



Assessing the impact of hurricane Fiona on the coast of PEI National Park and implications for the effectiveness of beach-dune management policies

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Abstract

The impact of waves, storm surge, and aeolian transport associated with Post-tropical Storm Fiona (offshore significant wave height ~ 8 m, storm surge up to 2 m) on the sandy beaches and foredunes of the north shore of Prince Edward Island National Park (PEINP), Canada, are assessed. Management policies and practices, as they apply to sandy beach systems within PEINP, are reviewed in the context of the shoreline changes attributed to Fiona. The effectiveness of these policies and practices are evaluated to inform the potential performance of beach-foredune systems as natural protection measures that mitigate the impacts of large-magnitude storms and relative sea-level rise (RSLR) on shoreline change. The analyses utilise survey data, ground photography, and unoccupied aerial vehicle (UAV) imagery collected before (October 2021 to July 2022) and after (October 2022 and May 2023) Fiona. In general, the largest dunes were characterised by erosion of the stoss slope, with landward retreat of the dune toe by < 6 m and minimal impact on crest height and position. Small foredunes (< 5 m in height) generally showed significantly greater erosion in terms of dune profiles, with dune breaching occurring at some locations. Foredunes perched on bedrock and till, which were typically smallest in size, were subject to complete erosion, thereby exposing the hard underlying surface. Overall, the impact of Fiona on sandy beach systems in PEINP was relatively modest in many locations, reflecting the success of existing management policies and practices that protect and maintain the integrity of foredunes by minimizing human impacts and avoiding ‘coastal squeeze’.

Keywords Sandy beach systems · Storm impact on coastal dunes · Coastal management.

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Introduction

Most mid-latitude sandy beach-dune systems are characterized by a seasonal cyclical response with erosion during moderate fall and winter storms that produce a smooth, gently-sloping beach, and a spring and summer period that yields onshore sediment transport by wave action leading to beach recovery and the development of a berm with steep foreshore (Shepard 1950; Wright and Short 1984; Castelle et al. 2017). Occasionally, a major storm accompanied by large waves in association with extreme storm surge disrupts this annual cycle. Large volumes of sediment are eroded from the beach and the stoss slope of the fore-dune leading to significant change in the beach-dune profile. Over succeeding years nearshore processes and aeolian transport rebuild the beach-dune profile, with rebuilding of the foredune by aeolian processes generally taking several years or more (Psuty 1988; Hesp 2013; Houser and Ellis 2013; Ollerhead et al. 2013; Walker et al. 2017; Cohn et al. 2019; Bullard et al. 2019; Davidson et al. 2020; George et al. 2021; Kombiadou et al. 2021; Burvingt and Castelle 2023; McLean et al., 2023). However, during particularly severe storms, sustained erosion of the foredune may lead to breaching, segmentation, and overwash, as is typical on narrow barrier systems and also where foredunes are characteristically small (Hosier and Cleary 1977; Donnelly et al., 2006; Claudino-Sales et al. 2008; Nienhuis et al. 2021). When significant overwash occurs, the dune recovery phase of the beach-dune cycle may take several decades rather than years (Mathew et al. 2010; Houser et al. 2015), making shoreline infrastructure vulnerable to potential damage by relatively normal storm events and prolonging the return to geomorphic equilibrium. Thus, the erosion and flooding accompanying intense, large-magnitude storms such as Fiona can pose a potential hazard for human life and for infrastructure located at or near the beach, as well as having long-term implications for the geomorphic resilience of the shoreline.

Coastal managers increasingly value foredunes as natural protection against wave action and flooding associated with severe storms (Nordstrom et al. 2011; Doody 2013; Arens et al. 2013; Nordstrom et al. 2018; Feagin et al. 2019; Garzon et al. 2022). Foredunes can be natural, highly managed, or constructed (Davis et al. 2024), but in all cases the controls on their evolution and efficacy in protecting against storm erosion and overwash are complex (Garzon et al. 2022), often affected directly or indirectly by human interventions in the coastal zone (Elko et al., 2016). As dunes increase in height and width (and therefore volume), they provide protection against storms of increasing severity (Pye and Blott 2016; Robin et al. 2020). Thus, there can be significant alongshore variability in the severity of erosion along

an extensive beach due to a single storm event that is related to dune size (Masselink et al. 2016; Splinter et al. 2018; Houser et al. 2018). The evolution of foredune size can vary spatially as a function of factors controlling the beach and dune sediment budgets (e.g., Miot da Silva and Hesp, 2010; Davidson-Arnott et al. 2018) and temporally as a response to the periodic migration of sandwaves alongshore (Davidson-Arnott and Law 1996) or the sequencing of storm events (Brodie et al. 2019; Héquette et al. 2019). Oceanographic and meteorological factors such as wind and wave orientation relative to the shoreline also control the magnitude of potential damage from storm waves and storm surge.

Hurricane Fiona ('Fiona'), which struck Prince Edward Island (PEI), Canada as a post-tropical storm on September 23–24, 2022, has been described as the most intense storm to strike PEI in nearly 100 years (Ollerhead et al. 2022; Mulligan et al. 2023; Cantelon et al. 2024). The storm generated offshore waves > 8 m in height and a storm surge on the order of 2 m (Mulligan et al. 2023), which resulted in erosion of mainland and barrier sandy beach systems including about 40 km of shoreline managed by Prince Edward Island National Park (PEINP; Fig. 1). Surveys of a large portion of the beaches in PEINP were carried out before and after Fiona, providing an opportunity to document the severity of impact on beaches and foredunes within PEINP and to assess the performance of management plans in maintaining the integrity of the beach-dune systems as nature-based mitigation strategies against climate change and sea-level rise.

The objectives of this paper are to:

1. Summarize and review management policies and practices as they apply to sandy beach-dune systems in PEINP, and assess the extent to which they are effective in maintaining intact foredunes, protecting park infrastructure from erosion, flooding and damage, and preserving the ecology of natural ecosystems;
2. Assess the impact of waves, storm surge, and aeolian transport associated with Hurricane Fiona on sandy beaches and foredunes within PEINP based on survey data, UAV (unoccupied aerial vehicle) photography, and observations collected before (October 2021 to July 2022) and after (October 2022 and May 2023) Fiona; and.
3. Determine, based on (1) and (2) above, whether changes to policies and practises might be initiated to enhance the performance of foredunes as natural protection from future storms and ongoing relative sea-level rise (RSLR).

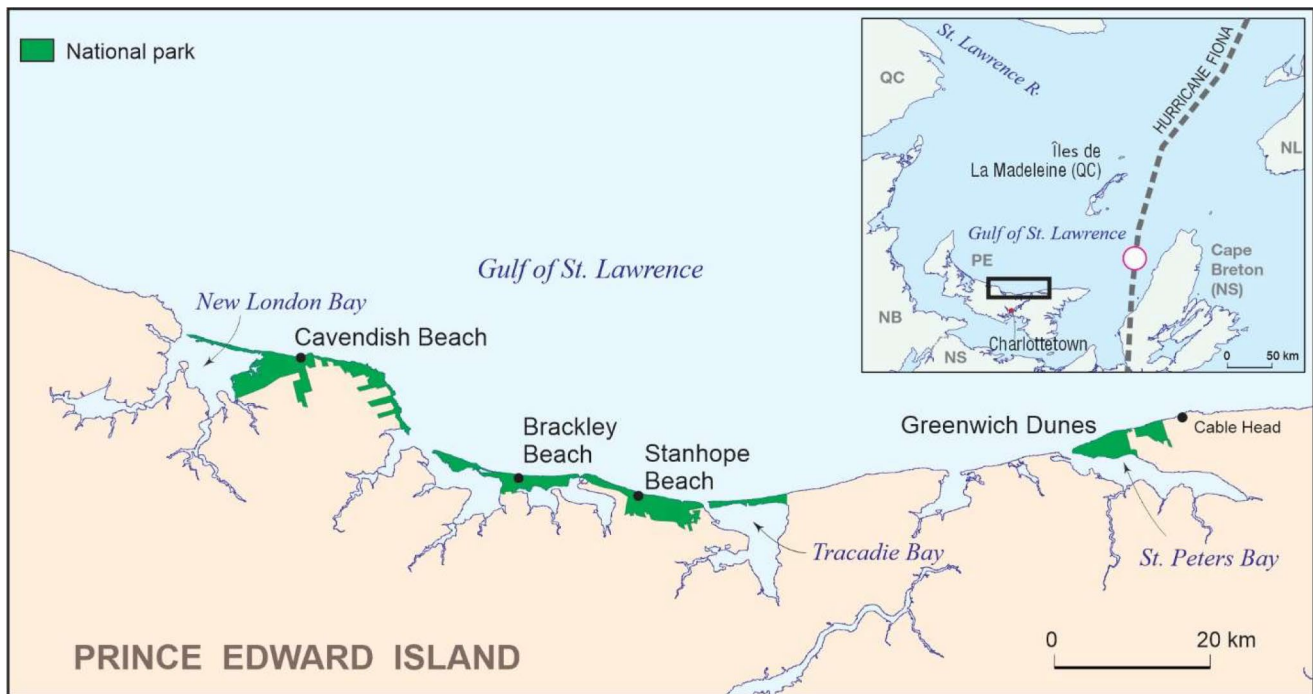


Fig. 1 The location of Prince Edward Island within the Gulf of St. Lawrence (inset), and the National Park on the north coast. The black rectangle on the inset shows the position of the main map within PEI.

The black dashed line shows the track of Fiona in the Gulf, and the white circle is the location of the centre at 12:00 UTC (8:00 AST) on September 24, 2022

Study area

The impact of Fiona was assessed along the north shore of PEI at three sites within PEINP: Greenwich Dunes on the east side of St. Peters Bay, and at Cavendish Beach and Brackley Beach in the main park (Fig. 1). The overall geomorphic controls, ecology, and climate are similar at all sites.

Rates of relative sea level rise (RSLR) for the Gulf of St. Lawrence are complex, reflecting the extent of glacial ice during the Last Glacial Maximum ~18–20 kya, the timing of deglaciation, the general eustatic rise in sea level worldwide, and spatial variations in crustal change and associated vertical land motions (Shaw et al. 2002; Stea 2001; Rémillard et al. 2017). Over the past 5000 years RSLR has been about 3–4 mm a⁻¹ (Forbes et al. 2004; Shaw et al. 2006) and as a result the beaches and dunes are all <2500 years old. Presently sea level is rising at more than 3 mm a⁻¹ and is expected to rise a minimum of 0.6–1.0 m over this century (James et al. 2014).

The geology and geomorphology of the north coast is spatially variable, containing a combination of more resistant red sandstone headlands, pocket beaches, barrier islands and spits (Van de Poll, 1983). Erosion of the headlands, and adjacent sandstone outcrops in the nearshore, produces sediment that is transported alongshore and deposited on the beach and in the dunes. Much of the existing sand is

continually reworked as barrier transgression takes place. The longshore drift of sediment occurs predominantly from east to west (Manson et al. 2016), but sediment transport between littoral cells is interrupted by headlands (Owens and Bowen 1977; Forbes et al. 2004; Coldwater Consultants, 2011). Much of the sand reservoir in the beach-dune system is reworked as barrier transgression takes place over the long term. The median diameter of beach sand ranges from 0.22 to 0.28 mm (Lunardi 2021).

Study sites

Greenwich beach

The Greenwich section of PEINP is located on the north-east coast of PEI at the entrance to St. Peters Bay (Fig. 1). The shoreline extends about 6.5 km eastwards from the Bay entrance (Fig. 2). An extreme storm on October 1 1923 completely removed the foredune along the stretch of shoreline now within the park (Mathew et al. 2010). Rebuilding of the foredune along sections of the coast was evident in 1953 aerial photography, and a nearly continuous foredune was present in 1971 aerial photography (Mathew et al. 2010). Since then, the foredune has continued to grow in height and width (Ollerhead et al. 2013; Davidson-Arnott et al. 2018), and it has not been significantly breached in over 50 years, including during the passage of Fiona.



Fig. 2 Satellite image showing the shoreline at Greenwich. The locations of the 9 Lines across the beach and foredune which were monitored from 2002–2023 are shown together with the three reach boundaries and the location of the two dune crossings on the exposed beach

Prior to creation of the **Greenwich Dunes** section of PEINP in 1998, uncontrolled pedestrian access to the beaches and use of ATVs and other recreational vehicles had created a series of trails and roads on the lee slopes of the foredunes and the interior dunes (Fig. 3A). The management focus for this area since incorporation into the National Park is on preservation of the natural and cultural features of the region and, while there is an extensive trail and boardwalk system, including the iconic floating boardwalk across Bowley Pond (Figs. 2 and 3B), there is no overnight camping and there are only two access points to the beach. The eastern access is along 300 m of boardwalk, and it does have limited facilities in the summer. The western access point requires a 2 km hike and has no facilities. As a result, there is little human pressure on the foredune system, and management consists only of signage that encourages the use of the trails and boardwalks. The reduction in human pressure has led to increased vegetation cover on the foredune, and to the spread of shrubs such as bayberry on the lee side of the foredune (Fig. 3B).

Longshore sediment transport is from east to west within the St. Peters littoral cell (Coldwater Consulting Ltd., 2011). The eastern boundary is marked by a small bedrock headland at Cable Head, about 8.5 km east of the inlet to St. Peters Bay (Fig. 1), and the western boundary is at Pointe de Roche, about 12 km west of St. Peters Bay. Additional sediment is supplied from erosion of relic dunes inland (Fig. 2). Profile measurements carried out over the past 20 years

at Lines 1 through 9 (Ollerhead et al. 2013; Walker et al. 2017 – see Fig. 2) show a negative littoral sediment budget in the eastern Reach 1 (Lines 1–4) giving rise to shoreline retreat on the order of 10–20 m over the past 20 years. In the western Reach 2, the littoral sediment budget at Line 5 still shows a small deficit, but this decreases westward, and the littoral budget at Lines 7 and 8 appears to be neutral or slightly positive. The net foredune sediment budgets in Reach 2 are all positive. Along Reach 3 in St. Peters Bay (Line 9) there is a small positive littoral sediment budget with sand being brought into the Bay around the distal end of the Greenwich Peninsula. The beach in Reach 3 is narrow and the dynamics here reflect changes in the location of the tidal channels within the Bay as well as aeolian sediment transport from the tip of the spit. These alongshore differences in littoral and foredune sediment budgets are hypothesized to influence the response of the beach and dune system to major events such as Fiona.

Cavendish

The **Cavendish** section of PEINP is ~ 7 km in length and is characterized by a barrier spit, rocky outcrops and cliffs, and a discontinuous and eroded foredune (Fig. 4). The sandstone cliffs at the east end of Cavendish act as sediment supply for the main beach (Cavendish Beach) and the associated transgressive foredune. Moving westward from the main beach, the dune complex continues as a small barrier across

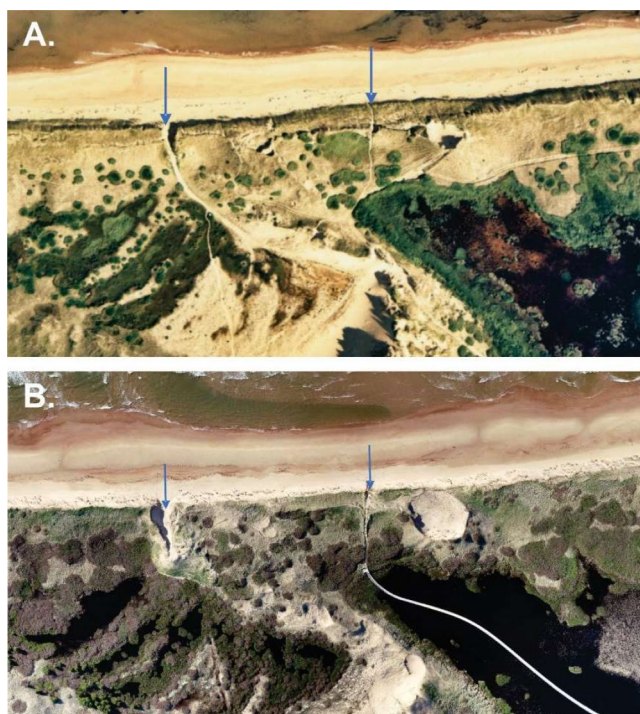


Fig. 3 Vertical aerial photographs of a section of the beach and foredune at Greenwich Dunes around the boardwalk across Bowley Pond and the beach access (marked by arrows). **A**) photograph taken in 1997 for Parks Canada showing the presence of ATV trails and pedestrian access across the foredune in several places; **B**) section cropped from an orthorectified mosaic constructed from a UAV flight on June 2, 2022. Note the increase in vegetation cover following establishment of the park and healing of access routes. The bowl blowout to the east (right) of the boardwalk access (white line across pond) has been allowed to evolve naturally (Hesp and Walker 2012)

Clarke’s Pond joining Cavendish Beach to a small headland with a relief of about 4 m. The campground complex is located inland from the headland.

The 4.4 km long Cavendish Spit extends west of the campground headland across New London Bay (Fig. 4). Cavendish Spit is characterized by large discontinuous dunes separated by washover channels that are occupied by runoff and overwash during storm events (Lunardi et al. 2023). Prominent washover fans can be observed in recent and historical imagery extending into New London Bay and are likely reflective of slow transgression due to RSLR and erosion of the headland, to which the proximal end of the spit is attached. Due to the distance of the spit from main access points such as the campground and main entrance, the distal end is less frequented by visitors. During peak summer visitation, Cavendish Spit is closed to pedestrian traffic to limit disturbance of Piping Plover nesting sites. As a result, the spit is evolving naturally without the need for active management interventions.

In contrast, high visitor traffic at Cavendish Beach and limited restrictions in the past resulted in anthropogenic fragmentation of the vegetated foredune complex (Fig. 5). In 1990, multiple paths existed through the foredunes and, due to frequent disturbance, the foredunes both east (towards the headland) and west (towards the campground) were sparsely covered in vegetation. By 2010, as part of ongoing relocation of vehicle access and parking, the road along the lee slope of the foredune in front of Lake of Shining Waters was closed and replaced with a walkway and pedestrian bridge (Fig. 5). However, a lapse in visitor control on the beach resulted in a complete breach to the east of the primary access point in 2014 (Davidson-Arnott 2014), requiring substantial intervention to repair it. Analysis of

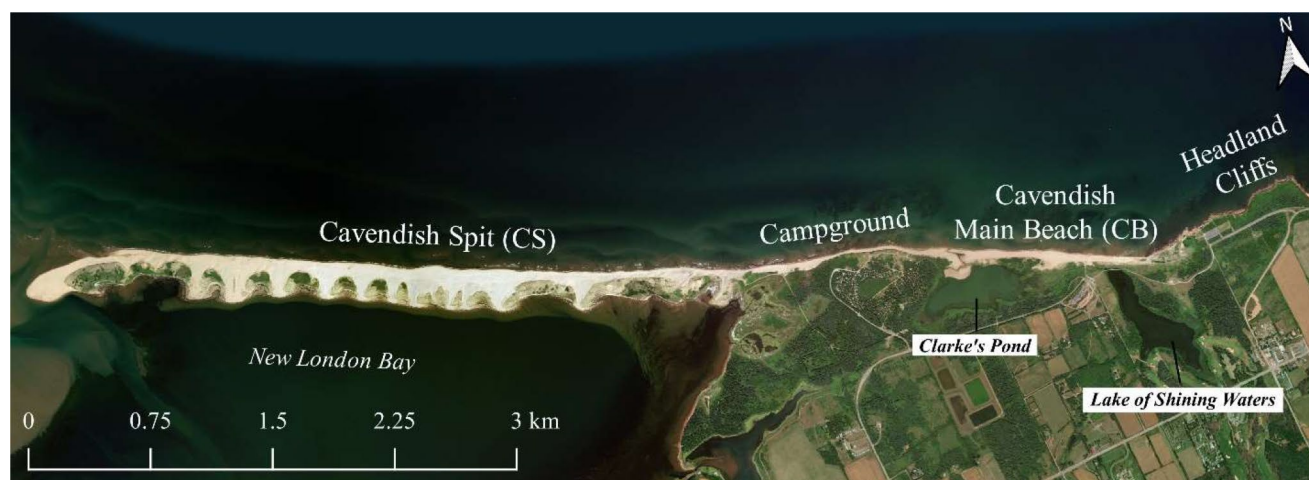


Fig. 4 Satellite image of Cavendish Beach. The eastern section is bounded by sandstone cliffs to the east and a sandstone outcrop at the beach by the main campground. A continuous foredune lies between the eastern headland to just west of the main boardwalk, followed

by low, overwashed dunes in front of Clarke’s Pond. Cavendish Spit extends westward from the campground outcrop with dunes between the washover channels decreasing in height towards the tip

Fig. 5 Cavendish Main Beach historical imagery, east of the spit and campground. By 1990, removal of a parking lot east of the boardwalk allowed vegetation to re-establish in this area and along the main foredune. By 2010 pressure on the foredune was reduced by removing the roadway across the lee of the foredune slope and replacing it with a trail and boardwalk across the Lake of Shining Waters



Fig. 6 Satellite image of Brackley Beach from Robinson's Island in the west to Covehead Harbour at the eastern end. The section of foredunes west of Brackley Main Beach (BB) are characterized by a large washover channel and prograding dunes of low crest elevation. BB contains a continuous foredune system ~ 4 m in height, and has the

historical digital elevation models (DEMs; George et al. 2024) shows ongoing erosion and landward migration of the foredune crest of up to 10 m between 2008 and 2020 east of the main entrance.

Brackley beach

Brackley Beach extends ~ 9.5 km and is bounded to the east by Cape Stanhope, an inlet opening Brackley Bay and Covehead Bay to the Gulf of St. Lawrence, and to the west by Robinson's Island (Fig. 6). Robinson's Island is a sandstone headland similar to that at the east end of Cavendish Beach. Dune height is consistent alongshore, with sections of foredune averaging from 4 to 6 m, and localized maxima of 8–10 m at complex blowout or relic dune features. Sediment transport is dominantly onshore to the southeast (Manson et al. 2016), and the nearshore is characterized by a low tide bar-rip morphology (Wright and Short 1984) and two straight to slightly crescentic outer bars. The continuous

highest visitation rates because the main entrance, secondary entrance, and parking lots are located here. Immediately to the east are low-lying foredunes that experienced overwash during Fiona, and farther east are taller dunes characterized by large blowouts

foredune system is backed by wetlands and bays and is bordered by estuaries on either side. The east end of the barrier is characterized by large foredunes and a long-lasting blowout complex, which is home to endangered Piping Plovers. This area appears to have a limited supply of sediment compared to the west end, with maximum crest retreat of up to 3 m since 2008. The west end of the beach is comprised of low, prograding foredunes, a wide beach, and large outcrops of sandstone forming headlands. A hinge point exists between the eastern and western sections, just west of the primary access point, where the foredunes back onto a rocky sandstone outcrop, the foot of which is uncovered and exposed during storm events. This area is also characterized by a notably narrow beach and very tall, secondary relic foredunes up to 12 m in height.

Management efforts at Brackley are concentrated on the ~ 1.5 km length of the beach extending ~ 500 m on either end of the primary and secondary access points, including Brackley Main Beach, where the highest visitor traffic

occurs (Fig. 6). At the primary and secondary access points, management has involved moving all parking to the landward side of the highway and restricting access to the backshore and dune through the creation of boardwalks. Similar to Cavendish Beach, dune integrity has increased notably since 1990 accompanied by a reduction in blowouts resulting from human activity. Virtual fencing at the base of the dune ramp has been utilized to prevent trampling of vegetation, and fencing deployed along the road landward of the foredune promotes visitor use of the boardwalk access.

Regional meteorology and oceanography

The Gulf of St. Lawrence is micro-tidal, mixed semi-diurnal, with spring tides ranging from about 0.5 m near Îles de la Madeleine (Fig. 1 inset) to nearly 2 m around the periphery. On the north coast of PEI, the spring tide ranges from 1.1 to 1.3 m. This coast is typically protected by sea ice for some part of each winter, but this protection is decreasing with time. Average annual sea-ice cover in the Atlantic region has decreased by 0.27% per year since the Canadian Ice Service began collecting data in 1968–1969 (Senneville et al. 2014; George et al. 2024). The increase in the open water season in the winter period will result in an increase in the number of storm waves reaching the coast and possibly in the average significant wave height (Perrie et al. 2015; Wang et al. 2018). In turn, this may lead to increased

frequency of dune erosion and reactivation and an increase in the rate of shoreline erosion.

The winds at North Cape, PEI are primarily from the NW to SW (Ollerhead and Davidson-Arnott 2021). Storm events with large waves and storm surges are associated with temperate mid-latitude cyclones (Nor'easters), which are most common and strongest in fall and winter months, and with tropical storms and hurricanes that track across the region several times a year from August to the end of October. Hurricanes such as Fiona have usually transitioned to post-tropical storms by the time they reach the Atlantic region, and are generally larger in extent, have lower maximum wind speeds, and travel faster than in tropical regions. As there are limited wave measurements in the GSL, most wave-climate data are derived from hindcast modelling, such as ERA5 produced by the Copernicus Climate Change Service at the European Centre for Medium-Range Weather Forecasting. There is considerable overlap in terms of storm surge elevation and significant wave height between Nor'easters and post-tropical storms affecting the north coast of PEI (Fig. 7).

Whether the frequency and/or intensity of storms impacting PEI has changed significantly over the past 100 years or so is difficult to determine. Analysis of the density of intense storm centers over North America for the period 1961–2000 indicates that the NW Atlantic Ocean and the Gulf of St. Lawrence are some of the stormiest areas in North America (Lemmen et al. 2016). Climate projections indicate that

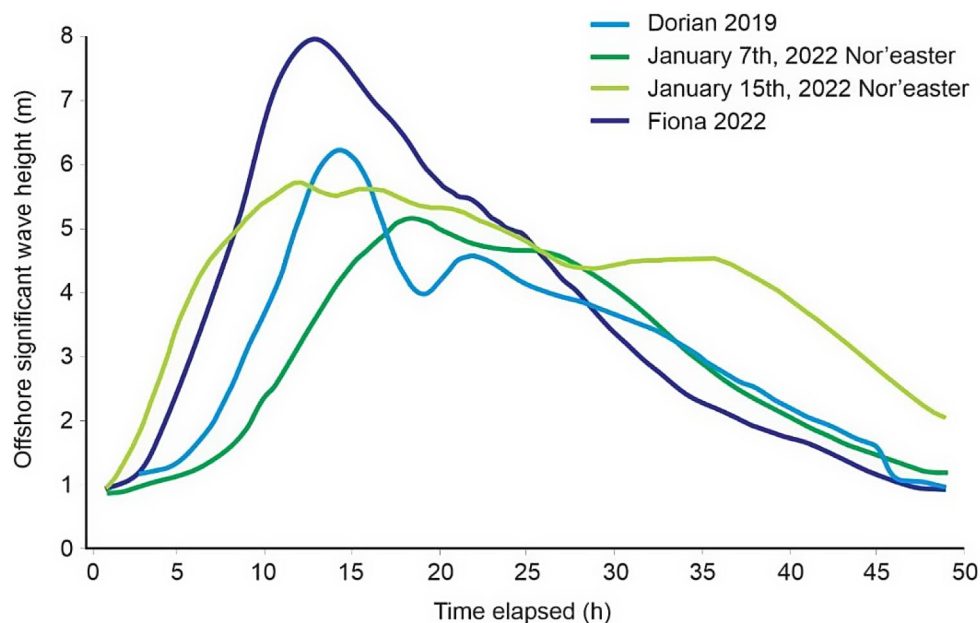


Fig. 7 Examples of beach and dune management at Cavendish Beach: **A)** View looking east of the main beach at Cavendish in June 2016, two years after restoration began on a large blowout resulting from trampling next to the boardwalk access point. Repurposed Christmas trees are used as a substitute for sand fences to trap sand, and marram grass is planted in the area between the trees. Fencing was used to keep

visitors off the regeneration area; **B)** View looking east of the beach in May 2022 showing the restored foredune on the right and virtual fencing along the high tide line to keep visitors away from the vegetation forming embryo dunes along the base of the stoss slope of the foredune. Signage, visible to the right of the buried tree trunk on the stoss slope, is used to inform visitors of the need to keep off the foredune

significant changes in wind speed are unlikely because of climate warming, but that there is likely to be a northward shift in storm tracks that will affect storm frequency in the Gulf (Jiang and Perrie 2007; Perrie et al. 2010, 2015; Lemmen et al. 2016). Modelling of the wave climate in the Gulf for the period 2071–2100 indicates an expected increase in wave height of up to 1 m, for a return period of 50 years, and a slight increase in overall mean wave energy due to decreasing sea-ice cover relative to 1981–2010 (Neumeier et al. 2013). This raises the question of whether a storm like Fiona is a harbinger of more frequent and intense storms to be expected over the next century.

The region experiences frequent storm events that can lead to widespread beach-dune scarping during the fall and winter months (e.g., Ollerhead et al. 2013; Smith et al., 2020). However, this period also sees increased aeolian transport, and this typically results in foredune building or recovery and the potential for embryo dunes to develop along the north shore beaches of PEI (Mathew et al. 2010; Ollerhead et al. 2013; Walker et al. 2017; Lunardi et al., 2023).

Post-tropical storm Fiona

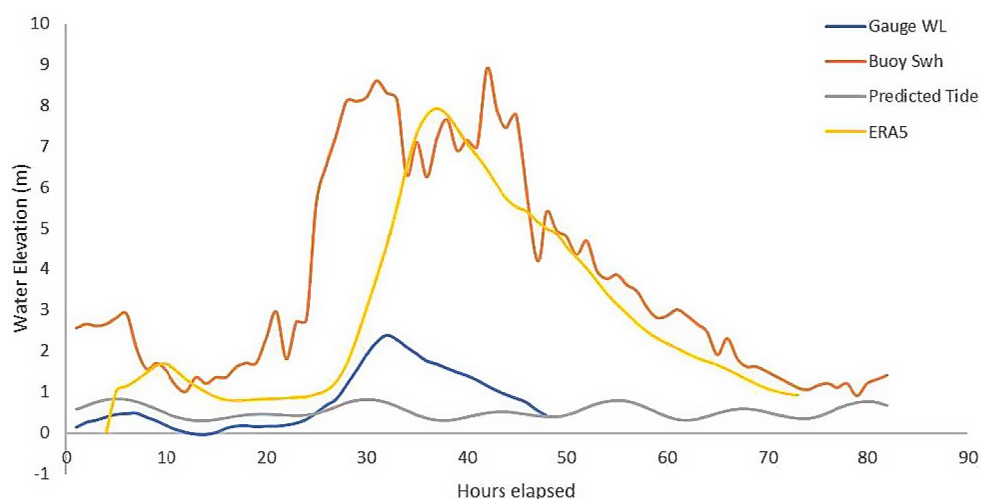
Hurricane Fiona reached the Canadian Maritimes as a powerful post-tropical storm, with strong winds up to 30 m s^{-1} and an atmospheric pressure of 932 mb, a record low for tropical storms making landfall in Canada (Mulligan et al. 2023). Fiona made landfall first in north-east Nova Scotia (NS) on September 23, 2022, and continued to track over Cape Breton, NS and into the Gulf of St. Lawrence (Bonnington et al. 2023; Cantelon et al. 2024). It then turned northward between Cape Breton to the east and PEI and Îles de la Madeleine to the west (Fig. 1 inset). Water level on the north coast at the Lennox Island PEI Storm Surge Warning System station began exceeding predicted tidal conditions

of 0.5 m at approximately 12:00 am September 24th, continuing to rise to a peak of 2.6 m at 7:00 am, before slowly receding to pre-storm conditions by 11:00 pm (Fig. 8). ERA5 data from offshore of Brackley Beach (Fig. 1) suggests that significant wave heights during Fiona reached $\sim 8 \text{ m}$ and that storm waves $> 2 \text{ m}$ persisted for nearly 30 h. This is in general agreement with significant wave height measured by a wave buoy located between PEI and Îles de la Madeleine (Fig. 1 inset).

Results of a modeling study by Mulligan et al. (2023) show that the total surge along the north shore of PEI was composed of two components: (i) the remote surge from the hurricane over the Atlantic Ocean that entered the Gulf through a wide channel (the Strait of Belle Isle between Cape Breton and Newfoundland), and (ii) the local surge generated by the cyclonic winds and low atmospheric pressures over the Gulf. The peaks of these two components did not occur at the same time and were out of phase with high tide. While the storm surge along the north shore of PEI was not as large as it could have been if these two components had been in phase, the strong winds, large waves, and storm surge across the Gulf of St. Lawrence resulted in significant flooding, beach/dune erosion, and damage to infrastructure.

Wind speeds and directions during Fiona were similar to that of Hurricane 5 in 1923, but the latter storm caused extensive overwash of the dune system and is also reported to have damaged or destroyed over 50 bridges crossing the estuaries (Simmons 1982; Mathew et al. 2010). While there is little meteorological data available to allow for a quantitative comparison, it is possible that the remote and local storm surges were in phase during the 1923 storm and responsible for the greater erosion. Regardless, it seems reasonable to characterize the magnitude of Fiona as an extreme event that may recur once in several decades or more, while Hurricane 5 in 1923 might have a longer recurrence interval. In this context, the impact of Fiona on sandy beach systems

Fig. 8 ERA5 hindcast significant wave height data offshore of Brackley Beach, for intense storms such as Hurricanes Dorian and Fiona, as well as recent Nor'easter storms in January of 2022



within PEINP can be used to evaluate the effectiveness of existing coastal management policies and practices and as a guide to identifying the vulnerability of different shoreline types and the appropriate adaptation strategy on a timescale of several decades.

Methods

The data presented here were collected separately by two research groups, one based primarily at Cavendish and Brackley Beaches (George and Houser) and the other based at Greenwich (remaining authors). There are differences between the methods used to collect data in the field, and therefore the results from Greenwich are not directly comparable to those from Cavendish and Brackley. Moreover, while both groups carried out post-Fiona surveys shortly after the passage of the storm, the pre-storm data collection efforts differed in timing because neither explicitly anticipated the storm.

CoastSnap photo-monitoring: coastie Canada

As part of the global CoastSnap program (Harley and Kinsella 2022), Coastie photo-monitoring stations were installed in 2021 along the north shore of PEI (George et al. 2024) in partnership with Parks Canada (coastiecanada.ca). The CoastSnap program allows park users to participate in coastal monitoring as citizen scientists by taking photographs at specially designed stands and uploading the images to a central data repository. The program provides daily to weekly repeat photographs that can be used to track change to the shoreline, beach, and dune in response to storms or management interventions. Coastie stands at Cavendish, Brackley and Greenwich beaches are located at the primary boardwalks to provide easy access for park visitors, with each site having stands looking alongshore to the east and west. Coastie photographs are used in this study to create a timeline for qualitative storm impact and recovery analysis, complementing continuous alongshore data collected by means of UAV surveys.

Pre- and post-Fiona surveys

At Greenwich, pre- and post-Fiona topographic surveys were carried out as part of activities marking 20 years of research and monitoring of the beach and dune system (Ollerhead et al. 2013; Walker et al. 2017; Davidson-Arnott et al. 2018). The nine lines established in 2002 (Fig. 2) were surveyed on June 1 and October 18, 2022, using an RTK GNSS (Leica 1200). Ground photography was carried out at each of the lines and along the beach between lines. Oblique

and near-vertical aerial photography was obtained in June 2022 using two UAVs (DJI Phantom 4 and DJI Mini 2), primarily to carry out topographic modelling using Structure-from-Motion (SfM) software. The photography is used here to supplement the ground surveys and Coastie photographs. One UAV (DJI Mini 2) was used to complement the Greenwich post-storm surveys in October 2022.

UAV surveys were completed at Brackley and Cavendish in October 2021 and 2022 with a DJI Mavic 2 Pro at an altitude between 60 and 80 m. The grid flights encompassed the beach and dune area within 500 m of the primary access points and were programmed to contain an end lap and side lap of 70 and 80% between Nadir images. Ground control points (GCPs) used for UAV processing were spread between the beach and foredune area and measured with RTK GPS. Orthomosaics, point clouds, and DEMs of each Coastie site were processed using Pix4D SfM software., Supplementary 2008 elevation data in 1 × 1 m resolution DEM format was acquired courtesy of Natural Resources Canada (NRCAN).

Volumetric change between the pre-storm 2021 and post-storm 2022 datasets for Brackley and Cavendish was based on the total volume of foredune above 1.5 m elevation, as this elevation was found consistently on both the landward and seaward sides of the foredunes when examining the 2008–2022 historical time series (George et al. 2024). A single elevation was used to indicate surficial changes, due to recent research on how dune toe interpretation can affect analysis of foredune morphology (Smith et al. 2022). Furthermore, SfM derived crest positions were aligned to 2021 values to minimize error in volume calculations caused by vegetation and lack of GCPs behind the crest line (Smith et al. 2022).

Management of sandy beach systems in PEINP

Two specific objectives within PEINP's Management Plan are relevant to management of beach and dune systems in the park (Parks Canada 2017):

Objective 2.3

Stewardship projects with partners, stakeholders and visitors result in improved dune integrity.; and.

Objective 2.6

Coastal erosion is managed by restoration and retreat as a first priority and armouring may be applied in specific cases where infrastructure investments require it. Where possible, facilities/infrastructure at risk due to coastal erosion are

relocated inland to ensure visitor safety and natural/cultural resource protection.

With regard to Objective 2.3, over the past three decades damage to dunes from visitor traffic has decreased (e.g., there are fewer unauthorized trails through the dunes), and since 2012 dune integrity has improved. In the most heavily used parts of the park, managing human impact is important, especially in locations where the foredune is recovering and the dune ramp is rebuilding after a significant storm (e.g., Brackley Beach after Hurricane Dorian; see George et al. 2021). Boardwalks are used extensively to manage access to the beach from parking lots and campgrounds as well as on portions of trails within dune systems. Fencing is used to keep visitors off areas where vegetation has been destroyed and/or where active rehabilitation of trails and blowouts is



Fig. 9 Significant wave height and water level data during Fiona. ERA5 is the plot of hourly estimates of wave height for the offshore hindcast point closest to Brackley Beach; Buoy SwH is the significant wave height (Hs) measured by Fisheries and Oceans Canada's AZMP Viking wave buoy located between PEI and Îles de la Madeleine; Gauge WL is water level measured by a still water gauge located on Lennox Island and operated by the PEI Storm Surge Early Warning System; and the tide predictions are provided by the Canadian Hydrographic Service for nearby Rustico Harbor, which is located approximately 4 km west of Brackley and 12 km east of Cavendish

taking place (Fig. 9A). Virtual fencing on the beach is used to keep visitors off vegetation on the backshore and base of the stoss slope of the dune, especially close to the point where steps and ramps meet the beach (Fig. 9B). Signage is used to inform the public wherever access restrictions are emplaced. Active rehabilitation of blowouts is carried out where it is known that the blowout developed because of human interference, but natural dune blowouts are allowed to evolve without intervention.

With regard to Objective 2.6, PEINP allows dune systems within the park to evolve naturally in response to ongoing coastal processes driven by waves and wind, as well as to long-term coastal erosion due to a changing climate and RSLR. By allowing natural geomorphic and ecological dune processes to operate without interference, management is focused on ensuring that there is sufficient area inland for dune transgression due to RSLR to take place - i.e., that 'coastal squeeze' does not occur (Pontee 2013; Davidson-Arnott and Bauer 2021). PEINP has some infrastructure, including roads, that is located close to the shoreline. The management plan acknowledges that it cannot prevent erosion and sea level rise and thus the threats these pose to the infrastructure in this zone. It therefore recognizes the need to ensure that a strategy for sustainable maintenance of built assets along the coast is in place (Parks Canada 2017). One consequence of this is that campgrounds and facilities for day use are located well inland from the coastal dune system and thus the risk of damage or destruction from individual storm events is reduced. The approach is in line with managed retreat projects aiming at creating space for coastal areas to evolve dynamically (see examples in Esteves 2014).

Impact of Fiona on beach-foredune systems in PEINP

The impact of Fiona on the beach and foredune within PEINP is described separately for Greenwich Dunes and the main areas of Cavendish and Brackley beaches. A summary of changes to key geomorphological parameters is given in Table 1.

Greenwich dunes

There are clear differences in the impact of Fiona on the dunes in Reach 2 (Greenwich W) where there is a positive littoral sediment budget, a wide beach, and the beach and dune profile is developed entirely in sand, relative to those in Reach 1 (Greenwich E), where the beach is narrower, and bedrock is close to the surface under the beach and foredune (Fig. 2). Significant winter storms of January 7–8 and January 14–15, 2022 (see Fig. 7) resulted in erosion of the beach

Table 1 Average change values for select beach and dune attributes pre- and post-Fiona. Values are in m except for foredune volume, which is in m³ per m width alongshore. The length of shoreline overwash associated with the passage of Fiona is given for each location and the proportion of length overwashed relative to total length is provided in (%). Note that the data for change in crest elevation, position, and foredune volume for Greenwich E (Lines 1–4) are for Line 2 only, since the foredune at the other three lines was completely eroded

Location Attribute	Cav- endish W	Cav- endish E	Brack- ley Main	Green- wich W	Green- wich E
Crest elevation (m)	-1.0	-0.5	-1.0	0.12	-1.13
Crest position (m)	-9.9	-1.2	-6.0	-0.05	-2.07
Foredune volume (m ³ /m)	-23.1	-26.5	-31.6	-18.0	-27.4
Length of shoreline (m)	450	450	1100	2350	1500
Length overwashed (m)	200 (44%)	0	0	0	210 (14%)

and embryo dunes as well as cliffing of the foredune along much of the north coast of PEI, including the Greenwich shoreline (Fig. 10A). These precursor events and the associated retreat of the stoss slope and widening of the beach, may have preconditioned the beach-dune system in a manner that reduced the potential impact of Fiona in terms of measured retreat of the foredune stoss slope, especially in Reach 2.

The stoss slope of the foredune in Reach 2, which includes Lines 5–8 (Fig. 2), was eroded to the dune crest in most areas during Fiona, leaving a cliffed profile (Figs. 10B and C and 11). The exception was a short section around Line 6, where some of the upper stoss slope present before the event was preserved (Fig. 11B). The pre-Fiona beach profiles show the presence of a small berm near the low tide level; the post-storm beach profiles are smooth and relatively steep (Fig. 11). The dune toe elevation was higher after the storm than before due to landward migration of the toe region by erosion of the stoss slope (Conlin et al. 2023). Subsequent redevelopment of a dune ramp may lead to seaward migration of the dune toe and some decrease in elevation. Change in elevation resulting from erosion during Fiona is shown for Line 8 (Fig. 11D). Dune erosion was concentrated on the stoss slope, with the crest remaining intact and little to no deposition recorded on the lee slope. A similar pattern was recorded for the other three lines in Reach 2, except that the crest on Line 7 was eroded slightly (Fig. 11). Three different measures of horizontal retreat of the foredune due to the event, changes in the position of the crest, toe and mid-stoss, are shown in Fig. 12. In Reach 2, for all four Lines (5–8), the crest position changed < 0.5 m and so the lee slope was not affected. Horizontal recession of the mid-stoss and toe were similar, and ranged from 4 to 6 m. There was no overwash or breaching of the foredune along this section of the coast.



Fig. 10 Oblique UAV photos of the beach and foredune in Reach 2, Greenwich Dunes: A) view west from near Line 6 taken May 31, 2022 (i.e., before Fiona but after the January 2022 storms). Bowley Pond can be seen toward the top of the photo. Note the vegetated slump material and the developing sand ramps; view west (B) and east (C) from near Line 5 taken on October 22, 2022 (after Fiona), showing the near vertical foredune cliff and absence of dune ramps. The bright red colour is a surface coating of fine silt and clay deposited by wind-blown spray from surf bores during the storm event

Along Reach 1 erosion caused by Fiona was more complex than in Reach 2 because of bedrock outcrops and the presence of relic dunes at Lines 2 and 4 formed landward of the present shoreline following the catastrophic shoreline change associated with the 1923 storm (Fig. 2). At Lines 1 and 3, measurements over the past 20 years (Ollerhead et al. 2013; Walker et al. 2017; Davidson-Arnott et al. 2018) have shown a small foredune present as a cover over bedrock,

Fig. 11 Profiles of Lines 5–8 in Reach 2 surveyed on May 31 (before) and October 18, 2022 (after) Fiona. Elevation datum is CGVD2013. See Fig. 2 for locations of the lines. The elevation change along the profile is shown only for Line 8 (Panel D)

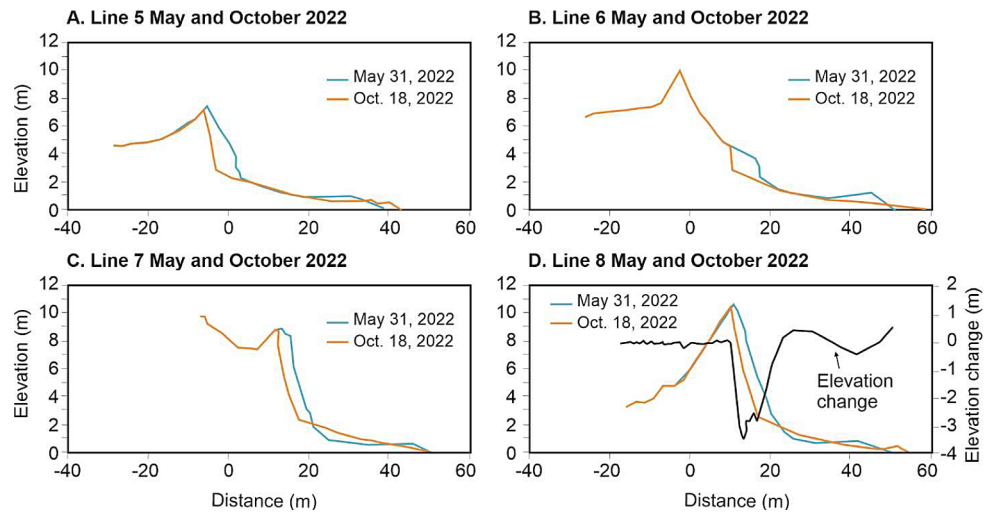
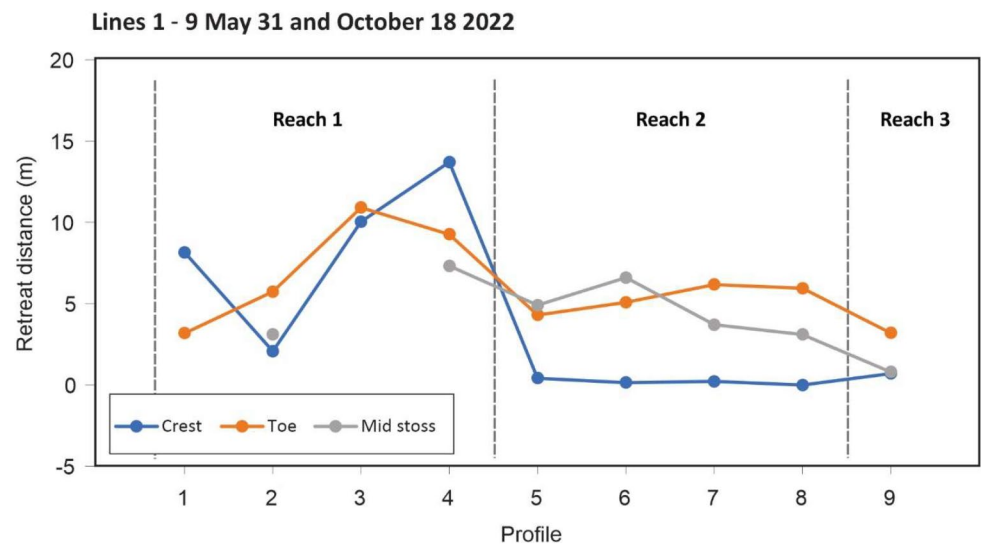


Fig. 12 Horizontal recession of the crest, toe and mid-stoss slope of the foredune at each line. There are no data for the mid-stoss for Lines 1 and 3 because the dune was eroded to bedrock and the toe values reflect the junction of the bedrock scarp with the beach. The large retreat for the crest of Line 4 reflects complete removal of the foredune and retreat to the relic dune



with portions of the bedrock exposed on several occasions after major winter storms. After Fiona the aeolian cover was almost completely removed (Figs. 13A and C and 14A). The position of the crest retreated about 8–10 m and at Line 3 there was a small overwash channel and fan reaching into the low area landward. At Line 2 the large foredune that developed on an older relic dune retreated about 15 m over the past 20 years and decreased in height. A reduction in height of about 1 m occurred because of Fiona along with retreat of the crest and mid-stoss of 2.5–3 m (Fig. 13B). At Line 4 the small foredune retreated about 30 m over the past 20 years. Fiona removed the existing foredune, exposing the next inland relic dune ridge (Fig. 13D) and leaving the new dune crest located nearly 15 m inland from its position in May 2022.

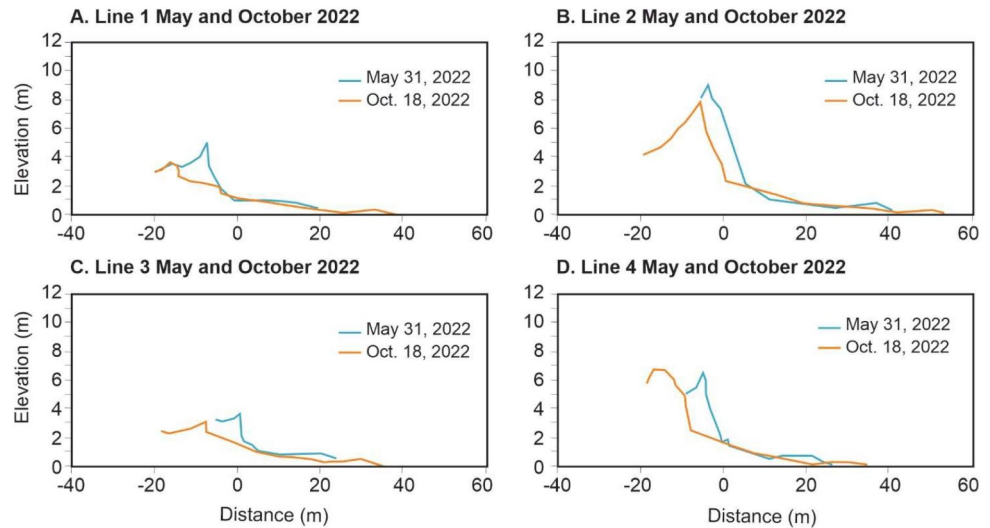
The Greenwich area of PEINP, like much of the island, suffered damage and destruction of infrastructure and especially trees during Fiona. Along the park shoreline within St. Peters Bay there was little impact from storm surge and

wave action, in part because winds were generally along-shore or obliquely offshore at the bayside beaches. At Line 9 near the entrance to the Bay, there was little change in the dune profile and only small change to the narrow beach profile. Damage to infrastructure at the Greenwich site was confined to stair portions of the two access points to the beach (Fig. 14B), which are simple structures that are easily repaired or replaced. While not directly on the shoreline, there was more serious damage done to the floating boardwalk across Bowley Pond because of wind rather than wave action (Fig. 14C; see Figs. 2 and 3B for location).

Brackley and Cavendish beaches

Similar to Greenwich, the foredunes at Brackley and Cavendish were scarped during two winter storms in January, 2022. No significant dune ramp had formed prior to the arrival of Fiona thereby exposing the stoss slope of the foredunes to direct wave attack.

Fig. 13 Profiles of Lines 1–4 in Reach 1 surveyed on May 31 (before) and October 18, 2022 (after) Fiona. See Fig. 2 for locations of the lines



Following the impacts of Fiona, foredunes at Brackley averaged 5 m of crest retreat, with localized maxima of 10 m. Overwash occurred in some areas with a low pre-storm crest elevation outside of the immediate study area. These include an area east of the secondary access point (Figure 15A, B) at Brackley Main Beach (Figure 6) and at the far west end near Robinson's Island where there are prograding dunes separated by a pre-existing overwash channel. Wave action and storm surge near Robinson's Island resulted in damage to the road behind the foredunes, and restriction of vehicular access to this end of Brackley well into 2023. The high-water wrack line within isolated overwash sections was found up to 70 m inland of the foredune ridge (Figure 15). At Brackley, localized maxima of crest retreat occurred adjacent to ridge areas, such as those beside a series of blow-outs on Brackley Beach that were nearly penetrated during Fiona. In the future transgression of the foredunes will need to be monitored as they begin to encroach into limited space between the road and foredune.

The impacts of crest retreat were further reflected in damage to boardwalk infrastructure such as complete removal of the seaward staircase within the secondary access point (Fig. 15D). Prior to the onset of Fiona, lower sections of the main entrance boardwalk were removed to mitigate potential impact. Although the main entrance boardwalk structure remained intact, there was some damage to the western staircase, as shown by the almost complete removal of this piece of the boardwalk in the post-storm Coastie photographs (See Fig. 16 for location; Figs. 17-4b).

Representative profiles derived from the Coastie images at Brackley highlight substantial cross-shore morphological changes to the beach and dune compared to previous UAV surveys conducted in October 2021 (Fig. 16; George et al. 2024). The Brackley East profile (~ 150 m from the boardwalk) experienced complete removal of the stoss

dune slope, corresponding to a ~ 5 m crest retreat, ~ 0.5 m decrease in crest elevation, and 34 m^3 of volume loss from the stoss face (Fig. 16). The remaining stoss slope was very steep, and the mid-back beach slopes were similar in angle to the pre-storm profile. The beach widened due to erosion of the foredune and small amounts of sediment accumulation were documented on the lower beach. In comparison, the profile ~ 150 m to the west of the boardwalk assumed a low-angle post-storm beach slope and lost 43 m^3 of sediment from the front of the dune resulting in a cliffed profile with exposed bedrock at the base (Figs. 17-4b). Crest retreat within this section was ~ 2 m as opposed to the ~ 5 m experienced east of the boardwalk, yielding a reduction in crest height of ~ 1.2 m.

Cavendish Beach experienced overwash and stoss slope erosion similar to that at Brackley (Fig. 18). The previous outlet to Clarke's Pond, where the foredunes have been re-establishing over the past 20 years, experienced overwash and deposition of sediment ~ 30 m into the backbarrier. This area is directly adjacent to the main entrance boardwalk, which experienced damage on the sections closer in elevation to the beach. Overwash also occurred 100–200 m west from the historical recovered outlet, where the pre-storm crest elevation was 2–3 m above the beach. Prior to the arrival of Fiona, the bottom section of the boardwalk was removed, to mitigate impacts to infrastructure. Restoration efforts at the location of the old main entrance boardwalk location were able to decrease vulnerability to this previously unstable area, which was not penetrated during Fiona (Fig. 18B).

Representative Coastie profiles at Cavendish Beach, located 150 m east and west of the main entrance boardwalk, highlight pre- and post-storm morphological differences at these areas (Fig. 19). The profile east of the Coastie site experienced 5 m of crest retreat, accompanied by a 1 m

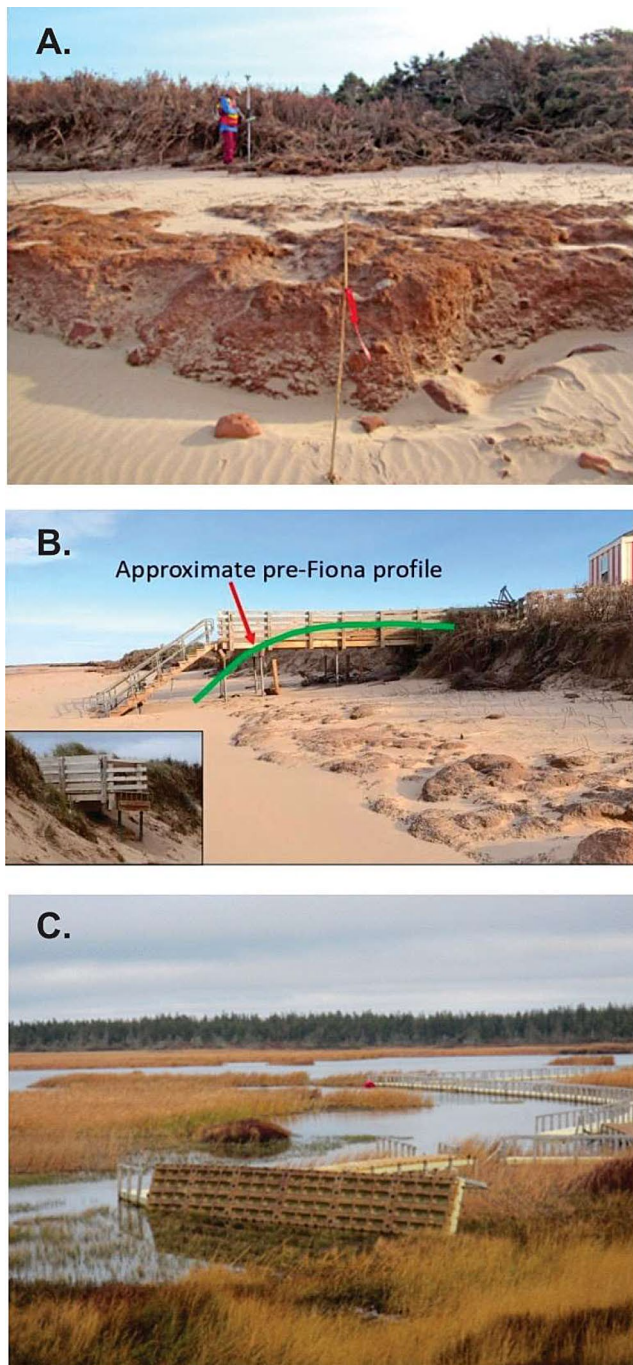


Fig. 14 **A)** Line 1 October 15, 2022, showing the removal of the foredune overlying the till and bedrock surface; **B)** beach access point just west of Line 1 after Fiona (after Ollerhead et al. 2022). The green line indicates the approximate position of the sand surface on May 31, 2022. The end of the boardwalk in May is shown in the inset before the stairs allowing access to the beach had been attached; **C)** six floating segments of the boardwalk across Bowley Pond were displaced or overturned during Fiona

decrease in crest elevation, and 18 m^3 of volume loss. At the base of the profile, sandy bedrock was exposed, and there was limited erosion to the stoss face of the dune due to the protective bedrock. Landward of the bedrock towards the crest, the stoss slope was nearly vertical, similar to that of the Brackley Beach profiles. Aside from complete removal of the beach berm, the post-storm beach slope was very similar to the pre-storm beach slope. In comparison, the profile west of the Coastie site lost 40 m^3 of volume, but the crest position remained unchanged. The stoss slope had a gentle gradient and extended further seaward, whereas the pre-storm Cavendish East profile was steeper (Fig. 19). Therefore, volume loss is higher than the Cavendish East side, but the crest position remained intact as the beach and foredune was wider here.

Recovery from the impact of Fiona

While erosion of the beach and foredune by Fiona occurred within less than one day, the recovery process will last for months in the case of the beach, and years for rebuilding of the dunes. Initiation of recovery was already evident a few weeks after the passage of the storm with accretion apparent on the beach and aeolian processes transporting sediment to the base of the eroded stoss slope of the foredune both at Cavendish and Greenwich Dunes. At Greenwich Dunes, observations in May 2023 showed that building of a sand ramp was quite advanced along the beach in the study area, and that over the fall and winter considerable volumes of sand had been deposited on the stoss slope, crest and, in some areas, on the lee slope (Fig. 20A, B). Deposition over the period October 18, 2022, to May 16, 2023, for Line 6 is evident in the profile change between the two dates (Fig. 20C).

Recovery from the erosion associated with Fiona will vary spatially, depending on sediment availability, but at Greenwich it may only take 4–5 years assuming the area is not hit by additional high-magnitude storms. Evidence for this is based on the recovery from a storm in the winter of 2004–5 (Fig. 20D). Comparison of the 2004 and 2005 profiles (before and after the storm) shows toe erosion at this location of about 5 m and 3 m midway up the stoss slope – values that are of the same order of magnitude as that due to Fiona at this location. Profiles in 2006 and 2007 (not shown) provide evidence of rapid deposition on the beach and stoss slope and by 2008 the profile was very similar to the pre-storm condition (Fig. 20D). Subsequently, a small storm in 2009 created a small scarp at the base of the stoss slope and a much larger one in the winter of 2010–11 scarped the stoss slope nearly to the crest, thus initiating another cycle of erosion and recovery.



Fig. 15 Overwash penetration and crest retreat at Brackley Beach following the impacts of Fiona. Photograph A was taken above Brackley Main Beach, the arrow delineates approximately 30–40 m of overwash deposition, further depicted in image B. Image C was taken above Shaw’s Beach to the east of Brackley Main, facing west towards

the secondary and main access boardwalks. The secondary access is denoted with an arrow in image C. Above the secondary access, image D highlights damage to the boardwalk during the storm, where the entire stoss slope of the foredune and entrance stairway was removed

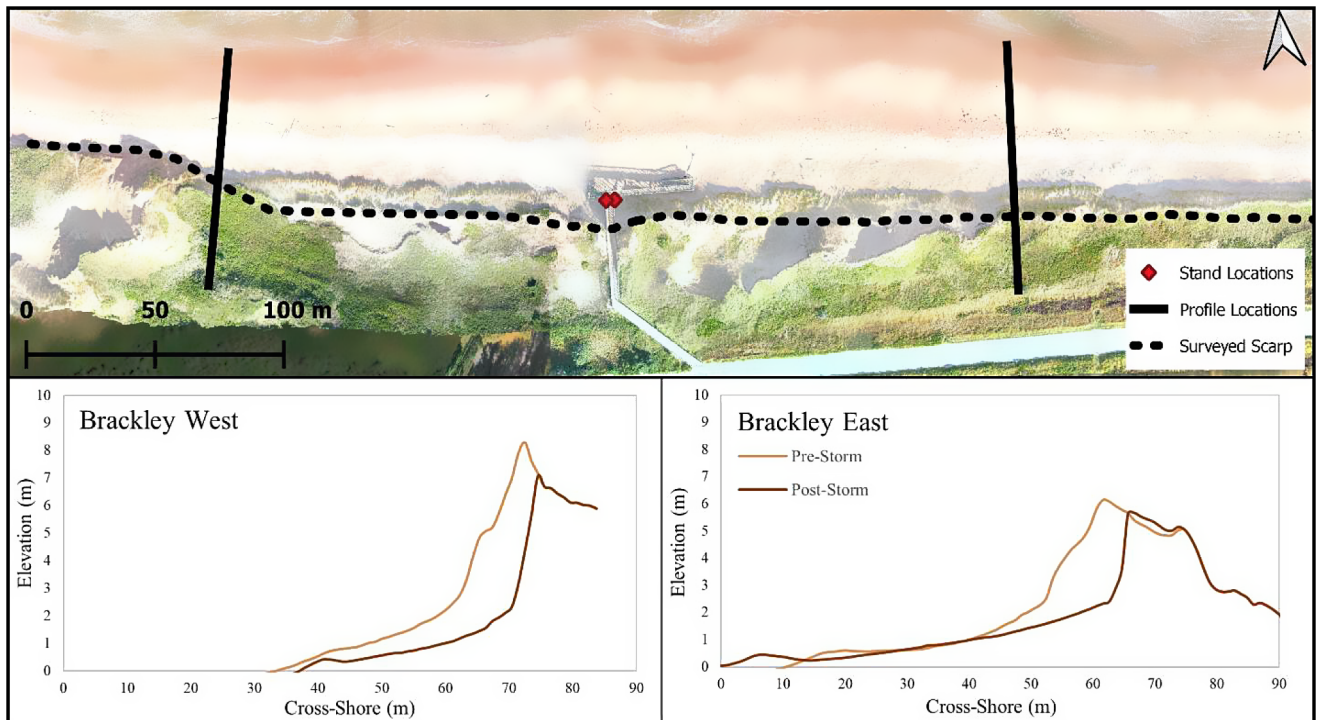


Fig. 16 Brackley West and East profile locations, in relation to the entrance boardwalk at Brackley Main Beach. The basemap consists of UAV survey imagery collected in October 2021. Note the differences in beach width and dune height between these profiles



Fig. 17 Pre-Fiona (upper panels) and post-Fiona (lower panels) Coastal images at Cavendish (1) facing east from the main entrance boardwalk towards the continuous foredune section and cliffs and (2) facing

west of the main entrance boardwalk towards the lower lying dunes that were subject to overwash, (3) facing east of the Brackley boardwalk, and 4) facing west of the Brackley main entrance

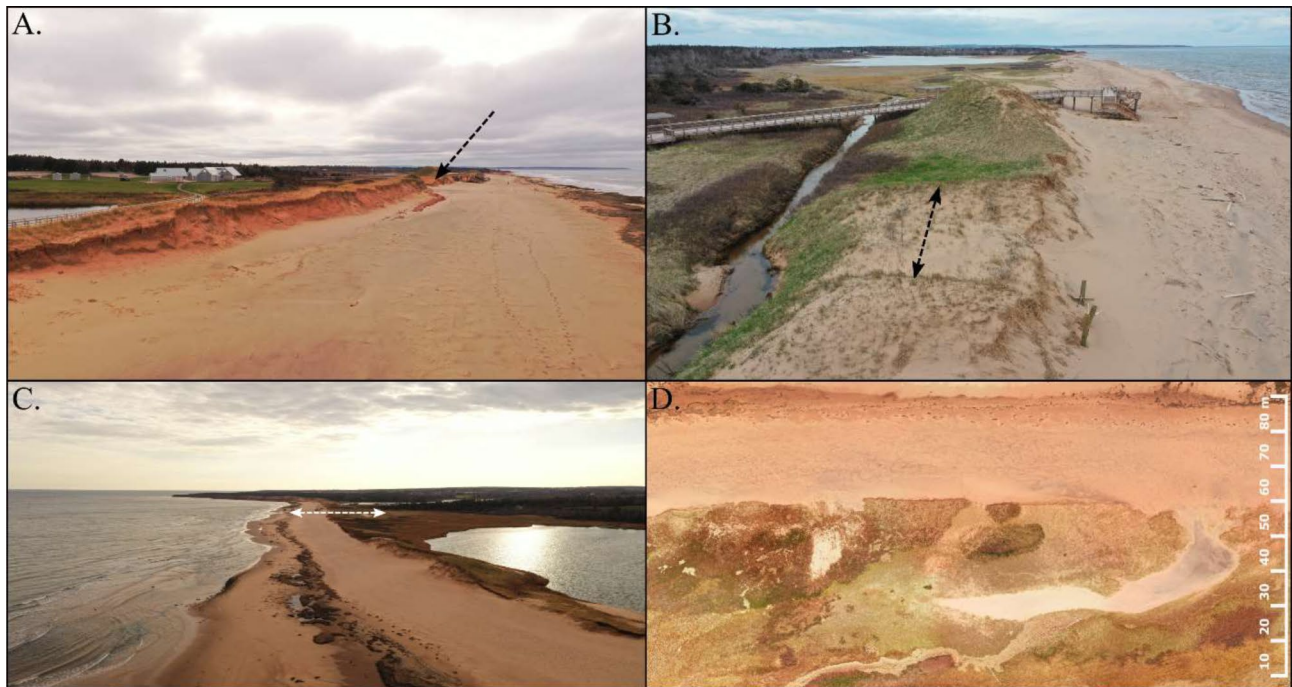


Fig. 18 Post-storm images of Cavendish Main Beach. Image A was taken from the east end, facing west towards the main entrance boardwalk, the location of which is denoted by the arrow. Image B shows the location of the previous main entrance boardwalk, the crest line of which is still recovering. Image C was taken from the west end of the

main beach, facing east toward the main entrance with Clarke’s Pond on the right (see Fig. 5 for location). A small zone of overwash west of the main access point, (marked by the white arrow in C), is shown in D. Clarke’s Pond is located off the bottom of photo D

Discussion

Storm magnitude

Fiona has been characterized as the most intense storm to hit PEI in nearly 100 years in terms of damage to infrastructure

and economic losses (e.g., Globe and Mail, November 15, 2022). It is also possible to rank storms in terms of meteorological measures such as barometric pressure, maximum wind speed, significant wave height and storm surge elevation that reflect potential impact on the coast. On sandy coasts, the impact of storms is often assessed by the degree

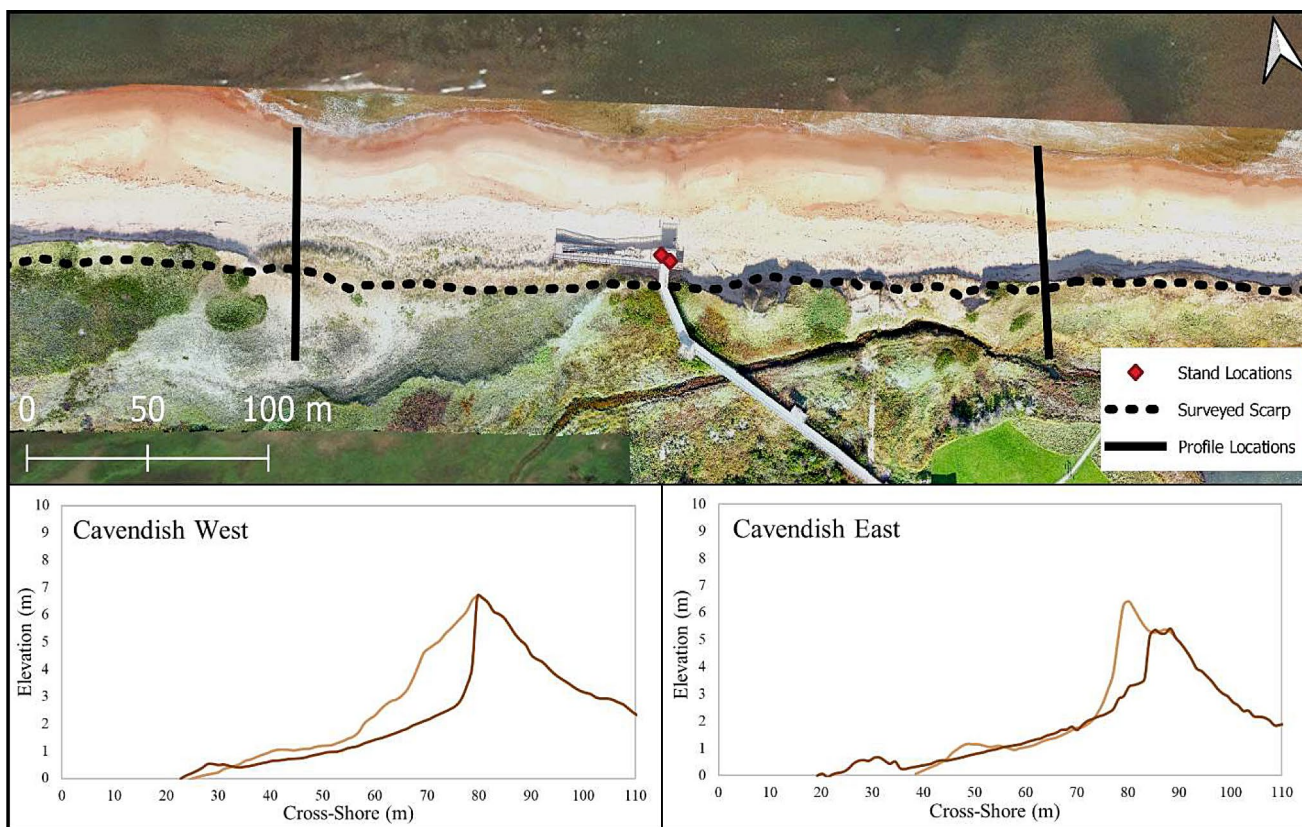
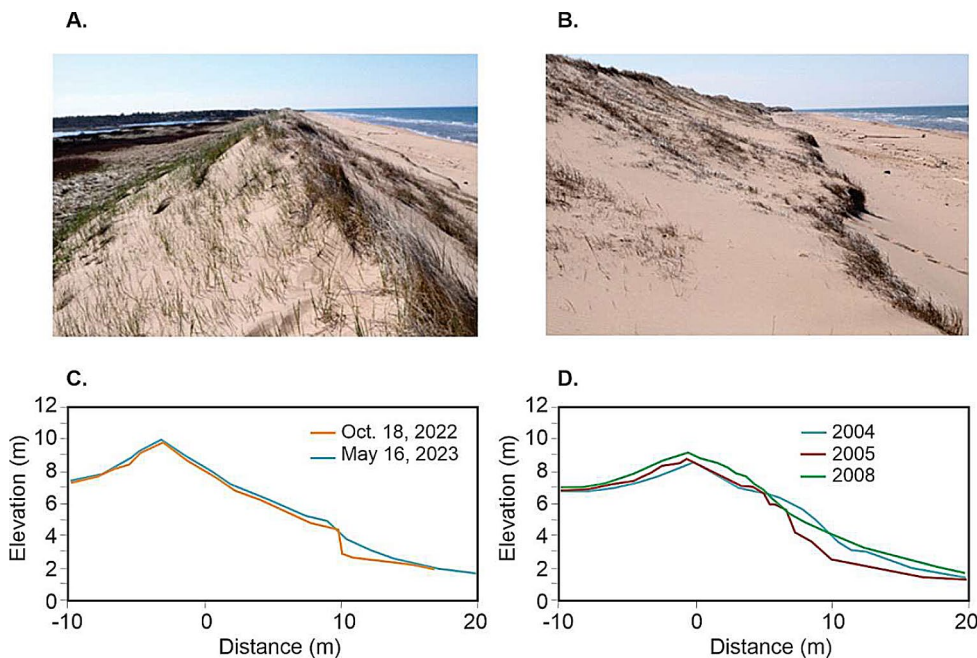


Fig. 19 Cavendish West and East profile locations, in relation to the entrance boardwalk, and pre- and post-Fiona profiles. The basemap consists of pre-storm UAV survey imagery collected in October, 2021, and Bing Virtual Earth basemap imagery

Fig. 20 Beach and foredune recovery at Line 6, Greenwich Dunes following Fiona. Photographs taken on May 16, 2023 show deposition on the crest and lee slope (A) and deposition on the dune ramp and stoss slope (B); C shows the profile surveyed October 18, 2022 and May 16, 2023 illustrating growth of the dune ramp and deposition on the foredune; D shows profiles for 2004, 2005 and 2008 following a major storm in winter 2004–2005



to which beaches and sand dunes are eroded and the extent of dune breaching and overwash (Morton and Sallenger, 2003). Our study suggests that the actual impact of an event on sandy beach and dune systems depends not only on

storm magnitude but also on a range of local factors such as: shoreline orientation relative to wind and wave direction, tidal pattern and range during the storm, effects of antecedent storm events on the nearshore, beach and dune

profile configuration, the presence of near-surface bedrock and/or till, and local littoral and foredune sediment budgets. The combined effect of multiple storms in short sequence (i.e., storm groups) can lead to erosion rates that are higher than single storm events of larger intensity (Ferreira 2005; Splinter et al. 2014). Additionally, the creation of persistent mega-rips also affects the ability of beaches to recover (Loureiro et al. 2012). Changes to extreme wave climate can lead to enhanced beach-dune erosion (Masselink et al. 2016). As a result, making quantitative predictions of the impact of future storms is difficult, even when assuming a constant climate, and made more difficult when trying to include estimates of future effects such as decreasing winter ice cover, shifting storm tracks and ongoing coastal evolution. Nevertheless, comparisons between Fiona and other recent storm events (Fig. 3) suggest that Fiona may have been the most effective storm to impact the north shore of PEI in a century, probably since Hurricane 5 of the 1923 season (Mathew et al. 2010).

Variable storm impact and management implications

The impact of Fiona on the north-shore sandy beaches of PEINP was variable depending on the configuration of the beach-dune system along the shoreline. Three different shoreline types can be identified: (1) Beaches with abundant sand storage and/or ample supply that are characterized by a nearshore profile developed entirely in sand and backed by high (> 6 m), wide dunes that are laterally continuous and extensive alongshore. These beaches may be stable or characterized by a transgression rate $< 0.5 \text{ m}\cdot\text{a}^{-1}$. (2) Beaches with limited sand availability and/or supply that are characterized by low dunes and the development of washover fans during moderate storm events. These beaches have a rate of transgression on the order of $0.5\text{--}1 \text{ m}\cdot\text{a}^{-1}$. (3) Beaches with limited to moderate sand availability and/or supply with bedrock and /or till outcropping at the beach. The dunes backing the beach are $< 6 \text{ m}$ in height and are perched on the bedrock surface. These beaches have variable transgression rates depending on the local lithology and the elevation of the bedrock surface. More detail on each type and their response during Fiona is provided below.

1) High dunes

Beaches with high, wide dunes such as the main Cavendish Beach (Figs. 4 and 7) and the west end of Greenwich (Figs. 2 and 10) had their stoss slopes eroded but there was little impact on the height and position of the foredune crest. Dune erosion was greater during Fiona than for other recent storms, with erosion reaching close to the dune crest but

without breaching. In areas characterized by abundant sand and positive littoral and dune sediment budgets, foredunes will remain intact and will provide protection for infrastructure in the area landward, as was the case at Greenwich despite only passive management. The stoss slopes of the foredunes will experience periodic erosion during major storm events, but will be rebuilt and even experience net growth in the periods between storms, as is characteristic of the cycle of beach-dune interaction (Short and Hesp 1982; Psuty 1988; Sherman and Bauer 1993; Ollerhead et al., 2013; Houser and Ellis, 2013; Masselink et al. 2016; Castelle et al. 2019; McLean et al. 2023; Burvingt and Castelle 2023). The stability of the foredune at the main beach at Cavendish east following Fiona demonstrated that a combination of active management intervention in the choice of location for the new boardwalk, and revegetation of a blow-out from 2014 and the area disturbed by the old boardwalk was sufficient to maintain the integrity of the dune at this location. Recent studies (e.g., Crapoulet et al. 2017; Garzon et al. 2022) suggest that the height and volume of sediments in the backshore is a major control on the extent of dune erosion during a large storm. Thus, deployment of fencing and virtual fencing during the months of high visitor usage may have helped to encourage the development and preservation of pioneer vegetation at the toe of the stoss slope, thereby enabling the building of ephemeral embryo dunes. In turn, this facilitates the trapping of sand at the base of the foredune, thus building up the volume of sand storage in the backshore and enhancing the resistance of foredunes to wave erosion.

Areas with high dunes and a positive dune sediment budget have a greater likelihood of protecting infrastructure landward of the lee slope of the foredune from flooding and erosion during major storm events. Where these beach and dune systems are subject to large visitor numbers it is recommended to minimize the impact on the vegetation of the foredune and embryo dune, and to restore areas of significant human disturbance. Blowouts resulting from trampling of vegetation, for example, represent areas of potential weakness to the integrity of the dune and thus, rapid restoration is the most judicious mitigation strategy. The present management approach within PEINP for such high, stable dunes seems sufficient to ensure this.

2) Low dunes with overwash

There are several areas within PEINP where littoral sediment supply to the foredune system is insufficient to replace sediments eroded by storms, giving rise to a net neutral or negative dune sediment budget. Examples of this include portions of Reach 1 at Greenwich Dunes and the area of low dunes west of the boardwalk at Cavendish (Figs. 14 and 18C

and D). The spit at the west end of Cavendish may also be categorized as such because it is characterized by the presence of overwash channels between stretches of foredune that are active during most large storm events, as was the case during Fiona. However, many of the foredune sections at the proximal end of Cavendish Spit are more than 10 m in height and are not likely to experience overwash.

Areas characterized by occasional overwash are usually ones where there is ongoing transgression at rates $> 0.5 \text{ m}\cdot\text{a}^{-1}$, reflecting the combined effects of a negative littoral sediment budget and RSLR. Overwash healing between storms is hampered by the lack of sediment supply. As a consequence, foredunes of sufficient height and width to prevent severe scarping are precluded from evolving, and overwash channels are reoccupied during storms of smaller magnitude than Fiona. Management interventions should focus on restricting infrastructure development close to the area of potential overwash and should recognize and accommodate the relatively large rates of landward migration of the shoreline.

3) Foredunes perched on bedrock and till substrate

There are many areas along the north coast where foredunes are perched on till and/or a bedrock surface, which slopes gently towards the north in the areas between prominent cliffs and headlands. During Fiona, the foredunes in these areas within PEINP were often eroded completely thereby exposing the underlying till and bedrock (Fig. 14A, B). Weathered sandstone and till are eroded at the seaward margin of the outcrop and also from the exposed top of the substrate. The absence of infiltration on the bedrock surface and removal of the foredune increases the extent of wave uprush leading to erosion of vegetation and infrastructure for considerable distances inland.

Inland penetration of flooding during Fiona provides a guide to future threats to infrastructure and to the lateral extent of the appropriate setback. Even though the bedrock and till substrate along the coast is relatively weak, it should be noted that the actual recession of the exposed bluff may only be 1–2 m in any storm event, much less than the scarping of the foredune. Thus, the long-term recession rates may be smaller than for shorelines developed entirely in sand. The local slope of the bedrock surface inland adds some complexity to predicting such long-term recession rates.

A key aspect of coastal planning within PEINP is to manage infrastructure and beach use to adapt to large-magnitude storm events – events with combined wave height and storm surge that produce erosion of the base of the foredune slope and potential overwash of low dunes (Doody 2013; Walker et al. 2017). There is a continuum of significant event magnitudes from storms that occur once every 2–3 years to

much larger and consequential events that may occur once every few decades to a century. In terms of the impact on sandy beach and dune systems, the data and observations presented here suggest that Fiona can be viewed as an event at the upper part of that continuum in terms of recurrence but perhaps not in overall impact. Recovery may take a decade or less depending on the storm climatology over that period (Fig. 20D). Adaptation to Fiona can therefore be based on the same principles that guide adaptation to storms that affect this coast several times a decade with a focus on infrastructure such as boardwalks, dune crossings and facilities that need to be at, or close to the beach (Haldane et al. 2023). Coastal dunes respond well to passive restoration techniques (Delgado-Fernandez et al. 2019) such as elevated boardwalks and fencing; both have proven to be effective tools to reduce the effect of human trampling and the improvement in plant community structure and species diversity (Santoro et al. 2012; Prisco et al. 2021). The restoration of damaged vegetation leads to more resilient dunes because roots can slow down structural failure during storms and reduce scarp retreat (Sigren et al. 2014; Davidson et al. 2020).

RSLR, accommodation space, and long-term coastal evolution

In contrast to the effects of Fiona on the north coast of PEI, the storm event of October 1, 1923, resulted in overwash and complete destruction of the foredune along almost all of the sandy beach systems from Cable Head West to Cavendish and changed the shape of the coast in several areas. Recovery of sandy beach systems from the 1923 storm event took at least half a century and is still influencing the littoral transport system, for example, through the addition of sediment supply from erosion of relic dunes such as those at Lines 2 and 4 at Greenwich. Adaptation to a storm event of this magnitude, one with a return period of a century or longer, will require a different management approach and will need to account for long-term RSLR. The focus should be on resilience planning for semi-permanent infrastructure such as campsites, administrative buildings and roads, including highways within the park boundaries, which have a longer life expectancy than similar facilities near the beach. Adaptation to coastal recession due to long-term RSLR and erosion of the bedrock substrate should focus on providing sufficient accommodation space for the inland migration of all coastal systems, and sandy beach systems in particular (Davidson-Arnott 2005; Davidson-Arnott and Bauer 2021) and thereby avoid ‘coastal squeeze’. Such accommodation space is clearly mandated by an event of the scale of the 1923 storm – both in terms of the inland

location of infrastructure and the space and time needed for recovery (Mathew et al. 2010).

Conclusions

Having assessed the impact of Post-tropical Storm Fiona on the sandy beaches and foredunes within PEINP and having considered the extent to which existing PEINP management policies and practices are effective, the following conclusions are reached:

1) The impacts of Hurricane Fiona on natural sandy beach and dune systems on the north of PEI, despite its significance as an extreme meteorological event, were not unusual and similar in character and magnitude to other severe storms over the past 3–4 decades. Changes to the shoreline geomorphology were moderate rather than catastrophic, with beaches largely preserved and recovery of the foredune underway and likely to persist over the next few years to a decade unless disrupted by another major event. This is consistent with our current understanding of beach – dune interaction and local beach and dune sediment budgets.

2) Damage and loss of infrastructure in PEINP from wave action, storm surge, and dune erosion were largely confined to boardwalk access points at, or very close, to the beach. Management strategies designed to locate physical structures sufficiently far inland, and away from erosion-prone areas, as well as mitigating human impact on the foredune, are therefore deemed to have been successful in accomplishing the primary objective of minimizing damage and expense.

3) The impact of Fiona on PEINP serves to reinforce the need to prioritize natural biotic and abiotic components of sandy beach and dune systems as a key management strategy. Planning should continue to focus on the potential short-term impacts of severe storms similar to Fiona, as viewed in the context of ongoing coastal evolution on a decadal to century timescale driven by geomorphic processes that control local and regional erosion and sediment transport (Walker et al. 2017). Over the long term, RSLR is a key driver of shoreline change and management adaptation, and for the next few decades at least, it will only continue to accelerate.

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Declarations

Ethics approval and consent to participate All authors have reviewed the paper prior to submission and all consent to its publication.

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