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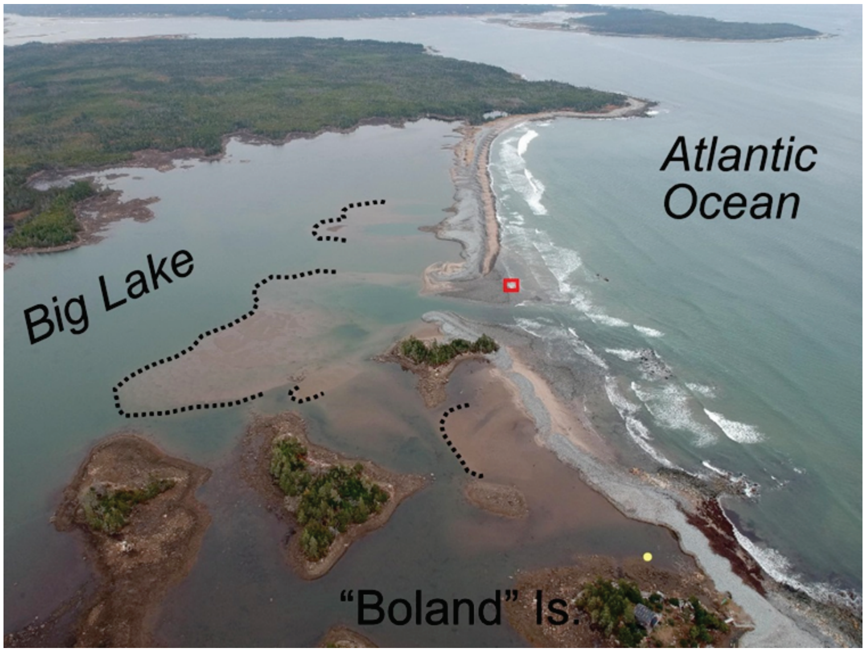

High water levels in Big Lake, caused by Hurricane Dorian (Sept. 7, 2019) and changes to Long Beach, Nova Scotia

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Abstract

Hurricane Dorian in September 2019 provided the first opportunity, since the present tidal channel opened through Long Beach in March 2019, to observe the impacts of storm generated waves and water level fluctuations along the inner shores of Big Lake. In-situ water pressure and CTD recording gauges within Big Lake provided new insights into changes in hydrology that are occurring. The accelerated deterioration of Long Beach in 2018 and 2019 and its response to the presence of an inlet marks a new phase in its evolution, which may have begun 20 years ago and possibly marks the renewal of a phase of barrier instability that prevailed before 1945.

Hurricane Dorian produced record water levels of 2.6–2.8 m (CGVD28) in Big Lake when it was tidal compared with 2.2 m (CGVD28) when it was non-tidal during Hurricane Juan (2003). In 2019, shore infrastructure along the exposed northern shores of Big Lake was damaged by strong easterly winds and waves that coincided with high tide. Waves extended onshore to a maximum elevation of 3.04 m (CGVD28). This elevation provides a basis for mapping flood hazards along this shore at present sea level. In contrast, wave run-up of 4.0 m was measured along the outer shore at Long Beach. Therefore, while the tidal inlet allowed the storm surge into the lake, the beach continued to protect inland properties against wave action during Hurricane Dorian. However, longshore changes to its crest elevation have caused differential landward shore migration. Physical response to future storms along each of the three segments of Long Beach will be different as each segment migrates landward. For the near future, the western barrier should provide the best protection for inland properties against wave attack however, with projected rises in sea level, natural stress on the barrier will continue.

Cover Photo: Aerial view looking east over Big Lake and Long Beach, Nova Scotia taken on 14 Oct. 2019, using an aerial drone, courtesy of R. Kraemer. The dashed lines highlight the extent of sediment deposited in Big Lake as a result of several temporary inlets that formed in 2018 and at the present inlet which formed in March 2019. Also marked are the location of a pressure-depth sensor (yellow dot) deployed in 2019 and bags of sediment used to close an inlet in Jan. 2010 (red box).

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High water levels in Big Lake, caused by Hurricane Dorian (Sept. 7, 2019) and changes to Long Beach, Nova Scotia.

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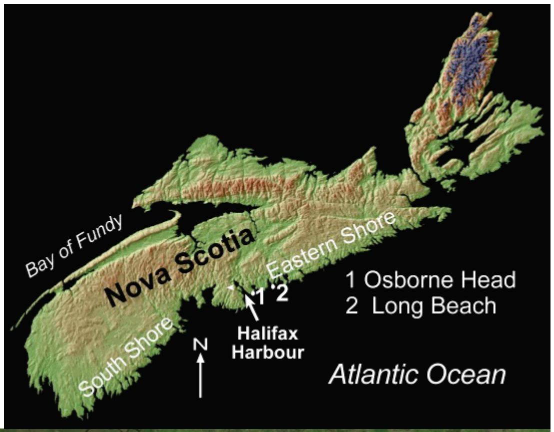
Introduction

When Long Beach began deteriorating and breaking apart in January 2018, a concern of local residents living along Big Lake (Fig. 1) was the switch to tidal conditions and the anticipated increase in water levels, and storm wave impacts on waterfront properties. The Nova Scotia Department of Natural Resources (NSDNR) had issued a contract to CBCL to investigate the implications of long-term coastal change for potential increased erosion and property flooding, as well as recommendations for future coastal damage mitigation (CBCL, 2018). Results presented by CBCL at a public meeting in March 2018, and the decision by DNR not to repair the barrier beach, failed to alleviate the concerns of citizens.

Long Beach, located east of Halifax along Eastern Shore of Nova Scotia (Fig. 1) forms a 1.4 km long barrier fronting Big Lake. The Geological Survey of Canada Atlantic (GSCA) has been monitoring physical changes and the impacts of storms on the stability of Long Beach since 1985 (Taylor et al. 1995, in prep). Long Beach was selected for study because it represented a specific shore type observed in Atlantic Canada — a high gravel barrier beach (Forbes et al. 1990). Long Beach also provided a contrast to another shore type - a low gravel barrier beach — that had been studied at nearby Story Head Beach, at the mouth of Chezzetcook Inlet, Nova Scotia (Fig. 1). Documenting changes occurring along these two types of barrier beaches contributed to an understanding of gravel beach response to storms and their long-term evolution during a rising sea level (Forbes et al. 1995; Taylor et al. 2014). The GSC contributed background information to CBCL for their study, and have continued to investigate changes at Long Beach and Big Lake as part of their mandate to investigate coastal hazards to Canadians.

Hurricane Dorian in September 2019 provided the first opportunity, since the present tidal channel opened through Long Beach earlier that year (cover photo, Fig. 2), to observe the impacts of storm-generated waves and tidal fluctuations along the inner shores of Big Lake. Long Beach, when it was continuous, was able to recover naturally and rebuild after being struck by storms such as Hurricane Juan in 2003. The presence of a tidal channel now raises questions about its impact on the natural ability of Long Beach to rebuild after a major storm.

Figure1. Long Beach, Story Head Beach, and other places mentioned in the text. Also shown are the cross-shore lines (-1, 0, 1, 2, 3, 4-white lines) used to monitor beach changes, the locations of water depth pressure sensors (a, b, c – yellow dots) and the stream channel (red dash line) which drains water from Big Lake toward Chezzetcook Inlet when lake levels exceed 1.4 m (CGVD28). Flood debris lines resulting from Hurricane Dorian were surveyed in three areas outlined by white boxes and specific flood lines are shown in Figure 7 and listed in Table 2. (The base photo is from ESRI Digital Globe 2016).



Process Environment

The Atlantic coast of Nova Scotia (Fig. 1) is storm wave dominated and characterized by sharp seasonal contrasts in wind, wave and ice conditions (Forbes and Taylor, 1987). Water level which varies over a wide range of time scales is an important factor controlling inshore waves. Sea level has been rising for thousands of years, since the last post-glacial low stand. The rise is a combination of crustal subsidence relating to deglaciation, and eustatic factors. In Halifax, the tide gauge records show a rate of sea-level rise of 32 cm/century since 1920, of which 10 –13 cm/century is due to crustal subsidence (Forbes et al., 2009, James et al. 2015). The projected median sea level rise will accelerate from 21.0 –24.4 cm (2020 to 2050) to 46.6 – 65.9 cm (2020 to 2100) for Halifax (James et al. 2015). These projections were based on low to high carbon emission scenarios RCP2.6, to RCP8.5 (Representative Concentration Pathway) published in the fifth Assessment Report of the Intergovernmental Panel on Climate change (IPCC AR5), and on GPS observations of vertical crustal motion.

Storm conditions are generated by extratropical cyclones known as northeasters passing across the region between October and March and by tropical cyclones moving north along the US seaboard in the months of June to November. Tides are mixed semi-diurnal with a spring range of 2.1 m in Halifax Harbour (Fisheries and Oceans Canada, 1997). Storm surges greater than 0.6 m occurred on average 2 to 4 times annually between 1980 -1995 and a surge of 1m was an unusual event occurring once a decade (Parkes et al. 1997). The highest recorded water level and surge in Halifax was 2.9 m CD (2.1 m CGVD28) during Hurricane Juan in September 2003.

Methodology

Between 1985 and 2011, repetitive surveys were completed at 5 to 7 cross-shore transects (Fig. 1-lines) and along the crest of Long Beach using conventional survey technology (levels, theodolites, paired rods, electronic total station, and real-time kinematic GPS). Surveys were completed on average 3 to 4 times each year, focussing on the impacts of significant storms (Taylor et al. 1997a,b, 2008, 2010, 2013, 2014, in prep). Visual observations of changes at Long Beach were continued by the lead author from 2011 to 2016. GSCA resumed monitoring of Long Beach in 2016 using consumer grade aerial drones, or unpiloted aerial systems (UAS), to collect topographic 'Structure-from 'Motion' (SfM) photogrammetry data. This technique allows for rapid collection of elevation and photogrammetric data for temporal monitoring or following storm events. Elevation data are limited to portions of the barrier that are above water and are not obscured by wave swash.

UAS photogrammetry surveys are conducted by capturing overlapping vertical and oblique aerial photos while flying in a predetermined grid at a fixed elevation (Fig. 3). Photographic targets (7 – 20 targets per survey) are dispersed throughout the survey area to be used as Ground Control Points (GCPs). Target positions are surveyed to an accuracy of ~1 — 2 cm horizontally and ~2 – 4 cm vertically using geodetic GPS. Horizontal coordinates are referenced to UTM Zone 20 N (CSRS). Vertical coordinates are on the Canadian Geographic Vertical Datum of 1928 (CGVD28).

On 10 September 2019, SfM photos were collected with a DJI Phantom 4 Pro from an altitude of 70 m to yield an average ground sampling distance of 2 cm (Fig. 3). A total of 15 GCPs were collected with an RMS error of 1 cm. The survey on 26 August 2019 was collected without ground control and the back side of the barrier was not completely imaged because the primary purpose of the flight was to test a recently repaired UAS. The August survey was later corrected using 11 GCPs (RMS 1.5 cm), which were obtained from stable features identified and located on the 10 September 2019 and 18 April 2019 surveys (Fig. 3). The commercial photogrammetry software, Pix4D Mapper, was used to produce 3D point clouds, Digital Elevation Models (DEMs) and orthophoto mosaics for each survey. Point clouds were classified in Pix4D Mapper to aid in the removal of vegetation and man-made features where required. DEMS were edited manually to remove waterline artifacts. The resultant point clouds, DEMs, and orthophoto mosaics were then used for analysis in GIS software.

After Big Lake became tidal in January 2018, there was a new emphasis to document and better understand the changes in its water level and chemistry. Pressure (depth) and CTD (conductivity-temperature-depth) sensors were deployed to monitor changes in lake conditions (Fig. 1, sites “a, b, c” Appendix A). The location of the sensors was changed when mooring sites were threatened by the migration of Long Beach. The second pressure sensor, deployed on 17 May 2018, (Fig. 1 site”a”) was not removed before ice formed on the lake late that year; as a result, it was not discovered until 28 March 2019 that the gauge had stopped recording on 15 October 2018. For this reason, water level associated with the event that severed Long Beach on 23 March 2019 was not captured by the gauge. In March 2019, a CTD recorder was deployed with a pressure sensor (Fig. 1 site”b”), but it was removed on 30 May 2019 and not replaced until 29 August 2019. Both sensors were removed on 25 October 2019. On that date, a replacement pressure sensor was deployed at a new location (Fig. 1 site “c”) along the northern shore of Big Lake, opposite the present tidal inlet (Appendix A).

The gauges in Big Lake were established on the lake bed, anchored to a metal bar and not contained within a stilling well. Absolute pressure was measured by the sensor which included atmospheric pressure and water head. Pressure sensor depths were converted to water depths by subtracting the air pressure recorded at the Osborne Head coastal weather station (Fig. 1), 20 km west-southwest of Long Beach. Surface elevations of Big Lake were obtained by adding the sensor water depths to the surveyed elevation (CGVD28) for each gauge (Appendix A).

Figure 2. Aerial drone images of central Long Beach taken between October 2018 and September 2019 showing the narrow barrier that existed prior to when the inlet was cut in March 2019 and subsequent changes to the inlet and landward migration of the adjoining shores before and after Hurricane Dorian in September 2019. Sediment transferred into the inlet from the adjoining shores made them vulnerable to increased wave overwash and landward migration. During Hurricane Dorian the inlet was expanded eastward as the barrier migrated landward of the island. The red triangles mark the position of markers on the survey lines and provide a visual reference of the landward migration of Long Beach during 2019.

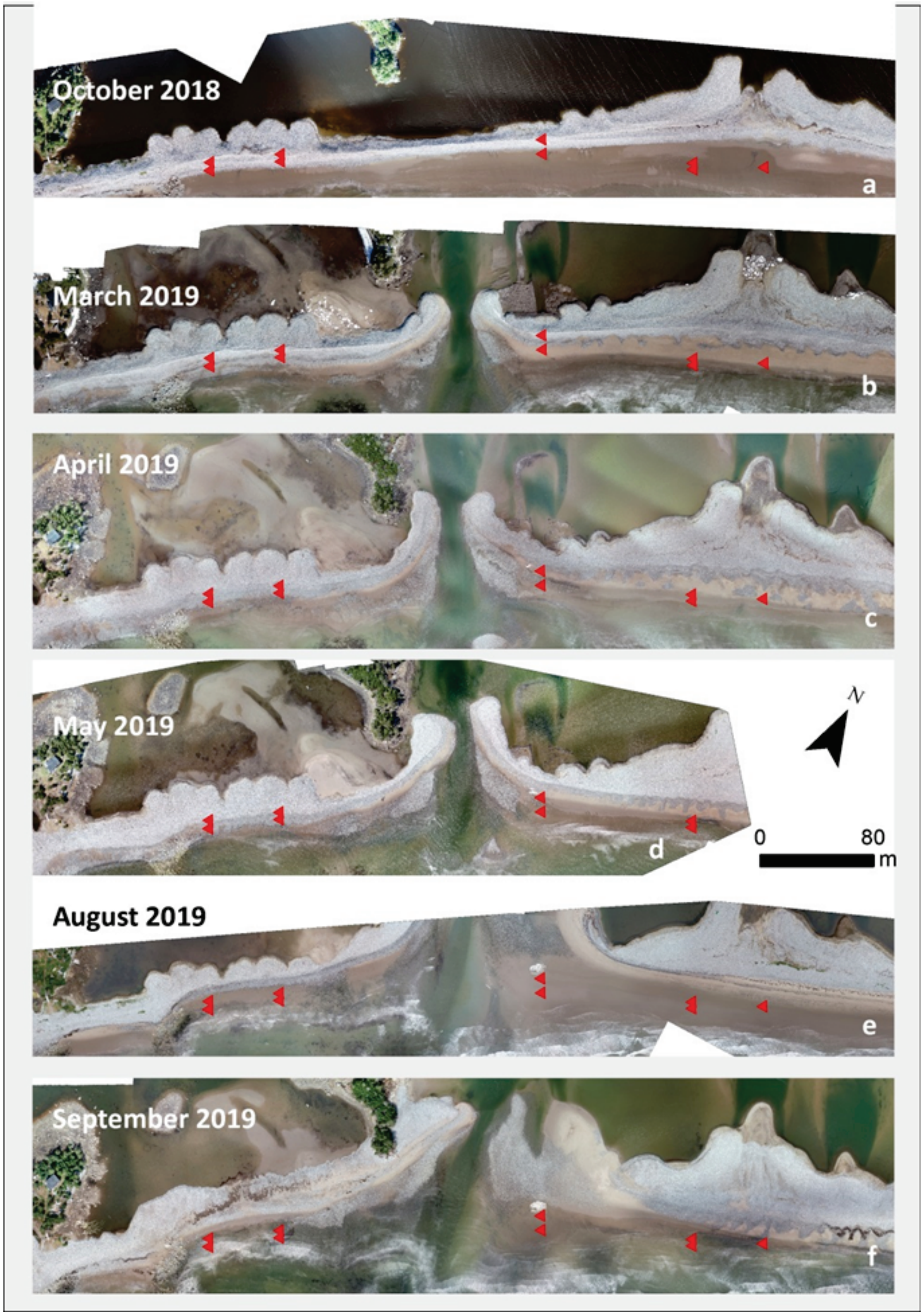
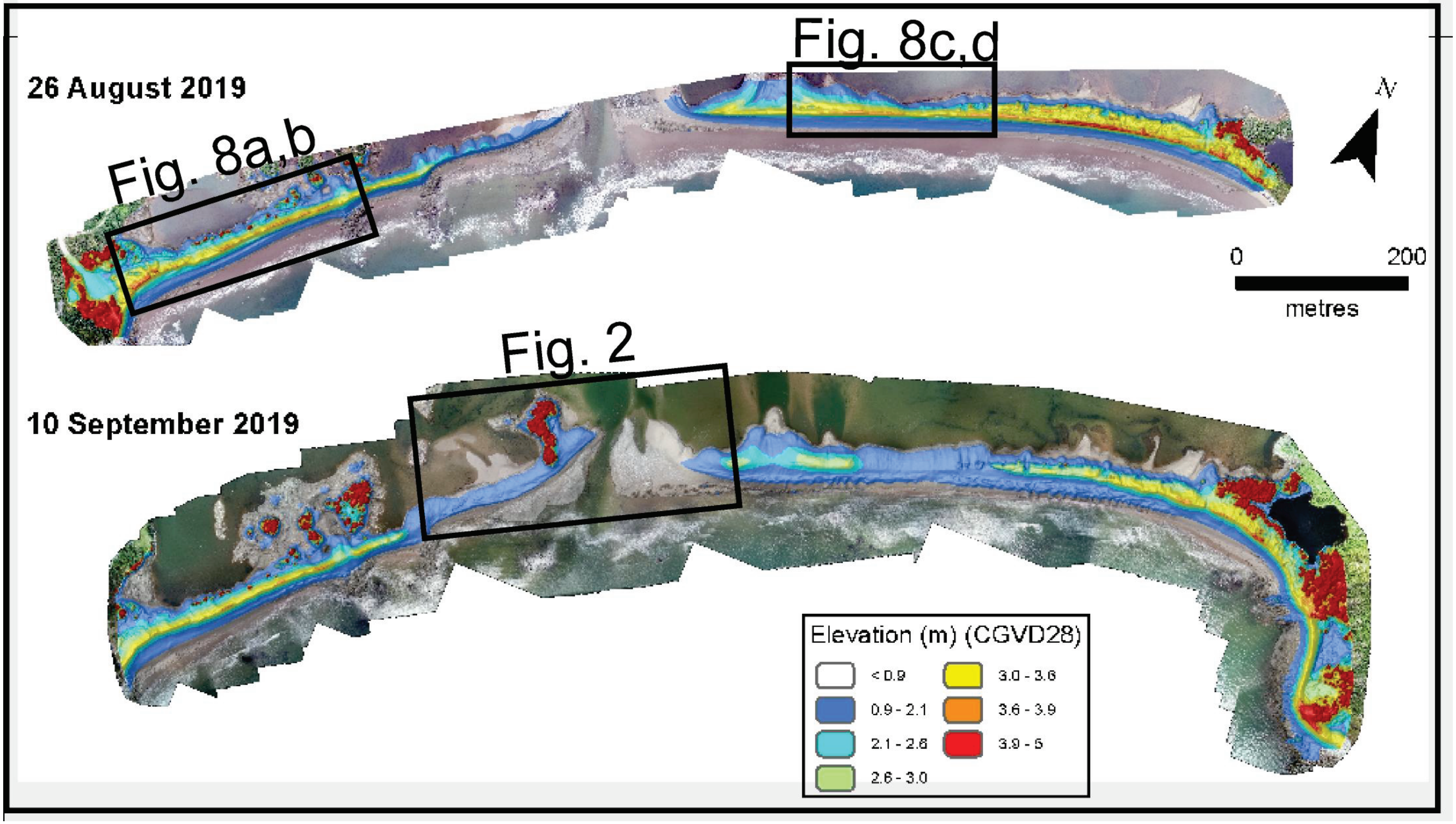


Figure 3. Digital surface elevations of Long Beach compiled from aerial drone surveys showing the elevation of the barrier beach crest that existed in August 2019 and Sept. 2019 and the relationship between barrier crest elevation and wave overwash during Hurricane Dorian. Wave overwash and landward barrier migration progressivly increased as the crest elevation decreased from 3.9 to 0.9 m (CGVD28). Enlarge the image to distinguish the different crest elevations.



During Hurricane Dorian wave data were obtained from buoy C44258 situated in 58 m of water south of Halifax Harbour (Fig. 1) (Fisheries and Oceans Canada http://wwwmeds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/waves-vagues/index-eng.htm) and water levels were from station 491 at the Bedford Institute of Oceanography (BIO) Dartmouth, Nova Scotia (Fig. 1) (Data courtesy of the tidal section, Canadian Hydrographic Service). Weather observations were obtained from Environment Canada weather stations at Halifax Airport, Shearwater, and Osborne Head DND site (Fig. 1) (44°36'46.002"N, 63°25'23.007"; 30 m elevation; Environment Canada Historical Data web site) https://climate.weather.gc.ca/historical_data/search_historic_data_e.html.

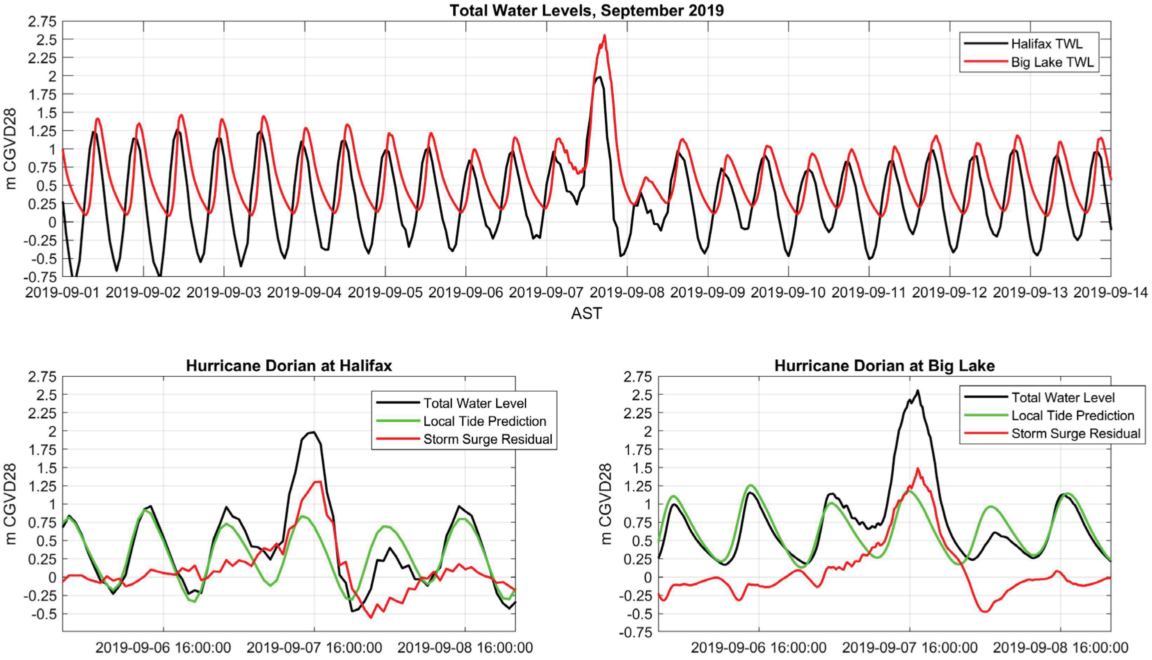
Hurricane Dorian

Climatic and Oceanographic Conditions: During Hurricane Dorian on 7 September 2019, the highest significant wave height reported at buoy C44258 was 9.5 m with a period of 12.2 seconds at 20:20 UTC (17:20 ADT). Sustained wind speed was 20.1 m/s (72 km/hr) from the ESE, then shifted to NW. Atmospheric pressure at the wave buoy was 963 hPa and dipped to its lowest level (960 hPa) an hour later (18:20 ADT). Significant wave heights exceeded 4 m between 11:20 and 00:20 ADT on 7- 8 September and they exceeded 1.5 m for a total of 37 hours (Table 1). Sea surface temperature was 17.9°C. Onshore, at the Osborne Head weather station, the air pressure during Hurricane Dorian reached a minimum of 956 hPa slightly later at 20:00 ADT. Winds exceeded 50 km/hr for 19 hours on 7 September and peaked at 101—102 km/hr from the east to east-northeast from 15:00 to 17:00 ADT.

Water levels (Fig. 4) recorded at tidal station 491 (BIO) on September 7 reached a maximum of 2.83 m (CD) or 2.03 m (CGVD28) at 17:30 ADT (15-minute averaging interval) one hour after predicted high tide and 2.09 m (CGVD28) at 17:24 ADT (1-minute recording interval). The storm surge, which coincided with the highest water, peaked at 1.38 m. Storm surge conditions (> 0.6 m) lasted for eight hours. Water levels reached during Hurricane Dorian were similar to those observed during Hurricane Juan in 2003 (2.91 m CD), given the local differences in wind and set-up at the two stations used to obtain the data (Halifax and BIO 491 BIO). Water levels during Hurricane Dorian were slightly higher than those during other storms (January 2010, January 2018, and March 2019; Table 1) when Long Beach was severed temporarily.

Water Levels and Conditions In Big Lake: During Hurricane Dorian, the pressure gauge in Big Lake (Fig. 1 - location b) recorded (15-minute averaging interval) a surge of 1.5 m which coincided with high tide to produce a total water level of 2.56 m (CGVD28) at 18:15 ADT, 7 September (Figs. 4, 5). A spectral analysis of observed 1-minute water levels in Big Lake for September 7 indicated a maximum water level in Big Lake of 2.78 m (Fig. 5). The spectral

Figure 4. Comparison of water levels filtered to 15- minute interval for Big Lake (Location b, Fig. 1) and tidal station 491 in Halifax Harbour in early September 2019 and during Hurricane Dorian. Note: the tide prediction for Big Lake is based on a tidal analysis of the local tide gauge data.



analysis also detected the presence of a sub-tidal energy peak of period 3-4 minutes (Fig. 5) which may be due to nearshore infragravity (IG) wave energy propagating into the lake and/or lake seiching, i.e. resonant oscillation during high tide.

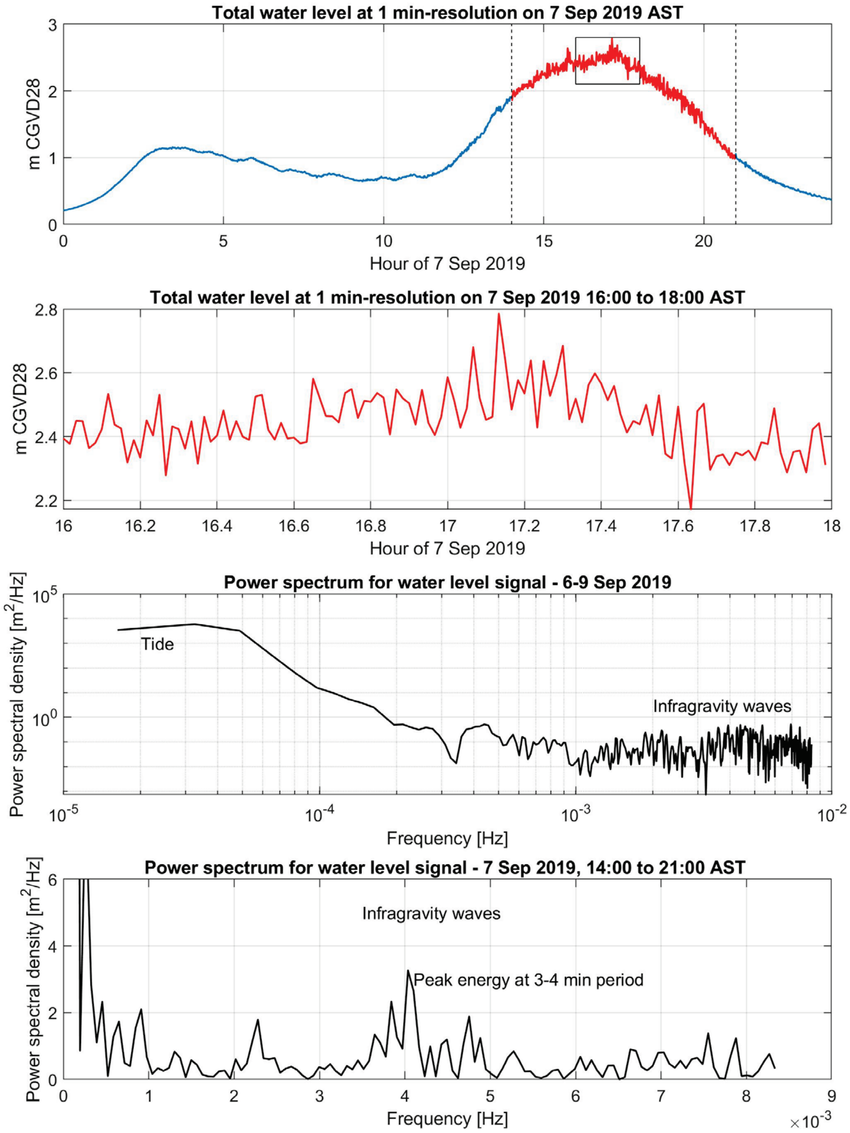
IG storm wave energy has been observed along Nova Scotia's wave-exposed Atlantic Coast where it has produced elevated water levels, increased current velocities in tidal passes and significant resonance in harbour basins (Leys et al. 2018). The implications of the presence of longer period waves in Big Lake will require further observation and analysis but the impact of IG waves is a very small component of the total storm surge produced. However, the impact on tidal pass dynamics maybe an important topic to examine.

*Table 1. Marine conditions during storms that severed or contributed to the cutting of Long Beach between 2010 and 2019. Tidal data were derived from CHS gauge 491 at BIO, Halifax Harbour (Fig. 1). Wave data were available from two buoys (a) C44258 in 2010 and 2019, located in deeper, more exposed water, and (b) the Smart Buoy at Herring Cove (Fig. 1) in 2018 and March 2019, when C44258 was not available (Data courtesy of CHS/DFO, MEDS, and Smart Atlantic). *To convert GMT time to ADT subtract 3 hours.*

Date	**Tidal Conditions**		**Wave Conditions**		
	Surge Duration (hrs)	Peak Water Level Elevation CD (m) (Time (GMT), Date)	Max. Sig. Wave Ht. (m) (Time (GMT), Date)	Duration (Hrs) Sig. Wave Ht. Exceeds 1.5 m	Wave Peak Period (sec)
02-Jan-2010	9.5	2.79 (21:30, Jan.2)	7.4	101	12.8
04-Jan.-2018	12.5	2.72 (22:00, Jan. 4)	7.3 (22:53, Jan. 4)	27.5	14
03-Mar.-2018	20	2.60 (09:45, Mar. 3)	3.7 (12:23 Mar. 3)	70—168	13.3
25-Feb.-2019	----	2.52 (04:00, Feb25)	6.5 (08:20, Feb.25)	62	10.7—13.5
23-Mar.-2019	0	2.43 (13:30, Mar 23)	5.1 (15:20—16:20)	69—77	11.6
07-Sept.-2019	8	2.83 (20:30, Sept.7)	9.5 (20:20, Sept.7)	37	12.2—15.0

Note: the breach was artificially repaired after the 2 Jan 2010 storm and closed by natural processes within 19-36 days after the storms of 4 Jan. and 3 Mar. 2018. However the barrier remained low and narrow in a number of areas making it possible for a series of smaller storms in early 2019 to breach the barrier again on 23 March 2019. (See the section Long Beach as a protective barrier for details).

Figure 5. (a, b) Observed 1-minute lake water levels for 7 Sept. 2017 with a spectral analysis (c, d) of the water level signal indicating the presence of nearshore infragravity (IG) wave energy propagating into the lake and/or lake seiching, i.e. resonant oscillation, causing a sub-tidal energy peak of period 3—4 minutes during the highest water levels produced by the storm.

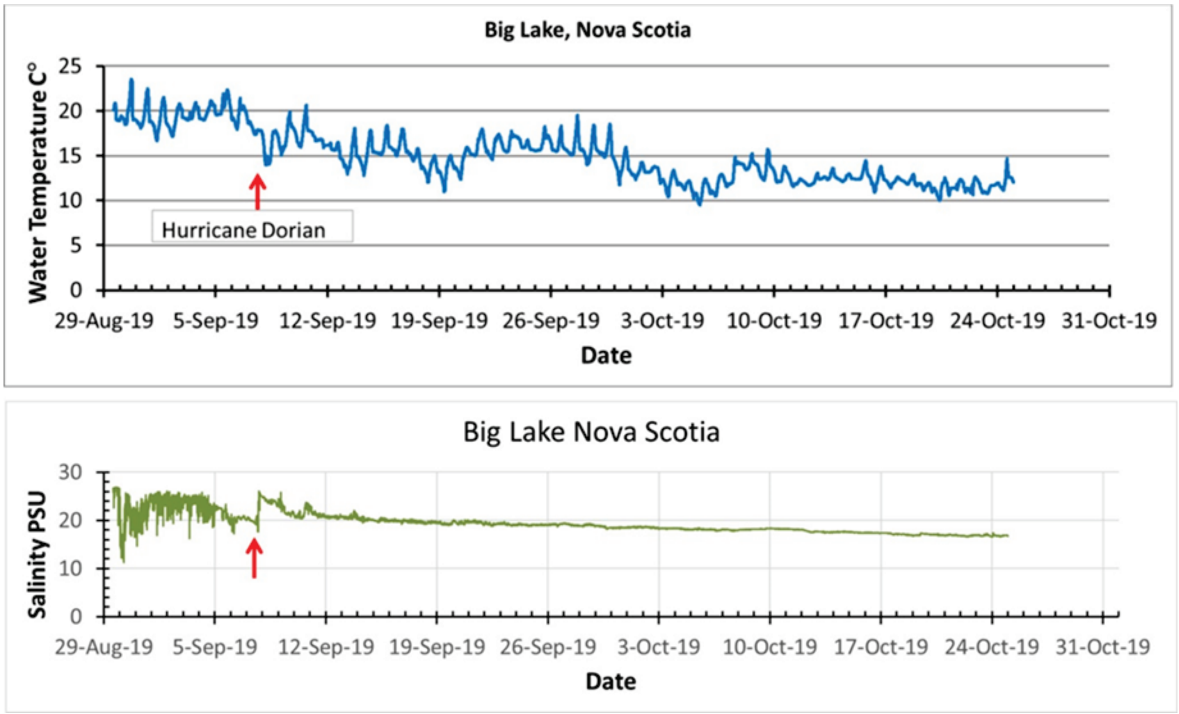


Note: Infragravity (IG) waves are ocean surface waves with a typical period of 25-250s. Formation of infragravity waves can be related to the merging of two wave trains of slightly different wave lengths, but the same amplitude which can induce a long bound wave, or *to the varying breakpoint of short-wave groups in shallow water. The first mechanism is strongest on gently sloping beaches; the second mechanism occurs on steep beaches. Infragravity waves are generally small on the open ocean, but close to shore, swash heights can be in excess of 0.5 meters on low- gradient sand and steep gravel beaches (Billson et al. 2019).* Infragravity waves can play a crucial role in wave run-up, overwashing and barrier breaching.

Water salinity in Big Lake dipped from 20.0 to 17.6 PSU at 18:34 ADT, then rose sharply to 23.9 PSU by 19:19 ADT, and reached a maximum of 26.1 PSU at 19:39 ADT (Fig. 6). These changes in salinity document the peak of the storm, when the maximum influx of seawater and mixing of Big Lake occurred. The salinity of Big Lake decreased to 16.7 PSU by 25 October 2019.

Water temperature in Big Lake was less responsive than salinity. During the storm, temperature in Big Lake was 17.8 °C at 18:30 ADT, similar to the temperature at the wave buoy off Halifax Harbour (Fig. 6). Water temperature remained fairly constant until roughly 22:30, when it started to drop and fell below 15 °C after 02:50 ADT on September 8. Water temperature had recovered to pre-storm levels of 17.8 °C by late afternoon on September 8 and decreased to 12°C by October 25.

Figure 6. Changes in water temperature and salinity recorded during 2019 at sensor" b" (Fig. 1) in Big Lake. A sharp drop in water temperature and increase in salinity was observed during Hurricane Dorian. It is not clear why the graph of salinity was smoother before and after the hurricane.



Wave Run-up, Flood Levels and Changes to Long Beach: The impacts of Hurricane Dorian on Long Beach and Big Lake were documented from repetitive ground and aerial drone surveys completed on 26 August and 10 September 2019 (Fig. 3).

Debris lines were surveyed to record the extent and elevation of wave run-up and flooding (Fig. 7, Table 2). During the storm, wave run-up extended across all of Long Beach but the magnitude of overwashing and the extent of landward beach migration depended on beach crest elevation, barrier width and whether trees or other shrubs existed along the backshore prior to the storm, e.g. at Line 0 (Figs. 1, 3, 8, 9, 10). Where the crest and backshore were higher than 4 m, i.e. at the western headland and island at the central barrier, waves scoured the slopes and toppled trees (Fig. 9a). Between 3.9 and 4.0 m (CGVD28) elevation, waves extended to the crest and water flowed over it, but with little movement of pebble cobble clasts across the backshore. The lack of backshore change on the higher western barrier is represented by changes at Line -1, (Figs. 1, 3a, 8a, 10). Where the beach crest was less than 3.9 m (Fig. 3a) increased volumes of water overwashed the crest and transported sediment and debris down the back-barrier slope, in many cases into Big Lake (Figs. 8, 9b, 10). For comparison, during Hurricane Juan in 2003, wave run-up commonly reached 2.4 to 2.8 m and a maximum of 3.3 m at the east end.

The greatest physical changes to Long Beach were recorded along the central barrier, between "Boland" Island and the tidal inlet. Prior to the storm, the barrier crest was commonly less than 3 m (CGVD28) elevation and its width was less than 10 m (Fig. 3a). This section of barrier, represented by Line 2 (Figs. 1, 9c, 10b), was flattened, pushed 3 to 15 m landward, and rebuilt on the former lake bed. Significant amounts of sand were deposited landward of the low barrier. Organic lakebed deposits were exposed seaward of the new barrier, confirming its landward movement (Fig. 9d).

East of the inlet, represented by changes at Line 4 (Figs. 1, 10c), low washover channels were flooded, scoured, and rebuilt as washover fans in Big Lake. Large volumes of sediment were needed to rebuild the barrier above water level (Fig. 10c). Sediment was supplied from the adjoining shores, which consequently became narrower, lower, and more vulnerable to wave overwash (Fig. 8d).

The only flood level surveyed at Long Beach was on "Boland" Island, (Front cover, Fig. 7) where water level, close to high tide, reached the lower steps of the residence (Susan Boland, pers. comm. 2019). The elevation was 2.48 m (CGVD28), compared with 2.15 m recorded during Hurricane Juan in 2003 (Table 2).

Although wave energy was dissipated in the inlet to Big Lake during the hurricane, inner shores opposite the inlet were impacted. The coincidence of waves and higher water levels produced by winds blowing from an east to northeast direction dislodged docks and wharfs along the northern shore of Big Lake (Fig. 11). Along the shore at and adjacent to the Hawkins residence, storm surge combined with wave run-up extended to elevations of 2.4 to 3.0 m (Fig. 7,points 1-7, Table 2).

In comparison, during Hurricane Juan in 2003, when Long Beach remained intact with no inlet, water level reached 2.2 m at the Hawkins residence and there was little wave damage to shore infrastructure.

Farther west along the outer coast, at the east end of Story Head Beach (Fig. 1), wave run-up reached 2.3 to 2.4 m elevation (Fig. 7, Table 2). During Hurricane Juan in 2003, wave run-up at the same location was 0.4 m higher (Table 2) and debris was deposited as high as 3.7 m where waves broke against the shore armour rock. Lower wave run-up at the eastern end of Story Head during Hurricane Dorian was attributed to its location being more sheltered from the strongest winds and waves with an easterly component.

Figure 7. Location of high water levels and storm debris lines surveyed after Hurricane Dorian at Long Beach and the adjacent shores. The geographic coordinates and elevations (CGVD28) of specific points are listed in Table 2. An enlarged map of points 1 to 7 along northwestern shore of Big Lake is provided on the photo to the right.

Flood waters also were surveyed along the inner bay and road leading to Story Head Beach and farther inland at a highway culvert that joins Big Lake to Chezzetcook Inlet (Figs. 7, 12). Flood debris elevations decreased from 2.3 m to 1.8 m toward the head of the embayment and to 1.7 m near the top of a highway culvert (Figs. 7, 12, Table 2).

Table 2. Elevation at one residence and flood and wave debris lines surveyed after Hurricane Dorian in September 2019 along the inner shores of Big Lake (1-7), the outer coast at Story Head Beach and at the highway culvert connecting Big Lake to Chezzetcook Inlet (8-21). The locations of survey points are shown in Figure 1, 7. Bracketed elevations in red are from debris lines and flood levels surveyed at roughly the same locations after Hurricane Juan in 2003.

Point	Easting	Northing	Elevation*	Comments
1	483570.6	4948319.3	5.89	Patio stones—Hawkins Residence
2	483591.8	4948314.1	2.43	Flood level Dorian (debris line)
3	483587.6	4948304.4	2.96	Wave Run-up (debris line)
4	483599.1	4948309.9	2.18	Top Corner seawall
5	483597.0	4948307.3	2.23	Juan 2003 flood level
6	483589.1	4948296.9	2.91	Wave Run-up (debris line)
7	483588.3	4948285.8	3.04	Wave Run-up (debris line)
8	483007.7	4947190.3	2.39 (2.89)	Wave debris line, Story Head parking area
9	483016.0	4947192.9	2.38 (2.66)	Wave debris line, Story Head parking area
10	483021.8	4947198.7	2.32 (2.66)	Wave debris line, Story Head parking area
11	483025.3	4947209.8	2.34	Wave debris line, Story Head parking area
12	483070.0	4947425.7	2.31	Wave debris line inner bay along road
13	483093.9	4947495.3	1.83	Wave debris/ Flood Line inner bay
14	483094.6	4947507.0	1.78	Wave debris/ Flood Line inner bay
15	483096.7	4947521.4	1.81	Wave debris/ Flood Line inner bay
16	483217.1	4947948.5	1.74	Flood line debris, south side Hwy
17	483218.0	4947956.7	1.75	top culvert south side Hwy
18	483204.0	4947961.0	1.84	Top culvert, north side Hwy
19	483203.6	4947961.4	0.44	Base Culvert, north side Hwy
20	483736.6	4947737.9	2.48 (2.15)	Flood water level, Boland Island Big Lake
21	483777.9	4947723.3	-0.14	Big Lake -Water level 13:21 ADT Sept. 10, 2019

* Elevations are relative to CGVD28 (2.66) Elevations recorded at or near same location after Hurricane Juan 2003.

Figure 8. Views of (a,b) western and (c,d) eastern Long Beach before and after Hurricane Dorian showing the extent of wave overwash. At the western end, (a,b red square) the backshore road was buried by pebble cobble which also built against trees, preventing the material from reaching Big Lake. At the eastern end (c,d) washover lobes were expanded landward in former inlets and into Big lake (red circle) where barrier crest elevations were <3.9 m and least where the backshore was wider and higher > 3.9m (right side of red circle). The cross shore line markers are marked by red triangles.

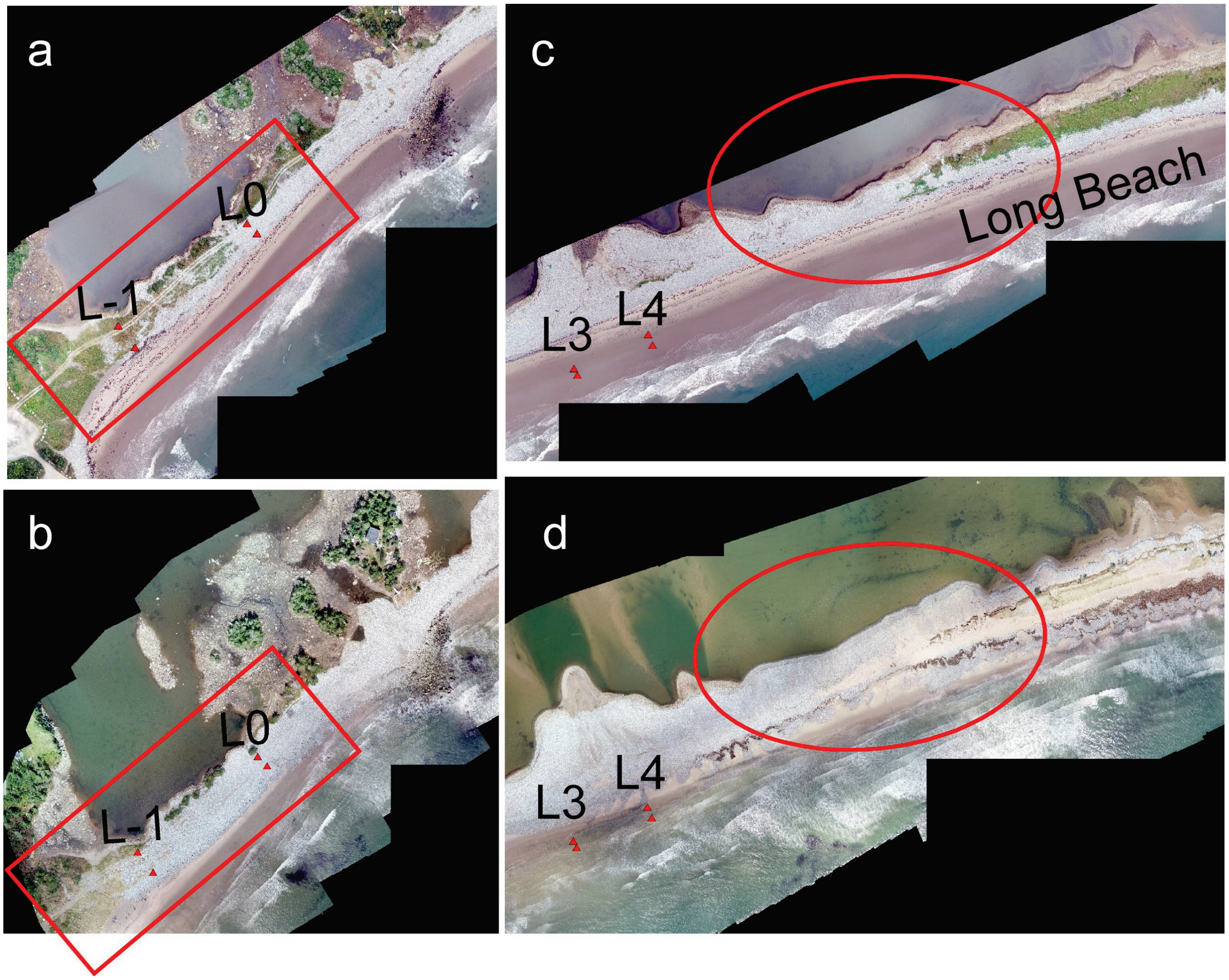
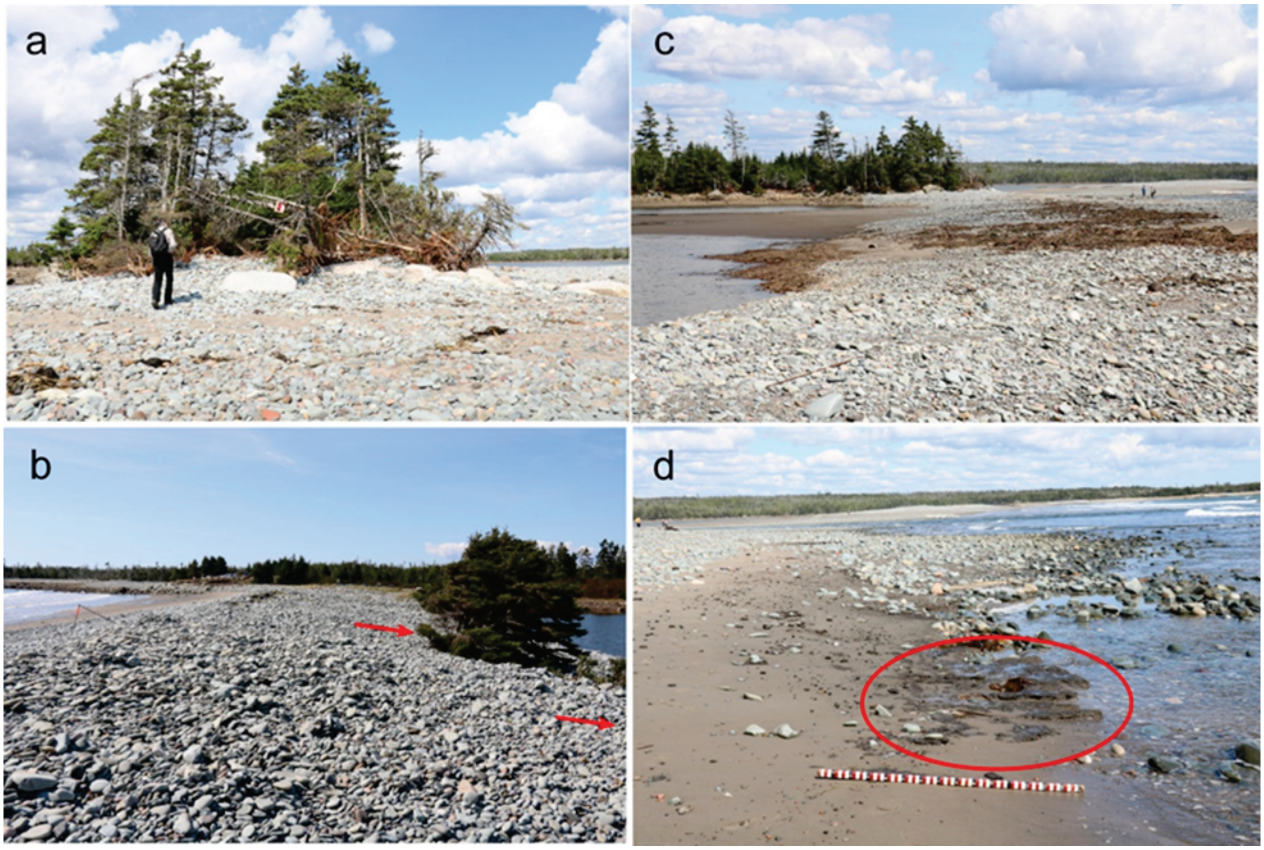


Figure 9. The impact of waves during Hurricane Dorian depended on backshore elevation before the storm. Where elevations were more than 4 m such as at the island (a) or western headland, waves eroded the backshore. Where elevations were lower, i.e. between 3.0 and 3.9 m (b) there was substantial wave overwash of pebble cobble across the backshore into Big Lake or the tree line e.g. Line 0. Where crest elevations were less than 3 m and the barrier was less than 10 m wide prior to the storm (c, d) e.g Line 2 (Fig. 1), waves flattened the barrier as it was pushed landward, exposing former organic lake bed (d-circled) on the seaward side of Long Beach. Photographs by R. B. Taylor, NRCan photos 2020-853 to 2020-856).



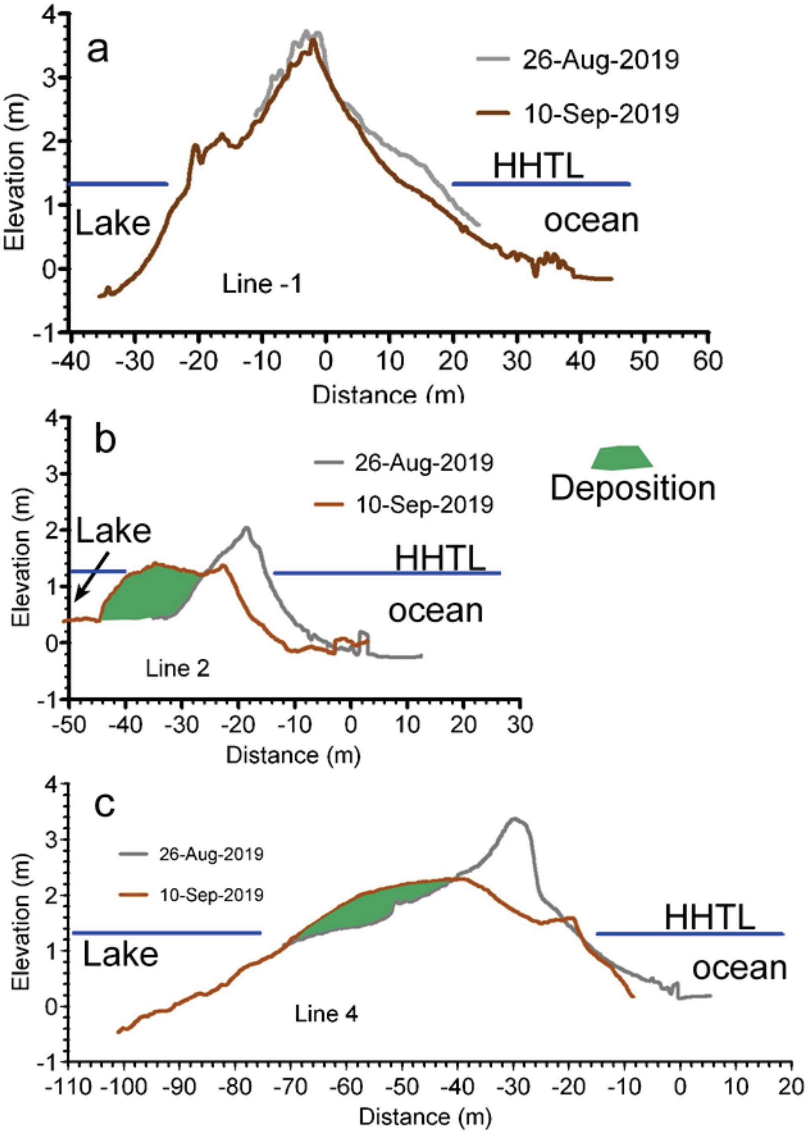


Figure 10. Examples of barrier beach changes at Long Beach where the crest elevations were (a) highest along the western end, (b) lowest in the middle and (c) intermediate elevation farther east. (a) At Line -1 wave washover of pebble cobble was minor. (b) At Line 2 where the crest was < 2.5 m elevation, extensive wave overwash rolled the barrier crest 15 m landward. (c) At line 4, waves pushed the narrow barrier crest 9.8 m landward and built the backshore platform higher.

Figure 11. Views of debris lines and damage caused by waves and elevated water level during Hurricane Dorian at the Hawkins property, Big Lake, Nova Scotia (Photographs by R.B. Taylor, 19 Sept. 2019, NRCan photos 2020-857, -858).

Figure 12. View of the south side of a highway culvert (red dash) that allows water to flow from Big Lake toward Chezzetcook Inlet when lake levels exceed 1.4 m (CGVD28). Water ponded along the highway to just above the top of the culvert at 1.74 m (CGVD28) during Hurricane Dorian. The location of the culvert is shown on Figures 1, (white circle on hwy) and 7 (points 16-19). Photograph by R.B. Taylor, NRCan photo 2020-859.

Potential for Flooding and Wave Damage to the Shores of Big Lake

Along a submerging coastline such as Atlantic Nova Scotia, it is a natural progression for coastal lakes and ponds to become tidal when the shores that protect them breakdown or become submerged. That time has arrived for Long Beach and Big Lake so it is important to understand the changes that are occurring so that any hazards to local residents can be minimized and future residential planning be modified accordingly.

When assessing the potential for flooding and wave damage to properties along Big Lake it is important to understand 1) water level fluctuations in Big Lake and 2) the evolution of Long Beach and its capability to withstand future storms and continue to protect back barrier areas, now that a tidal inlet exists.

Implications of Big Lake becoming Tidal: The hydrology of a back barrier water body is controlled either by cross-barrier seepage or flow through a tidal channel. Where permeability of a barrier is unable to sustain seepage, then a surface channel may form. The opposite effect (i.e. changing from a channel to seepage) may occur as a barrier widens, causing an increase in absorption. Barrier permeability and outlet type can be impacted by small changes in barrier grain size and morphology (Carter et al. 1984). The amount of sediment transport by seepage is very small whereas an inlet or tidal channel is a natural mechanism for transporting sediment in and out of back-barrier water bodies.

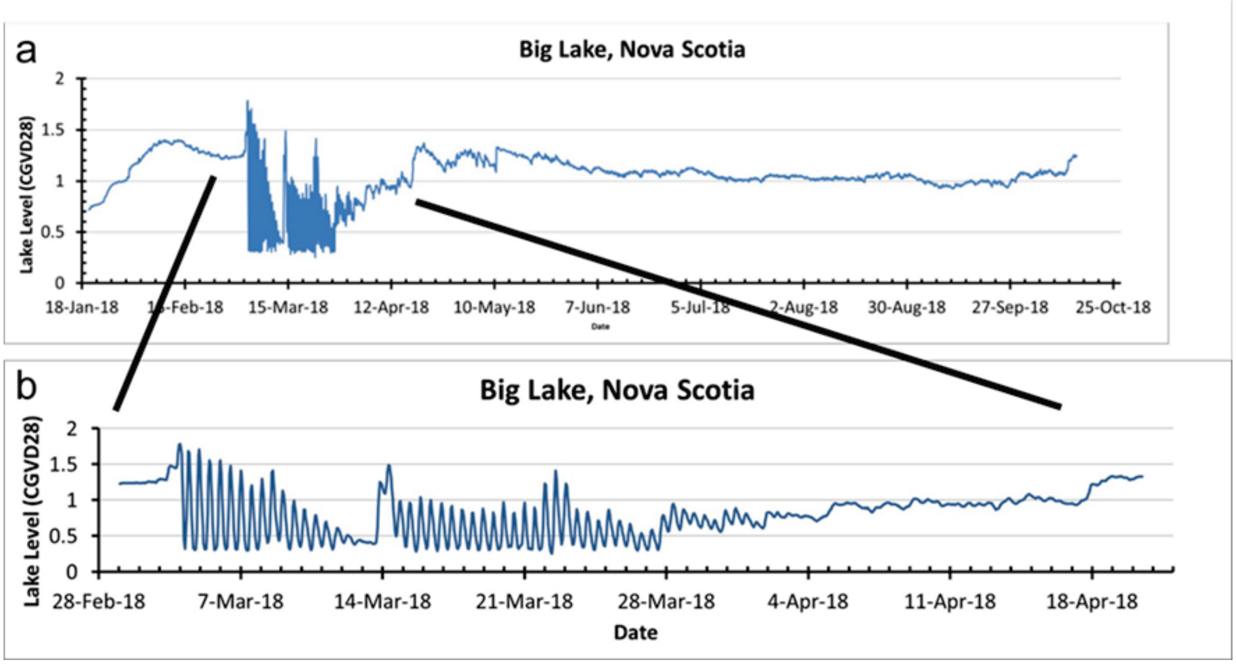
For example, at Long Beach significant amounts of sand have been transferred into Big Lake through washover channels and tidal inlets (front cover). The stronger flood currents caused by the tidal asymmetry contribute to permanent trapping of beach sediment in the lake, further weakening the barrier beach. The loss of sediment from the seaward side of the barrier also decreases the buffer provided by shoreface sand against wave attack. Sediment transported into Big Lake alters the lake bed composition and provides the foundation for future barrier beach rebuilding.

When Big Lake was non-tidal, its surface elevation was controlled by inputs from local streams, seepage through the barrier and outward flow through the stream leading to Chezzetcook Inlet (Fig. 1). Before a tidal inlet formed, the mean lake surface was 1.27 m, i.e. close to HHWLT (CGVD28). The small fluctuation in water level constrained wave attack onshore which naturally armoured the shoreline as fines were winnowed away leaving large clasts (thermal expansion of lake ice may also have played a role).

After a channel was cut through the barrier, mean lake level was lowered and maximum lake levels (prior to Hurricane Dorian) reached 1.78 m (Table 3).

The hydrograph for Big Lake in 2018 (Fig 13) illustrates lake level recovery after an inlet closed in late January and early April. The hydrograph is much more consistent when the lake is non – tidal. When temporary inlets formed the low tide signal was truncated relative to the inlet channel depth (Fig. 13a, b). The tidal signal on the hydrograph disappeared briefly on March 13 (Fig. 13b) when neap tides were too low to enter the lake and after April 2, when the channel infilled to an elevation of 0.7 m (CGVD28) despite the channel not being physically closed, with water flow not stopping until April 8. The tidal signal became more irregular and disappeared as the lake was recharged and reached its upper level of 1.4 m (CGVD28) (Fig. 13b).

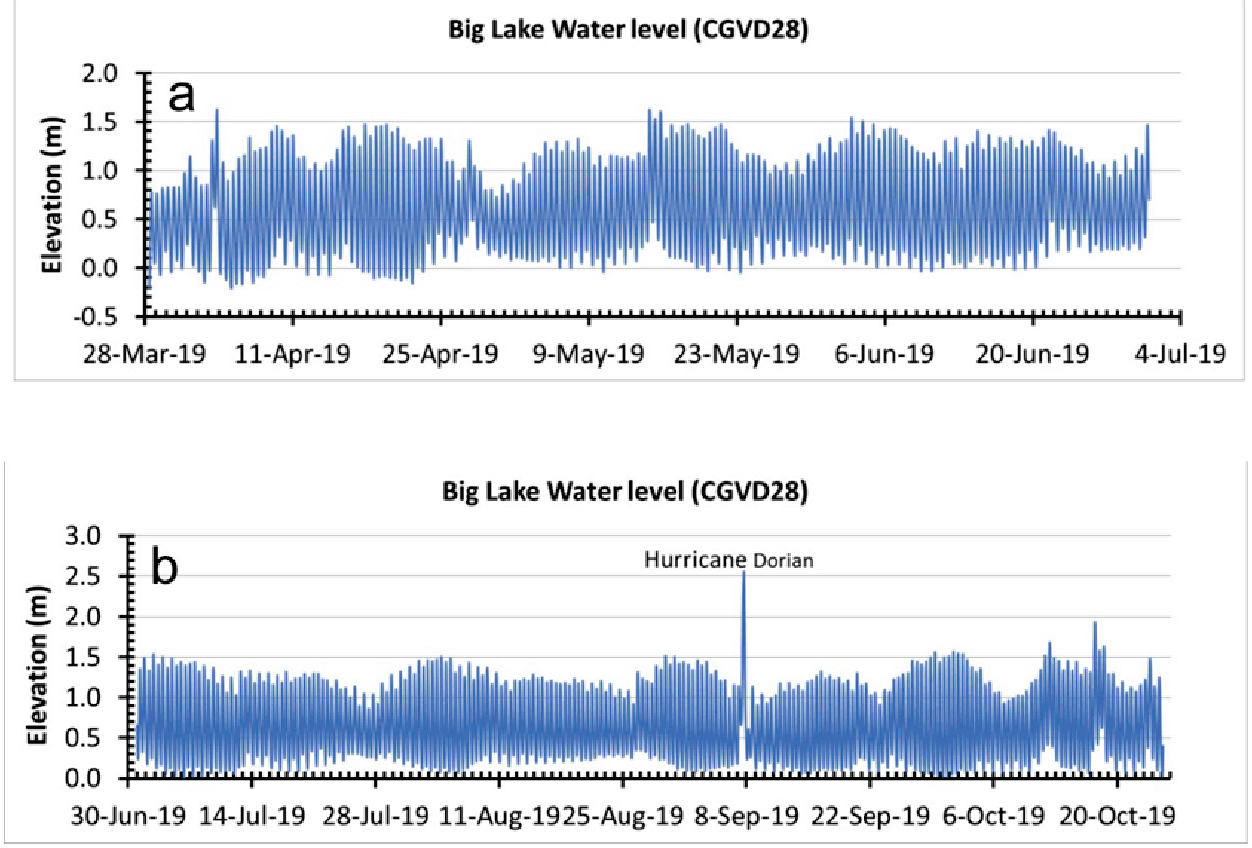
Figure 13. (a) Lake levels recorded in Big Lake from January to October 2018 illustrating the recovery of water levels after temporary inlets (cut through Long Beach) were closed January 18 and April 8, 2018. (b) An enlarged view of the hydrograph highlighting the tidal signal in Big Lake with a temporary inlet and the well-defined truncation in the low tide signal as a function of tidal channel depth.



After a deeper more permanent inlet formed in March 2019, the tidal cycle became better defined (Fig. 14). Water level rarely exceeded 1.5 m (CGVD28) and the largest spike in water level was recorded during Hurricane Dorian (Fig. 14b). Mean water level in the lake was typically 0.3 m above the ocean. In addition, tidal flow in the inlet switched from ebb to flood about 3 hours after the ocean low tide as represented by the Halifax tide gauge. The high tide level in the Lake was typically 0.1 to 0.2 m above the ocean's, and started to recede approximately 1 hour later (Fig. 4). The inlet's flood phase lasted 3.5 to 4 hours, while the ebb was 8 to 9 hours. This significant asymmetry in the tidal gradient caused much stronger flood currents.

Observed ebb flow in the channel was commonly 1—2 m/sec and flooding occurred as ebb flow decreased to less than 0.5 m/sec and waves pushed water into the lake. There was no slack tide in the inlet. Ebb flow did not stop before the flood began which made it very difficult to artificially close off the inlet, as was discovered in 2010.

Figure 14. Surface water levels in Big lake recorded by a pressure sensor (Fig 1 -location b) (a) from March to July 2019 and (b) June to October 2019, and the sharp peak in water level caused by Hurricane Dorian on September 7, 2019 (see Figs. 4 and 5 for enlarged views of water conditions during Hurricane Dorian).



It appears that the natural drainage channel from Big Lake into Chezzetcook Inlet (Figs. 1, 12) remains an important flood control mechanism during normal conditions but is less effective during a major storm event when water is unable to drain into Chezzetcook Inlet. During Hurricane Dorian, water level in Big Lake remained at or above 1.5 m for six and a half hours, from 14:30 to 21:00 ADT.

At high lake level, outflow to the north is controlled by the size and elevation of the highway culvert (Top 1.75 m (CGVD28) Fig. 12) and the near coincidence (1 hr later in Big Lake) of high tide in Chezzetcook Inlet. Furthermore, if strong winds blow from the north at a lower tidal stage, it would be difficult for water to flow out of Big Lake into Chezzetcook Inlet. Dorian produced the highest water level recorded in Big Lake. Any future major storms that coincide with high tide, could potentially present a flood hazard along the shores of Big Lake but only for a few hours, until the lake naturally drains, as the tide falls.

The switch to tidal conditions in Big Lake also increased the vertical range of wave attack on the shores. The highest flood/ debris line surveyed following Hurricane Dorian of 3.04 m (CGVD28), provides a basis for mapping flood-prone shores and residences along Big Lake. Based on the survey of residences by CBCL (2018), five buildings existed within this flood zone. The house on "Boland" Island (Front cover) at 1.9 m and the lake-side shed (Fig. 11) on the Hawkins property at 2.3 m elevation were the lowest buildings. Most of the cottages along western Big Lake were mapped at 3.2 to 3.5 m elevation which puts them close to wave-run-up, but fortunately they are more sheltered from waves by Long Beach than the properties farther east. However, their elevation of less than 4 m makes them potentially vulnerable to flooding or wave damage in the future when Long Beach becomes lower, breaks apart, or migrates landward, all in the context of a sea-level rise of 0.5 to 0.7 m by 2100 (James et al. 2015).

Table 3. A comparison of water levels observed in Big Lake when it was non-tidal and tidal.

Water Body Condition	**Time Frame**	**Lake/Lagoon Water Level (m) (CGVD28)**		
		Mean	**Max.**	**Min.**
Lake-seepage	**1991—2008 ^**	1.26	1.58	1.0
	2010			
Lagoon-tidal	Jan. 2—13	----	----	0.20
	2018	**Mean**	**Max.**	**Min.**
Lake-seepage	Jan—Mar	1.18	1.40	0.72
Lake-seepage	Apr.—Oct.	1.08	1.37	0.70
Lagoon-tidal	Mar.3—Apr.2	0.68	1.78	0.25*
	2019	**Mean**	**Max.**	**Min.**
Lagoon-Tidal	March—Oct.	0.63	2.56**	-0.22

* Lower tidal level was truncated by the elevation of tidal channel

**Extreme water level (15minute interval) during Hurricane Dorian Sept. 7, 2019

^ Prior to 2008: 17 surveys of lake edge at Line 2, max. level was after Hurricane Hortense.

Long Beach as a Protective Barrier: Long Beach continued to protect the inner shores of Big Lake during Hurricane Dorian but not to the same extent as in the past because of significant changes to its continuity, height and breadth. To better understand the recent accelerated changes to Long Beach, a brief summary about earlier changes at the beach is provided. Results from repetitive surveys of three cross-shore lines -1, 2 and 4 (Figs. 1, 8, 10, 15) are used to illustrate changes along different parts of the barrier.
Between 1945 and the mid-1980s, when our study began, Long Beach remained fairly stable (Forbes et al. 1990; Taylor et al. in prep). The seaward edge of Long Beach migrated landward at an average rate of only 0.6 m/a and the backshore slope, some of which had lichen growth, remained unchanged except for a few small washover lobes that occurred along the central barrier just east of "Boland" Island. The change was much less than at nearby Story Head Beach (Fig. 1) which retreated at more than 8 m/a between 1954 and 1982 (Forbes et al. 1991, 1997). However, when changes at Long Beach were examined over shorter time periods, a disturbing trend of increasing landward barrier migration was observed. The rate of barrier retreat nearly doubled to 0.92 m/a between 1974 and 1982, compared with 1945 to 1974. Increased shoreline retreat and loss in barrier width along its eastern end may have reflected the loss of sediment during commercial extraction activities in the 1950s and 1960s. The net reduction in barrier width between 1945 and 1982 was 28 m at the eastern end, 8 m at the central part (Fig. 1, Lines 1 and 2 area) and a slight building at the western end (Fig. 1, L-1 area).

A time-series of cross shore surveys since 1994 (Fig. 15) illustrates the dramatic reduction in barrier size and crest elevation over 26 years. Landward migration of the seaward barrier and absence of change along the lake shore suggested the barrier was able initially to adapt and to rebuild itself following a number of storms; however, deeper wave washover channels cut through the barrier in the mid-1990s were a precurser to future breakdown along the central barrier.

The first significant change to the barrier crest occurred during the winter of 1990-1991 and during the Halloween storm of 28 Oct-to 2 Nov. 1991 (Taylor et al. 1997a). Between 1994 and 1998 the barrier was impacted by a number of storms, e.g. Hurricane Hortense, but it was the nor'easters of February 1995 and 1998 that pushed significant amounts of sediment landward, burying the backshore dunes and road (Taylor et al. in prep). Following Hurricane Juan in 2003, the barrier crest was lowered and overwashed (see Lines 2, 4, Fig. 15 b,c) and it was not until a winter storm on 1 February 2006 that the barrier crest recovered to its pre- Juan elevation of nearly 4.5 m. During the same storm, two deep washover channels were cut, one just west of L3 and the other east of L4 (Fig. 1), but by 2010 the barrier crest had rebuilt, albeit farther landward across the backshore (Taylor et al. 2013). The western end of the barrier continued to experience alternate erosion and building as its crest retreated slightly (L-1, Fig. 15a).

A turning point in the stability of the central barrier occurred in 2010—2011. First, a nor'easter on 2 January 2010 cut through Long Beach, resulting in the drainage of Big Lake through a channel that remained open for 12 days before it was closed by machinery. The low artificial dyke that was constructed provided backing for natural processes to rebuild Long Beach by April 2010. Sediment for rebuilding the cut was supplied from the shoreface and adjoining barrier. Both lines 2 and 4, located west and east respectively of the channel, experienced erosion between January and June 2010, as sediment was transferred into the cut (Fig. 15).

The next cross-shore surveys were not completed until May 2017 when the beach crest had retreated nearly 4 m landward and had built 0.4 m higher. During a nor'easter in February 2013, waves overwashed the barrier where the crest was less than 3.9 m elevation, and they nearly breached the barrier between L3 and L4 (Taylor, 2014). By 2017, Long Beach was continuing to rebuild itself farther landward across the backshore that was disappearing.

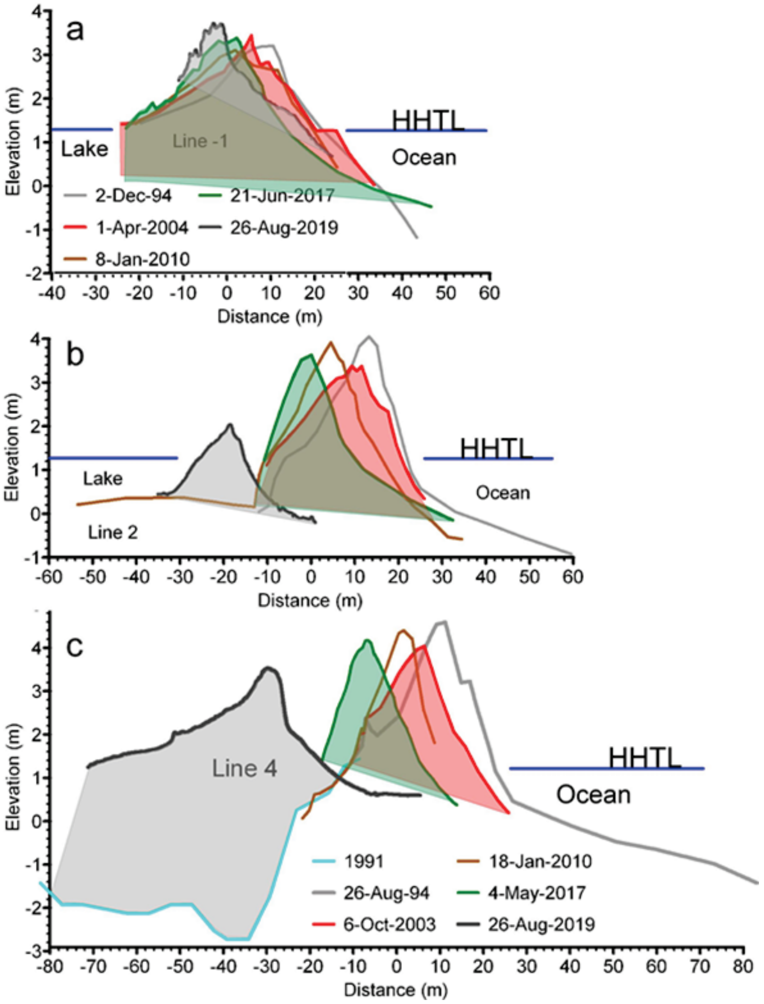
In January 2018, Long Beach was severed just east of Line 4 (Fig. 1). Waves also cut several large washover channels through the barrier at lines 1 and 2, pushing and lowering the crest landward across washover lobes built into the lake. At Line 4, sediment transfer from the adjoining barrier into the channel resulted in a 6 m landward shift and 0.8 m lowering of the crest.

Within 16 days, the inlet was closed off by waves and the beach began rebuilding. On 3 March 2018, a large winter storm coincided with spring high tide (Table 1). A channel was cut through Long Beach 60 m west of the earlier channel and an extensive section of the barrier between Line 2a and Line 4 was lowered by wave overwash. Although the channel temporarily closed on two occasions, seawater continued to flow in and out of Big Lake until 13 April 2018.

The first complete rollover of the central barrier, at Lines 3 and 4, occurred by April 2018. A barrier rollover is when the barrier is rolled far enough landward, that the seaward edge reaches the former landward edge of the barrier. In this case, the rollover took roughly 30 years to complete. Central Long Beach has remained low and slow to rebuild because of its migration into a deep area of Big Lake and the requirement for more sediment to rebuild itself (L4 in Fig. 15c). Once a barrier rolls over, sediment compaction within the barrier decreases and barrier mobility increases. In contrast, along the western section of Long Beach, a wider backshore (L-1 in Fig. 15a) facilitated continued barrier crest rebuilding, albeit landward.

Between January and March 2019, eight significant storms occurred, five producing sea levels of 2.3 m (CD) or greater, during which waves overwashed and weakened Long Beach, particularly in the central part. Large seepage channels (Fig. 16) were observed, with seaward flow from the barrier, near where a previous channel had been cut and at Line 2a where the barrier was less than 10 m wide (Fig. 2).

Figure 15. Repetitive cross-shore surveys at three locations between the early 1990s and 2019 illustrate the physical response to wave activity along three parts of Long Beach: (a) Line -1 at the west end, (b) Line 2 at the central barrier, and (c) Line 4 located east of centre (Fig. 1). The graphs illustrate the impact of Hurricane Juan in 2003 (red shade), natural barrier beach recovery and migration by January 2010 when Long beach was first cut and the accelerated barrier migration by 2017 (green shade). Beach changes during Hurricane Dorian (grey shade) illustrate how the beach at Line -1 was able to rebuild across the backshore platform, whereas at Line 4 increased sediment was required to infill Big Lake before the barrier could rebuild. At Line 2 the barrier in 2019 was rebuilding on washover deposits that accumulated in Big Lake because of a previous cut that existed before 1945.



On 23 March 2019 a deep channel was cut through Long Beach close to L2a, (Figs. front cover, 1, 2) where it cut through in 2010. The inlet has remained open as of writing (July 2020), despite large volumes of sediment being transported into the inlet from the adjoining shores which had been severely weakened by the time Hurricane Dorian hit in September 2019.

The occurrence of several nor'easters in close succession in the winter of 2019 that led to the severing of Long Beach was reminescent of the winter of 1998, when a similar series of storms transformed Story Head Beach into a shoal. Although Long Beach remains above high tide, its differential landward migration alongshore has produced a series of smaller beach segments which limit the supply of sediment to rebuild adjoining shores impacted by storms. For example, the central barrier between "Boland" Island and the present inlet can no longer supply sediment to infill the channel; however, sediment continues to be supplied from the eastern barrier and offshore. Physical response to future storms along each of the three segments of Long Beach will be different but some form of barrier will continue to exist as it migrates landward.

Accelerated changes at Long Beach since 2010 reflect the absence of a new sediment supply and the depletion of natural sediment reserves stored within the barrier itself.

Figure 16. Seepage channels at Line 2a Long Beach where the barrier was cut in January 2010 and in March 2019. Seepage through coarse-clastic barrier beaches is a natural alternative to surface flow through a tidal inlet to maintain water levels in back-barrier water bodies. The larger seepage channels observed at this location (03 Feb. 2019) may have been a precursor to changing conditions that led to a change in drainage from Big Lake (graduated staff marked at 2 cm intervals provides scale). Photograph by R. B. Taylor, NRCan photo 2020-860.

Summary

Warnings of deteriorating barrier beach conditions and possible breaching of Long Beach began in 1998, and were repeated in 2006 with the formation of several deeply incised washover channels. Breaches eventually occurred in 2010 (artificially closed), 2018 (naturally closed), and 2019 (still open). Natural infill of the breaches by sediment supplied from the adjoining shores temporarily closed off the inlets but left the adjacent shores vulnerable to further cuts and wave overwash. Development of the present tidal inlet, cut through Long Beach in March 2019, was caused by a number of factors including:

1) the narrow width (<10 m) and elevation (<3 m) of the central barrier prior to breaching;
2) the absence of backshore on which the barrier could rebuild;
3) the extensive transfer of sediment into the lake by wave overwash and reduced gravel availability for rebuilding low crest sections and washover channels;
4) the presence of deeply incised seepage channels just prior to the new cut, (Fig. 16);
5) the occurrence in close succession of several high water storm events in early 2019 and the inability of the barrier beach to recover.

The persistence of the tidal channel for more than one year is attributed to its depth, the presence of an island controlling one side of the inlet, and the reduction in sediment supply to close it.

The switching of Big Lake from a lake to a lagoon, has had a number of significant consequences.

1) Big Lake is now tidal. Mean water level in Big Lake has decreased from 1.3 to 0.6 m (Table 3) and high and low water levels are more extreme, e.g. ranging from surface elevations of -0.26 m to 2.78 m (CGVD28) during Hurricane Dorian.
2) Along Big Lake, low to moderately sloping shores exposed to strong onshore winds at high tide were impacted by waves to an elevation of 3.04 m (CGVD28) during Hurricane Dorian. Long period infragravity waves and seiching were detected in Big Lake during the peak of Hurricane Dorian which adds another element of water motion however the impacts were small relative to tidal surge produced during Dorian. Questions about whether infragravity waves are contributing to scouring the tidal pass and preventing its closure are worth further investigation.
3) Water levels in Big Lake rose faster through the inlet i.e. 3.5—4 hours, on a flood tide than they fell (8.5—9 hours) on an ebb tide. This flood dominance will draw sediment into the lagoon. Water levels lower than 1.75 m (CGVD28) produced during storms will naturally drain as the tide falls, through the tidal inlet and the stream and highway culvert leading to Chezzetcook Inlet. Present drainage through the culvert is impeded by its size, elevation and vegetation cover.
4) In 2019, the salinity of Big Lake averaged 18 PSU and peaked at 26.1 PSU during Hurricane Dorian. Water temperature was more responsive to local ocean temperatures. In 2019, only the western end of Big Lake was ice covered in winter.
5) Increased transport of sand from the seaward side of the barrier into the back-barrier water body has changed the sediment composition of the “lake” bed (front cover),

increased water turbidity during storms, and provided sediment for the foundation of future barrier beach building.

6) Sediment reserves in Long Beach have been depleted and are no longer capable of supplying sufficient sediment to repair cuts through the barrier without severely weakening the continuity and stability of the adjoining shores.
7) Long Beach has evolved from a continuous barrier beach into three segments. Physical response to future storms along each segment of Long Beach will be different as each migrates landward. For the near future, the western barrier should provide the best protection for inland properties against wave attack however natural stress on the barrier will continue with the projected rise in sea level.

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Appendix A

Table A1. Instruments installed to measure changes in water level, temperature, and salinity in Big Lake, Nova Scotia. The lake was intermittently connected to the ocean until March 2019, when a permanent inlet was cut through Long Beach. Refer to Figure 1 for the location of the gauge sites a, b, and c.

Gauges Site a	**Start Record (Date/time)**	**End Record (Date/time)**	**Gauge Removed (Date/time)**
RBR TDR2050 (pressure gauge)	19-Jan-2018 13:59 (AST)	17-May-2018 15:55 (AST)	17-May-2018 15:55 (AST)
HOBO U20 (water level recorder)	17-May-2018 ~16:00 (AST)	15-Oct-2018 03:55 (AST)	28-Mar-2019 (10:30 AST)
Gauges Site b	**Start Record (Date/time)**	**End Record (Date/time)**	**Gauge Removed (Date/time)**
RBR TDR2050 (pressure gauge)	28-March-2019 10:30 (AST)	25-Oct.-2019 12:50 (AST)	25-Oct-2019 12:50 (AST)
RBR Concerto	28-March-2019 10:30 (AST)	30-May-2019 11:50 (AST)	30-May-2019 11:50 (AST)
Seametrics CT2x CTD recorder	29-Aug-2019 13:44 (AST)	25-Oct.-2019 12:50 (AST)	25-Oct.-2019 12:50 (AST)
Gauges Site c	**Start Record (Date/time)**	**End Record (Date/time)**	**Gauge Removed (Date/time)**
HOBO U20 (water level recorder)	25-Oct-2019 13:50 (AST)	06-Jun-2020 05:31 (AST)	22-Sept-2020 08:45 (AST)
HOBO U20 (water level recorder)	22-Sept-2020 08:45 (AST)		