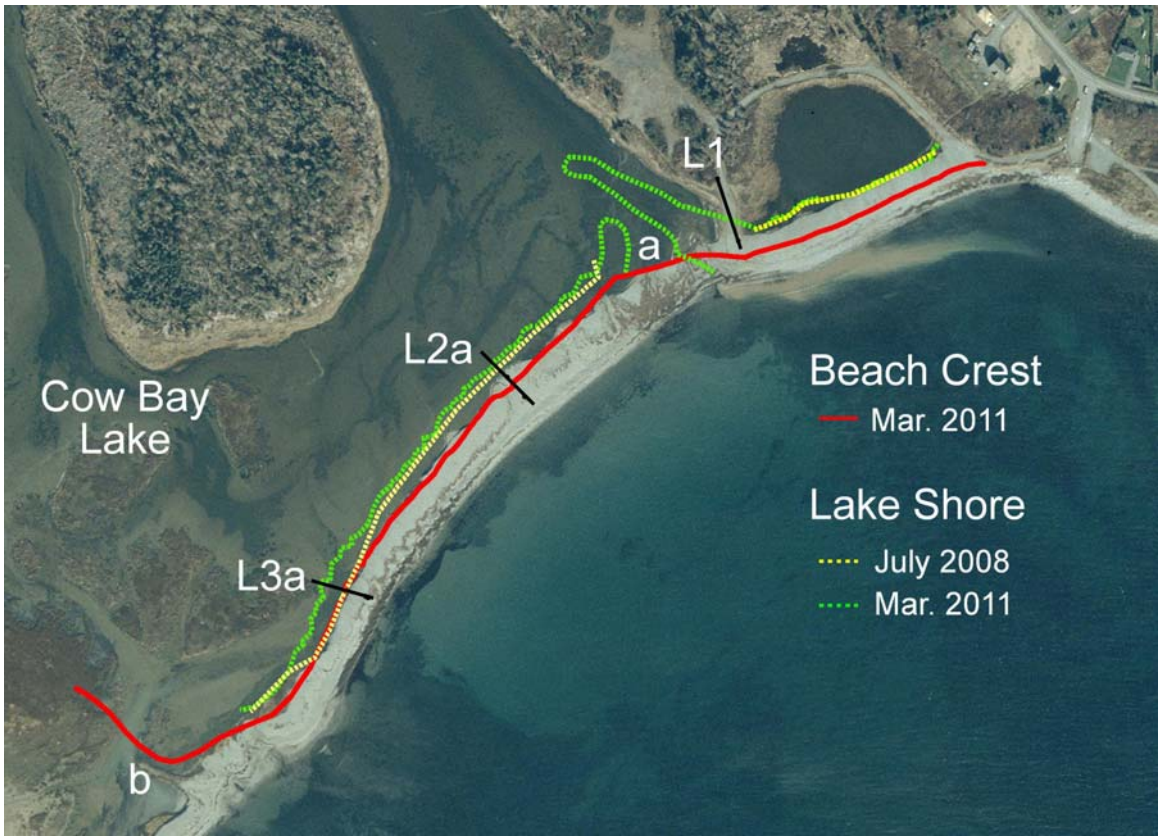


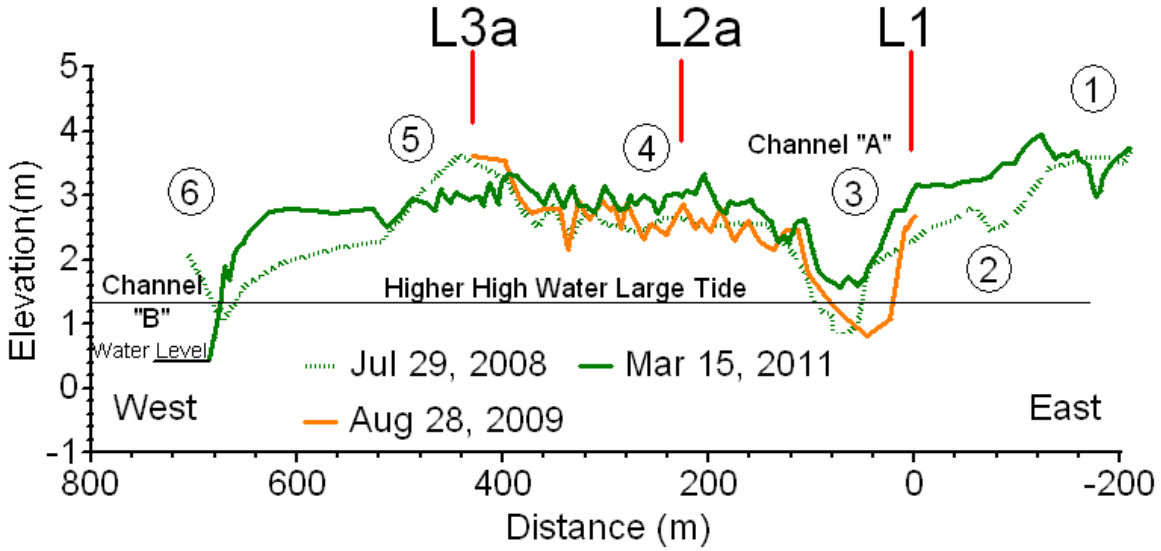
Cow Bay Beach, Ground views of (a) washover channel b, December 8, 2010 when flow was increasing from Cow Bay Lake and (b) dry channel c (the "run") at the western end of beach (see map) on January 20, 2011 (photo a-PC088406, P1039118, and b- P1100828,by H. Kwindt).

During the December 2010 storms, channel b expanded and began to capture the main flow from Cow Bay Lake. By January 3 (inset photo a) flow had increased through channel b and had ceased through inlet c (the "run") by January 20, 2011 (photo b).

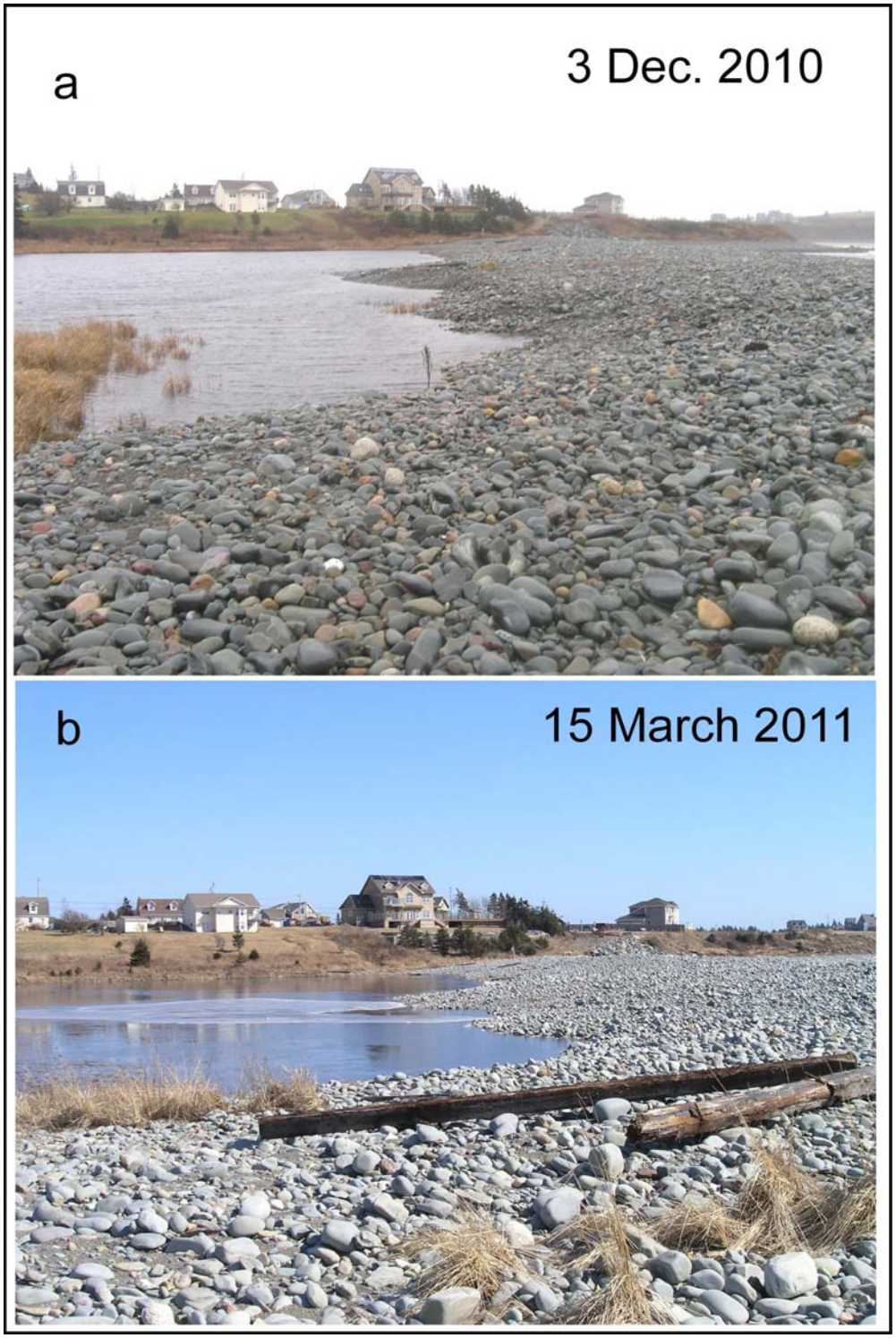
The position of outlets from Cow Bay Lake has shifted eastward over time. Water flowed through "The Run" since 1976 following the closure of another outlet farther west.

Cow Bay Beach, Beach crest, back barrier shore and channels a & b positions in March 2011 are plotted on a 2003 air photo. During the December storms the greatest landward thrust of this beach was east of L3a where the barrier was the highest and narrowest. Less change occurred near L2a because the backshore was sufficiently wide to allow crest rebuilding without pushing farther into the lake (see cross shore surveys). Least change was east of Line 1 where the crest was building higher and becoming more narrow. By 2011 the beach crest (red line) along mid Cow Bay Beach had reached the back barrier shore of 2003.

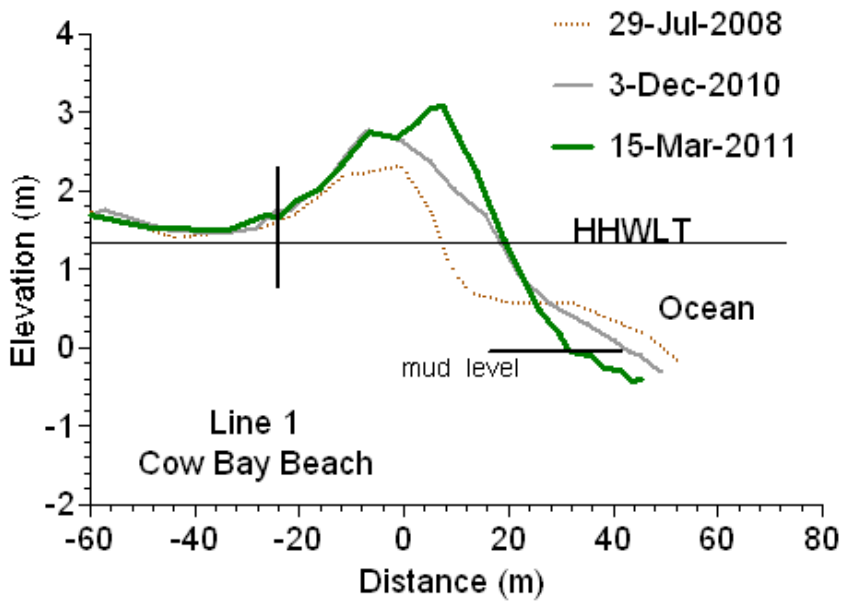




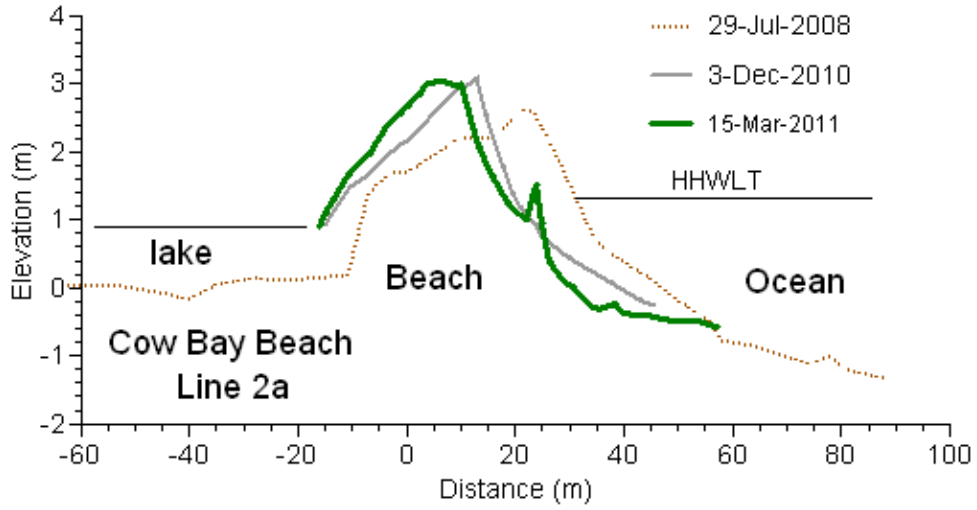
Cow Bay Beach, Longshore beach crest survey with position of cross-shore survey lines (L1, L2a, L3a). To better understand this graph pretend you are standing offshore looking back along the top of the beach. Following the December 2010 storms the beach was highest east of L1 and had a fairly consistent elevation along the middle barrier west of channel "A". The jagged profile between lines 2a and 3a was caused by discrete washover channels. Significant changes observed alongshore included: 1) increased cutting into adjacent headland slope and development of a new washover channel; 2) building of beach crest and infill of old washover channel; 3) beach progradation at L1 and beach extension westward across channel "A"; 4) washover channels cut across middle barrier and barrier crest was built up as it migrated landward; 5) lowering and landward migration of highest part of beach near L3a (photo below) ; 6) channel "B" was scoured sufficient to form a tidal connection with Cow Bay Lake.

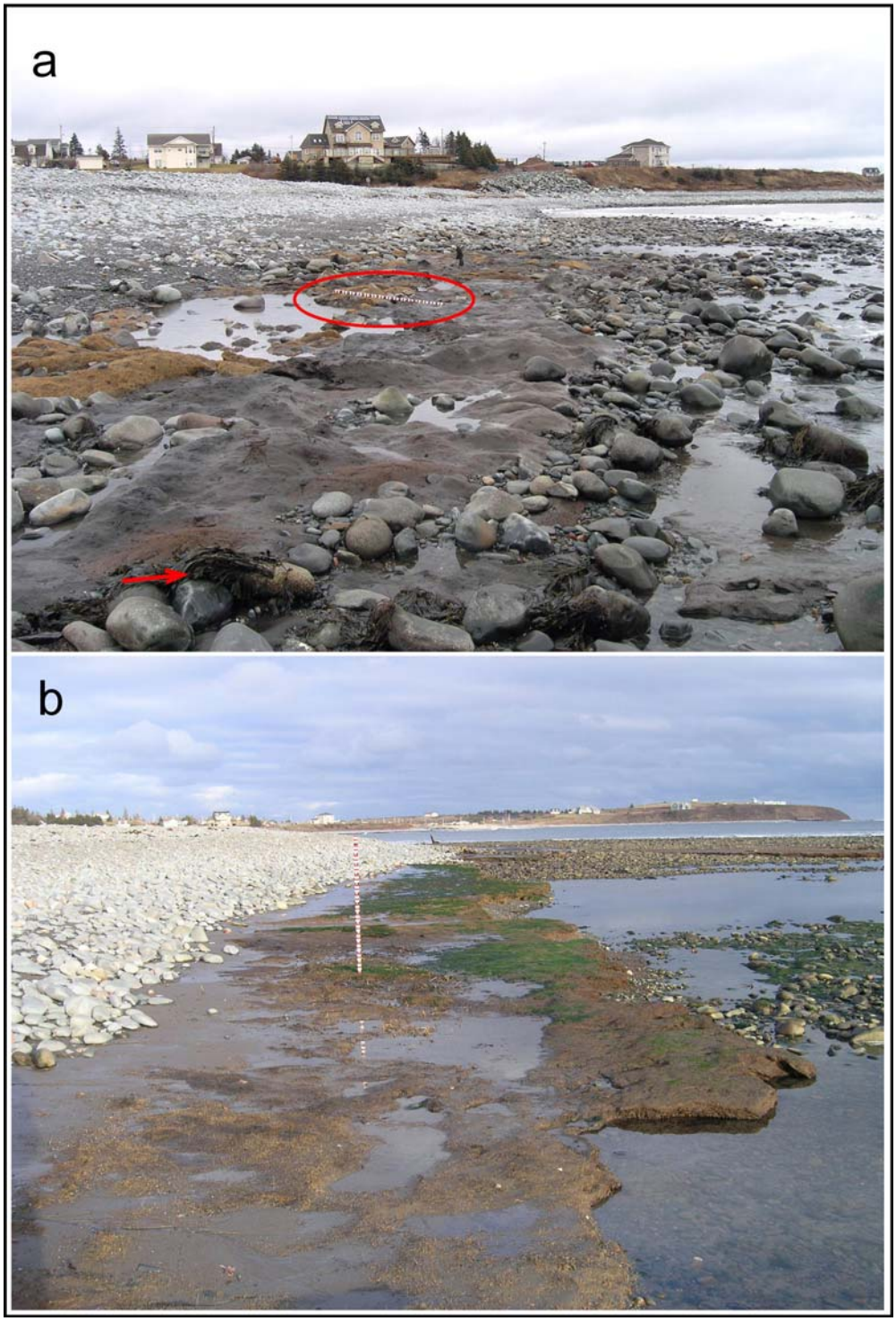


Cow Bay Beach, View toward east end of beach from L1. During the December storms although there was initially some water and debris washing over the lower beach, e.g. at L1 there was no significant change along this part of the beach because of continued crest build-up.



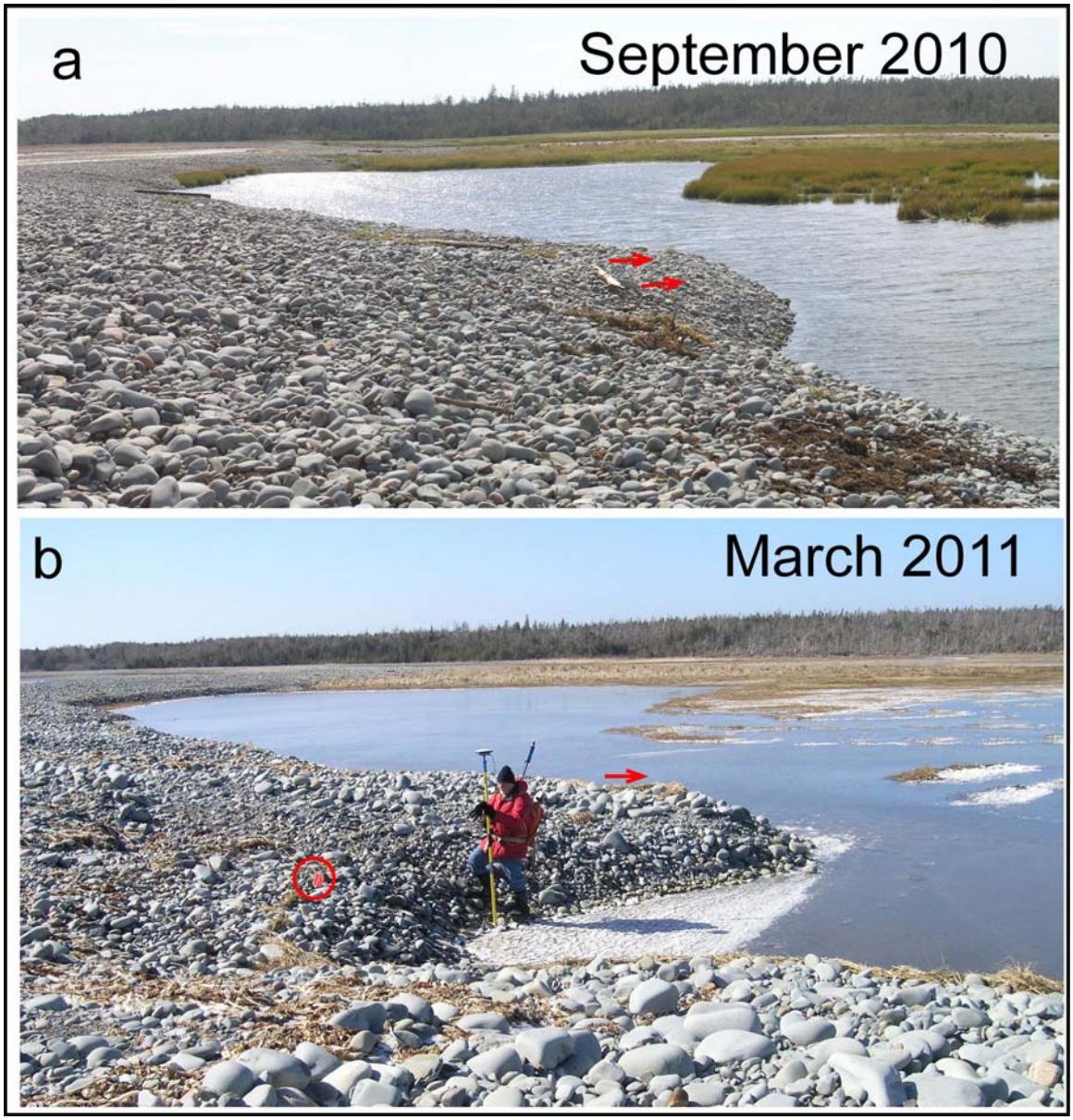
Cow Bay Beach, During the December 2010 storms the beach crest was rebuilt as the beach slope was eroded and scoured downward at the base. At Line 1 the beach crest was extended 14.5 m farther seaward and at L2a the beach crest retreated 6 m landward.

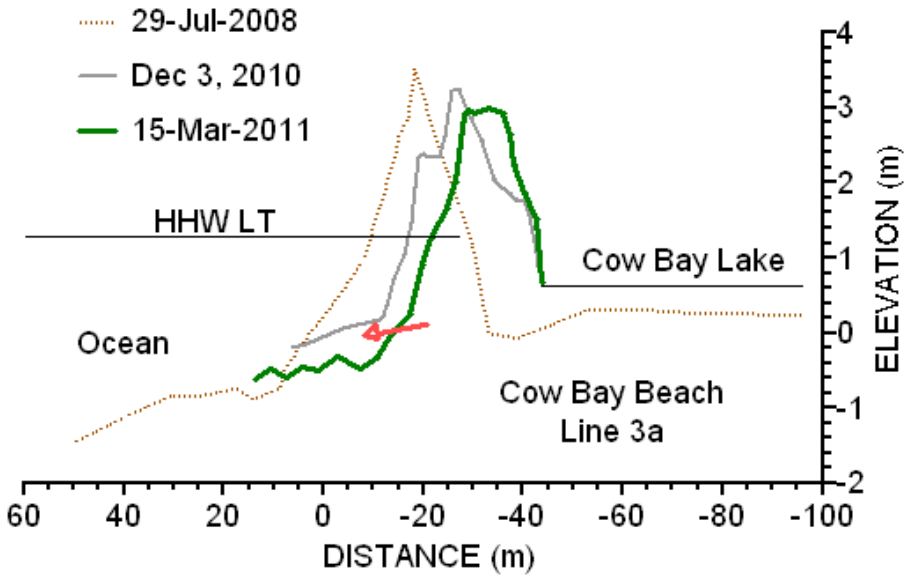




Cow Bay Beach, Views of the thin mud/peat over a coarse substrate (arrow) (a) just east of L1 and (b) east of channel "b" that was exposed as the beach migrated farther landward over older lake deposits. For now, the mud marks the base of mobile gravel, however as waves scour the mud additional coarse sediment below the mud will become available for beach building. The pole (circle) is 1.5 m long, graduated at 10 cm intervals between black marks.

Cow Bay Beach, Views west of L3a before and after the December 2010 storms. A wave washover lobe (arrows) had been initiated earlier in 2010 and was built farther into the lake during the December storms. The red flag (circled) marks the location of survey line 3a.





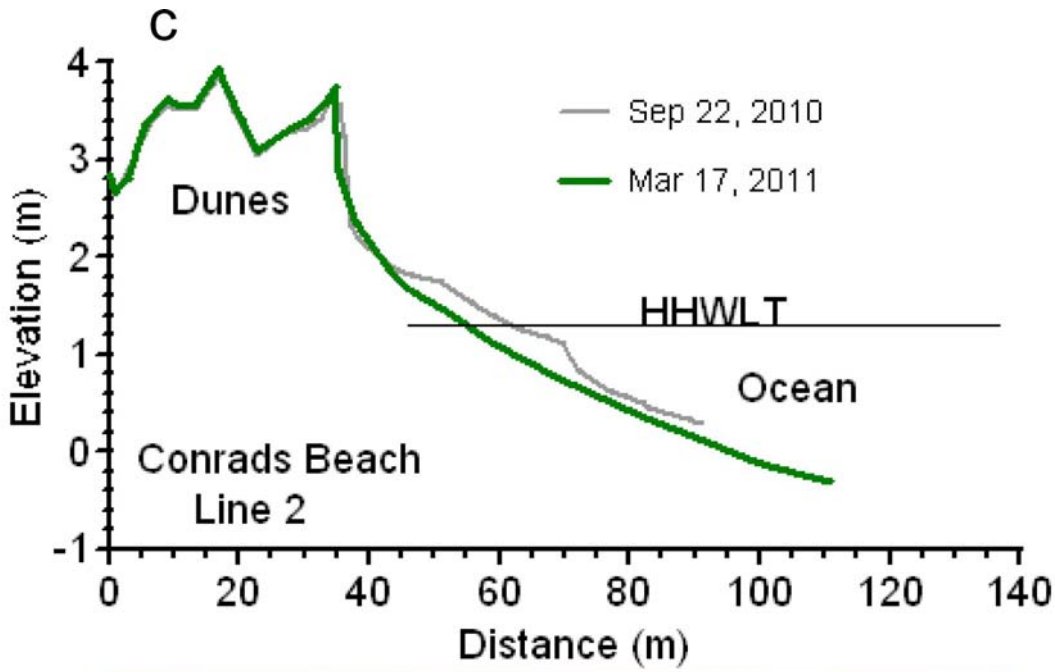
Cow Bay Beach, During 2010 the beach at L3a was pushed as much as 15 m landward, half during the December 2010 storms. Beach crest height decreased because more sediment was required to infill the lake bed (July 2008 survey) as the beach migrated landward. Steep washover lobes extending into the lake consisted of very loose, unstable, pebble-cobble clasts. At low tide, water was observed flowing seaward from the lake through the lower beach (arrow) which may decrease beach stability in the future.

Conrads Beach Sand-Dominated Beach

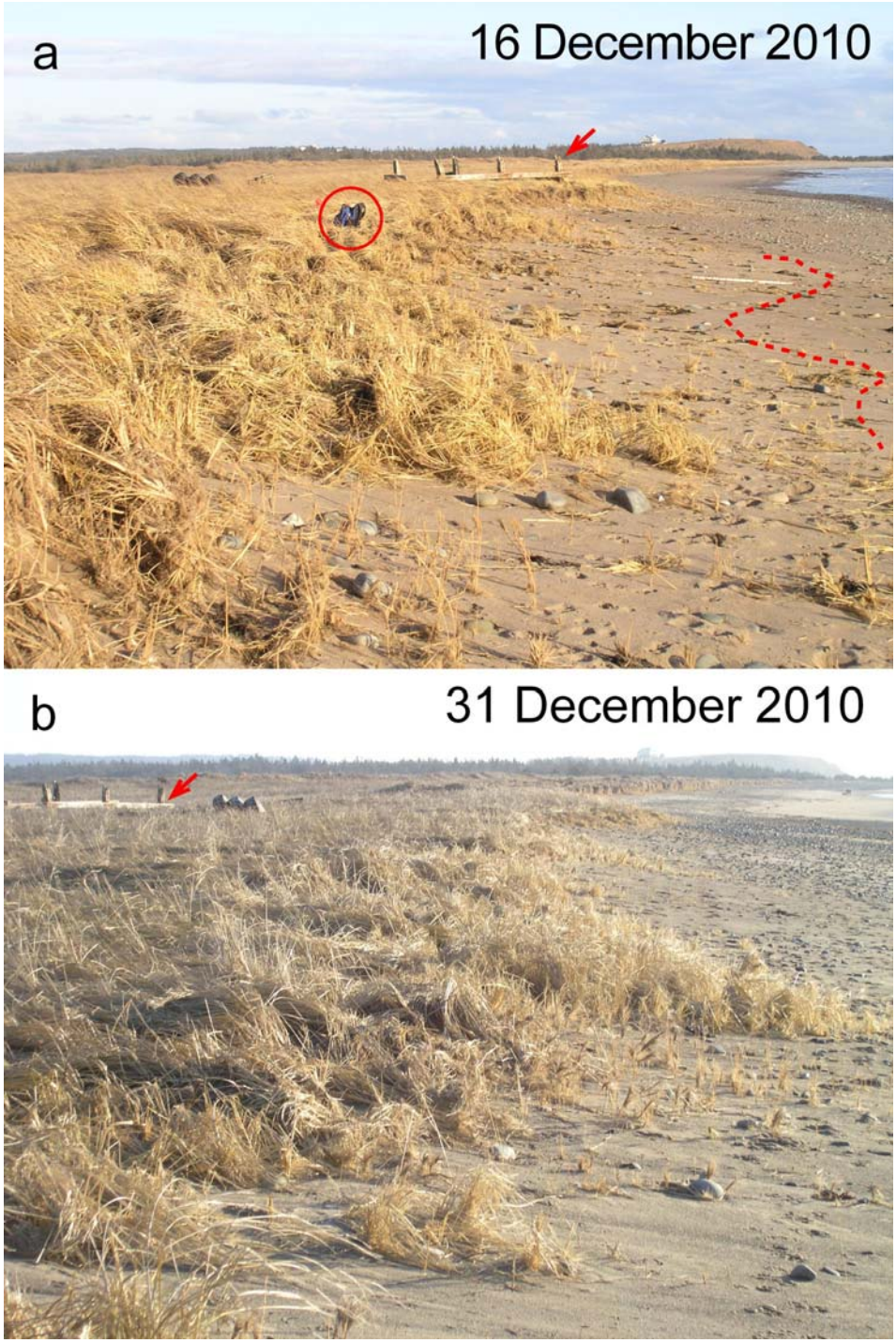
Conrads Beach, Location map of cross-shore survey lines 1 to 7 plotted on a 2003 air photo. The most frequent observations were completed at this beach during December however cross-shore surveys were only completed on December 16, 2010 and March 17, 2011. Photos were also taken on March 13, 2011.

Conrads Beach, Views of the boardwalk (a) December 21 at 09:30 AST and (b) December 31 at 08:45 AST which represent storm and non-storm conditions. Inability of the present channel under the bridge to handle higher tidal flows during storm events causes water to deflect around the former parking area and flood the adjacent backshore. The access highway and boardwalk at Conrads Beach were flooded during the December 6th event when a maximum water level of 2.06 m (2.86 m CD) was recorded at the Halifax (BIO) tide gauge (Photos PC218733, PC318840).

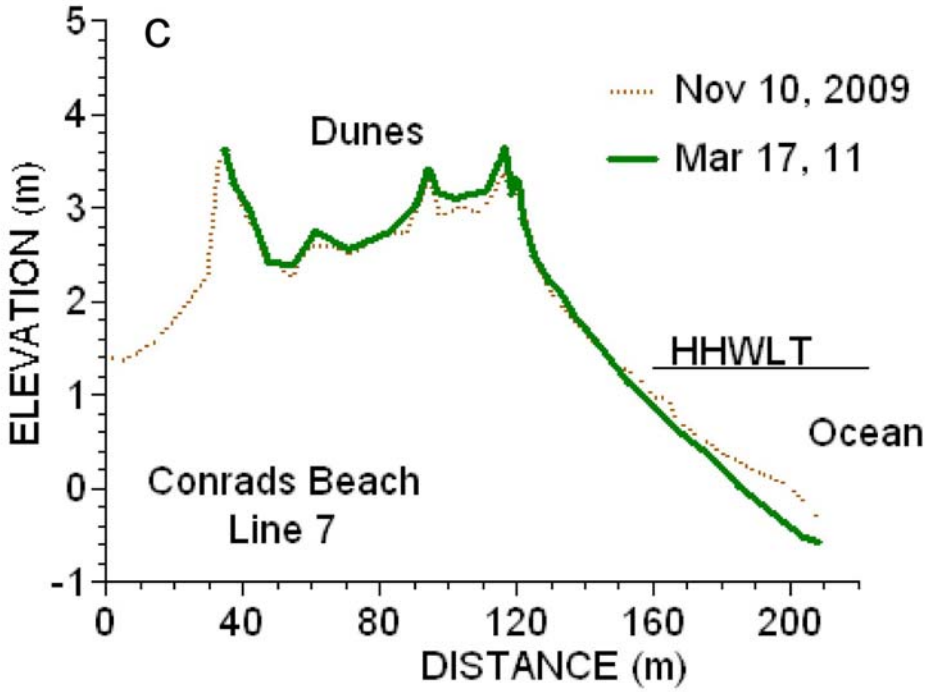
Conrads Beach, Views of the upper beach and dune at Line 2 on (a) 22 September, (b) 31 December 2010, c) graph of cross-shore changes and partial recovery by d) 13 March 2011. During the December 2010 storms the beach was progressively lowered exposing a wide band of pebble cobble along the dune base which retreated 1.8 m. Some cobble was tossed onto the dunes and waves etched furrows into the dune edge. By March 2011 (d) the upper beach was building and wind blown sand was reburying the coarse substrate (Photos P9227960, PC318874, P3139354, R. Taylor, GSCA).


c
Sep 22, 2010
Mar 17, 2011
Dunes
HHWLT
Ocean
Conrads Beach
Line 2
Elevation (m)
Distance (m)
4
3
2
1
0
-1
0
20
40
60
80
100
120
140


d
13 March 2011

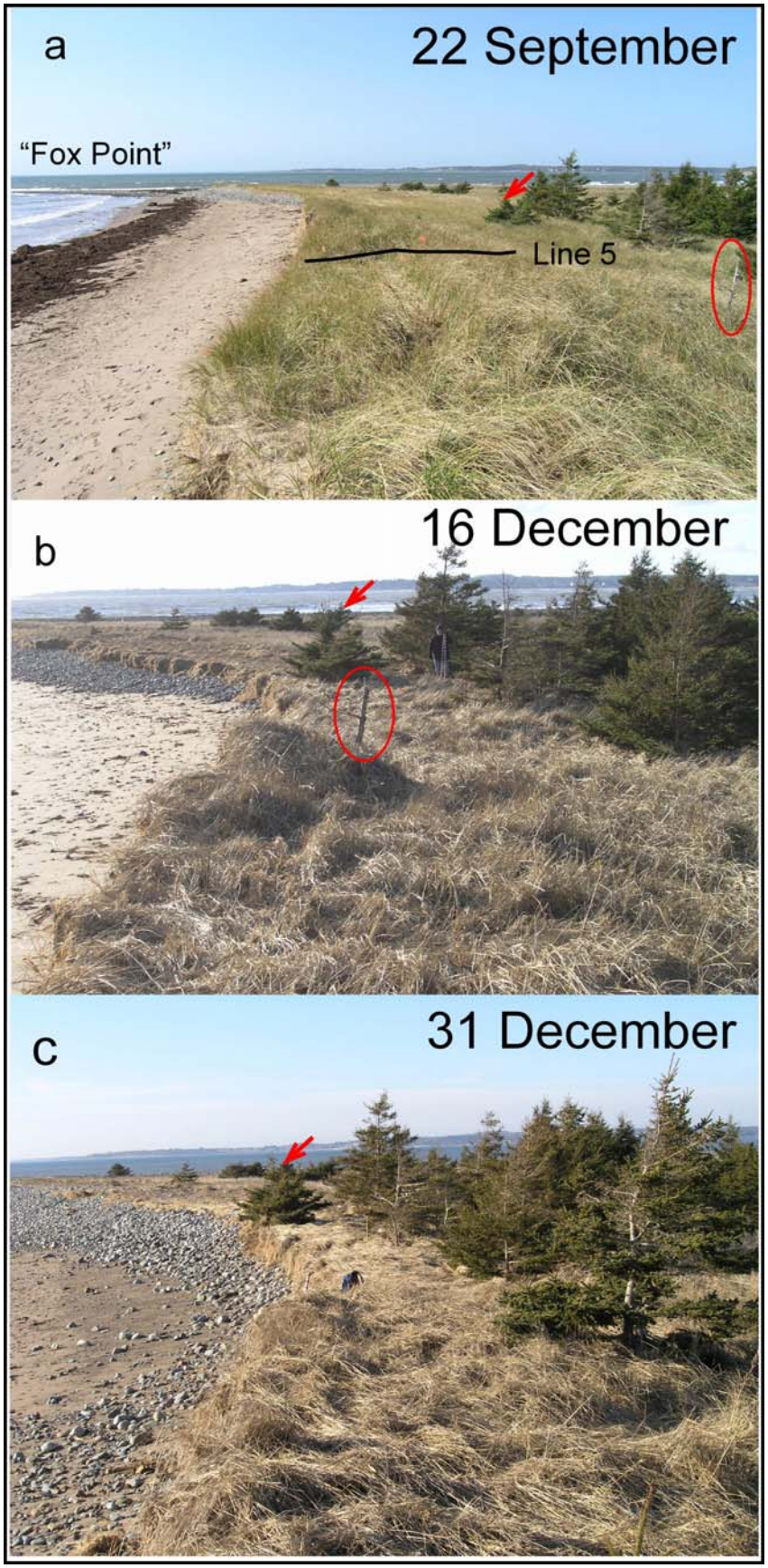


Conrads Beach, Between 1995 and 2009 low dunes along the western beach had been building seaward at an average of 1.4 m/a. During December 2010 waves mowed the marram grass (a dash line) and etched furrows into the embryo dune. In the first storm waves extended less than 4 m landward at Line 7a (pack on line, circled) and on December 27, waves extended 8 m inland at this location and as much as 53 m inland at the former inlet. (b) Large pieces of flotsam (arrows), which had not moved since at least August 2009, were also floated and moved inland (photos PC168703, PC318859). (c) The embryo dune had been cut back by nearly 3 m however net change since late 2009 was minimal. (d) by March 2011 sand and debris had accumulated across the seaward dune infilling many of the dune cuts from December (photo P3139373).

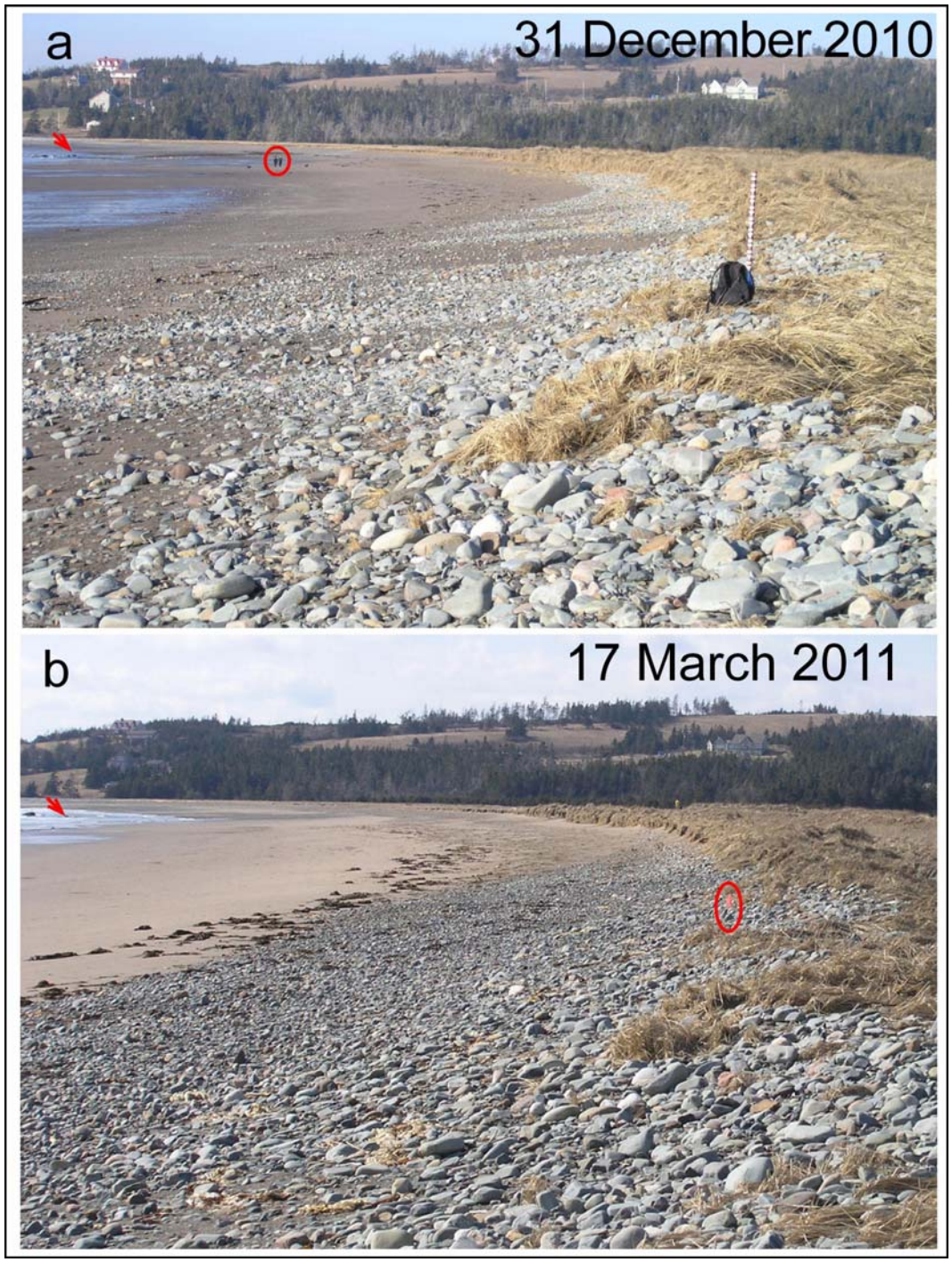

c
Nov 10, 2009
Mar 17, 11
Dunes
HHWLT
Ocean
Conrads Beach
Line 7
ELEVATION (m)
DISTANCE (m)
5
4
3
2
1
0
-1
0
40
80
120
160
200


d
13 March 2011

Conrads Beach, Views of upper beach and dune at L4 (graduated rod 1.5 m long and pack) on (a) 31 December 2010 and (b) 17 March 2011. Along the central part of the main beach, the foredune base was cut back 5 m as the beach slope was lowered. By March 2011 the dune scarp was nearly half covered by wind blown sand which should encourage the seaward spread of marram grass (photos PC318845, P3179482).

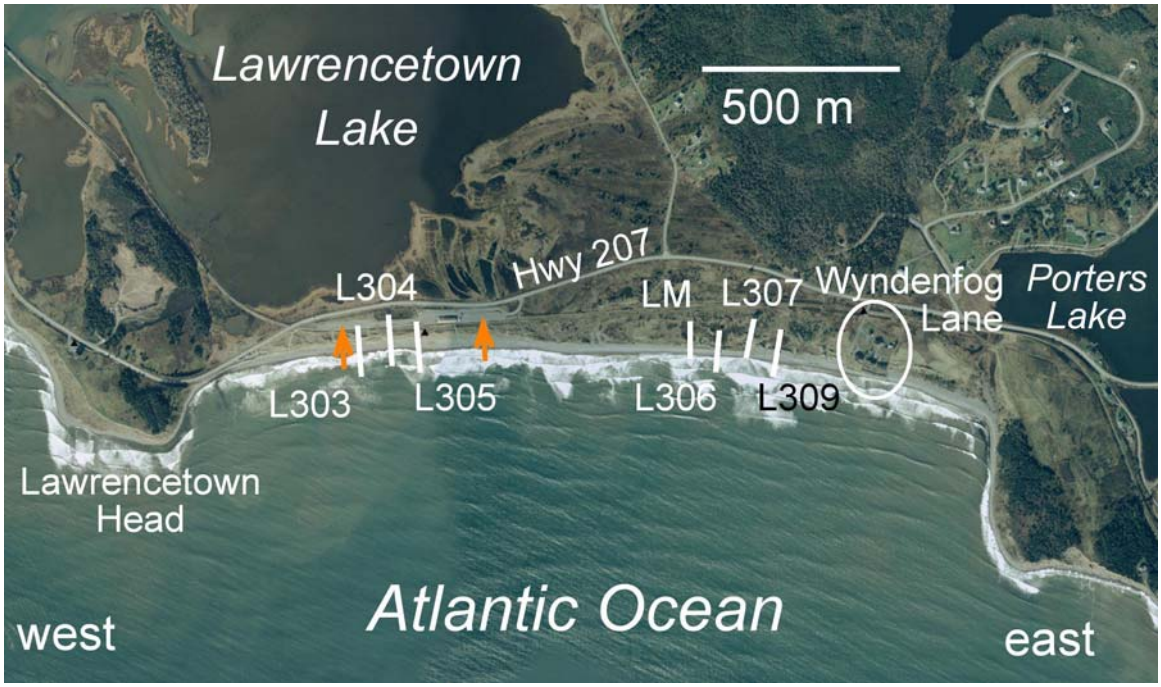


Conrads Beach, The largest impact of the December 2010 storms was observed along the eastern beach. At L5 (a) September 22, (b) December 16, and (c) December 31, 2010. Maximum dune retreat during the December 6th event was 4.3 m and the total dune retreat during December was 9.1 m. Where pebble cobble clasts were pushed higher against the dune face during storms on the 21st, they provided a natural defense against further wave attack. The same trees are marked for visual reference, the tree circled had eroded by December 31 (Photos P9227964, PC168691, PC318889).



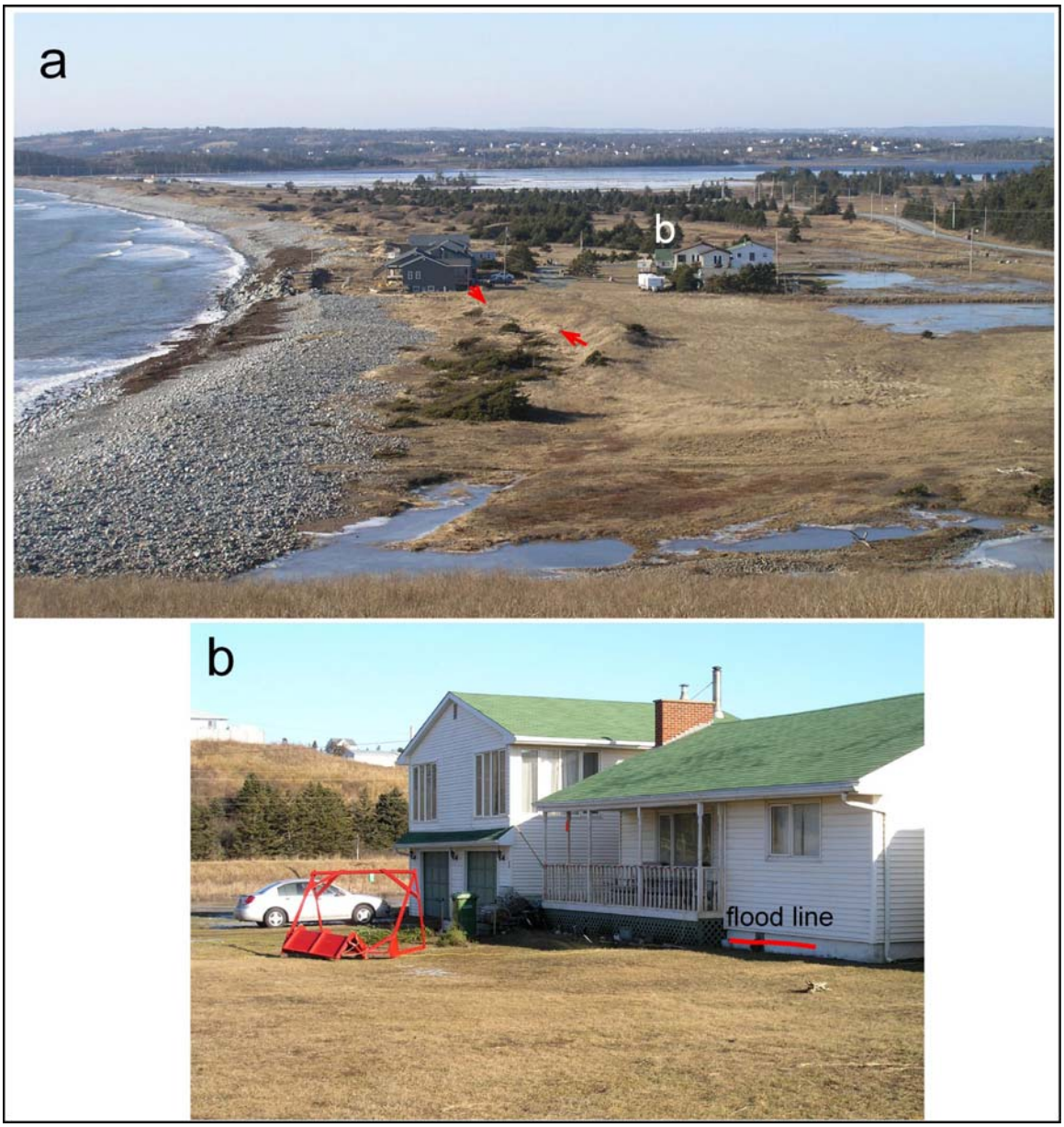
Conrads Beach, Views from L1 (pack and circled flag) on (a) 31 December 2010 and (b) 17 March 2011. The central beach slope was combed down and the dunes were cut back in the December storms. By mid-March beach recovery was in progress: sand had accumulated along the central beach and winds were blowing it farther upslope to rebuild the foredune. People walking (circled) provide scale and the same rocks are marked (arrows) for visual reference (photos PC318880, P3179506).

Lawrencetown Beach Sand and Gravel barrier beach

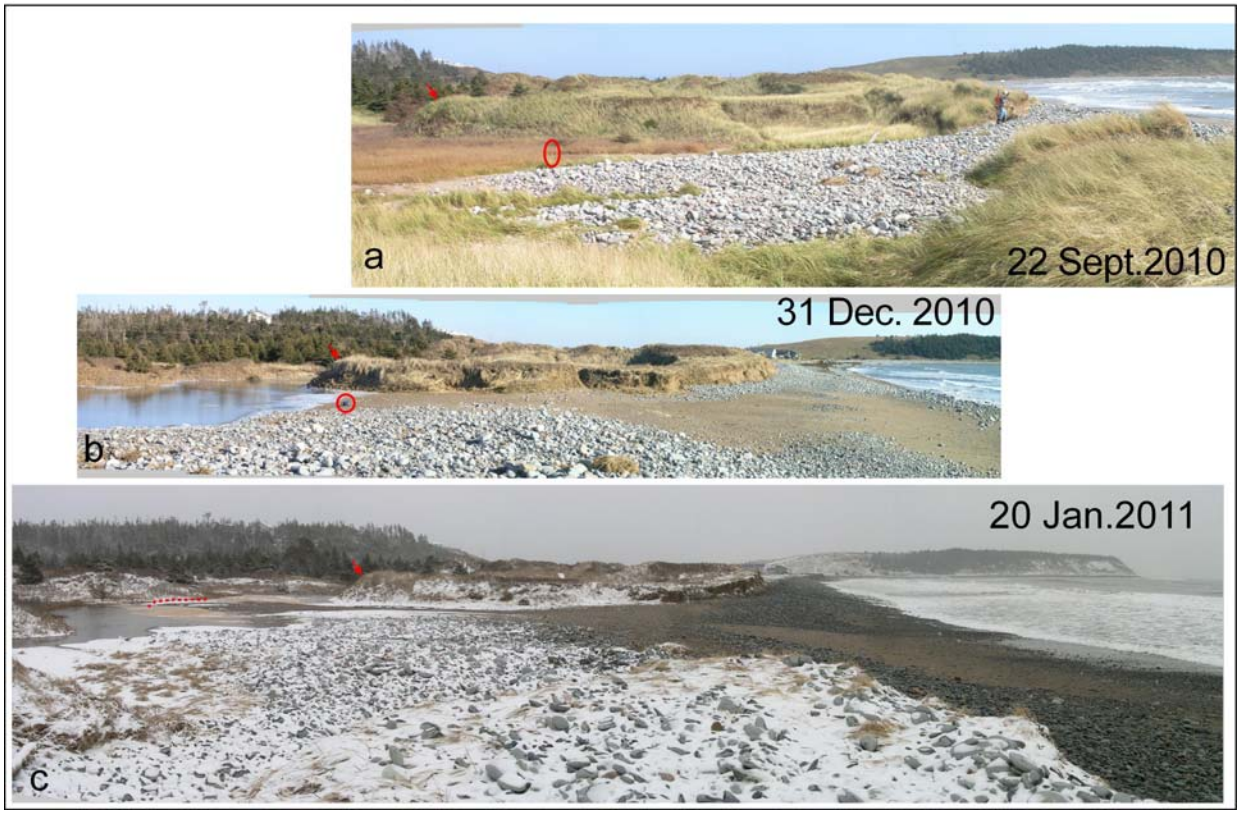


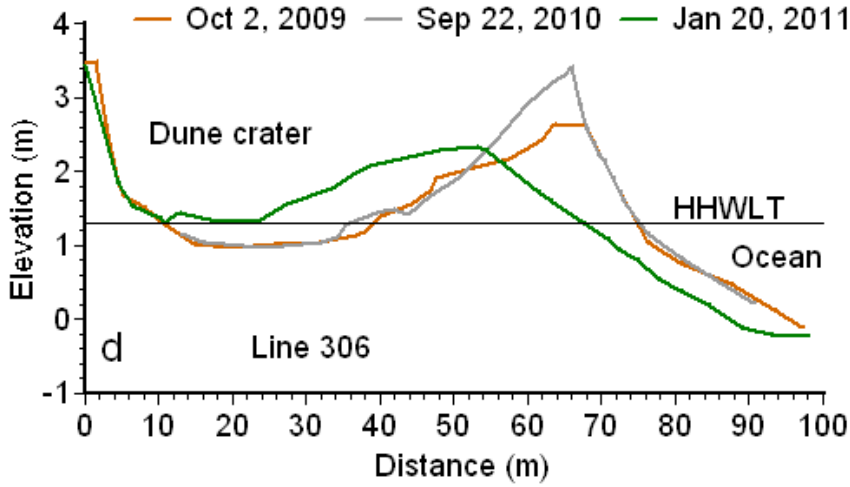
Lawrencetown Beach, Location of cross-shore survey lines plotted on a 2003 air photo. Impacts of the December storms on shoreline stability and flooding were surveyed on January 20, 2011. Water flowed through the dunes (orange arrows) to the parking lot along the west end of the beach during the December 6th event.

Lawrencetown Beach, View of Wyndenfog Lane from the eastern headland. During the early hours of December 28, 2010 waves overwashed all dunes less than 4.2 m elevation transporting sediment and debris inland (red arrows) and (b) waters reached 2.3 m elevation flooding some residences at Wyndenfog Lane (photos. PC318975, PC318922).



Lawrencetown Beach, Repetitive photos and surveys on (a) September 22, (b) December 31, 2010 (c) January 20, 2011, and (d) graph of shoreline changes at line 306. Waves during storms earlier in 2010, including Hurricane Earl on September 4, had built up the gravel ridge (a, d) across the mouth of the dune cut formed in November 2007. On December 6 waves washed over low dunes adjacent to line 306 (person on line in a) causing erosion and collapse of sections of dune as water flowed over it. During December 27-28 waves broke the weakened dune, expanded the opening into the backshore crater to 50 m width and transferred sediment into the backshore crater burying a line marker (circled in a). By January 20, 2011 washover deposits of up to 0.7m thickness (d) extended to the backdune (dash line -c). Future transfer of beach sediment into these backshore craters will have significant negative impacts on outer beach stability.



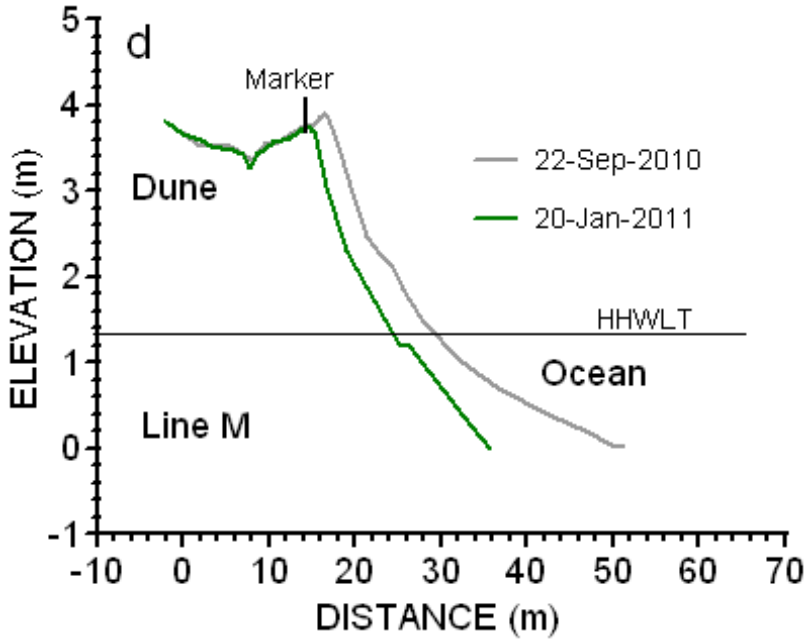


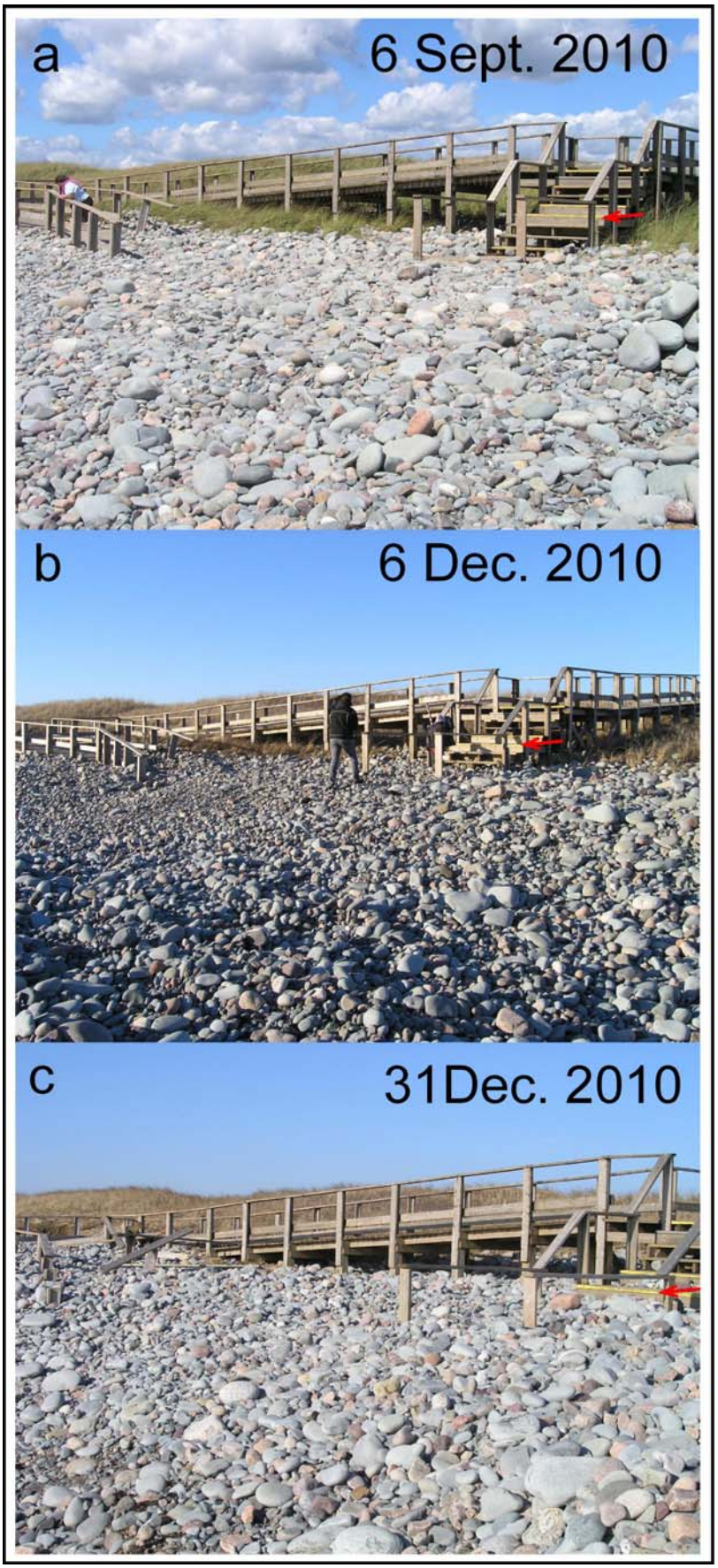
Lawrencetown Beach, Dune erosion and subsequent infilling of a dune cut and rebuilding of the beach crest at Line M was representative of changes observed along much of the central and eastern parts of this beach.

Repetitive photos of Line M on (a) September 22, (b) December 21, 2010 (c) January 20 2011 and (d) a graph of the cross-shore profile illustrate the changes (photos P9228033, PC218781, P1209213).

During the initial storm on December 6 pebble cobble was pulled downslope and the dune was cut back 1.7 m to the line marker (circled in photos). During the next two storms waves cut low scarps intermittently along the exposed backshore dune. During the December 27 storm, coarse material was transported upslope burying the dune scarp (c, d).

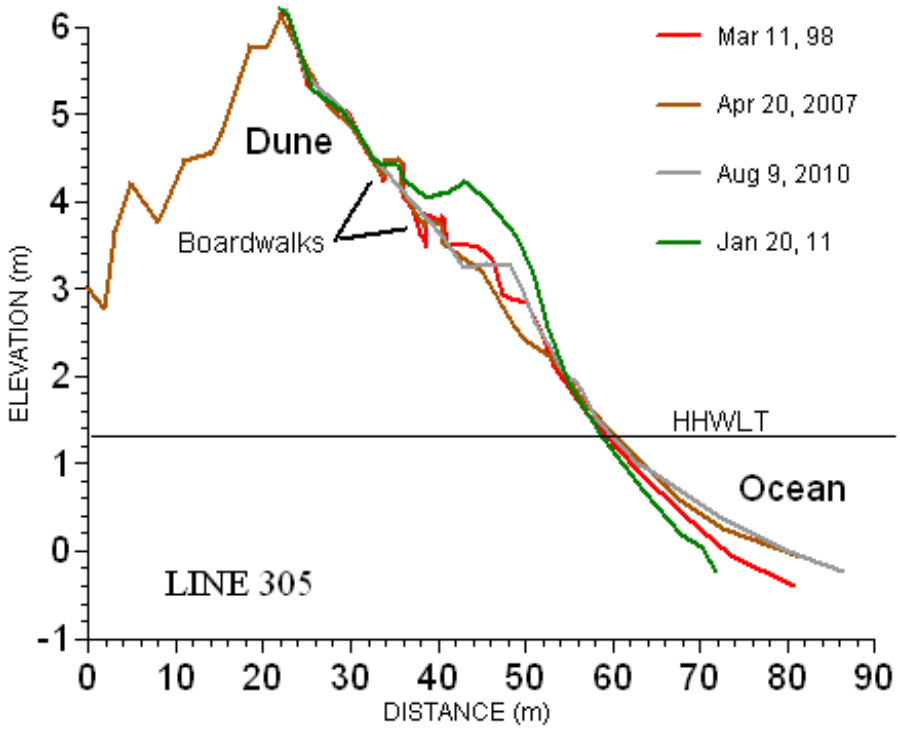
Lawrencetown Beach, (d) Cross shore surveys from September 2010 and January 2011 quantify the net shore change caused by storms in December. For example, the beach crest was pushed 2.1 m landward since September (c, d). The surveys were not frequent enough to show the detailed sequence of dune exposure, erosion and subsequent burial by pebble cobble observed during field visits.



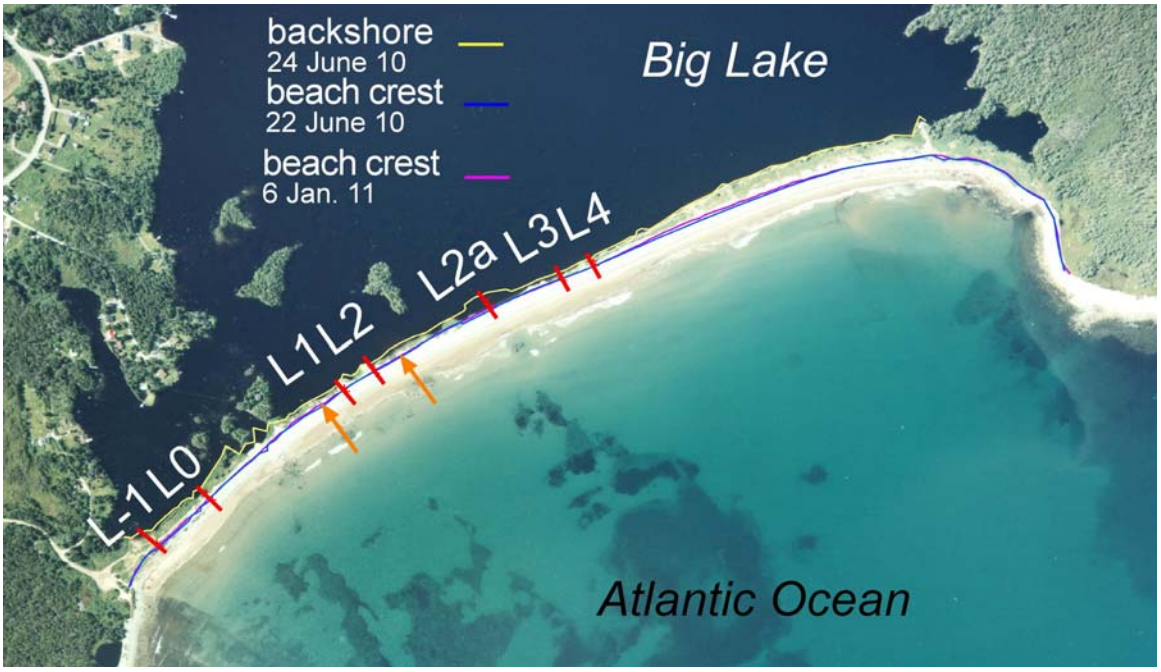


Lawrencetown Beach, Repetitive photos of beach access stairs adjacent to Line 305 on (a) September 6 (b) December 6 and (c) December 31, 2010 and (d) graph of cross-shore changes at Line 305. The largest upslope movement of coarse clasts since 1995 was observed during the December 2010 storms. (photos P9067758, PC108548, PC318916).

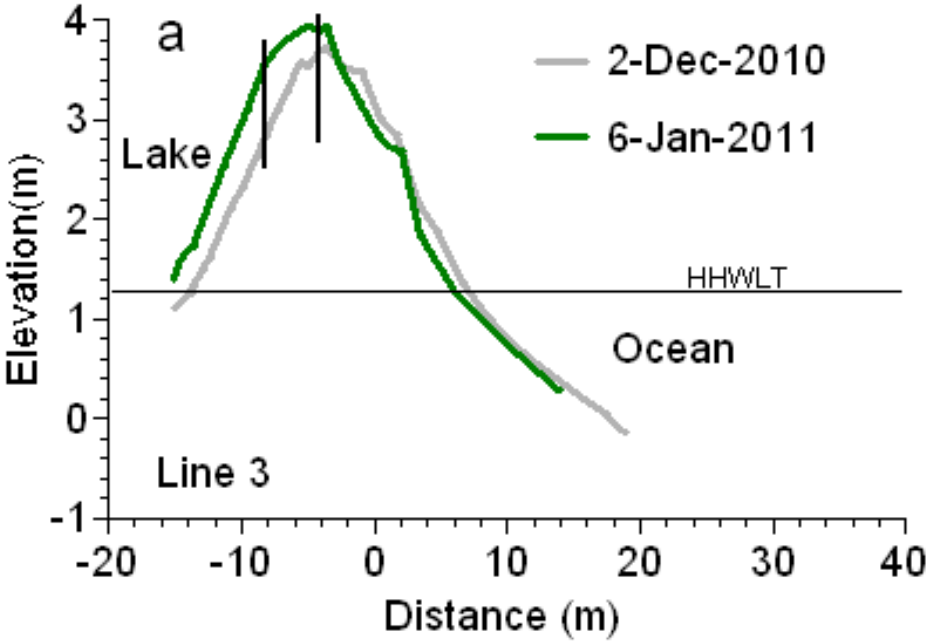
Lawrencetown Beach, (d) Cross-shore survey of L305 showing the burial of the boardwalk by 0.3 m of cobble and a massive increase in beach ridge growth during December 2010 (0.7m higher and 2.5 times the width of the ridge built by August 2010). Wave run-up in December 2010 extended to an elevation of 4.4 m.

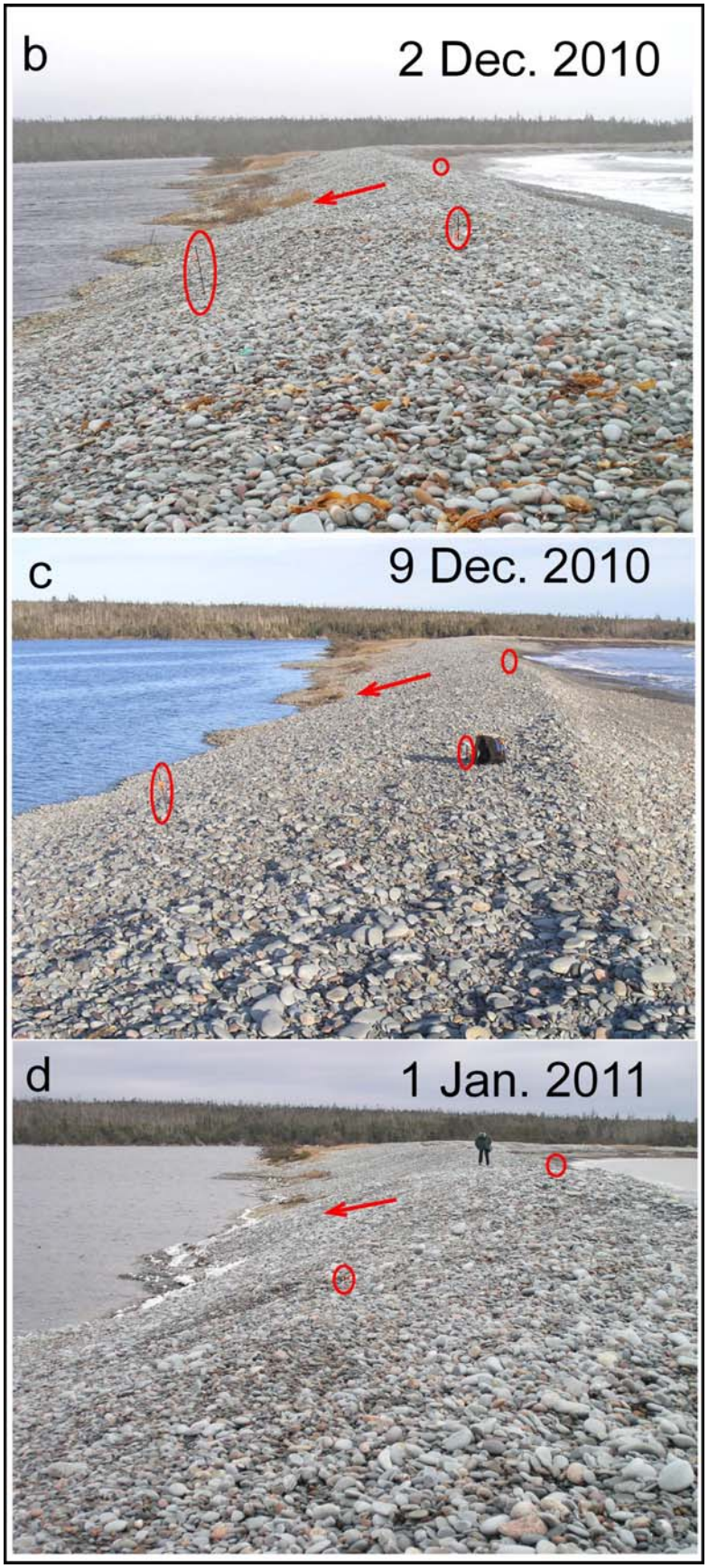


Miseners Long Beach High Gravel barrier Beach



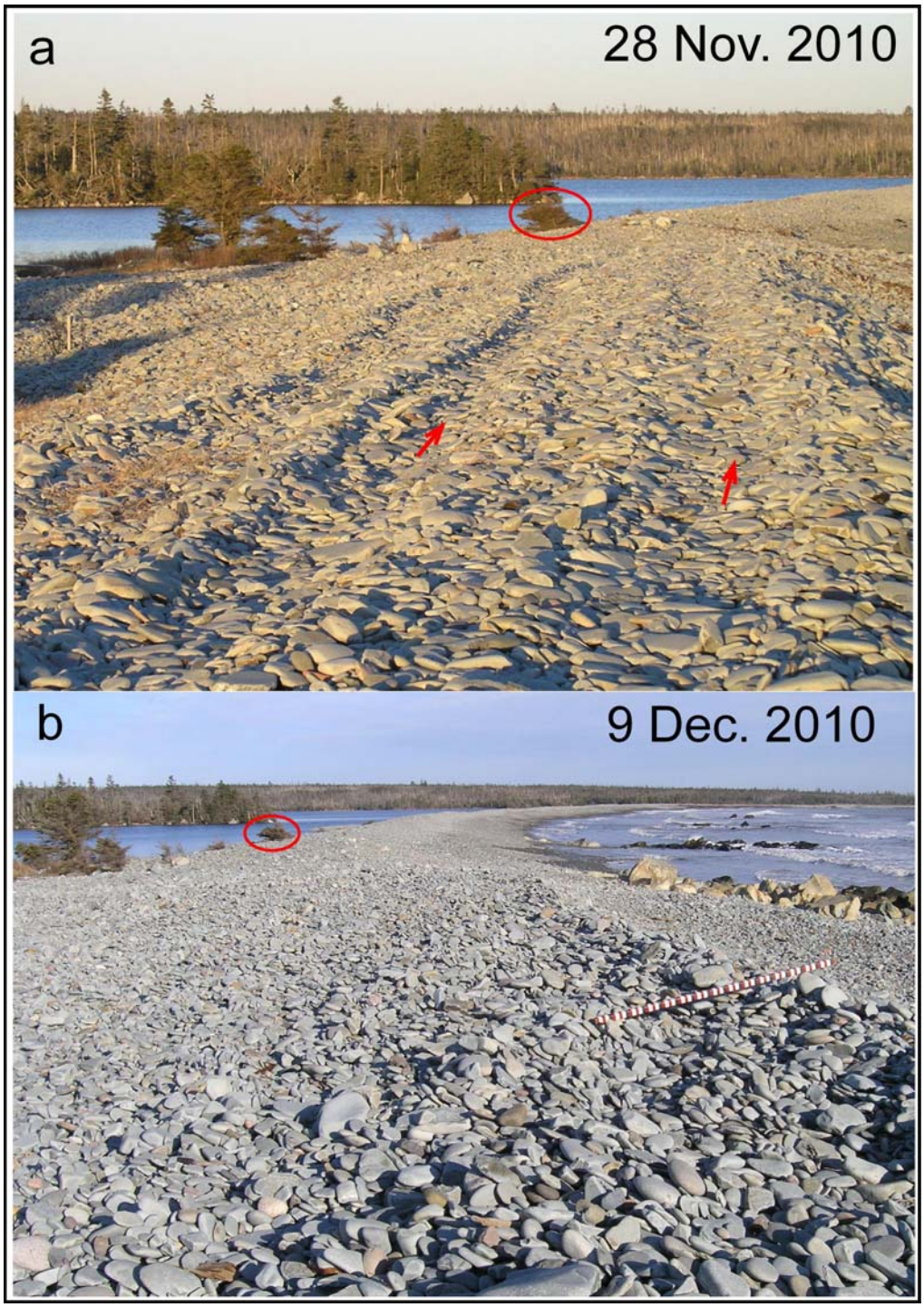
Miseners Long Beach, Location of survey lines -1 to 4 plotted on a 2003 air photo. Changes in back barrier shoreline (yellow line) in June 2010 were the result of the January 2010 storm which cut through the barrier at Line 2a. New washover channels (orange arrows) were cut through the barrier beach during the December 27 storm. The shift in barrier crest position from June 2010 (blue line) to January 2011 (purple line) was attributed mainly to the December 2010 storms although the period of time includes Hurricane Earl in September 2010. Maximum crest retreat between June 2010 and January 2011 was 2.2 m at Line 2a. (86% of retreat was during December storms).





Miseners Long Beach, the primary impact of the December 2010 storms was the progressive landward movement of sediment and infilling of the backshore by wave overwash as shown by cross-shore surveys (a) at line 3 on December 2 and January 6. Impacts of individual storms were recorded with more frequent photos and measurements at line markers. Photos show pre-storm (b) December 2, and post-storm conditions (c) on Dec. 9 and (d) Jan.1, 2011 at line 3 (line markers circled in foreground) and Line 4 (circled in background). (photos PC028290, PC098478, P1069162). During the Dec. 6th storm there was 0.3 m of sediment accumulation and subsequent buildup of the beach crest as the storm abated (c). During the Dec. 27th storm the beach crest was pushed landward and a 30% increase (compared with the 6th) in sediment deposition across the backshore and burial of line markers and dune grass (d) occurred. Crest buildup was less and in many places there was crest lowering, e.g. Line 4. (see longshore survey of beach crest).

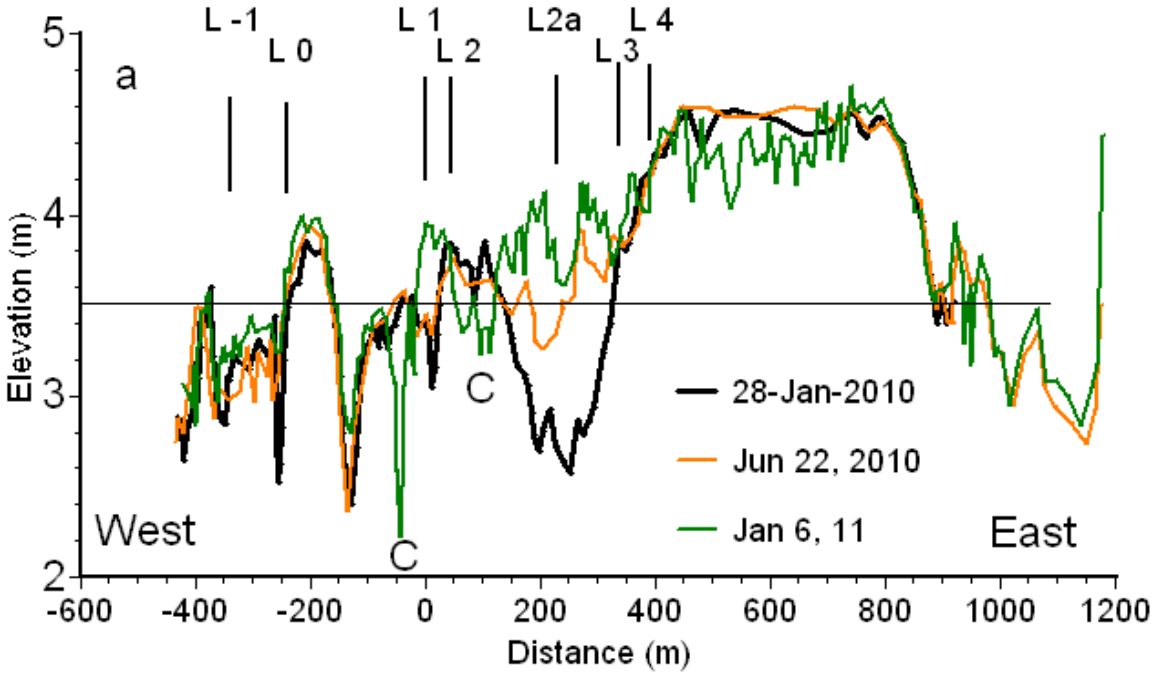
Miseners Long Beach, During the December 6th storm, the low (<3.5m elevation) western beach was severely overwashed by waves. Photos (a) on Dec. 2 and (b) Dec. 9 of the backshore adjacent to L-1 (line marker circled) show the accumulation of coarse clasts and natural build-up of a washover fan originally built with sand during Hurricane Earl (photos PC028325, PC098433).



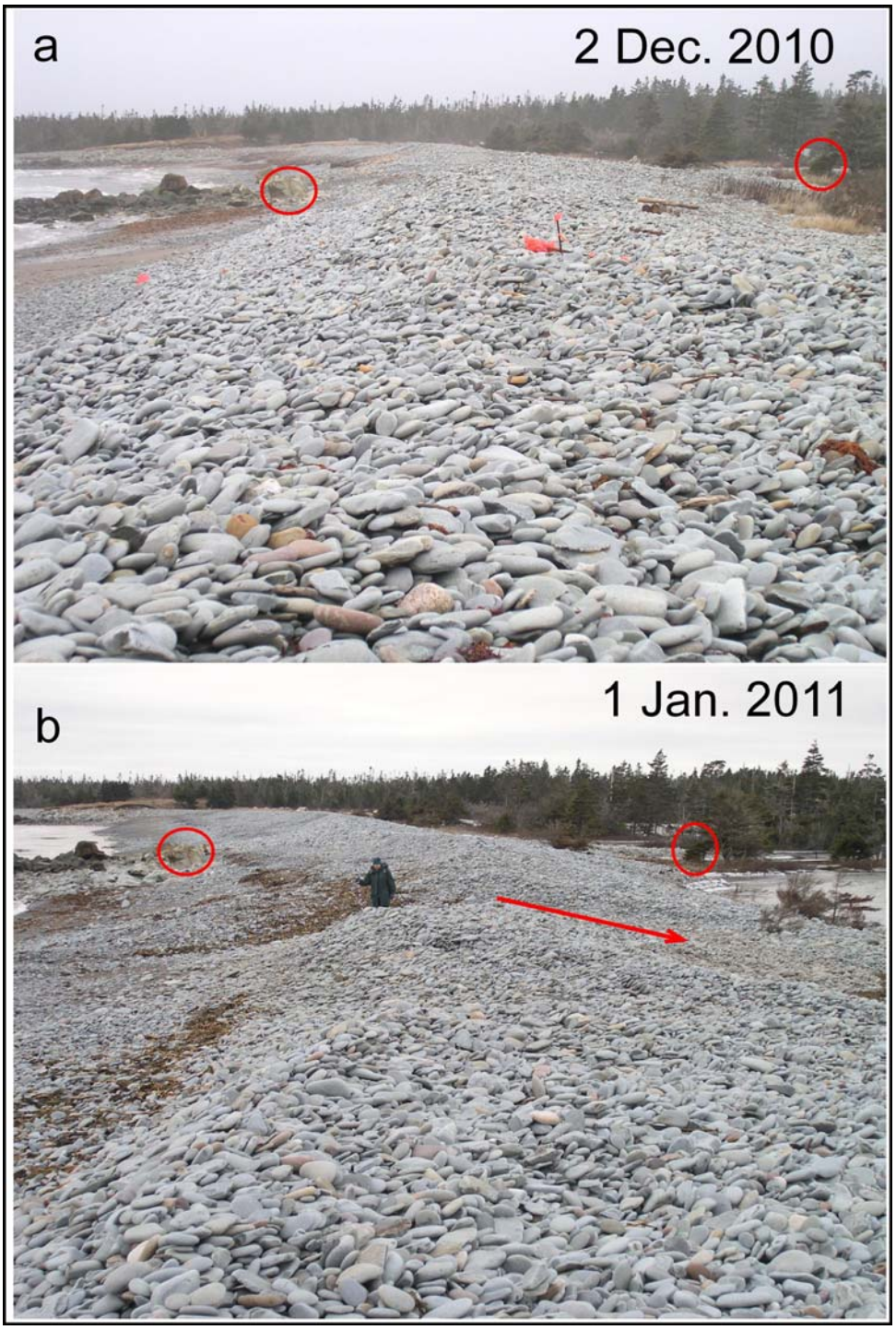
Miseners Long Beach, Burial of vehicle tracks (arrows a) along the beach crest west of line 0 following the Dec. 6 storm show the extent of backshore buildup and wave overwash. The 1.5m long measuring pole in (b) lies on a linear crest ridge built as the Dec. 6 storm subsided. The same tree is circled in both photos for visual comparison (photos PB288237, PC098444).

Miseners Long Beach, Views of the extreme east end on (a) 24 June 2010 and (b) 6 Jan. 2011 showing landward beach migration and infill of a small pond. The same tree is circled for visual reference. It is not possible to differentiate which storm(s) caused this change because of fewer field observations but the photos confirm migration occurred after June 2010 (photos P6247066, P1069144).

Miseners Long Beach, Repetitive surveys along the barrier beach crest in 2010 show the jagged surface morphology caused by wave overwash during December storms and differences in beach elevation and dissection alongshore. The barrier beach curves southward at distance 800 to 1200 m. Washover channel spacing and depth of scouring was greater along the lower east and west ends than along the higher beach east of L4. Repetitive surveys show the progressive build-up near L2a where waves cut through the beach in January 2010. New channels were cut through the barrier beach east of line 2 and west of Line 1 "C" during the December 27 storm. To understand this graph pretend you are standing offshore looking shoreward. The lines represent changes along the top edge of the barrier beach.

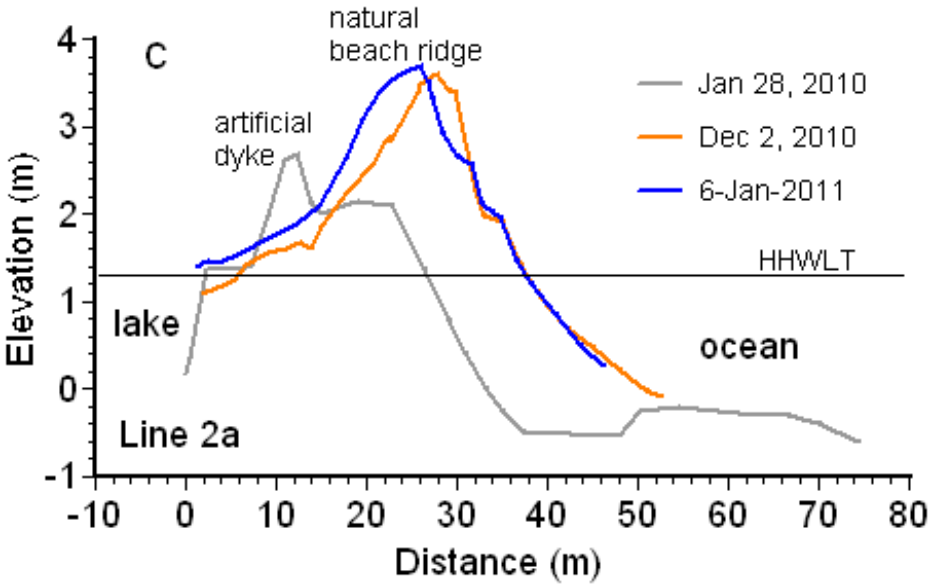


Miseners Long Beach, Views just west of line 1 on (a) Dec. 2, 2010 and (b) Jan. 1, 2011 where waves had cut into and narrowed the barrier beach during the Dec. 6 storm and cut a 1.3 m deep channel (red arrow-b) through the beach during the Dec. 27 storm. For visual reference, the same rock outcrop and tree are circled in both photos (photos PC028254, P1019013).

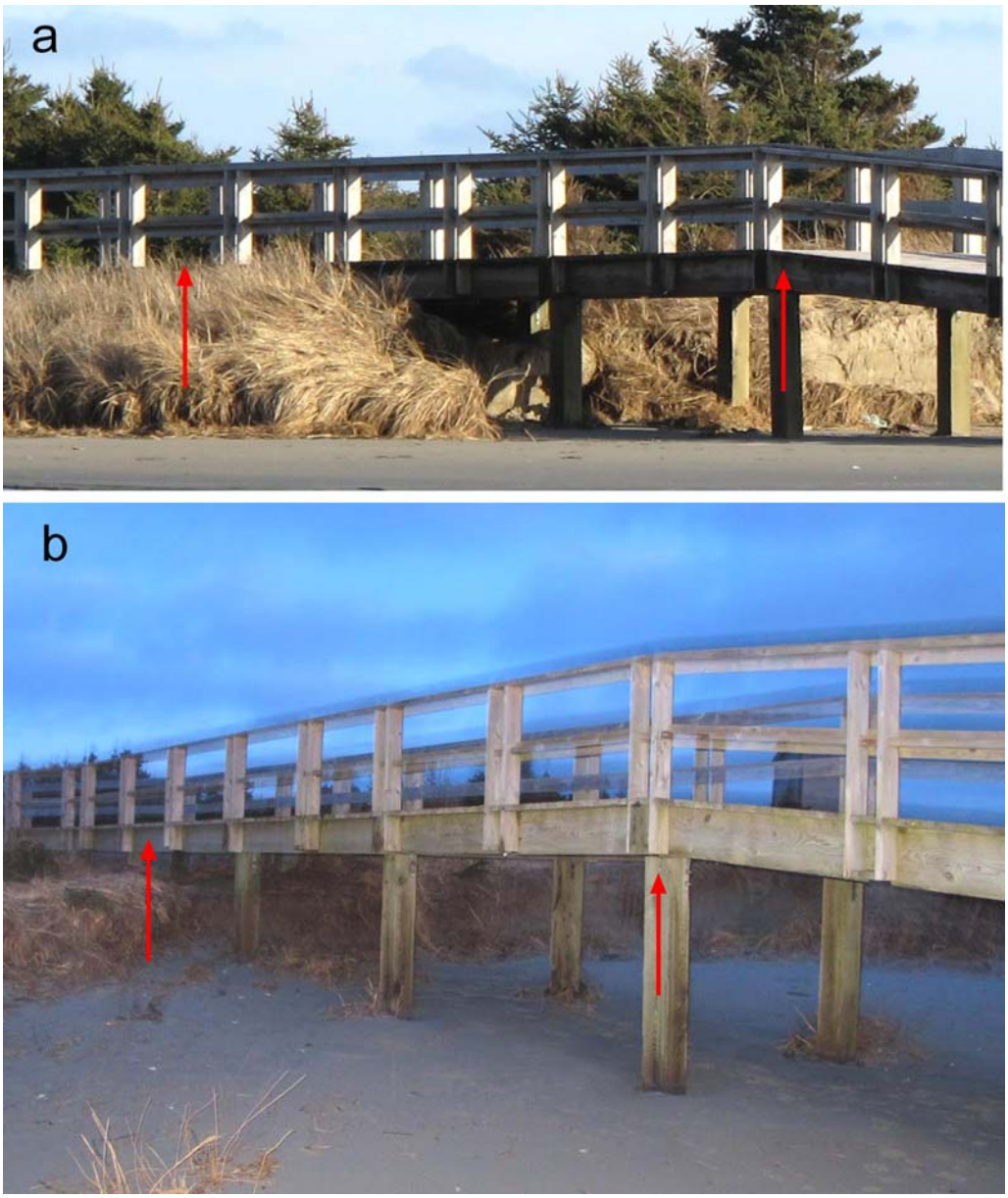


Miseners Long Beach, East of line 4 the beach substrate was revealed when large scale beach cusps developed during the December 6th storm and exposed backshore sand dune (arrow). Buried as the beach migrated landward, the sand dune has provided a wide foundation for barrier beach building between 2004 and 2010 (photo PC098487).

Miseners Long Beach, Repetitive photos at Line 2a (a) in 28 November 2010 and (b) 6 January 2011 and (c) surveys showing beach crest elevation was maintained as the crest was pushed 1.8 m landward by the December 2010 storms.



Clam Bay Beach **Sand Beach**



Clam Bay Beach, Repetitive photos of a boardwalk on (a) Dec. 12 2010 and (b) Jan. 1, 2011 (D. Mercer, AES). The 1.5 m high dunes were cut back 3-3.7 m during the last three storms (based on an upper support post spacing of 1.5 m (5 ft)). Red arrows mark same locations for visual reference.

Summary

Impacts of a series of storms occurring in quick succession during December 2010 were documented by frequent field observations and at least two repetitive cross-shore surveys at four representative shore types along the Eastern Shore, Nova Scotia. The first storm with high sea level and large waves caused the most flooding and left the shores vulnerable to subsequent wave attack. The second and third storm coincided with lower water level or smaller waves but their impacts were noteworthy because of their quick succession and lack of interim beach recovery. The last storm coincided with high water level and estimated higher waves which caused the largest physical impacts to these shores.

The length of beaches examined were sufficient that storm impacts varied alongshore depending on antecedent beach condition. This summary of impacts to specific shore types emphasizes impacts critical to individual beach integrity and focuses on where contrasts in response between different parts of each beach are increasing.

At Miseners-Long Beach, representative of a high gravel barrier, increased development of small washover channels, deep cuts into the beach face, increased beach crest migration and significant localized backshore deposition all imply increased beach mobility, instability and shift toward a low gravel barrier beach.

At Cow Bay Beach, representative of a low gravel barrier, specific small segments of high, narrow barrier were being thrust landward and old anchor points were impacting inshore wave attack more, a backbarrier mud substrate was more exposed and the primary tidal channel switched location. All imply continued rapid barrier migration into Cow Bay lake.

At Lawrencetown Beach, representative of a mixed sediment barrier, contrast in beach response is increasing as the east and west portions become more embayed from the mid-barrier anchor. In the east, narrow foredunes are collapsing and washover channels have extended into large backshore craters (dug during beach mining activities) which are capturing sediment and accelerating the breakdown of adjoining shores. To the west, the movement of large quantities of coarse clasts to the upper beach has separated the foredune from lower beach sand supply. Increased dominance of the massive pebble cobble swash ridge and dune burial suggest this part of the beach is evolving into a high gravel barrier similar to Miseners-Long Beach.

At Conrads Beach, representative of a sand barrier beach, contrasting beach responses east and west of Fox Island are increasing. Foredune retreat was accelerated by repeated wave attack along the shores east of Fox Island. The sand appears to be supplying Stoney Beach east of Conrads Beach and a tidal channel discharging from Lawrencetown Lake. The foredune west of Fox Island was also cut back by waves, however aeolian deposits accumulated along parts of the foredune crest and sand was infilling the dune scarp by March 2012. Along the west shore, longer term foredune progradation was only temporarily interrupted whereas the east shore was in an erosional phase of its evolution.

Table 2. Physical impacts of the December 2010 storms to specific barrier beach types along the Eastern Shore of Nova Scotia. Cumulative impacts are listed and highlighted in the last row.

High Gravel Barrier	***Low Gravel Barrier***	***Mixed Sediment Barrier***	***Sand Barrier***
wave overwash of low areas and subsequent initiation of new channels with lobes built into lake	extensive wave overwash of low backshore	narrow dunes weakened and collapsed by wave run-up, forming new washover channels	severe scouring of dune face, waves overwash low dunes
sand at lower beach transported seaward; variable upper beach response; exposure of old dune substrate	variable beach crest response: landward thrust of high, narrow beach; building at another area.	beach sand combed offshore massive pc ridge built seaward of foredune	repetitive scouring of dune face leads to exposure of pebble cobble substrate and building of beach cusps
localized landward crest migration and significant backshore deposition	deep scouring of lower beach and exposure of mud substrate.	new washover channels widened and backshore deposition accelerated	beach slope lowering and seaward transport of sand
	sediment infill of old tidal channel; channel switching with lake flow capture		sand infill along western dune scarps by March 2012
Barrier Mobility and Instability Increasing. lower beach crest, increased number of washover channels and localized large-scale backshore deposition	***Barrier Breakdown Continuing***:-with landward thrusts of small beach segments and inlet switching	***Backshore Changes Increasing*:** Large deposition of pebble - cobble upslope to west; washover channels link with man-made backshore craters to east	***Increased Contrasts in Foredune Evolution:*** Dune erosion accelerated to east; dune building temporarily interrupted to west.

Table 3. Largest impacts measured at four beaches before and after the four storms in December 2010.

1. High Gravel Barrier **(Miseners-Long Beach),**

Max. Distance of Beach Crest Retreat	1.9 m
Highest Beach Crest overwashed	4.6 m
Max. Backshore Deposition:	0.8 m
Max Distance of Beach Change at HHWLT	±1.9 m
Beach lowering at HHWLT	0.2 m

2. Low Gravel barrier Low **(Cow Bay Beach)**

Max. Distance of Beach Crest Retreat	8.5 m
Highest Beach Crest overwashed	3.6 m
Max. Backshore Deposition:	1.0 m
Max Distance of Beach Change at HHWLT	± 4.0 m
Beach lowering at HHWLT	1.3 m

3. Mixed Sediment Barrier (Lawrencetown Beach)

Max. Distance of Dune Retreat	8.0 m
Max. Distance of Beach Crest retreat	12.9 m
Highest Beach Crest Overwashed	4.1 m
Max. Backshore deposition (in washover channel)	0.6 m
Max. Distance of Beach Retreat at HHWLT	8.0 m
Beach Lowering at HHWLT	0.7 m

4. Sand Barrier **(Conrads Beach)**

Max. Dune Erosion in one storm	4.3 m
Max. Total Dune erosion (Dec.2010)	9.1 m
Max. Elevation of wave run-up	4.1 m on SE facing shore 3.3 m on SW facing shore
Max. Elevation of flood line	1.8 m
Max. Distance of Beach Retreat at HHWLT	7.6 m
Beach Lowering at HHWLT	0.3 m