Assessing climate-impact risk to Piping Plover (*Charadrius melodus melodus*) breeding sites in Nova Scotia, Canada

by

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Dalhousie University is located in Mi'kma'ki, the
ancestral and unceded territory of the Mi'kmaq.
We are all Treaty people.

This thesis is dedicated to all the shorebirds that call Mi’kma’ki (Nova Scotia) home.

"All conservation of wildness is self-defeating,
for to cherish we must see and fondle,
and when enough have seen and fondled,
there is no wilderness left to cherish."
– Aldo Leopold, A Sand County Almanac

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Abstract

The Piping Plover (*Charadrius melodus melodus*) is a shorebird assessed as 'Endangered' by the Committee on the Status of Endangered Wildlife in Canada. They nest in coastal habitats and are vulnerable to climate change impacts associated with sea-level rise and increased storm events. A mixed methods approach was utilized to assess these potential impacts in Atlantic Canada. This included statistical modelling of temporal trends in piping plover in relation to storms, analysis of satellite imagery of breeding habitat in relation to a single storm event, and an estimation of future sea-level rise and its impact on habitat. A weak relationship was found between Piping Plover abundance and storm frequency in Nova Scotia and New Brunswick. The majority of habitat within Nova Scotia was resilient to impacts from Hurricane Dorian. However, sea-level rise projections predicted that ~82% of Piping Plover habitat in Nova Scotia will be below sea level by 2100.

List of Abbreviations Used

AIC_c	Akaike's Information Criterion corrected for small sample sizes
ANOVA	Analysis of variance
AT	Atlantic Standard Time
BIO	Bedford Institute of Oceanography
CAN-EWLAT	Canadian Extreme Water Level Adaptation Tool
CHC	Canadian Hurricane Centre
COSEWIC	Committee on the Status of Endangered Wildlife in Canada
CWS	Canadian Wildlife Service
DFO	Department of Oceans and Fisheries Canada
ECCC	Environment Climate Change Canada
ESRI	Environmental Systems Research Institute
GIS	Geographic Information System
GLMER	Generalized linear mixed-effects model
GLMM	Generalized linear mixed models
NABCIC	North American Bird Conservation Initiative Canada
NAD	North American Datum
NB	New Brunswick
NOAA	National Oceanic and Atmospheric Administration
NRCAN	Natural Resources Canada
NS	Nova Scotia
NSDEM	Nova Scotia Department of Energy and Mines
NSDNRR	Nova Scotia Department of Natural Resources and Renewables
SARA	Species at Risk Act
SD	Standard Deviation
SI	Storm-Induced
SLR	Sea-level rise
SNS	Southern Newfoundland Shelf region
SR	Storm-Resilient
SV	Storm-Vulnerable
UTM	Universal Transverse Mercator

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Chapter 1: Introduction

Climate change, the long-term alteration of weather patterns caused by continuous anthropogenic activity, is one of the most significant driving factors in habitat degradation and biodiversity declines over the last century (Bellard et al., 2012; Environment Climate Change Canada [ECCC], 2019). Birds are especially at risk of climate change, with predictions estimating that 43% of avian habitats will become altered or lost by the next century (Mantyka-Pringle et al., 2015). Coastal areas and shorelines are highly vulnerable to climate change processes, such as sea-level rise [SLR], storm surge events, and coastal erosion, which can cause an increase in flood risk and dune collapse, and thereby negatively affect migratory shorebirds (Seavey et al., 2011; Vitousek et al., 2017; Brooks, 2020). Presently, global beaches are at risk of deteriorating as a result of these climate impacts in addition to anthropogenic influences, such as restricted sand availability through dredging and the alteration of watercourses (Sims et al., 2013; Vitousek et al., 2017). In conjunction with climate change, SLR and storm surges threaten to challenge the existence of natural beaches throughout the world, which will threaten coastal ecosystems and the shorebirds that fulfil ecological roles therein (Moreira, 1997; Seavey et al., 2011; Vitousek et al., 2017; Brooks, 2020).

1.1 Problem Statement and Importance of the Issue

The eastern subspecies of Piping Plover (*Charadrius melodus melodus*) is assessed as 'Endangered' by the Committee on the Status of Endangered Wildlife in Canada [COSEWIC], and is listed under Schedule 1 of the *Species At Risk Act* [SARA] (COSEWIC, 2013; ECCC, 2021). In the province of Nova Scotia [NS], the shorebird is currently listed as an endangered species-at-risk (Endangered Species Act [ESA], 2017). Despite recent recovery initiatives, such as predator exclosures, increased surveying, and monitoring of human interference, Piping Plover populations continue to decline and face multiple threats (Barber, 2010; Maslo et al., 2018; ECCC, 2021), which include the impacts of coastal climate change on breeding and nesting habitats (Seavey et al., 2011; Galbraith et al., 2014). Piping Plovers, which nest in these coastal habitats, are highly susceptible to climate change, including SLR, increasing frequency and severity of storms, and coastal erosion (Hanson et al., 2006; Sims et al., 2013). As a result, they face both the direct and indirect impacts of climate change on their habitats (Bourque et al., 2015), which ultimately reduce habitat availability, nesting success, and chick survival (ECCC, 2021). Previous research suggested that strong winter storms may potentially create short-term climate-induced habitats for shorebirds by the removal of vegetation and the alteration and expansion of sand (Bourque et al., 2015; Maslo et al., 2019; Walker et al., 2019; Zeigler et al., 2019). When climate-induced habitat creation does not occur, beach alteration by strenuous climate processes may progress to a point where the habitat would no longer be suitable (Boyne et al., 2014). However, current conservation strategies and coastal management may not provide for these potentially positive gains due to a lack of research and awareness of climate-induced habitats and the associated impacts of storms on beaches (Boyne et al., 2014; Bourque et al., 2015; Maslo et al., 2020).

1.2 Research Goals and Objectives

In this thesis, the research sought to determine if climate-influenced storms and SLR impacted habitat quantity and quality for Piping Plover (*Charadrius melodus melodus*) before and after a storm event (Hurricane Dorian) and longitudinally over a thirty-year time series (1991-2020). This spatial and statistical modelling study aimed to identify the impacts on the distribution and size of existing and potential Piping Plover habitats in NS from SLR and coastal erosion processes associated with climate-influenced weather events (storms). The study objectives were:

1. Examine long-term Piping Plover population declines in NS and New Brunswick [NB] and potential correlations with annual storm events;
2. Quantify potential change in sand coverage on NS beach habitat for Piping Plover pre- and post-Hurricane Dorian; and,
3. Assess interactions with coastal sea-level rise in the context of Piping Plover habitat in NS.

1.3 Significance of Study Species and Study Area

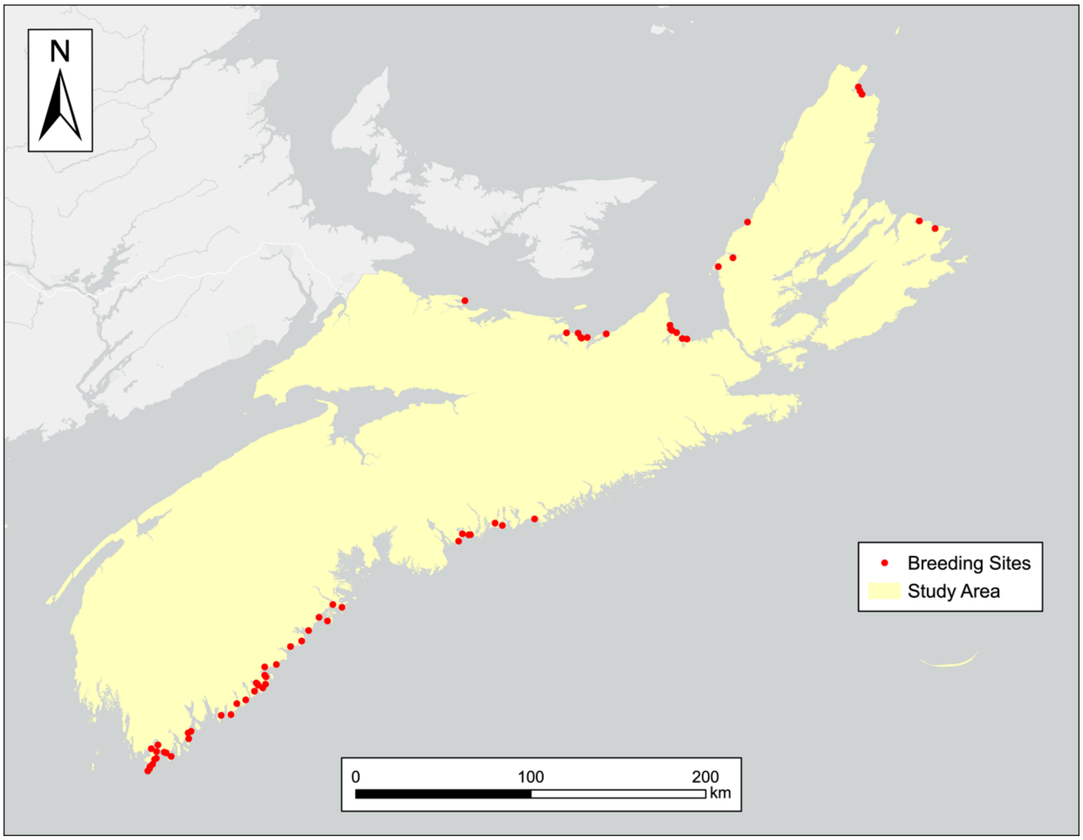
The Piping Plover is a migratory shorebird exclusive to North America that breeds and nests on the beaches and sandbars of Canada and the United States (COSEWIC, 2013). It is a small plover species with a pale, sand-coloured back, short, stout bill, and orange legs which depends on its cryptic plumage to avoid predators (COSEWIC, 2013; ECCC, 2021). During the breeding season, their plumage resembles the colour of dry sand, varying between light grey and pale brown with white underparts, black bands across the breast and forehead, and a black tip on their bill (COSEWIC, 2013; ECCC, 2021). Adults of the species weigh between 43 to 63g, are approximately 17-18cm long, and can breed at one year of age (ECCC, 2021). When nesting, the Piping Plover prefers habitats with open sandy beaches, sandbars, and inlets with sparse or minimal vegetation cover (Boyne et al., 2014; ECCC, 2021). The eastern subspecies breeds along the coastlines of Atlantic Canada, which includes NS, NB, Prince Edward Island, Newfoundland and Labrador, and the Magdalen Islands of Quebec (COSEWIC, 2013).

Avifauna, including shorebirds and the Piping Plover, are significant health indicators for ecosystems due to their roles as bioindicators of environmental contaminants and diseases, such as avian influenza (North American Bird Conservation Initiative Canada [NABCIC], 2019). Shorebirds are also crucially important to the function and balance of estuarine food webs and their respective energy fluxes (Moreira, 1997). They consume large amounts of invertebrate biomass along the swash line of beaches during low tide, which ensures the balance of the coastal food web (Moreira, 1997; Schlacher et al., 2016; Booty et al., 2020). In addition, the expelled fecal matter from foraging is involved in nutrient cycling, which reduces levels of nitrate fluxes into beach sediment, lowers nitrate efflux, and reduces phosphorus uptake in areas where shorebirds are present (Booty et al., 2020). In addition to these factors, recent evidence on the ecological importance of shorebirds suggests that the presence of these species, such as the Piping Plover, may potentially contribute to carbon sequestration processes and erosion protection of intertidal habitats (Booty et al., 2020). Overall, shorebirds are essential components of coastal ecosystems, valued by the general public, exhibit immense and impressive aggregations during migration, and can act as flagship species representing climate change in coastal areas (Galbraith et al., 2014; Stewart et al., 2015).

Endangered species, such as Piping Plover, have intrinsic value regardless of their role or utility (Smith, 2016). Intrinsic value, combined with our role in endangering species, such as through habitat destruction, resource exploitation, and anthropogenic development, underlies the moral imperative for humans to conserve and protect species (Smith, 2016). Unfortunately, shorebird populations across Canada have declined by over 40% since 1970 due to climate change, ongoing coastal development, and other human disturbances (NABCIC, 2019). Additional climate change risk factors for shorebirds include long and energetically expensive seasonal migrations where they are vulnerable to more intense storms, changes in wind patterns, dependence upon coastal migration stopover sites that are vulnerable to SLR, and dependence upon ecological synchronicities (i.e., invertebrate prey availability) that may be disrupted by the delayed warming of coastal areas (Seavey et al., 2011; Galbraith et al., 2014).

The study area for this thesis research encompassed all coastal regions in NS, and a portion from NB, in which current Piping Plover habitats were situated and subject to annual monitoring for nesting pairs (Bourque et al., 2015; ECCC, 2021). Approximately ~51% of known critical habitat for the Piping Plover in Canada is located in NS and NB (ECCC, 2021). Piping Plovers tend to select nesting habitats with a sandy beach surface, mixed pebble and rock substrate, sparse vegetation, and a low slope to the shoreline (Boyne et al., 2014). Therefore, study areas were defined as habitats that were known to contain plover populations from previous surveys in addition to being characterized as an oceanic beach, which are narrow landforms characterized as sloping strips of land that lay along an ocean (Davis & Browne, 1996; Evers, 2012). The beaches that were examined for this study were described as having a sandy shore, where sand is exposed between extreme levels of high and low tide and have limited vegetation (i.e., dune grasses), which are crucial for the foraging, breeding, and nesting for shorebirds such as plovers and sandpipers (Davis & Browne, 1996). On average, the extent of potential Piping Plover habitat area for sites in NS is estimated to be 133km^2 and covers approximately 64 potentially active sites from 1991 to 2020 (J. Rock, personal communication, January 20, 2022) (Figure 1.1).

Figure 1.1 Map detailing known Piping Plover (*Charadrius melodus melodus*) habitats ($N = 64$) the study area of the province of Nova Scotia, Canada, located in the Atlantic region; aspect ratio 1:2,200,000. Land cover of the province is approximately 55,284km^2 (NSDNRR, 2021). Piping Plover demographics data was obtained from Environment Climate Change Canada and Canadian Wildlife Service.



1.4 A Changing Coastline

In the Atlantic provinces of Canada, the coastlines are dominated by cliffs and gravel beaches and are characterized by steep offshore bathymetry (NRCAN, 2008). Beaches in NS tend to be comprised of varying amounts of sand and cobble sediment with minimal vegetation presence due to the high mobility of the beach substrate, which is usually sandstone or slate (Davis & Browne, 1996; Boyne et al., 2014). These sandy beaches at low tide are prime foraging habitats for shorebirds, such as sandpipers and plovers, as they host infaunal invertebrate biomass such as polychaete worms, molluscs, and arthropods (Davis & Browne, 1996; Moreira, 1997). Sand-dominated beaches in NS tend to exhibit seasonal variations in the distribution of sand on the shore due to wind and tidal action, as sand is transferred from the beach to shallow water in the winter months and is 'returned' in the summer (Davis & Browne, 1996). Dune systems, which are present on a majority of sand beaches, are habitats resulting from the deposition of sand on the upper levels of the beach by the winds and tides, which become stabilized by the growth of dune grasses (i.e., American Marram Grass) (Davis & Browne, 1996; Dunsford, 2021; Palmer, 2021). These portions of beach habitat are crucial for shorebirds and their breeding success, as the dune system provides sufficient shelter for chicks from predators and climate impacts such as storm surges (Dunsford, 2021; Palmer, 2021). Dune systems promote natural hardening and coastal resilience by preventing erosion and protecting from the effects of SLR due to the presence of stabilizing vegetation (Dunsford, 2021; Palmer, 2021). However, the extent to which a coastal dune system will develop depends entirely upon sediment supply and the risk of erosion in the local environment, which is presently exacerbated by the increasing rate of SLR by climate change (Davis & Browne, 1996; Palmer, 2021).

The climate of NS consists of high relative humidity, extensive amounts of rainfall, a reasonably wide temperature range, a late and brief summer, skies that are often cloudy or overcast, and frequent occurrences of fog along the coastline (NRCAN, 2008; Davis & Browne, 1996; Taylor & Garbary, 2003; Garbary & Hill, 2021). The province's climate can be attributed to strong westerly winds, the converging of air masses that batter the east coast, the province's position relative to storms heading eastward, and the influence of the tides (Davis & Browne, 1996). Storm occurrence varies annually in NS, with autumn as the season with the most significant cyclonic activity due to offshore waters still warmed from the previous summer months, which helps to prolong the season (Davis & Browne, 1996). Further, temperatures in NS have increased in the late twentieth century due to climate change, causing the waters surrounding the province to remain warmer into the fall months (Garbary & Hill, 2021). In recent decades, hurricanes have begun to increase in their presence and intensity in the Atlantic region due to global warming and climate change effects, which causes significant damage to coastlines and coastal communities (Camelo et al., 2020). Hurricanes, often referred to as tropical cyclones, are extreme weather events that originate within the tropics of the Atlantic (i.e., Gulf of Mexico, Caribbean) and bring devasting storm surge waves, winds and rainfall to Atlantic Canada (Canadian Hurricane Centre [CHC], 2018). These storms contain a low-pressure centre, with wind gusts as low as 63km/h, such as in tropical depressions, to intense hurricane gusts surpassing 250km/h (CHC, 2018).

Extreme high tides caused by seasonal hurricanes may flood nesting habitats for shorebirds, such as the Piping Plover, which can result in considerable mortality if high tides coincide with the peak breeding season (i.e., June) (ECCC, 2021). Additionally, hurricanes and consequent periods of cold weather may contribute to adult mortality (ECCC, 2021). Conversely, when unimpeded by coastal development or infrastructure, these severe weather events may create new habitat through the deposition of sand and may also maintain the early successional stage habitat required for breeding (ECCC, 2021). Other ways hurricanes may benefit Piping Plover habitat include reducing vegetation by shifting and exposing sand for nesting habitat (Cohen et al., 2009; Hunt et al., 2018, Walker et al., 2019; Robinson, 2020), and exposing sections of shoreline for productive foraging habitats by increasing both the habitat's quality and its carrying capacity (Cohen et al. 2009; Robinson, 2020). Further, storm impacts may be beneficial to barrier beaches as storm-induced over-wash is crucial for marsh accretion, which allows these ecosystems to remain stable with changes in tide level (Baumann, 1980; Zeigler et al., 2019). In short, the Piping Plover depends on storms as critical habitat creation events, as the species relies on the expansion of early successional habitat for breeding, nesting, and foraging (Cohen et al., 2009; Schupp et al., 2013; Zeigler et al., 2019). However, when considering the management of these induced habitats concerning storms, conservation managers may need to weigh conflicting objectives related to economic and social issues in addition to effectively implementing protection for the species' habitat, which may be difficult due to the negative impacts of storms on human infrastructure (Zeigler et al., 2019; Maslo et al., 2019).

1.5 Conservation of a Threatened Shorebird

The Piping Plover is among the most well-known threatened avifauna in North America, primarily due to its status as a flagship species for shoreline conservation (Stewart et al., 2015). Recovery approaches towards the species' conservation include targeted educational outreach to beachgoers, protection of critical habitats by minimizing human disturbance (i.e., barrier fencing, signage, beach closures), predator management, increased enforcement in coastal areas, and population monitoring through volunteer surveying (Burger et al., 2004; ECCC, 2021). However, despite gains in the reproductive output of chicks, the species' population growth remains on the decline (Gibson et al., 2018). In addition to climate change, the Piping Plover is threatened by human activity in their habitats, which is generally negatively correlated with chick survival (Flemming et al., 1988; DeRose-Wilson et al., 2018). Human activity, which includes beach recreation (i.e., walking, running, vehicle use, kite-flying, dog-walking, fireworks), has dire consequences for the species, as it is a significant factor in the incidence of crushed nests and chicks, reduced foraging rates, and the exclusion of chicks from preferred foraging habitats (Burger, 1994; DeRose-Wilson et al., 2018). Beach recreation limits access and availability of foraging habitat to Piping Plover, which results in the shorebirds spending their energy responding to these nearby threats either by observing or avoiding approaching humans (Burger, 1994; Fitzpatrick & Boucher, 1998; McCrary & Pierson, 2000). Although some beach recreation, such as walking, may be considered low disturbance, these activities can inadvertently cause harm as their nests as the eggs are camouflaged amongst the substrate, and unaware pedestrians may trample them (ECCC, 2021). In some cases, human activity also directly affects their habitats (ECCC, 2021). Vehicle use on beaches disturbs the birds themselves and causes the compaction of the substrate (i.e., sand), which may reduce the abundance of invertebrate food items and limits the amount of sand available for foraging (Wolcott & Wolcott, 1999).

Further, coastal development on or near beaches negatively impacts the Piping Plover and their breeding habitats (Seavey, 2009). For example, in North America, many coastal areas with vital infrastructure are 'hardened' or artificially stabilized with seawalls, jetties, and artificial dunes (Finck, 2006; Zeigler et al., 2019). These artificial structures are routinely replenished with sediment from other sources to reduce negative storm impacts, but they risk causing further coastal erosion and threatening coastal wildlife (Finck, 2006). In short, anthropogenic shoreline modifications can ultimately prevent early successional habitats from forming and can adversely affect coastal ecosystems and their resiliency to storms, which threatens the Piping Plover and their habitats (Brown et al., 2002; Gittman et al., 2016; Zeigler et al., 2019).

1.6 Organization of Chapters and Thesis Contribution

This thesis comprises four chapters that chronologically address the objectives and process of the research. Chapter 2 outlines the methodology, including limitations and mitigations of the geographic information system [GIS] study. In Chapter 3, the results of the analyses are explored and discussed through a series of statistical outputs and maps organized around the objectives of the thesis. The final chapter, Chapter 4, highlights the most significant conclusions emerging from the study, identifying key themes and patterns observed across the thesis.

Study findings should aid in the recovery of Piping Plover within the province and in Canada by identifying habitats likely to be altered due to past and present climate change impacts. Provincial biologists have expressed interest in this research methodology and outputs and anticipation that they will support future Piping Plover recovery planning (D. Sam, personal communication, October 16, 2020), and the efforts of federal governmental organizations such as ECCC and Canadian Wildlife Service [CWS] (J. Rock, personal communication, January 20, 2022). In addition, the research produced through this study will contribute to the further development of a nascent, yet promising, field of study and body of literature on climate-resilient and climate-induced habitats for the coastal species in this region and beyond, with potential applicability to other at-risk and endangered shorebird species.

Chapter 2: Methods

2.1 Methodology

This study employed a mixed-methods approach towards analyzing climate data in the context of Piping Plover recovery. The methodology was based on quantitative and qualitative practices previously utilized by Bourque et al. (2015), which incorporated spatial analysis and aerial imagery interpretation, as well as from previous studies by Walker et al. (2019) and Zeigler et al. (2019). It encompassed the following stages: 1) literature review and statistical modelling of obtained secondary data of Piping Plover demographics in NS and NB (i.e., breeding pairs and fledglings); 2) spatial analyses and habitat classification assessment of a selected sample of Piping Plover beaches in NS using Hurricane Dorian as a case event; 3) SLR analysis of historical data and current projections in the context of Piping Plover habitat in NS. The methods are organized by research objective and presented in the following sections: 2.2) Examining Long-Term Piping Plover Population Declines in Nova Scotia and New Brunswick and Potential Correlations with Annual Storm Events; 2.3) Quantifying Potential Change in Sand Coverage on Nova Scotian Beach Habitat for Piping Plover Pre- and Post-Hurricane Dorian; 2.4) Assessing Interactions with Coastal Sea-Level Rise and Piping Plover Habitat in Nova Scotia.

2.2 Examining Long-Term Piping Plover Population Declines in Nova Scotia and New Brunswick and Potential Correlations with Annual Storm Events

2.2.1 Piping Plover Demographics Data

Piping Plover breeding pairs and fledglings recorded from 1991 to 2020 within NS were examined to determine potential population declines due to coastal storms. The thirty-year time series was chosen due to reliable and consistent data availability from governmental and research-based non-governmental organizations sources: CWS, ECCC, Nova Scotia Department of Natural Resources and Renewables [NSDNRR], and the Piping Plover Conservation Program through Birds Canada (Bartlett & Maillet, 2019). For examining demographic changes in Piping Plovers for NS and NB, the time period of 1992-2020 was chosen on the basis that 1991 was an anomalous year for data collection, and no data was available for fledglings for either province at this year. The time series also facilitates the identification of any significant changes that may have occurred in the species' demographics in response to changes in habitat quality and availability.

Annual surveys for breeding pairs and fledglings of the eastern subspecies have been conducted in the Atlantic region since 1991 and consistently since 1996 (J. Rock, personal communication, January 20, 2022). These abundance surveys usually occur during the first two weeks of June, and in mid-August, towards the end of the breeding season, year-end counts are conducted of the total numbers of adults and fledgling success (COSEWIC, 2013). During surveys, trained observers walk the length of the beach and record present individuals of the species seen at each site (Gautreau & Stewart, 2008; Bourque et al., 2015). Breeding pair and fledgling count data for NS from 1991 to 2020 was provided by ECCC (J. Rock, personal communication, January 20, 2022). Changes in Piping Plover populations (i.e., breeding pairs, fledglings) over time in NS and NB were described using lambda (λ), where λ represents population growth and N_t represents time intervals (Hecht & Melvin, 2009). The use of lambda in this thesis was non-traditional, but was utilized to replicate methods from previous research on Piping Plover population analysis by Hecht and Melvin (2009). To replicate the methods utilized by Bourque et al. (2015), data for breeding pairs and fledglings of NB were obtained from ECCC for the same time series.

Equation 1. Population growth rate of Piping Plover (*Charadrius melodus melodus*) breeding pairs and fledglings between generations (1992-2020) (Hecht & Melvin, 2009).

$$\lambda = \frac{N_t + 1}{N_t}$$

2.2.2 Extreme Weather Events Data

To determine the potential impacts of climate change on Piping Plover and their habitats, extreme weather events (storms) were assessed using secondary climate change data obtained through ECCC, Department of Oceans and Fisheries [DFO], and National

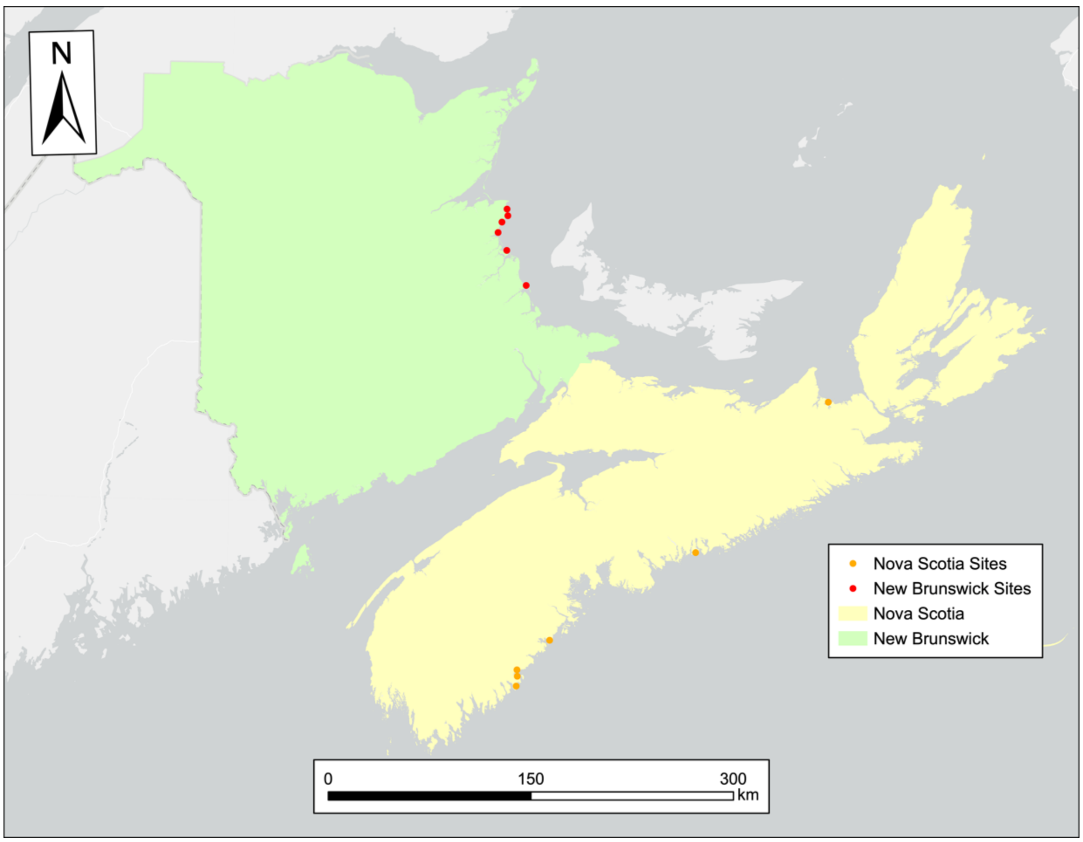
Oceanic Atmospheric Administration [NOAA]. Storm events impacting NS between 1991 and 2020 deemed significant by ECCC were examined upon meeting the following criteria: 1) deemed a significant storm surge; 2) highest water level recorded for the month; and 3) event occurred between June and December during the Atlantic hurricane season. The time series for storm events was selected because the data was publicly accessible through government and open-data platforms (i.e., ECCC, NOAA), as a majority of water level and storm surge data for NS are digitally available post-2005 through comprehensive reports. However, aerial satellite imagery between 1991 to 2004 was scarce and inconsistent on online imagery databases. In addition, characteristics such as event name, event date, surge (m), water level (m), wind direction, wind speed (km/h), wind gust (km/h), and landfall are identified for each weather event from ECCC and CHC. Finally, to replicate the models Bourque et al. (2015) established, the criteria were applied to NB for the same time series (i.e., 1991-2020). This selection process yielded approximately forty storms ($N = 40$) for the study area in NS and 18 storms ($N = 18$) for the study area in NB (see Appendix A; Table A1; Table A2).

2.2.3 Generalized Linear Mixed-Effects Modelling

Modelling with Generalized Linear Mixed-Effects Models [GLMER] was used to perform analyses of Piping Plover population responses to extreme weather events (storms) over the time series. GLMERs are part of the Generalized Linear Mixed Models [GLMM] family of statistical models and are used to analyze data that contain random effects (Bolker et al., 2009). Due to the presence of null (i.e., missing) data at some Piping Plover sites, a subset of six Piping Plover beach habitats were chosen in each of NS and NB, for a total of 12, on the basis that there was consistent breeding and fledgling data recorded annually from 1994 to 2020 (Figure 2.1). The habitats chosen for NB were the same as the reference habitats used in Bourque et al. (2015), which was a study on Piping Plover responses to storms in NB. The six sites selected were replicated from Bourque et al. (2015) for consistency with the previous research. The starting year of the time series for these GLMER models was changed from 1991 to 1994 because of missing data before 1994. Habitat (notated as ‘beach’) was used as a random effect. To fit the previous model design by Bourque et al. (2015), the models used Piping Plover response (annual abundance of breeding pairs and fledglings per habitat) as the dependent variable and storm occurrence (frequency of storms per year) as the independent variable. Because of the potential delay in Piping Plover response to habitat alteration due to storm effects, this study also modelled for response lags of one, two, and three years after the occurrence of storm events. Criteria for storm selection is discussed in section 2.2.2.

Separate GLMER models were constructed for breeding pairs and fledglings for each province (NS, NB) in combination with the abovementioned scenarios (i.e., response lags to storm events occurring one, two, or three years before a given year), in addition to a combined fledgling success model for NS and NB. There were twenty models in total, explored through five scripts (see Appendix C). These models examining Piping Plover population change in response to storms were created and analyzed in R with RStudio (R Core Team, 2022; RStudio Team, 2020). Packages used include lmerTest (Kuznetsova et al., 2017), car (Fox & Weisberg, 2019), and blmeco (Korner-Nievergelt et al., 2015). Data were overdispersed, which is the observation that variation is higher than would be expected in the model (Dormann, 2016). Therefore, negative binomial modelling was performed (Zeileis et al., 2008). Models were evaluated functionally using the Second Order Akaike Information Criterion [AIC_c] to quantify their associated measures and assess log-likelihood for best-of-fit. Additionally, models were evaluated on their Akaike Weight and other related measures with the AICcmodavg package (Mazerolle, 2014).

Figure 2.1 Map detailing the selected breeding habitats for modelling Piping Plover (*Charadrius melodus melodus*) demographics in Nova Scotia and New Brunswick from 1994 to 2020; aspect ratio 1:2,850,000. Beaches selected for analysis were: Pomquet, Cherry Hill, Martinique, Carters & Wobamkek, St. Catherine's River, and Summerville of Nova Scotia; Bouctouche Bar, North Kouchibouguac, North Richibucto, Point Sarin, and South Kouchibouguac of New Brunswick. Beaches of New Brunswick were the same chosen by Bourque et al. (2015).



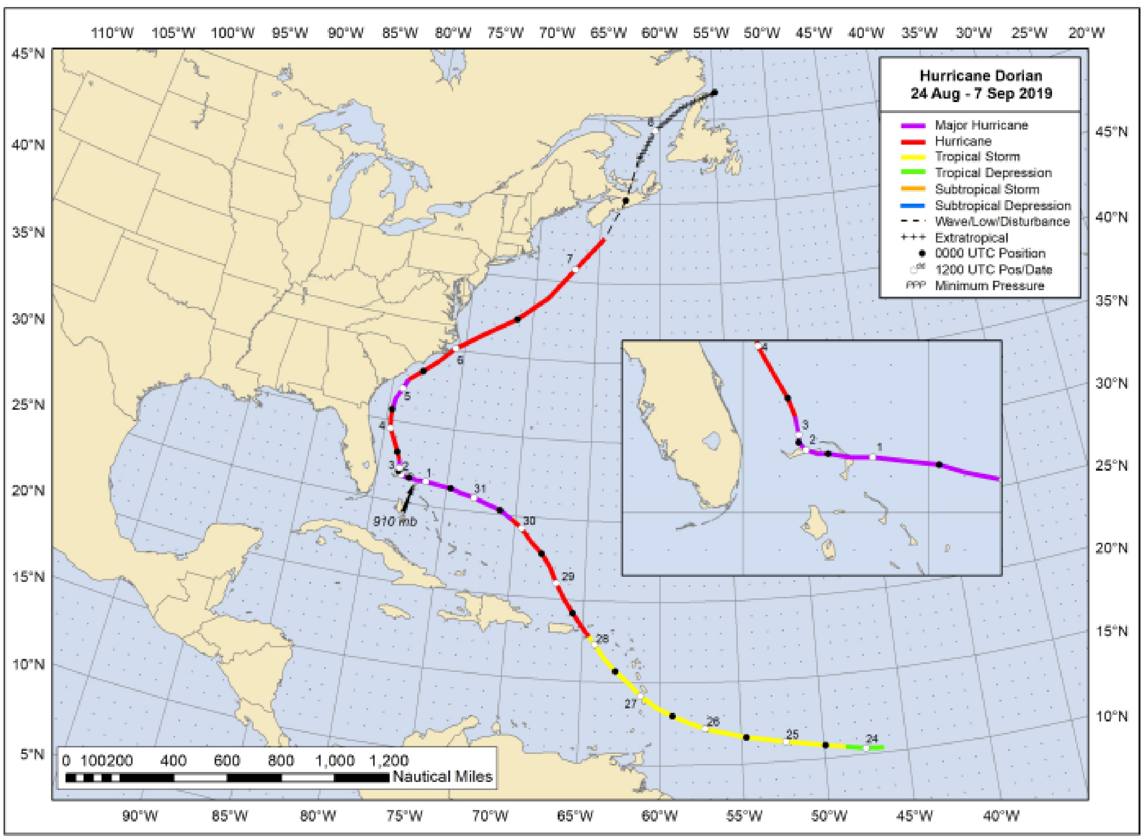
2.3 Quantifying potential change in sand coverage on Nova Scotian beach habitat for Piping Plover pre- and post-Hurricane Dorian

2.3.1 Hurricane Dorian: A Case Event

Storms (hurricanes) in NS were assessed to select one storm for performing pre- and post-storm analyses of potential habitat alteration. To minimize complexities associated with series of storms, storms occurring within the same time frame (i.e., hurricane season) as other storms were omitted. Storms with wind gusts <80km/h (i.e., lower than storm-level winds) were also omitted (NOAA, 2021). Further, storms before 2010 were eliminated due to lack of available aerial satellite imagery. Hurricane Dorian, which made landfall in NS on September 7, 2019, met these requirements, and was selected due to its relatively recent impacts within NS and availability of open-source aerial satellite imagery over the relevant pre/post-storm and beach/sand-response period (2019-2020). Hurricane Dorian caused significant inland flooding and devasting damage to shorelines and nearby community infrastructure (George et al., 2021; CBC, 2021), making the storm a considerable candidate during the selection process.

Hurricane Dorian was a strong post-tropical storm system that made landfall in NS on September 7, 2019 (NOAA, 2019). The central circulation of the storm moved rapidly across Sambro Creek, NS, at 10:00pm Atlantic Standard Time [AT], bringing hurricane-force wind gusts to a large portion of Atlantic Canada and causing widespread damage to infrastructure (NOAA, 2019; Snoddon, 2020). The winds increased at impact, and the storm's circulation expanded due to baroclinic effects, and the mild, humid weather conditions present on land (NOAA, 2022). Hurricane Dorian became fully extratropical over the Gulf of Saint Lawrence at 6:00am AT on September 8 and was absorbed by a more significant low by 6:00pm AT on September 9 over the far northern Atlantic Ocean (NOAA, 2019) (Figure 2.2). In the months following the storm, Hurricane Dorian was considered by climatologists to be the most destructive storm on record to hit NS due to its widespread heavy rainfall and associated inland flooding (Snoddon, 2020). Storm surge waves destroyed wharves, caused coastal erosion, and powerful wind gusts toppled trees, tore roofs from residential homes and businesses, and caused other infrastructural damages (Snoddon, 2020). The Insurance Bureau of Canada estimated the total cost of Hurricane Dorian's damages in NS was $62.2 million, with a total of $102 million for the Maritimes (i.e., NS, NB, Prince Edward Island) (Snoddon, 2020). Hurricane Dorian surpassed Hurricane Juan of 2004 as the most expensive storm to impact the region until the arrival of Hurricane Fiona on September 24, 2022, a Category 2 hurricane which cost the province an estimated $385 million with a total of $660 million for the Maritimes (Snoddon, 2020; The Canadian Press, 2022).

Figure 2.2 Track positions of Hurricane Dorian from August 24 to September 8, 2019. The storm was downgraded to a post-tropical storm when it made landfall in Sambro Creek, Nova Scotia, at 10:00pm Atlantic Standard Time on September 7, 2019. Image was obtained from the National Oceanic Atmospheric Administration (NOAA, 2019).



2.3.2 Aerial Imagery Acquisition

Aerial satellite imagery was obtained through Google Earth Pro and ESRI World Imagery Wayback (Google, 2022; ESRI, 2021b) for use in assessing potential impacts of Hurricane Dorian. The aerial photographs of each sample site were set relative to the date of the storm (September 7, 2019): imagery of pre-Dorian conditions was <6 months prior to Hurricane Dorian ranging between April and August (early to late breeding season); and imagery of post-Dorian conditions was >6 months after the storm ranging between April and June (early breeding season), approximately one year after the pre-Dorian images. The exact dates for the aerial imagery varied for each beach due to image availability. These time ranges chosen for pre-storm and post-storm imagery were based on previous studies conducted on shorebird response to climate-influenced weather events, which focused on the alteration of breeding habitat from hurricanes (Walker et al., 2019; Zeigler et al., 2019; Robinson, 2020).

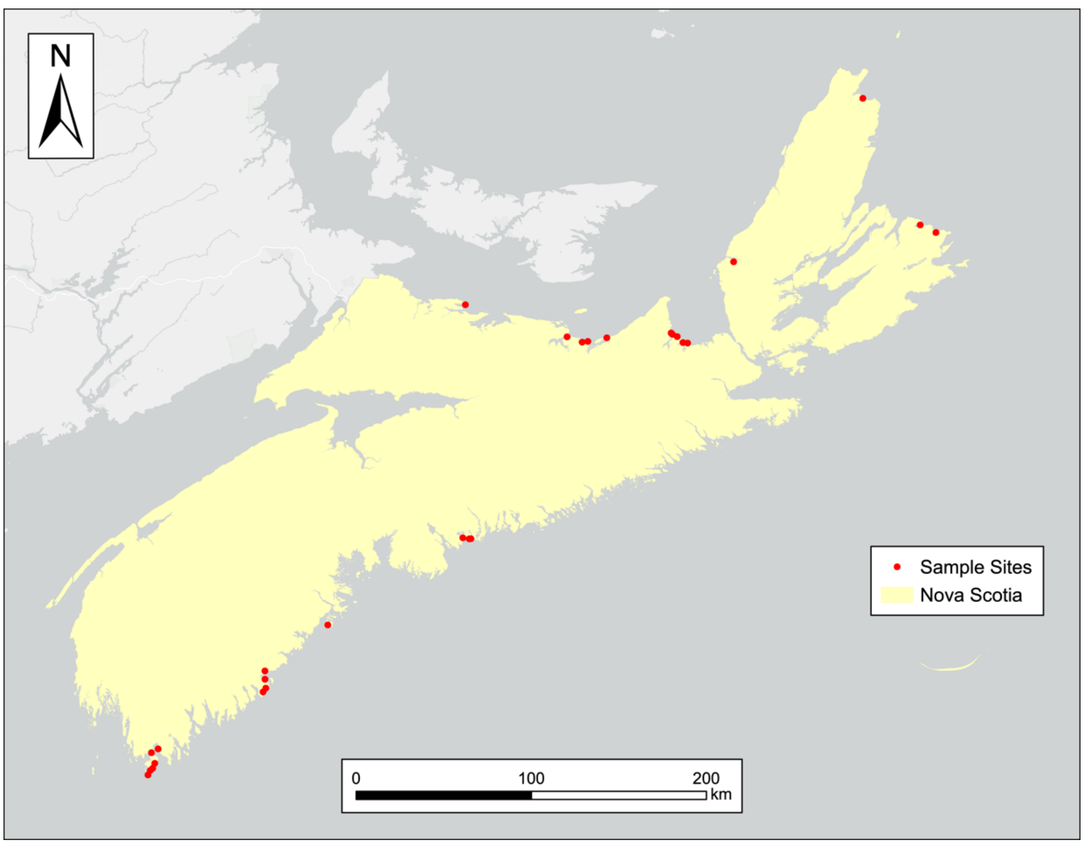
The images ranged from 1:3,000 and 1:24,000 to ensure the complete coverage of the area denoted as the beach was captured (i.e., Google Earth Pro, ESRI World Imagery Wayback). Images were then converted into raster image files and georeferenced to ArcGIS Pro using ground control points before the initialization of spatial analyses (ESRI, 2021a). All maps were projected using the North American Datum of 1983 [NAD 1983, CSRS] coordinate system (NAD 1983 CSRS, Universal Transverse Mercator [UTM] Zone 20) (NOAA, 2018; NRCAN, 2021). Due to the known tidal variations of the study area and the volatile nature of tides in NS, georeferencing aerial satellite imagery of beaches may yield potential sources of error for the land-water boundary due to the inconsistency of shorelines over differing periods (Davis & Browne, 1996; Warnasuriya et al., 2020). To mitigate this potential error in shoreline measurements, each sample site condition was subject to tide level analysis by manually cross-referencing tide charts available from DFO to ensure the tide levels encapsulated by the pre- and post-Dorian images at each specific site remained consistent (DFO, 2021).

2.3.3. Sample Site Selection and Beach Characteristics

Piping Plovers prefer wide sandy beaches with mixed substrate and little to no presence of vegetation for their nesting habitats (Boyne et al., 2014; ECCC, 2021). Key habitat features have been previously identified as beach gradient (i.e., slope) and beach width, with plovers preferring low-sloped and high-width beaches with sparse vegetation cover as their primary nesting and foraging habitats during the breeding season (Boyne et al., 2014). With these characteristics in mind, a sample of the known Piping Plover habitat sites in NS ($N = 64$), where at least one nesting pair was present between 1991 and 2020, was selected. In addition, a parity of sites representing the coastlines surrounding the province (i.e., Atlantic Ocean, Gulf of Saint Lawrence, Southern Newfoundland Shelf [SNS]) was sought, as well as sites across the various provincial counties. No sites were examined in NB for this part of the study due to time constraints and limitations regarding the acquisition of data. Criteria for the selection process were: 1) site is not listed as a 'null' (missing) value in 2020 (i.e., indicates an absence of Piping Plover survey for that given year); 2) site was subject to consistent annual surveys by governmental research and conservation organizations from 1991 to 2020; and 3) site was considered a critical habitat for Piping Plover in NS by ECCC (J. Rock, personal communication, January 20, 2022) in 2020. Following these criteria, 28 sample sites were selected to be examined in this part of the study, totaling approximately 65.28km of shoreline (Figure 2.3). Of these selected sites, 14 are located on the Atlantic coast, 11 are located along the Gulf of Saint Lawrence, and the remaining 3 are on the SNS (Figure 2.3).

The entire extent of the beach for each sample site was examined, beginning from the swash line (i.e., line of wet sand from the most recent and visible high tide) and extending widthwise to the closest crest (i.e., visible dune boundary) or to water if the site was a barrier beach (George et al., 2021; Boyne et al., 2014). Beaches were grouped according to their respective shorelines (i.e., Gulf of Saint Lawrence, SNS, Atlantic coast). After obtaining the aerial imagery, beach characteristics were determined, such as beach type (i.e., sand spit, barrier, inlet, mainland), orientation (i.e., heading), shoreline composition (i.e., cobble, mixed sediment, sand), bedrock geology (i.e., sandstone, limestone, slate, etc.,), beach length (km), and distance from the community (km). Beach characteristics were identified using the criteria outlined by Boyne et al. (2014) and visually examining the aerial imagery. Shoreline composition was defined using the Atlantic Shoreline Classification layer by ECCC (2019), and dominant bedrock geology was determined by manually cross-referencing the Nova Scotia Geoscience Atlas (Nova Scotia Department of Energy and Mines [NSDEM], 2022). Beach length (km) was measured along the visible shoreline perpendicular to the water for each sample site using ArcGIS Pro (ESRI, 2021a). In contrast, the distance from the community (km) was estimated with the measurement tool in Google Earth Pro (Google, 2022), with the reference point located from the beach's approximate centre.

Figure 2.3 Map detailing selected sample sites of Piping Plover (*Charadrius melodus melodus*) breeding habitat in Nova Scotia ($N = 28$) to determine potential habitat alteration after Hurricane Dorian, aspect ratio 1:2,200,000. Half of the sample sites were located along the Atlantic coast ($n = 14$), followed by the Gulf of Saint Lawrence ($n = 11$), and Southern Newfoundland Shelf ($n = 3$).



2.3.4 Spatial Analysis

Following identification of the beach characteristics, sand coverage (km^2), beach width (m), and beach gradient (%) were measured and compared for pre- and post-Dorian conditions at each site using ArcGIS Pro and its associated spatial analyst tools (ESRI, 2021a). Other variables recorded pre- and post-Dorian include observed tide level (m) and elevation (m). Tide level data were obtained during the aerial imagery acquisition stage using tide charts from DFO, based on the respective time and date the satellite image was taken. The elevation for beaches was measured based on the previously established Emery methodology (Emery, 1961; Krause, 2004), with the starting point beginning at the dune boundary and ending at the shoreline and averaged using 8 points of collection, and was recorded using Google Earth Pro (Google, 2022). The recorded quantitative measurements of each site were then compared between conditions (pre-Dorian vs. post-Dorian) using paired t-testing to determine if there were any potential changes in their size and structure. Paired t-tests were performed for habitat variables to determine if there was significant change from pre-Dorian (2019) to post-Dorian (2020). These analyses were performed using Minitab Version 19 (Minitab, 2020). Sand coverage (km^2) and beach gradient (%) were further analyzed through the calculation of estimated percent change between conditions (ESRI, 2021c) to determine the amount of observed change pre- and post-Dorian. Estimated percent change for sand coverage and beach gradient between pre- and post-Dorian conditions was calculated using a defined formula based on resources by ESRI (2021c) (Equation 1).

Equation 1. Estimated percent change of habitat structure between time periods (ESRI, 2021c).

$$\text{Percent Change (\%)} = \frac{(\text{PostDorian} - \text{PreDorian})}{\text{PreDorian}} \times 100$$

Further, Stepwise Multiple Regression analysis (Sokal & Rohlf, 1995) was used to identify predictive relationships between habitat change pre- and post-Dorian (as measured by percent change in sand) and beach characteristics. Stepwise Multiple

Regression analysis was also used to examine relationships between changes in Piping Plover breeding pair and fledgling abundance and pre- and post-Dorian, habitat conditions (percent change in sand), and beach characteristics. Beach length (km), pre-storm elevation (m), and pre-storm beach gradient (%) were used in analyses as continuous predictors, and beach type, orientation, shoreline, and dominant bedrock were used as categorical predictors. A significance level of 0.05 was used for all statistical tests. These abovementioned statistical analyses were conducted using Minitab Version 19 statistical software (Minitab, 2020).

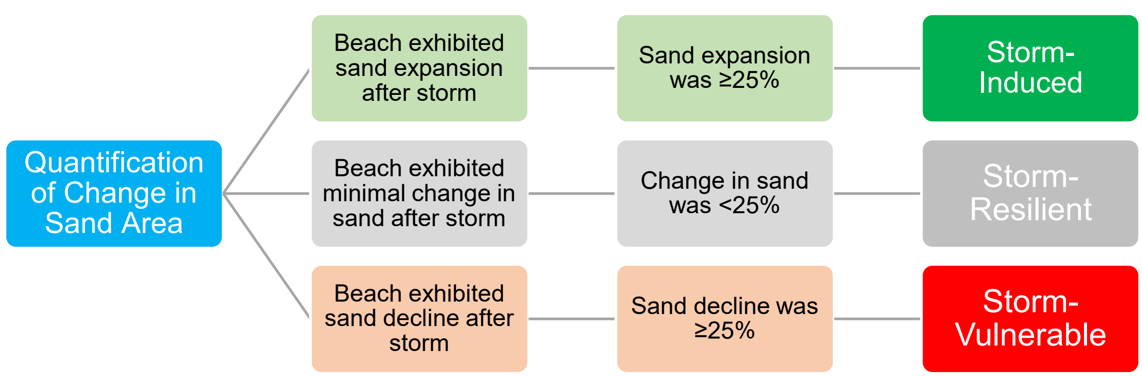
2.3.5 Critical Habitat Classification

Following spatial analyses of beach characteristics following Hurricane Dorian, the sample sites ($N = 28$) that appeared to have potentially experienced beach-feature habitat alteration (i.e., expansion or contraction of sand) were classified according to the interpretations and results of the spatial analysis. Sample sites were initially classified according to a four-level classification (i.e., Storm-Induced; Storm-Resilient; Storm-Vulnerable; Lost). However, no sites were completely 'lost' and constraints were encountered in attempting to define a threshold whereby a beach would be considered 'lost' rather than 'vulnerable.' Taking the qualitative nature of the assessment of the sample sites into account, 'Lost' was eliminated from the habitat classification tool. The sites were then assigned to one of three categories: 1) Storm-Induced [SI]; 2) Storm-Resilient [SR]; 3) Storm-Vulnerable [SV] (Figure 2.4). These three classes were operationally defined utilizing natural breaks occurring within the spatial analysis results for change in sand coverage (%) between pre- and post-Dorian conditions.

Beaches that exhibited sand expansion following Hurricane Dorian were classified as SI, which inferred existing habitat was partially expanded. SI habitat was defined by a ≥25% increase in sand coverage. Beaches that showed partially expanded or contracted sand coverage were considered as SR, defined by <25% change in sand coverage. In contrast to SI and SR, beaches that exhibited a loss in sand coverage area were classified as SV, defined by a decrease of ≥25% sand coverage. Degradation of beaches caused by storms can lead to an increase in coastal erosion and removal of sand from the shoreline, leading to less area that may be hospitable habitat (Russell, 1993;

Bourque et al., 2015). Once all sample sites were classified, sites were subject to statistical examination to determine which of the pre- and post-Dorian parameters (i.e., sand coverage, beach gradient, width, etc.,), if any, may have potential for use in predicting future climate change risk to Piping Plover beach habitat from storm impacts. Piping Plover demographics (i.e., breeding pairs, fledglings) were examined for pre- and post-Dorian responses to determine if there was any relationship between habitat classification (SI, SR, or SV) and change in plover numbers. Analyses for the Repeated Measures ANOVA were performed with Minitab Version 19 (Minitab, 2020).

Figure 2.4 Flowchart representing the rationale of the study's habitat assessment. If the sand expansion post-Hurricane Dorian was ≥25% of the sand area pre-Dorian, the habitat was considered Storm-Induced [SI]. However, if the sand expansion or contraction post-Dorian was <25% of the sand area pre-Dorian, the habitat was considered Storm-Resilient [SR]. If the sand decline post-Dorian was ≥25% of sand area pre-Dorian, the habitat was considered to Storm-Vulnerable [SV].

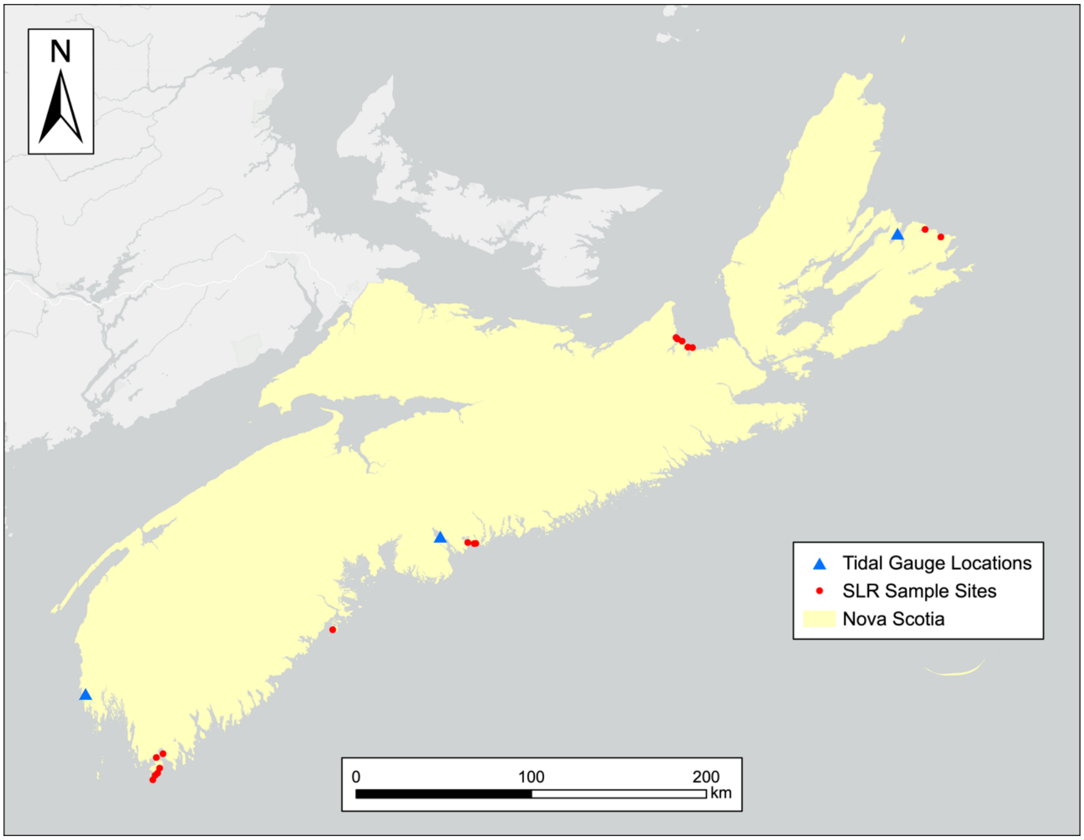


2.4 Assessing Interactions Between Coastal Sea-Level Rise and Piping Plover Habitat in Nova Scotia

2.4.1 Historical and Projected Sea-Level Rise Data

The potential influence of SLR on Piping Plover habitats was examined with historical data on annual water level (m) obtained from the open-access Tides and Water Level Station Data Archives (DFO, 2022). From the tide gauge station records available through the tool, the study identified three stations in NS with consistent historical data: 1) North Sydney of the Cape Breton Regional Municipality; 2) Bedford Institute of Oceanography of the Halifax Regional Municipality; 3) Yarmouth of Shelburne County (Figure 2.5) (DFO, 2019b; DFO, 2019c; DFO, 2019d). Together, these tide gauge stations represent three regions in the province: North Sydney represents Cape Breton Island, Bedford Institute represents the Halifax peninsula, and Yarmouth represents the South Shore (Figure 2.5). Historical SLR from 1991 to 2020 was analyzed for each station using regression with Ordinary Least Squares regression models. The response variable was ‘annual mean water level (m),’ and the predictor variable was ‘year.’ Analysis of Covariance (ANCOVA) was used to compare regression slopes between the three stations. Regression and ANCOVA analyses were performed using Minitab Version 19 (Minitab, 2020).

Figure 2.5 Map detailing the locations of the selected tidal gauge stations ($N = 3$) relative to the province of Nova Scotia, in addition to the selected sample sites ($N = 17$) used to monitor historic and projected sea-level rise with respect to the breeding habitat of Piping Plover (*Charadrius melodus melodus*), aspect ratio 1:2,200,000.



2.4.2 Sea-Level Rise Interactions with Piping Plover Habitat

To determine if SLR may have expanded or degraded Piping Plover habitat, aerial satellite imagery of the sample sites (*N* = 28) was subject to examination in the context of available historical water level data. To source the relevant archived satellite imagery, Google Earth Pro was examined to determine for which years images were available for the sample sites between 2000 and 2011 (Google, 2022). The time period of 2000 to 2011 was chosen based on the general availability of aerial satellite imagery through Google Earth Pro and to ensure there was at minimum a 10-year buffer between them and images of post-Hurricane Dorian conditions. The most consistent sets of imagery were from 2002, 2003, 2009, and 2011. However, satellite imagery was not available for all sample sites: 2002 (*n* = 4), 2003 (*n* = 4), and 2009 (*n* = 4) each yielded imagery for 4 beaches for a total of 12 beaches, while 2011 (*n* = 22) yielded imagery for 22 beaches, including the 12 beaches already covered in the earlier (2003, 2004 and 2009) images. Consequently, the 2011 imagery (*n* = 22) was selected for use in the analysis. The sample was cross-examined to remove beaches that did not have images taken at consistent tidal periods, and archived tide tables for 2011 were consulted to mitigate this potential error (DFO, 2011). The final SLR sample sites consisted of 17 (*N* = 17) beaches, with imagery taken between April and August 2011, consistent with the Piping Plover's breeding season (Figure 2.5).

Beach width (m), beach gradient (%), and sand coverage (km^2) were compared between 2011 and 2020, in addition to determining whether there were any changes in Piping Plover demographics (i.e., breeding pairs, fledglings) over this selected time period. Beaches were also qualitatively assessed through manual visual inspection of satellite images to determine whether beach structure may have been altered, possibly due to SLR and its associated effects. This allowed for pinpointing the impact or lack thereof of erosion, such as delta creation, overwashes and breaches, or the revegetation of Piping Plover habitat (Bourque et al., 2015). The scale of the images ranged from 1:3,000 to 1:24,000 to ensure the complete coverage of the area denoted as the beach was captured by the software (i.e., Google Earth Pro, ESRI World Imagery Wayback). To facilitate the analyses, images were converted to raster image files and georeferenced to the base layer using ground control points. Beaches were spatially analyzed using

ArcGIS Pro (ESRI, 2021a) and the NAD 1983 coordinate system (NAD 1983 CSRS, UTM Zone 20). Paired t-tests were performed for all variables to determine if any exhibited a significant change from 2011 to 2020. The significance testing with paired t-test was performed using Minitab Version 19 (Minitab, 2020). Further, these sampled Piping Plover habitats were assessed to determine which available breeding habitat would be at risk of being at or below sea-level (0m) by 2050, 2080, and 2100. This was based on an estimated projected relative SLR increase of 0.83cm/year by the Bedford Institute of Oceanography [BIO] (BIO, 2021). SLR in NS is relative as it accounts for the land subsidence surrounding the province sinking at ~1mm/year (Greenan, Blair, personal communication, 27 October, 2022; BIO, 2021). This SLR rate was based on the average slope estimated from regression models of tide level in relation to year for the three NS tidal stations from 2030 to 2100. This analysis was described in section 2.4.1 of this thesis. Beach elevation (m) taken in 2020 was used as a baseline.

2.5 Integrating Results Across Assessments

The three components of the analysis (i.e., demographic modelling, spatial analysis and classification, and SLR implications) were structured with considerations of the research progression in mind. Starting from the thirty-year period (1991-2020) encompassing both NS and NB, the methodological stages then narrowed in scope to focus solely on sites in NS within a pre- and post-Dorian time period, and subsequently to a smaller subset of sites in NS but with an expanded window of time to assess SLR-influenced habitat alterations. From these cohesive analyses, findings should reveal the state of Piping Plover demographic trends in the Maritimes region of Canada (excluding Prince Edward Island) and the state of their current, future, and historical habitats.

From these findings, increased understanding of relative habitat availability and risks to habitat associated with climate-change impacts such as storm surges and SLR should support conservation policies and practices. Areas for further conservation attention and mechanisms such as beach habitat protection may be identified from careful interpretation of the results. This integral contribution from the data synthesis, if implemented, may help to support the recovery of Piping Plover by safeguarding both current and future-projected habitats from human developments and activities, including from potential further degradation by climate change processes, while also anticipating climate-resilient and climate-induced habitats. As noted by Walker et al. (2019) and Zeigler et al. (2019), newly created habitats resulting from climate-influenced weather events (i.e., storms) are only valuable for Piping Plover conservation if they are implemented into coastal management practices, in addition to enforced protection from human disturbance. Thus, this research's results and findings are time-restrictive and contribute to the continued protection of the species in NS and throughout North America.

2.6 Summary of Chapter

This chapter has described the research methodology, organized in accordance with the research objectives, which were designed to measure and assess Piping Plover demographic and breeding habitat responses to climate-change impacts. The methodology employs a mixed methods approach using quantitative statistical and spatial analyses and qualitative imagery assessment to determine the scope of potential change in Piping Plover demographics and habitat alteration from climate change processes (i.e., storms, SLR). When synthesized together in succession, the three components of the analysis provide succinct and significant methodological contributions, which may be further replicated and advanced by conservation researchers, planners, and managers to assist in recovering the species and their habitats in NS, Maritime Canada, and at large, in other locations in North America with similar contexts.

Chapter 3: Results and Discussion

3.1 Introduction

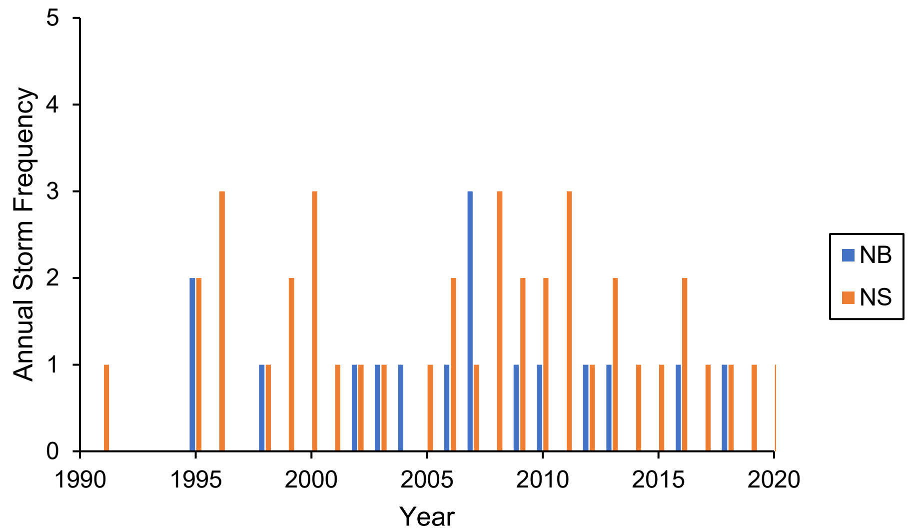
In this chapter, the results are reviewed and discussed. They are presented by order of research objective, starting as follows: 3.2) Examining Long-Term Piping Plover Population Declines in Nova Scotia and New Brunswick and Potential Correlations with Annual Storm Events; 3.3) Quantifying Potential Change in Sand Coverage on Nova Scotian Beach Habitat for Piping Plover Pre- and Post-Hurricane Dorian; and 3.4) Assessing Interactions with Coastal Sea-Level Rise and Piping Plover Habitat in Nova Scotia. Finally, these results are integrated further into the context of climate change and Piping Plover demographics.

3.2 Examining Long-Term Piping Plover Population Declines in Nova Scotia and New Brunswick and Potential Correlations with Annual Storm Events

3.2.1 Results

From 1991-2020, there were 40 storms recorded in NS and 18 recorded in NB, for a total of 58 storms (Figure 3.1) (see Appendix A; Table A1; Table A2). Mean water level during storms was 1.90m (SD = 0.45) for NS and 2.24m (SD = 0.63) in NB, and mean storm surge level was 6.45m (SD = 8.28) for NS and 6.59m (SD = 10.02) in NB. The frequency of storms in NS was highest during the period of 2011-2020 (n = 14), while the highest frequency of storms for NB was in 2001-2010 (n = 9). There were variations in storm frequency observed within NS and NB over the thirty-year study period. Only one storm occurred in 1991 in NS, and there were no storms recorded in either of the provinces between then and 1995. No storms were recorded in NS and NB for 1997, and at least one storm occurred every year between 1998 to 2020 (Figure 3.1). In NS and NB, out of 58 storms, 51.72% (n = 30) did not make landfall. Regression analysis found no significant relationship between the frequency of storms and year within the thirty-year time period (no pattern observed for increasing or decreasing of storms over time) for NS (R^2 = 0.33, F(1, 28) = 0.97, p = 0.334) and NB (R^2 = 0.003, F(1, 28) = 0.08, p = 0.776).

Figure 3.1 Frequency of storms between 1991-2020 in the Canadian provinces of Nova Scotia and New Brunswick. Data was obtained from Environment Climate Change Canada and Canadian Hurricane Centre.



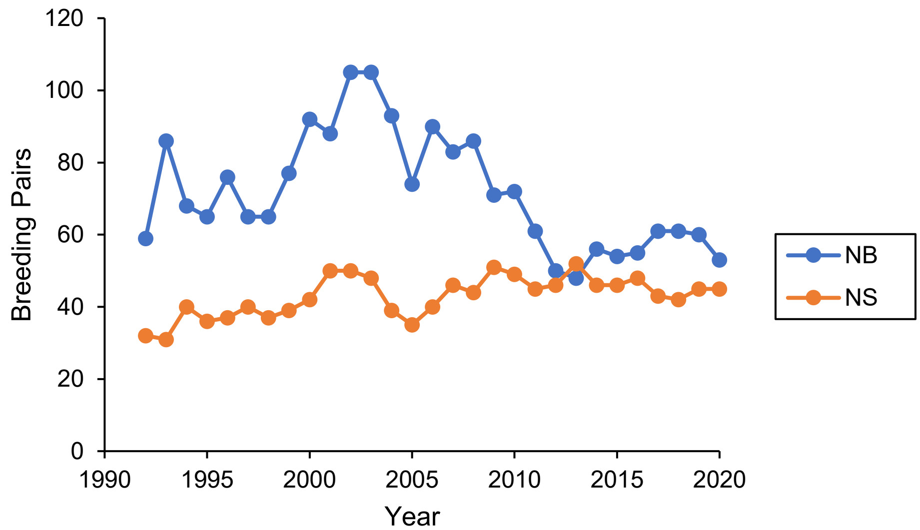
Between 1992-2020, annual Piping Plover breeding pairs ranged from a maximum of 52 to a minimum of 31 in NS, and from a maximum of 105 to a minimum of 48 in NB; during the same time period, fledglings ranged from a maximum of 92 to a minimum of 14 in NS, and a maximum of 175 to a minimum of 11 in NB (Figure 3.2). Within the study period for both provinces, overall Piping Plover demographics (breeding pairs, fledglings) in the region decreased until the late 1990s and increased gradually in the 2000s before decreasing again in the 2010s. Overall, breeding pairs in NS decreased slightly from 59 in 1992 to 45 in 2020. In NS, breeding pairs decreased between 1992 and 2000, from 59 pairs to 42 pairs ($\lambda = 0.71$); slightly increased between 2000 and 2010, up to 49 pairs ($\lambda = 1.17$); and decreased again between 2010 and 2020, declining to 45 pairs ($\lambda = 0.92$) (Table 3.1). In NB, breeding pairs between 1992 and 2000 decreased slightly ($\lambda = 1.56$) and decreased again between 2000 and 2010 ($\lambda = 0.78$) and 2010 to 2020 ($\lambda = 0.74$) (Table 3.1). Fledglings in NS exhibited a nearly six-fold increase, from 14 fledglings in 1992 to 80 fledglings in 2020. In NB, fledglings more than doubled, increasing from 38 in 1992 to 94 in 2020. The largest and most rapid population growth in fledglings occurred between 1992 and 2000 for both NS (λ = 5.07) and NB (λ = 3.47) (Table 3.1). In NS, fledglings increased again between 2000 and 2010 up to 92 individuals (λ = 1.30) but decreased between 2010 and 2020 to 80 individuals (λ = 0.87); for NB, fledglings decreased between 2000 and 2010 down from 132 individuals to 102 (λ = 0.77) and again between 2010 to 2020 to 93 individuals (λ = 0.91) (Table 3.1).

Table 3.1 Population growth rate (λ) of Piping Plover (*Charadrius melodus melodus*) breeding pairs and fledglings in Nova Scotia and New Brunswick from 1992 to 2020. Population growth represents the ratio of the population from previous generations. Data was obtained from Environment Climate Change Canada and the Canadian Wildlife Service.

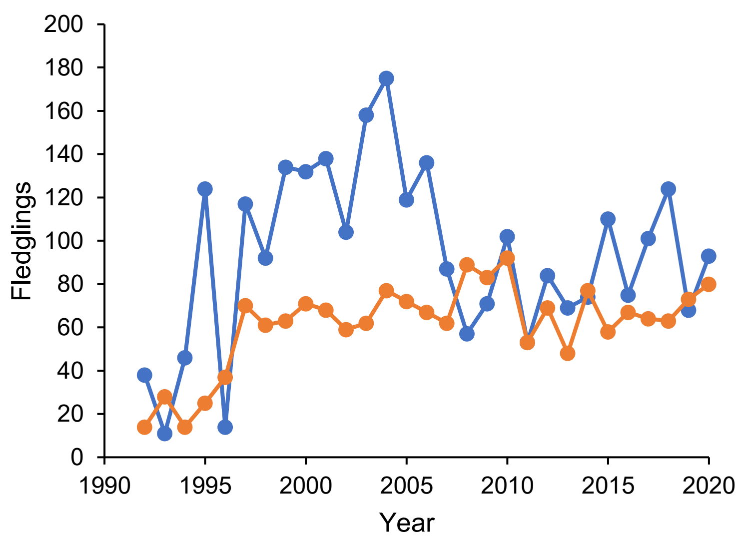
	NS				NB			
	Breeding Pairs		Fledglings		Breeding Pairs		Fledglings	
Year	N	$\lambda = \frac{N_t + 1}{N_t}$	N	$\lambda = \frac{N_t + 1}{N_t}$	N	$\lambda = \frac{N_t + 1}{N_t}$	N	$\lambda = \frac{N_t + 1}{N_t}$
1992	59	0.71	14	5.07	59	1.56	38	3.47
2000	42	1.17	71	1.30	92	0.78	132	0.77
2010	49	0.92	92	0.87	72	0.74	102	0.91
2020	45		80		53		93	

Figure 3.2 Abundance of Piping Plover (*Charadrius melodus melodus*) a) total breeding pairs and b) total fledglings observed in the Canadian provinces of Nova Scotia and New Brunswick from 1992 to 2020. Data was obtained from Environment Climate Change Canada and the Canadian Wildlife Service.

a)



b)



GLMER modelling assessing potential relationships between frequency of annual storm occurrences and Piping Plover abundance was carried out for NS and NB from 1994-2020 (see Appendices A and B). For NS, the best-of-fit model for breeding pairs was occurrence of storms with a two-year lag, with 42% of the model support (Akaike weight = 0.42) and a weak positive trend (increase in pairs), $X^2(1)$, = 2.05, $p = 0.152$ (Table A3; Figure B1). The best-of-fit model for fledglings was occurrence of storms with a one-year lag, with 28% of the model support (Akaike weight = 0.28) and was a weak positive trend (increase in fledglings), $X^2(1)$, = 0.342, $p = 0.559$ (Table A3; Figure B2). For NB, the best-of-fit model for breeding pairs was storm occurrence with no lag, with 60% of the model support (Akaike weight = 0.60), and was positive (increase in pairs), $X^2(1)$, = 3.22, $p = 0.073$ (Table A3; Figure A3). The best-of-fit model for fledglings in NB was storm occurrence with no lag, with 33% of the model support (Akaike weight = 0.33), but was negative (decrease in fledglings), $X^2(1)$, = 1.08, $p =$ 0.298 (Table A3; Figure B4), although the three-year lagged model had weak support. For the combined model of both provinces, the best-of-fit model for fledgling success was storm occurrence with no lag, with 46% of the weight (Akaike weight = 0.46), and was negative (decrease in fledgling success), $X^2(1)$, = 0.117, $p = 0.732$; although the three-year lagged model also had support (Table A3; Figure B5).

3.2.2 Discussion

There was a trend for increasing storms over time for NS and NB, but no statistically significant relationships were found between frequency of storms and year (1991-2020) for both provinces. Although not statistically significant, these observed trends in storm occurrence are consistent with previous research that found hurricanes occurring in the Atlantic Basin, which encompasses the North Atlantic, Gulf of Mexico, and the Caribbean Sea, have exhibited increased frequency in recent years due to the accelerated warming of the ocean (Karl et al., 2009; Camelo et al., 2020). Further, hurricanes have been increasing in intensity over recent years due to the associated effects of climate change, such as the rising global surface temperature of the earth and the incidence of warmer waters which carry their trajectories to further latitudes inland (Mann et al., 2006; Walsh et al., 2016). Research suggests that future tropical storms in the Atlantic Basin will be more powerful in impact, surpassing Category 4 and 5 classifications, and will pose significant risks to coastal areas and communities through storm surge and inland flooding (IPCC, 2013; NRCAN, 2016; Camelo et al., 2020). Storms, such as those occurring during the Atlantic hurricane season, which were the subject of this thesis, may impact shorebird breeding habitat positively or negatively. For example, storms may increase the amount of suitable nesting and foraging habitat through the expansion of sand area and creation of early successional habitat (Bourque et al., 2015; Walker et al., 2019; Robinson, 2020; Weithman et al., 2020), and thereby may positively affect the reproductive output of Piping Plovers (Catlin et al., 2015, Hunt et al., 2018). Over half of the storms examined in this study did not make landfall in NS and NB.

Piping Plover demographics in NS and NB have undergone a gradual decline in population size. particularly from 2010 to 2020. However, breeding pairs in NS appeared somewhat stable, whereas breeding pairs in NB decreased from 1992 to 2020 (Figure 3.2). Fledglings in both provinces increased between 1992 to 2000 but exhibited declines from 2010 to 2020 (Figure 3.2). This variability of Piping Plover population growth between provinces may be due to the unique features and suitability of individual habitats where they nest and breed, in addition to being located at differing geographical areas (i.e., Piping Plovers in NS compared to Piping Plovers in NB) operating independently from another in terms of growth and productivity, which was found by a similar study of two Piping Plover populations in New Jersey (Weithman et al., 2019). In Atlantic Canada, population declines of Piping Plover were historically driven largely by low rates of chick and fledgling survival (Calvert et al., 2006; Weithman et al., 2019). Further, the occurrence of storms in the region may have affected population growth through the creation, expansion, and potential degradation of habitat (Bourque et al., 2015; Walker et al., 2019). Thus, these trends observed for the region may reflect a potential response to storm occurrence and their associated benefits, such as increased and created habitat (Boyne et al., 2014; Bourque et al., 2015). Alternatively, it could be caused by other factors not examined in this study, such as increased predation or human disturbance (Burger et al., 2004; Cohen et al., 2009; Barber et al., 2010).

The findings of the GLMER models support the previous research by Bourque et al. (2015) in that there were visible trends, although not significant, between Piping Plovers and the occurrence of storms in the models generated for NS and NB. The model with the strongest support for breeding pairs was storms in NS with a two-year lag, where a positive relationship was observed, and pairs increased two-years post-storm. For fledglings, the model with the strongest support was storms in NB with no lag, where a negative relationship was observed, and fledglings decreased post-storm. For the combined model of both provinces, the best-fit model was storms with no lag, with a negative trendline indicating decline in fledgling success post-storm (Table A3). Although not statistically significant, the model for NB breeding pairs was marginally significant, indicating that breeding adults may increase in response to storm occurrences sooner (i.e., no lag) than initially anticipated (i.e., three years after storm event; Bourque et al., 2015; Wentzell, 1997). These previous studies by Wentzell (1997) and Bourque et al. (2015) suggest that it may take three years after a storm event for Piping Plover to utilize created or expanded habitat via alterations caused by climate change impacts (i.e., hurricanes), as also found by Wilcox (1959) and Cohen (2009). This absence of a lag in response to storms may be due to the creation or expansion of early successional habitat which is required for foraging and nesting (Robinson, 2020).

In short, despite the findings not carrying any statistical significance, the results indicate that storms may have a potentially positive relationship with Piping Plover breeding pairs and a negative relationship with fledglings and fledgling success. These results may reflect other factors that may be present at their habitats, such as prey availability, vegetation regrowth, and human disturbances (Boyne et al., 2014; Zeigler et al., 2019). Further, these findings of demographics changes in response to storm events may be attributed to site fidelity of the species, as Piping Plover often return to the same beach annually to breed (DeRose-Wilson et al., 2018), which may explain why there were no significant changes in breeding pair and fledgling abundance pre- and post-storm. Habitats themselves may also be a factor in storm response of Piping Plovers due to the varying characteristics that comprise each beach, such as beach type (i.e., barrier, mainland), dominant bedrock, orientation (i.e., beach heading), and shoreline composition (Cooper et al., 2004; Roelvink et al., 2009; Feagin et al., 2015). Thus, individual beaches may respond differently to extreme weather events depending on their characteristics.

3.3 Quantifying Change in Sand Coverage on Nova Scotian Beach Habitat for Piping Plover Pre- and Post-Hurricane Dorian

3.3.1 Results

Potential impacts from Hurricane Dorian on the selected sample beaches ($N = 28$) in NS and their Piping Plover demographics (breeding pairs, fledglings) were assessed quantitatively (Table A4). Piping Plover abundance at the sample sites displayed some stability between the one-year pre- and post-Dorian conditions. Breeding pairs at each site pre-Dorian ($\sum = 19$) ranged from a low of 0 to a high of 4 (M = 0.83, SD = 0.98), and post-Dorian ($\sum = 19$) from 0 to 4 (M = 0.83, SD = 1.19). Fledglings pre-Dorian ($\sum = 31$) ranged from 0 to 6 at each site (M = 1.11, SD = 1.77), and post-Dorian ($\sum = 28$) from 0 to 6 (M = 1, SD = 1.79). No significant differences in the abundance of Piping Plover breeding pairs (Paired t-test: $t = 0$, df = 27, $p = 1$) and fledglings (Paired t-test: $t = 0.83$, df = 27, $p = 0.415$) between one-year pre- and post-Dorian conditions were observed. Some changes were observed in beach characteristics (Table 3.2; see Appendix D). There was no significant change in sand coverage (km^2) between pre- and post-Dorian conditions (Paired t-test: $t = 0.55$, df = 27, $p = 0.587$). However, there was a marginally significant decrease in beach width (m) post-Dorian (Paired t-test: $t = 1.85$, df = 27, $p = 0.076$), and the mean difference between conditions was 7.22m (SD = 20.67). Beach gradient (%) was significantly higher post-Dorian (Paired t-test: $t = -2.96$, df = 27, $p = 0.007$) with a mean pre- and post-Dorian difference of 0.81% (SD = 1.42). Beach elevation (m), the height above sea-level measured at the dune boundary, was also significantly higher post-Dorian (Paired t-test: $t = -3.66$, df = 27, $p = 0.001$), with a mean difference of 0.20m (SD = 0.28) between conditions.

Table 3.2 Descriptive statistics of beach conditions and changes at the sample sites (N = 28) pre- and post-Hurricane Dorian. Variables measured were sand coverage (km^2), change of sand coverage (%), beach gradient (%), and change of beach gradient (%),

Variable	Mean	Standard Deviation	Minimum	Median	Maximum
Pre-Dorian Sand (km^2)	0.08	0.06	0.01	0.07	0.28
Post-Dorian Sand (km^2)	0.08	0.05	0.01	0.06	0.26
Change of Sand (%)	6.91	35.64	-49.99	-3.98	92.87
Pre-Dorian Gradient (%)	0.91	1.22	0.00	0.68	5.26
Post-Dorian Gradient (%)	1.66	2.19	0.00	1.02	8.90
Change of Gradient (%)	54.40	91.30	-100.00	8.80	255.20

Stepwise multiple linear regression analyses were used to examine potential predictive relationships between Piping Plover demographics (breeding pairs, fledglings), beach characteristics (beach length, pre-storm elevation, and pre-storm beach gradient as continuous predictors; beach type, orientation, shoreline, and dominant bedrock as categorical predictors) and habitat changes (as measured by percent area of sand). The first model performed examined change one-year post-Hurricane Dorian. These analyses show a significant model, F(1, 25 = 3.74, p = 0.019), that included two independent variables, beach type and prevailing orientation, which explained 42% (expressed as R^2) of the total variation in percent change in sand (Table A5). The model suggests that barrier beaches have minimal change in sand coverage pre- and post-Dorian whereas barrier island and mainland beaches show increasing sand area post-Dorian. The model also indicates that north-facing beaches show little change in sand area and south-facing beaches have increasing sand area post-Dorian.

Next, stepwise multiple linear regression analysis was performed for breeding pairs and habitat changes. The model was not significant, F(1, 21 = 2.57, p = 0.125), and included one independent variable, change of sand, that explained 11.38% (expressed as

R^2) of the total variation in change in number of pairs (Table A6). Finally, stepwise multiple linear regression analysis was performed for fledglings and habitat characteristics and habitat changes. A model was significant, $F(1, 25 = 16.16, p > 0.001)$, which included three independent variables: beach type, dominant bedrock, and pre-storm elevation. The model explained 80.16% of variation in fledgling abundance pre and post-storm (expressed as R^2) (Table A7). The model suggests that beach type and dominant bedrock are good predictors of changes in Piping Plover fledglings pre- and post-Dorian, and specifically, barrier island habitats underlain by shale are suspectable to fledgling declines.

Beach sample sites were classified according to operationally defined categories based on changes in the area of sand observed at the beach pre- and post-Hurricane Dorian (Table 3.3; Figure 3.3). Categories included: SI, defined by ≥25% increase in sand; SR, defined by an increase or decrease <25% of sand; SV, defined by a decrease of ≥25% of sand. SI beaches had a 57.94% mean increase (SD = 23.43), SR beaches had a 3.48% mean decrease (SD = 12.38), and SV beaches had a 38.20% mean decrease (SD = 10.71). Most beaches (60.71%) analyzed showed little change in sand area post-Hurricane Dorian and were categorized as SR. Twenty-five percent were categorized as SI with an observed ≥25% increase in the area of sand post Hurricane Dorian. Only 14.29% of beaches showed a ≥25% reduction in the area of sand and were therefore designated SV. Stoney Beach (Lawrencetown Head) in the Halifax Regional Municipality exhibited the greatest post-hurricane gain (92.87%) in sand area coverage; the beach that exhibited the greatest post-hurricane loss (-49.99%) of sand coverage was The Hawk in Shelburne County; and the beach that appeared the most resilient to Hurricane Dorian and showed the least change in area of sand (0.09%) was South Harbour of Victoria County (see Appendix D; Figure D17; Figure D28; Figure D9). Characteristics of beaches in the three categories (SI, SR, SV) are shown in Figure 3.6.

The majority (73%) of Gulf beaches examined (n = 11) identified as SR, two of the three SNS beaches were SR, and the largest percentage (43.86%) of Atlantic beaches (n = 14) were SR (n = 6) (Figure 3.4). The majority (75%) of northern-facing beaches (n = 16) were identified as SR and just under half (46%) of southern-facing beaches (n = 11) were SI. The majority (75%) of barrier beaches showed little change in sand area one year after Hurricane Dorian and were identified as SR. Half of the barrier island beaches and mainland beaches had an increase in sand and were designated as SI. Sixty-three percent of mixed sediment beaches and 50% of sand beaches also showed minimal impact from Hurricane Dorian and were designated as SR; and beaches comprised of both sand and mixed sediment showed little change and were identified as SR (Figure 3.4). Changes in Piping Plover abundances (i.e., breeding pairs and fledglings) in relation to beach habitat classifications are shown in Figure 3.5. The majority (78.26%; n = 18) of sample beaches studied had no change in breeding pairs within one year after Hurricane Dorian. Breeding pairs decreased in 13% of beaches (n = 3) and increased in 8.70% (n = 2) after Hurricane Dorian. No decreases in Piping Plover breeding pair abundance were observed in SV beaches (Figure 3.5). However, two of the four beaches that were designated as SV did see a reduction in fledgling abundance, as did one SI beach. Fledglings increased at one SR beach (Figure 3.5). Repeated Measures ANOVA was performed to examine whether changes in plover abundance before and after Hurricane Dorian were dependent on habitat classification of the beach (i.e., SI, SR, SV). The analysis found no significant interaction between time (one year before and one year after Hurricane Dorian) and habitat classification for breeding pairs ($F(2, 40) = 0.26$, p = 0.776) or fledglings ($F(2, 45) = 0.20$, p = 0.816) (Table A8); indicating no relationship between habitat classification and change in plover abundance.

Table 3.3 Habitat classification and percent change in sand (%) for all sample sites (N = 28) in Nova Scotia, Canada. Storm-Induced [SI] was defined by ≥25% increase in sand; Storm-Resilient [SR] was defined by an increase or decrease <25% of sand; and Storm-Vulnerable [SV] was defined by a decrease of ≥25% of sand. Majority of the habitats sampled were classified as SR.

Region	County	Beach	Change of Sand (%)	Habitat Classification
Gulf	Antigonish	Captains Pond	-8.95	SR
		Dunns	-2.59	SR
		Grahams Cove	-15.35	SR
		Mahoneys	25.60	SI

Region	County	Beach	Change of Sand (%)	Habitat Classification
		Pomquet	-5.14	SR
	Cumberland	Oak Island	5.44	SR
	Inverness	South West Mabou	57.02	SI
	Pictou	Big Merigomish Island	-23.48	SR
		Bowen Island	39.08	SI
		Melmerby	-11.36	SR
		Pictou Bar Spit	-15.69	SR
SNS	Cape Breton	Dominion	-6.58	SR
	Cape Breton	Glace Bay Bar	-28.34	SV
	Victoria	South Harbour	0.09	SR
Atlantic	Halifax	Conrads (East and West)	45.35	SI
		Rainbow Haven	66.92	SI
		Stoney (Lawrencetown Head)	92.87	SI
	Lunenburg	Cape Bay	78.75	SI
	Queens	Carters & Wobamkek	-3.56	SR
		Little Port Joli Bay	15.94	SR
		St. Catherines River	-14.60	SR
		Summerville	15.94	SR
	Shelburne	Daniels Head	-29.96	SV
		Northeast Point	22.41	SR
		Sand Hills	-4.41	SR
		Stoney Island	-44.53	SV
		The Cape	-7.27	SR
		The Hawk	-49.99	SV

Figure 3.3 Map detailing habitat classification of sample beaches ($N = 28$) in Nova Scotia within one-year following Hurricane Dorian, aspect ratio 1:2,200,000. Categories included: Storm-Induced [SI], defined by ≥25% increase in sand; Storm-Resilient [SR], defined by an increase or decrease <25% of sand; Storm-Vulnerable [SV], defined by a decrease of ≥25% of sand.

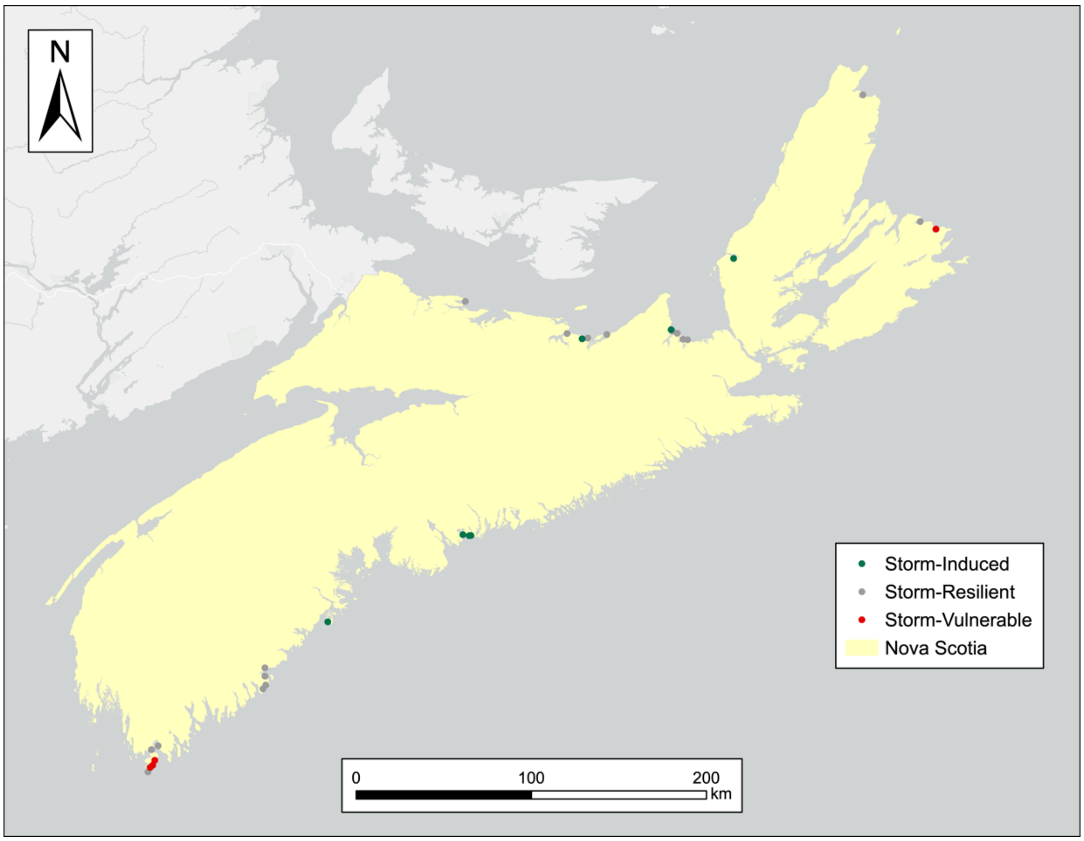


Figure 3.4 Percentage of sample beaches (*N* = 28) in Nova Scotia by habitat classification [SI, SR, SV] within one-year following Hurricane Dorian (April-August 2020) represented by beach characteristics: a) region, b) prevailing orientation, c) beach type, d) shoreline type. Categories included: Storm-Induced [SI], defined by ≥25% increase in sand; Storm-Resilient [SR], defined by an increase or decrease <25% of sand; Storm-Vulnerable [SV], defined by a decrease of ≥25% of sand.

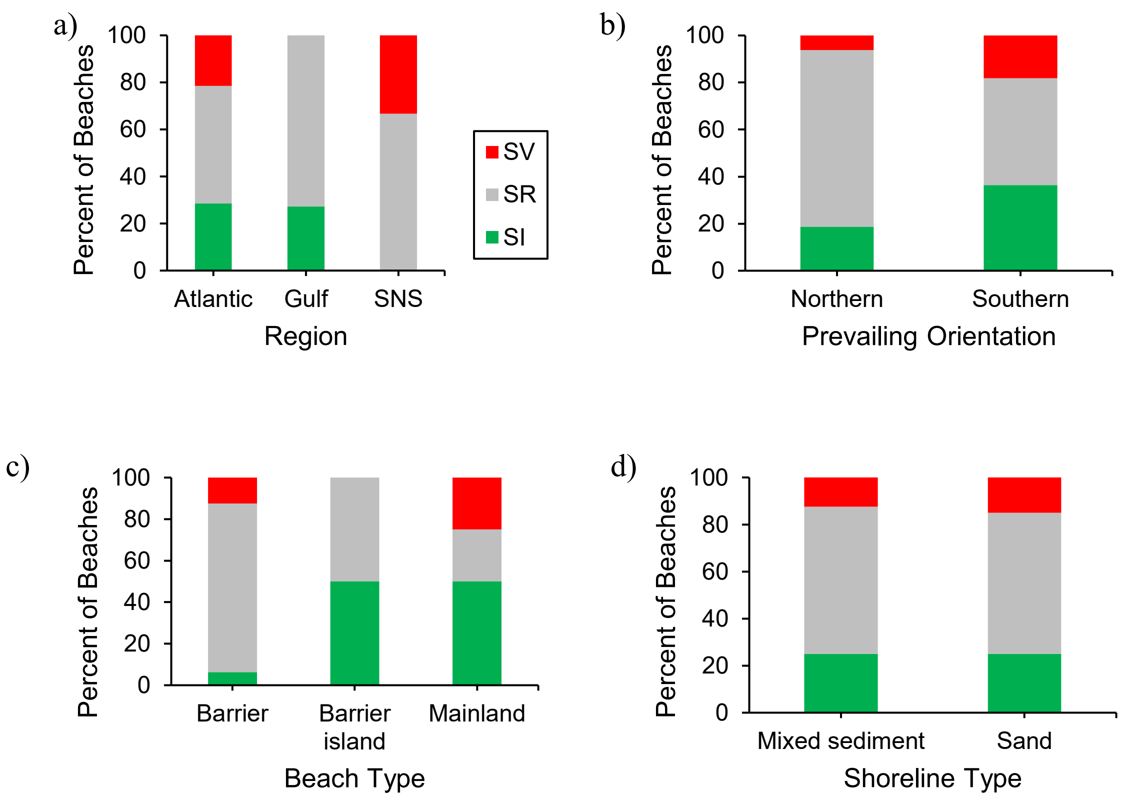
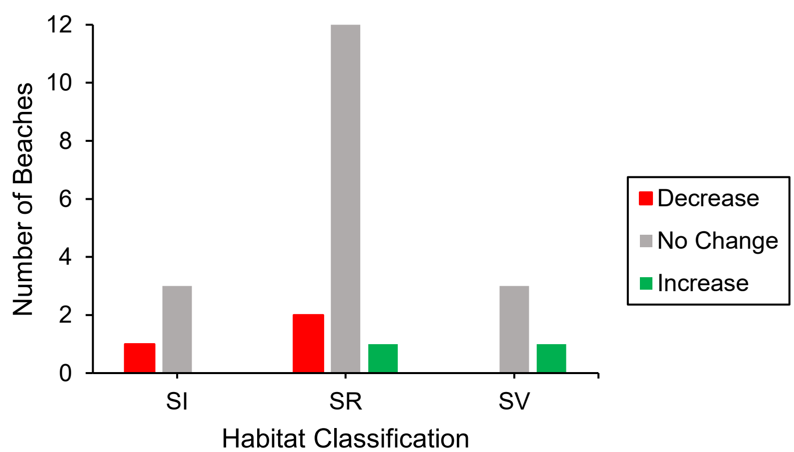


Figure 3.5 Estimated change in Piping Plover (*Charadrius melodus melodus*) a) breeding pairs and b) fledglings at beaches ($N = 25$) in Nova Scotia, Canada, one year following Hurricane Dorian in relation to habitat classification. Categories included: Storm-Induced [SI], defined by ≥25% increase in sand; Storm-Resilient [SR], defined by an increase or decrease <25% of sand; Storm-Vulnerable [SV], defined by a decrease of ≥25% of sand. Piping Plover demographics data was obtained from Environment Climate Change Canada and the Canadian Wildlife Service. Three of the sample sites ($N = 28$) were omitted from analysis due to missing values for breeding pairs and fledglings.

a)



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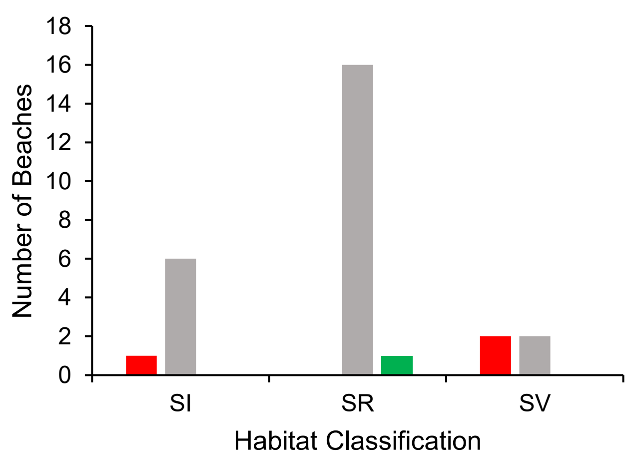


3.3.2 Discussion

Sand coverage at most of the sample beaches in NS used by Piping Plover did not appear to be significantly impacted one year after Hurricane Dorian. There was a marginally significant trend for some beaches to have decreased width post-Dorian. Beach gradient and elevation both significantly increased for beaches one-year post-Dorian. Storms may cause such changes as they have the force necessary to alter a beach's structure (George et al., 2021). When a storm occurs, the tidal surge level increases from the high nearshore winds (Birchler et al., 2014). The resulting large waves can cause overwash, inland flooding, dune degradation, and accelerate coastal erosion from the movement of sediment deposits (Birchler et al., 2014). After a storm, it can take days, weeks, or months for beaches to exhibit signs of recovery through expansion, habitat creation, or degradation (Wang et al., 2006; Coco et al., 2014). Further, wave energy reaches its maximum during the fall hurricane season (the season Hurricane Dorian occurred) and this may accentuate potential impacts (Forbes et al., 2004; Bourque et al., 2015). Recovery of a beach after a storm event depends on several factors, such as the nearshore bar welding under low energy wave conditions, transfer of sediment to the backshore, and the recolonization of dune-stabilizing vegetation (Christensen & Davidson-Arnott, 2004; George et al., 2021). A lack of a recovered backshore increases the risk of erosion from future storm events, which may prevent potential gains in habitat expansion or creation (Durán Vinent & Moore, 2015; George et al., 2021).

These post-storm changes in beaches after Hurricane Dorian potentially represent a change in nesting shorebird habitat quality. Wide beaches with low-lying slopes are preferable habitat for Piping Plover activities such as foraging and breeding, as they lower the risk of coastal flooding and predation by allowing breeding adults to nest away from encroaching vegetation while remaining far enough from the water (Espie et al. 1996; Boyne et al., 2014). Additionally, low-sloped or flat beach areas have been observed to have a decreased risk of predation due to improved visibility by adult pairs for any approaching threats (Anteau et al., 2012); although Piping Plovers occasionally nest on steeper, narrower beaches (Boyne et al., 2014). However, beaches with steeper-facing slopes towards the shoreline are difficult for plovers to transverse and contain less invertebrate biomass for foraging, which makes them unsuitable habitat for the species

(Jaramillo et al., 1993; Robinson et al., 2021). Research by Boyne et al. (2014) suggested that Piping Plovers may adapt to the limited availability of nesting sites in sub-optimal habitats by choosing to nest on narrow, steep beaches, such as observed by Anteau et al. (2012) in North Dakota. Maslo et al. (2011) determined that beaches with slopes <13% and elevations, which were heights measured from shoreline to nearest dune, <1.20m are most favourable for Piping Plovers. The maximum beach elevation (height) observed in this study was 2.97m pre-Dorian and 2.89m post-Dorian, and 32.14% of beaches (n = 9) exceeded the 1.20m threshold. For slope, the maximum beach gradient was 5.26% pre-Dorian and 7.43% post-Dorian, and no beaches exceeded the 13% threshold. These results suggest that the majority of Piping Plover habitat in NS are below these thresholds and any impact from Hurricane Dorian on habitat quality is likely minimal.

The stepwise regression model for change of sand area suggests that changes in Piping Plover habitat quantity, as defined by sand coverage, can be predicted by beach type and beach orientation. Barrier beaches were shown to be resilient for potential reductions in Piping Plover habitat as they lost minimal sand area following Hurricane Dorian, while mainland beaches displayed increased potential for vulnerabilities to storms (i.e., decreased sand coverage). Barrier and mainland beaches expanding in sand area after a storm can be attributed to their respective characteristics. Barrier beaches are similar to barrier islands in that they possess granular sands, except barrier beaches instead consist of low dunes, possess minimal vegetation cover, and maintain some attachment to the mainland, which can sometimes become submerged at high tide (Daniels, 1996). Barrier beaches are resilient yet dynamic ecosystems that move landward as storm surges move sand through overwash processes with the associated winds, waves, and tides (Sallenger et al., 2012; Walker et al., 2019). With severe storms, barrier beaches may exhibit breaches, which create new channels and expose vast amounts of sand area (Roelvink et al., 2009). Potentially, this may explain why these habitats may be more likely to retain a majority of their sand area or expand following an extreme weather event. In comparison, barrier island beaches are narrow, elongated landforms that lay parallel to the mainland and are separated by wetlands, marshes, or estuaries (Feagin et al., 2015). Their low elevations make them highly susceptible to storm impacts, in addition to their coarse sands and steep substrates with minimal vegetation coverage (Feagin et al., 2015; Walker et al., 2019). However, this thesis found that barrier island beaches had expansions of sand area and exhibited resilience to storm impacts.

Predictive models for change in fledglings suggest that barrier islands with shale as their dominant bedrock geology were more prone to post-Dorian reductions in fledglings than other types of beaches in NS. These results are inconsistent with previous literature concerning coastal erosion processes and barrier island beaches (Roelvink et al., 2009; Feagin et al., 2015) and their associations with dominant bedrock geology (Thorton & Stephenson, 2009), as barrier islands did not lose a significant amount of sand post-Dorian as would be expected. These characteristics may explain why fledglings may have reductions at barrier islands following a storm event, as the habitat at these beaches may not have completely settled following the advent of a storm (Wang et al., 2006; Coco et al., 2014). However, this model is not consistent with the change of sand model, which suggests that barrier island beaches are more likely to exhibit increases in sand area after the occurrence of a storm event. Therefore, by this reasoning, it should lead to an increase in potential habitat for Piping Plovers to breed, such as was found in some previous studies (Walker et al., 2019; Robinson, 2020; Ziegler et al., 2020). Due to these contradictions between the models, this may suggest that sand coverage is not an adequate or reliable indicator of habitat quantity for Piping Plover and future predictions in population density. Therefore, habitat loss or gain associated with storms may not be the driving force behind change in Piping Plover abundance over time. The models suggest that change in sand has minimal effect on Piping Plover breeding pairs one year pre- and post-Dorian, which suggests that sand may not be a limiting habitat factor in the short (one-year) term.

From the observed results, beaches in NS appear to respond differently to storm impacts. Storm resilience of beaches based on change of sand area, which was done in this thesis, may help conservation managers and planners predict which beaches are most and least susceptible to negative or positive storm impact from storms like Hurricane Dorian. This research revealed most of the sample sites examined in NS were designated SR with little change in sand coverage at one-year post-Dorian. Beaches that were SR were predominantly northern-facing, barrier beaches, in the Gulf or SNS region, composed of a mixed sediment shoreline. Beaches that were SI with increased area of sand coverage post-storm were mostly southern-facing, mainland or barrier island beaches, in the Atlantic or Gulf region, composed of a sand or mixed shoreline. Beaches that were SV were more likely to be southern-facing, mainland beaches, in the Atlantic or SNS region, composed of a mixed or sand shoreline.

It was predicted that beaches with increasing sand area (SI) would increase available nesting habitat, and beaches with reduced sand (SV) would have reduced nesting habitat for Piping Plovers. It would then follow that beaches with increasing sand (SI) would be expected to see increases in Piping Plover and locations with reduced sand (SV) would see reductions in Piping Plover, and sites with no change in sand (SR) would see no discernable change in Piping Plovers. However, these predicted trends were not clearly observed in this study, as there were no significant relationships observed between habitat classification and changes in Piping Plover breeding pair and fledgling abundance pre- and post-storm at the sample sites. This may be due to high site fidelity of Piping Plover in NS, as breeding pairs in the region are known to frequent the same sites annually regardless of potential habitat quality unless a great disturbance in human activity or habitat loss has occurred (Amirault-Langlais et al., 2014). There is also the potential for a lag effect in relation to Piping Plover demographics and habitat classification which this thesis found in the GLMER modelling for Piping Plover responses to storms. Previous research by Zeigler et al. (2019) found evidence supporting a lag in response of Piping Plovers in New Jersey to habitat creation by storm events approximately two years after Hurricane Sandy.

3.4 Assessing Interactions with Coastal Sea-Level Rise and Piping Plover Habitat in Nova Scotia

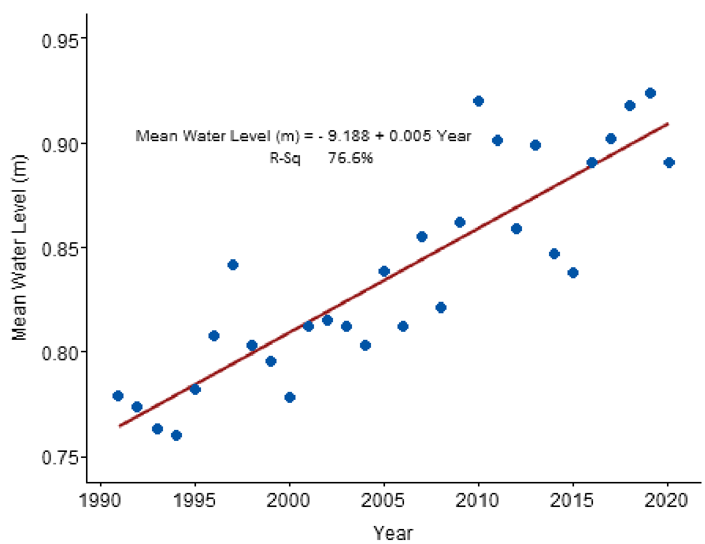
3.4.1 Results

Ordinary Least Squared regression analysis was conducted to examine the relationship between historical SLR and time in NS over a thirty-year period (1991-2020) for each of the selected three tidal gauge stations within the province. There was a significant increase in tide level (m) over time at all three tidal gauge stations: North Sydney, $R^2 = 0.76$, $F(1, 28) = 91.91$, $p < 0.001$; Bedford Institute, $R^2 = 0.75$, $F(1, 28) =$

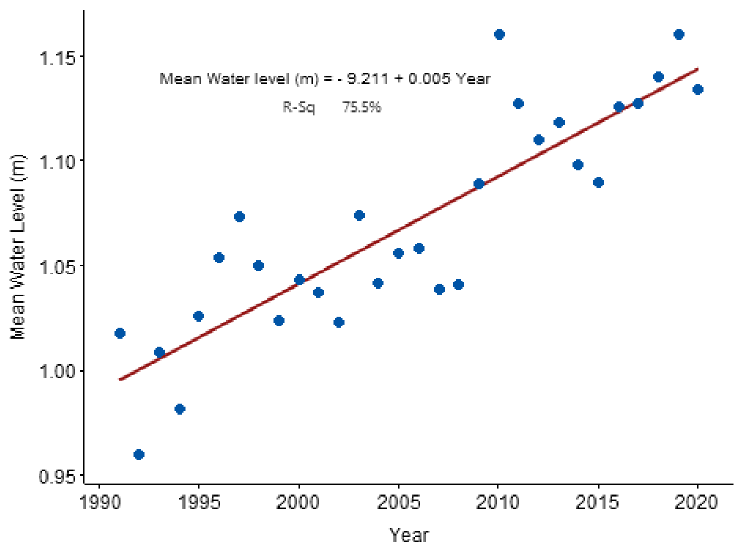
86.26, $p < 0.001$; Yarmouth, $R^2 = 0.79$, $F(1, 28) = 107.07$, $p < 0.001$ (Figure 3.6). The results indicate an estimated historical tide level increase of approximately 0.50cm annually (based on slope of regressions) across the study regions (Figure 3.6). ANCOVA results show no significant difference in the rate of increase (as estimated by regression slope) between the three tidal gauge stations studied ($F(2, 84) = 0.04$, $p < 0.96$).

Figure 3.6 Historical sea-level rise displaying an estimated sea-level rise rate of approximately 0.50cm/year from 1991 to 2020 for tidal gauge stations in Nova Scotia, located at a) North Sydney, b) Bedford Institute, and c) Yarmouth. Data was obtained from Department of Oceans and Fisheries Canada.

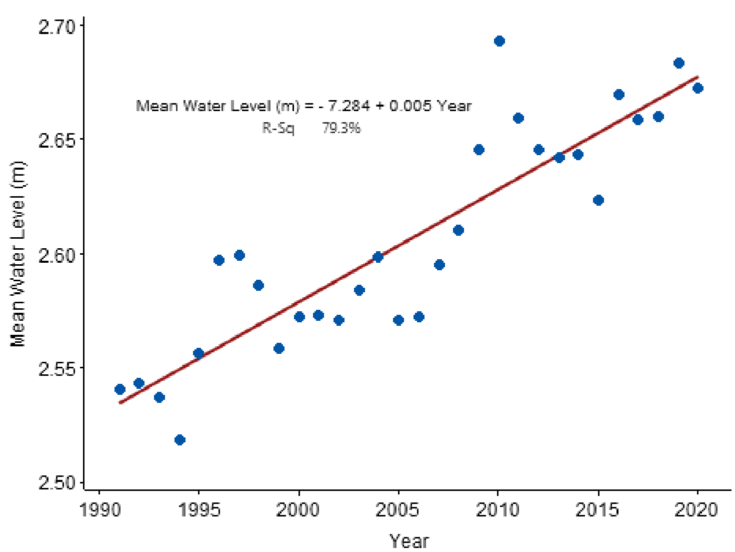
a)



b)


Mean Water level (m) = - 9.211 + 0.005 Year
R-Sq 75.5%
Mean Water Level (m)
1.15
1.10
1.05
1.00
0.95
1990
1995
2000
2005
2010
2015
2020
Year

c)


Mean Water Level (m) = - 7.284 + 0.005 Year
R-Sq 79.3%
Mean Water Level (m)
2.70
2.65
2.60
2.55
2.50
1990
1995
2000
2005
2010
2015
2020
Year

There were some changes observed in the selected sample sites ($N = 17$) between 2011 and 2020 conditions (Table 3.4). Paired t-tests were conducted to determine the degree to which beach variables were potentially influenced by SLR between 2011 and 2020 in NS. There was a marginally significant decrease in sand coverage (km^2) between 2011 and 2020 (Paired t-test: $t = 1.86$, df = 7, $p = 0.081$), with a mean difference of 0.01 (SD = 0.03) between conditions. There was no significant difference in beach width (m) (Paired t-test: $t = -0.06$, df = 7, $p = 0.953$). Elevation (m) change between 2011 and 2020 was not significant (Paired t-test: $t = 0.17$, df = 7, $p = 0.871$), and change in beach gradient (%) was not significant (Paired t-test: $t = 0.63$, df = 7, $p = 0.535$). Visual interpretation of the aerial imagery for the selected sample sites was performed after the spatial analyses of beach variables to assess for SLR interactions. In comparison to the 2011 imagery, 29.41% of the 2020 beaches displayed potential sand expansion events, such as delta creation and sand expansion ($n = 5$). In contrast, 47.05% exhibited incidences of overwash, breeches, and revegetation of beach area (n = 8). The remaining beaches ($n = 4$; 23.53%) exhibited no noticeable changes to habitat structure, appearing resilient to these predicted changes (see Appendix E). Further, over half (64.71%; $n = 11$) of the habitats sampled for change in sand area over the ten-year (2011 to 2020) period of assessed SLR exhibited results consistent with their previously assessed habitat classification over the one-year pre-to-post-Hurricane Dorian (Table 3.5). The majority (50%; $n = 10$) were SR, followed by SV (30%; $n = 3$) and SI (20%; $n = 2$). This may potentially indicate the resilience of Piping Plover habitats in NS to SLR while also indicating which habitats may be at further risk of SLR and its associated effects in the future.

Table 3.4 Descriptive statistics comparison of conditions at sample sites ($N = 17$) analysed for sea-level rise and Hurricane Dorian. Beach characteristics measured from satellite imagery for 2011 and 2020 were sand coverage (km^2), change of sand coverage (%), beach gradient (%), and change of beach gradient (%).

Variable	Mean	Standard Deviation	Minimum	Median	Maximum
2011 Sand (km^2)	0.09	0.07	0.02	0.07	0.29
2020 Sand (km^2)	0.08	0.06	0.01	0.06	0.26
Change of Sand (%)	-4.80	61.20	-71.80	-14.00	188.00
2011 Gradient	1.62	2.02	0.00	0.43	5.42
2020 Gradient	1.35	1.37	0.00	1.05	5.10
Change of Gradient (%)	72.00	282.70	-100.00	-2.50	1053.80
Pre-Dorian Sand (km^2)	0.08	0.07	0.01	0.06	0.28
Post-Dorian Sand (km^2)	0.08	0.06	0.01	0.06	0.26
Change of Sand (%)	7.60	42.00	-50.00	-5.10	92.90
Pre-Dorian Gradient (%)	0.64	0.72	0.00	0.46	2.66
Post-Dorian Gradient (%)	1.35	1.37	0.00	1.05	5.10
Change of Gradient (%)	60.10	107.00	-100.00	0.00	255.20

Table 3.5 Comparisons of habitat classification of sample sites ($N = 17$) between post-Hurricane Dorian and sea-level rise conditions in Nova Scotia, Canada. Categories included: Storm-Induced [SI], defined by ≥25% increase in sand; Storm-Resilient [SR], defined by an increase or decrease <25% of sand; Storm-Vulnerable [SV], defined by a decrease of ≥25% of sand. Post-Dorian represents change in sand area over a one-year period before and after the storm, whereas Sea-Level Rise reflects change in sand area over a ten-year (2011-2020) period. During both time frames, storms and sea-level rise occurred simultaneously. Majority (64.71%; n = 11) of the habitats were the same habitat classification between comparisons, while 35.29% ($n = 6$) had differing classifications.

			Habitat Classification	
Region	Beach	Beach Type	Post-Dorian	Sea-Level Rise
Gulf	Captains Pond	Barrier	SR	SR
	Dunns	Barrier	SR	SR
	Grahams Cove	Mainland	SR	SV
	Mahoneys	Barrier island	SI	SV
	Pomquet	Barrier	SR	SR
SNS	Dominion	Barrier	SR	SR
	Glace Bay Bar	Barrier	SV	SV
Atlantic	Conrads (East and West)	Mainland	SI	SV
	Rainbow Haven	Mainland	SI	SI
	Stoney (Lawrencetown Head)	Mainland	SI	SI
	Cape Bay	Barrier island	SI	SR
	Daniels Head	Mainland	SV	SR
	Northeast Point	Barrier	SR	SR
	Sand Hills	Barrier	SR	SV
	Stoney Island	Barrier	SV	SV
	The Cape	Barrier island	SR	SR
	The Hawk	Mainland	SV	SV

Piping Plover habitat in NS was further examined within the context of projected relative SLR increases to the years 2030, 2050, 2080, and 2100. Relative SLR considers the land subsidence of NS, which is estimated to be sinking at a rate of ~1mm/year (B. Greenan, personal communication, 24 October, 2022; BIO, 2021). By applying the projected relative SLR increase rate of 0.83cm/year in NS based on data from BIO (2021), this thesis investigated which Piping Plover habitats from the sample ($N = 17$) would be below sea-level (0m) by 2100. Beach elevation (m) taken from the start year of 2020 was used as the baseline. Based on this analysis 11.76% ($n = 2$) of beach habitats were projected to be at or below sea level by 2030, 41.18% ($n = 7$) by 2050, 41.18% ($n = 7$) by 2080, and 82.35% ($n = 14$) by 2100 (Figure 3.7). Only 17.65% ($n = 3$) of beaches were predicted to remain above sea-level by 2100 (Table 3.6; Figure 3.7). Eighty-three percent ($n = 5$) of mainland beaches were estimated to be below sea-level by 2100, as well as 75% ($n = 6$) of barrier beaches, and 100% ($n = 3$) of barrier island beaches (Table 3.6; Figure 3.8). All habitats in Lunenburg ($n = 1$) and Shelburne ($n = 6$) counties were projected to be below sea-level by 2100, followed by 80% ($n = 4$) of habitats in Antigonish, 50% ($n = 1$) in the Cape Breton Regional Municipality, 66.67% ($n = 2$) in the Halifax Regional Municipality. Only one habitat in each of the three regions (Gulf, SNS, Atlantic) was projected to remain above sea level by 2100 (Table 3.6; Figure 3.8).

Table 3.6 Projected beach elevation (m) based on relative sea-level rise estimates in Nova Scotia, Canada, for a sample of selected Piping Plover (*Charadrius melodus melodus*) habitats ($N = 17$). Relative sea-level accounts for land subsidence of ~1mm/year in NS (BIO, 2021). Projected beach elevation was calculated over time using an estimated rate increase of 0.83cm/year in relative sea-level rise from 2020-2100 (BIO, 2021). Beaches shaded in grey are predicted to remain above sea-level by 2100.

				Projected Beach Elevation (m)				
Region	County	Beach	Beach Type	2020	2030	2050	2080	2100
Gulf	Antigonish	Captains Pond	Barrier	0.86	0.77	0.61	0.36	-0.47
		Dunns	Barrier	1.50	1.42	1.25	1.00	0.17
		Grahams Cove	Mainland	0.00	-0.08	-0.25	-0.50	-1.33
		Mahoneys	Barrier island	0.14	0.06	-0.11	-0.36	-1.19
		Pomquet	Barrier	0.11	0.03	-0.14	-0.39	-1.22
SNS	Cape Breton	Dominion	Barrier	1.11	1.03	0.86	0.61	-0.22
		Glace Bay Bar	Barrier	1.57	1.49	1.32	1.07	0.24
Atlantic	Halifax	Conrads (East and West)	Mainland	1.20	1.12	0.95	0.70	-0.13
		Rainbow Haven	Mainland	1.56	1.47	1.31	1.06	0.23
		Stoney (Lawrencetown Head)	Mainland	0.67	0.58	0.42	0.17	-0.66
	Lunenburg	Cape Bay	Barrier island	0.90	0.82	0.65	0.40	-0.43
	Shelburne	Daniels Head	Mainland	0.14	0.06	-0.11	-0.36	-1.19
		Northeast Point	Barrier	0.00	-0.08	-0.25	-0.50	-1.33
		Sand Hills	Barrier	0.11	0.03	-0.14	-0.38	-1.21
		Stoney Island	Barrier	0.75	0.67	0.50	0.25	-0.58
		The Cape	Barrier island	0.61	0.53	0.36	0.12	-0.71
		The Hawk	Mainland	0.18	0.10	-0.07	-0.32	-1.15

Figure 3.7 Proportion (%) of selected Piping Plover (*Charadrius melodus melodus*) occupied beaches ($N = 17$) estimated to be at or below sea-level in Nova Scotia, Canada, by 2100. Beach elevation was calculated over time using a projected rate of 0.83cm/year increase in relative sea-level rise from 2020-2100, based on data obtained from the Bedford Institute of Oceanography (BIO, 2021).

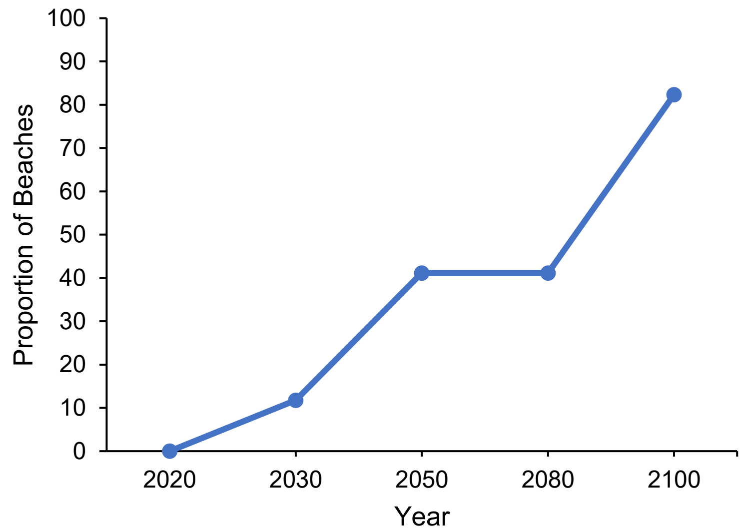
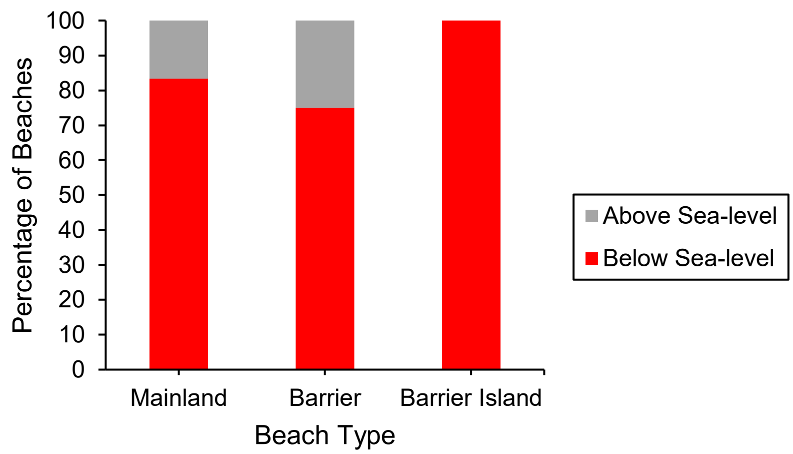
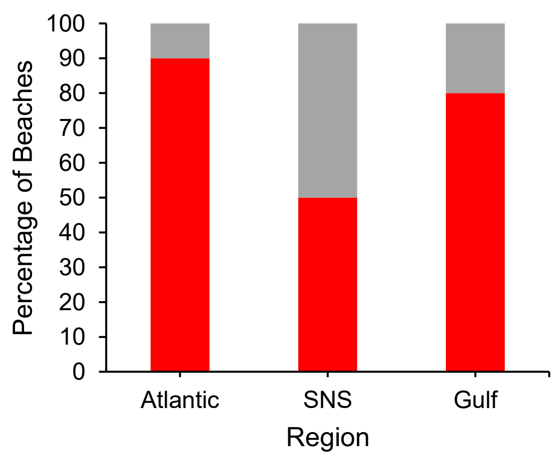


Figure 3.8 Percentage of sampled Piping Plover (*Charadrius melodus melodus*) breeding habitat ($N = 17$) estimated to be either above or below sea-level (0m) by 2100 in Nova Scotia, Canada categorised by a) beach type and b) region. Projected beach elevation was calculated over time using a rate of 0.83cm/year increase in water level from years 2020-2100 (BIO, 2021).

a)



b)



3.4.2 Discussion

Examination of historical water level data at selected tidal gauge stations for NS showed a significant increase in sea level over time between 1991-2020 with an annual SLR rate of approximately 0.50cm/year across the stations. This is similar to the estimate of rate of SLR increase found in other research in the region. Research by Han et al. (2014) estimated a sea-level rise rate of 0.20 to 0.40cm annually for North Sydney, Halifax, and Yarmouth, NS, based on data from 1993-2011; additionally, research by Greenan et al. (2014) estimated a SLR rate ranging 0.26 to 0.34cm annually for the Atlantic region based on tidal gauge data from 1990 to projections to the year 2050. These findings are comparable to global SLR rates, estimated as approximately 0.40cm/year from 1993 to 2010 (Church et al., 2013). The findings from this thesis indicate that NS experienced a higher rate of SLR than those reported for other regions on average. This may be due to land subsidence from isostatic rebound, estimated for the province as ~1mm/year (Zhai et al., 2015; BIO, 2021), which exacerbates the impacts of SLR in NS through a combined relative SLR. Research by Sallenger et al. (2012) found that the North Atlantic was a ‘hot-spot’ for observed SLR between the years of 1980-2009 and suggested projected SLR for the eastern seaboard region of the United States could exceed current levels by over 20cm by 2100. Tidal gauges for this thesis used to determine historical SLR in the region were selected based on the availability of accessible and consistent water level data through DFO (2019b; 2019c; 2019d), which were available for the selected three tidal gauge locations. However, tide gauge data was not available for other regions of the province due to missing or unrecorded data during the time series (1991-2020) (i.e., Richmond, Inverness, Victoria, Antigonish, Cumberland, Queens, Pictou, Annapolis, and Kings counties). While the three selected gauge locations may not adequately represent all NS tide levels, tide gauges remain important components as baseline measurements for SLR when used in conjunction with aerial imagery (Cazenave & Nerem, 2004).

The significant decrease in area of sand on NS beaches between 2011 and 2020 is consistent with the impacts of rising SLR. This may be because beaches composed mainly of sand, such as habitats preferred by Piping Plover and beaches selected for this study, are more susceptible to climate change and associated SLR than beaches composed of stronger sediments such as cobble, pebble, boulder, and outcroppings of bedrock (Davis & Browne, 1996; Boyne et al., 2014; Feagin et al., 2015). Aerial imagery analysis of selected Piping Plover habitats comparing 2011 to 2020 revealed the incidence of sand expansion for a portion of beaches, with the majority displaying some degree of decrease in sand coverage over time. Comparison of habitat classification of post-Hurricane Dorian (2019-2020) and SLR (2011-2020) changes in sand area remained consistent as the majority of habitats (64.71%) had the same classification for both conditions (Table 3.5). However, the ten-year period (2011-2020) was based on a longer timeframe than the post-Dorian condition, therefore potentially including all storms that may have occurred in addition to SLR. These observed phenomena may be due to coastal SLR, which this study assessed, but subsequent storm surge events must also be considered. A storm surge is a temporary increase in local tide level which is seen during low-pressure storm systems such as hurricanes (Kohno et al., 2018). Storm surges cause devastating damage to coastal areas and infrastructure, and occur worldwide during coastal storms (Dube et al., 2009; Kohno et al., 2018). Sand-dominant environments, such as the beaches observed in this study, are highly vulnerable to SLR-induced breaches and storm surges, as overwash and wind action moves sand vertically (i.e., sloped) away from the beach structure (O'Carroll et al., 2006; Taylor et al., 2008). This process can occur during high rates of SLR, even in scenarios without the presence of storm surge, and can result in the gradual drowning of coastal landforms (O'Carroll et al., 2006).

This thesis found that a majority of the Piping Plover habitat in NS was projected to be, at least partially, submerged by 2100 (Figure 3.6). This finding is consistent with research by Seavey et al. (2011), which suggested breeding habitat in eastern North America will be vulnerable to increasing SLR within the next 100 years. Further, mainland and barrier island beaches were predicted to be at or below sea-level by 2100. A potential reason for the high level of impact on mainland beaches may be due to these beaches comprising approximately a third of all sample sites. Mainland beaches in NS are anchored by bedrock deposits beneath the sand substrate and generally thought to be more resilient to SLR (NRCAN, 2016); however, mainland beaches are not immune to SLR as all low-lying sandy beaches of the North Atlantic coast are susceptible to future increases in SLR and its subsequent affects, such as coastal erosion and flooding (Seavey et al., 2011; Greenan et al., 2014). These findings are consistent with previous research on projected SLR in NS, which estimated relative SLR to increase between 80-100cm above 1985-2005 levels in the southwestern region of the province by 2100 (James et al., 2014; NRCAN, 2016). Factors that influence the rate and occurrence of global SLR, the rate at which sea-level is increasing globally, include ocean warming and ice melt from rising mean surface temperatures, which have become more prevalent in recent years due to anthropogenic activities that cause climate change (Cazenave et al., 2018; ECCC, 2019). However, studies have highlighted the inconsistency of using tide gauges to measure SLR, which may have a significant bias due to poor spatial sampling over time (Cazenave & Nerem, 2004); as was found with the absence of historical water level data for some areas of the province.

Due to Piping Plovers preferring to nest on sandy beach habitat with minimal to no cobble or vegetation, as well as their preference for beaches of low gradient and low elevation, the species is especially vulnerable to the future loss of their breeding and foraging habitats from SLR (Maslo et al., 2011; Seavey et al., 2011; Boyne et al., 2014). However, if Piping Plovers can migrate from their former flooded habitats, these negative effects from SLR may potentially be mitigated (Seavey et al., 2011). Nonetheless, due to the shrinking of available beach area from SLR and coastal flooding, more interaction between nesting Piping Plovers and humans may be inevitable; potential area for fledged young and adults to migrate has already become severely limited in North America due to increasing anthropogenic developments on the coasts (Seavey et al., 2011; Sims et al., 2013). These anthropogenic developments on beach habitats deteriorate dune structures, which maintain wave resistance and provide shelter through the presence of dune grasses and lower the abundance of invertebrate prey items for shorebirds (Schlacher et al., 2016; ECCC, 2021). Thus, it should be a priority for conservation managers and policy makers to protect areas along the coast and directly inland of what remains of breeding Piping Plover habitat from the effects of anthropogenic development and related disturbances if the species is to survive.

3.5 Chapter Summary

This chapter examined the results within the context of the research objectives. With respect to the first objective—assessing Piping Plover demographic changes over time within the Atlantic Maritimes region and potential response to storm occurrences—the findings are consistent with the previous literature (Bourque et al., 2015; Robinson, 2020; Walker et al., 2019). Piping Plover breeding pairs increased, and fledglings decreased after the occurrence of storms in NS and NB between 1991-2020; and Piping Plover demographics are responding to storms affecting their habitats within a two-year lag period after storms. Findings for the second objective— quantifying potential change in sand coverage on beaches for Piping Plover pre- and post-Hurricane Dorian—suggest that a minority of Piping Plover habitat in NS became steeper and narrower in the year following Hurricane Dorian, displaying declines in sand area and increases in beach gradient after the storm, whereas in the majority of habitats the effects were minimal. Stepwise regression modelling of change of area of sand supported a relationship with barrier beaches, which indicates a relationship between beach type and change in sand coverage before and after Hurricane Dorian. Stepwise regression modelling of change in fledglings displayed a negative relationship (fledglings decreased) with barrier island beaches with shale bedrock, suggesting these beaches may lose sand area following a storm which could decrease potential habitat for Piping Plover to fledge.

Habitat classification revealed that most selected Piping Plover sites are categorized as SR habitats, which may indicate habitats that are resilient to future climate change events. For the third objective—assessing interactions with coastal SLR—results suggest an annual historical SLR of 0.50cm/year from 1991 to 2020. Aerial imagery analysis indicated incidences of vulnerability to increasing SLR between 2011-2020 and found that loss in sand area was marginally associated with SLR over time. Further, this study found evidence to suggest the majority of Piping Plover habitat in NS will be submerged by SLR by 2100, based on an estimate of 0.83cm/year by BIO (2021). In the next chapter, these results are integrated and discussed, whereby the results of the various analyses are considered together.

Chapter 4: Conclusion

In this chapter, the key findings from the various components of this thesis are discussed and synthesized within the context of the research objectives, which concern the interaction between the potential effects of climate-influenced weather events (storms), SLR and piping plover demographics in NS and NB. Key findings from the results were identified.

1. There was a weak relationship between piping plover population abundance and storm frequency over time with a response lag of one to two years.
2. While a small portion of habitats had reduced sand area and a small portion had expanded sand area, the majority of piping plover habitats were resilient to Hurricane Dorian with minimal change in sand area one year after the storm. No significant change in NS piping plover demographics was observed one year after Hurricane Dorian.
3. Historical SLR was 0.50cm/year from 1991-2020 in NS. A reduction in sand area in NS habitat for piping plover was observed between 2011 and 2020 and this was consistent with expected impacts of increasing SLR over that time period. Piping plover abundance also decreased over the 2011-2020 time period. Projected relative SLR will potentially eliminate ~82% of available habitat by 2100 based on a projected relative SLR rate increase of 0.83cm/year in NS.

4.2 Integrative Discussion

4.2.1 Severe Storm Impacts

GLMER modelling of piping plover population abundance in NS and NB in relation to variation in frequency of severe storm events over time (1994-2020) showed non-significant trends. Models found that in NS, the strongest population response occurred two years after storm events for breeding pairs and one year after a storm event for fledglings, with both increasing in relation to increased storm frequency. In contrast, models for NB indicated that breeding pairs and fledglings increased and decreased, respectively, immediately after a storm event. These findings suggest that the relationship between piping plovers and severe storm events is weak and complicated. The modelling results also do not provide any evidence for what might be driving potential relationships between severe storm events and piping plover abundance. The closer examination of NS beaches one-year pre- and post-Hurricane Dorian set out to provide a clearer picture of the potential impacts of severe storms on piping plover nesting habitat and piping plover populations. However, as with the GLMER modelling this component of the thesis research also indicated that the impact severe storms have on piping plovers and their habitat is not straight forward. While most beaches in NS appeared resilient to Hurricane Dorian a small portion of piping plover beaches were impacted in a positive way (increasing sand area) and another set were impacted in a negative way (decreasing sand area). The lack of observed change in plover populations one-year post-Hurricane Dorian is consistent with the time lag in response observed in the GLMER modelling of NS piping plover abundance in relation to variation storms frequency over time. The lack of observable impact of Hurricane Dorian on the majority of piping plover habitat, along with evidence of negative and positive impacts occurring on a small portion of beaches is consistent with the weak and unclear relationships observed for piping plover abundance and storm frequency found using GLMER modelling of NS and NB piping plover populations.

Other research examining storm impacts on piping plover habitat also indicate a complicated relationship exists with both positive and negative impacts observed (e.g., Bourque et al., 2015; Robinson, 2020). A study by Wilcox (1959) observed the first recorded incidence of habitat creation by storms, in which a major storm event in the 1930s followed by subsequent storms over twenty years expanded sand area of beaches and caused breaches in the dunes through the removal of vegetation and movement of sand from the shoreline. This new habitat allowed more room for piping plovers to breed and nest, and numbers exhibited growth approximately three years after the storm occurrences (Wilcox, 1959). The two to three-year period (i.e., lag) after storms that it took for piping plovers to increase or decrease in storm impacted habitat may be due to delays associated with the time it takes for the immigration of individuals from unfavourable habitats to more favourable ones (Bourque et al., 2015). Several factors have been found to influence habitat selection by piping plovers, including predation, weather, beach substrate, habitat loss due to revegetation, and human disturbance (Boyne et al., 2014; Bourque et al., 2015; Robinson, 2020). Piping plovers in Atlantic Canada return to the same breeding site yearly regardless of potentially degrading habitat quality, demonstrating high site fidelity (Amirault-Langlais et al., 2014; DeRose-Wilson et al., 2018). More research on migration response, piping plover site fidelity, and habitat choice is needed to better understand why some breeding pairs select suboptimal habitats and how that might affect the impact of severe storms on piping plovers and their habitat (Amirault-Langlais et al., 2014; Boyne et al., 2014).

For this thesis research the expectation that piping plover population abundance will respond to storm impacts on nesting habitat assumes that nesting habitat (as measured by area of dry sand) is a limiting factor for the species. Research by Robinson (2020) of piping plovers in New York and New Jersey suggested that habitat may be a limiting factor for piping plover adults when breeding habitats reach overcapacity for available resources. Early successional habitat created by storms through the movement and expansion of sand area serves as new foraging and nesting area for piping plovers when their former habitats grow too crowded or become unfavourable from other factors (i.e., reductions in invertebrate biomass, presence of predators), which makes this early successional habitat crucial to their life cycle and may result in higher population densities if protected (Catlin et al., 2016; Robinson, 2020; ECCC, 2021). It is unclear if habitat is a limiting factor for piping plovers in Atlantic Canada. However, due to the localized decreases in recent decades, the available habitat may outnumber piping plovers currently in the region.

A better understanding of the actual impact that storm induced changes in habitat is having on plovers would also be valuable. Bourque et al., 2015 suggest that piping plover populations response to storms is related to availability of invertebrate prey species on beaches. Cohen et al. (2009) found that the creation of habitats from storms was correlated with increases in piping plover breeding pairs; however, the incidence of expanded nesting habitat alone did not always lead to growth in piping plover numbers. Previous research found that invertebrate abundance on beaches declines considerably after a substrate disturbance, such as through powerful coastal storms (Shepherd & Boates, 1999). Further, after a storm event and depending on the storm's severity, it may take weeks to months for the intertidal invertebrate biomass to recolonize to pre-storm abundance levels (Corte et al., 2017). However, in this thesis, the impacts of storms on invertebrate biomass in NS and NB and the time required for recolonization after storms were not addressed. In addition, the regional differences between NS and NB species composition of invertebrate prey items, as well as the presence of ice approximately five months per year, and structural differences between beaches potentially influence population dynamics of invertebrate biomass and their colonization of storm-created habitat (Defeo & McLachlan, 2013; Scapini, 2014; Bourque et al., 2015).

The effects that storms have on plovers in relation to habitat impacts will also depend on how quickly beaches take to recover after storm events. Habitat impacts may depend on the nature of the beach and the severity of the storm and beaches can take several months or years to return to pre-storm structure (Coco et al., 2014). After a storm, recovery of a beach depends on several factors, including the re-establishment of dune vegetation and the transfer of sediment to the shoreline (Christensen & Davidson-Arnott, 2004; George et al., 2021). If there is no recovered backshore (segment of the beach above the water line), there is an increased risk of erosion from future storm events, which may prevent potential gains in sand expansion or delta creation (Durán Vinent & Moore, 2015; George et al., 2021). Research by Feagin et al. (2015) suggested barrier island beaches were highly vulnerable to climate change (i.e., coastal erosion and storm surges) due to their lack of a bedrock substrate anchored to the mainland. Therefore, the resilience of barrier islands and their ability to maintain structure and necessary ecological functions depends on foredune recovery following a storm (George et al., 2021). As barrier islands are steep land masses composed of coarse sands, they are at the mercy of storm surge waves and winds (Roelvink et al., 2009; NOAA, 2021). Beaches comprised of mixed sediments, such as boulder, cobble, and pebble, with minimal sand, erode at a slower rate than sand-dominant beaches, which makes them potentially more resistant to the effects of storms (Davis & Browne, 1996). In addition, when responding to storms, mixed sediment beaches sometimes develop erosion from breaches of surge-level waves, although not as severe as sand-dominant beaches (Pontee et al., 2013). Beaches composed mainly of sand-dominant shorelines, such as those in NS, are susceptible to high tide levels, winds, and overwash from storm surges, which transport sediment to and from beaches (O'Carroll et al., 2006; Taylor et al., 2008).

It is possible that severe storms are also impacting piping plovers in ways that do not directly involve habitat. For instance, hurricanes may pose a risk to piping plovers during their migration south to their wintering habitats (Ellis et al., 2021). Hurricanes in the Atlantic region have increased in frequency and severity in recent decades due to the warmer waters caused by rising surface temperatures induced by climate change (Bender et al., 2010; Camelo et al., 2020). However, there is no evidence that piping plover mortality is directly affected by hurricanes during their migrations south to the Gulf coast of the United States, Mexico, and the Caribbean (Gibson et al., 2018; Ellis et al., 2021). Studies of wintering piping plovers during the non-breeding months (October-March) have reported high survival rates of adults and high site fidelity, which can be attributed to the species choosing to winter in coastal areas near predictable resources (Skagen & Knofp, 1993; Drake et al., 2001). Further, during the non-breeding season, wintering piping plovers travel only short distances during their daily foraging activities compared to other shorebird species, which is a consequence of high site fidelity (Drake et al., 2001). Research by Ellis et al. (2021) suggested that adult survival of piping plovers in non-breeding habitats was negatively associated with hurricanes but found no support significantly linking hurricanes with adult mortality in the non-breeding season. However, extreme weather events, such as hurricanes, have been observed to breach wintering habitats and destroy coastal ecosystems through the removal of macroinvertebrates which piping plovers and other shorebirds depend on for food (Gill et al., 2001; Ellis et al., 2021). Thus, the negative effects of storms on piping plovers are complex in their interactions and are not fully understood for non-breeding individuals (Ellis et al., 2021).

It is also unclear how storms might impact migrating piping plovers in future warming scenarios with climate change. Migratory patterns of piping plovers consist of breeding and non-breeding seasons (COSEWIC, 2013). The breeding season begins in late March when adults travel to the Atlantic provinces and stay from April to July to breed and forage (COSEWIC, 2013; ECCC, 2021). The non-breeding season begins in August, when plovers leave for their wintering foraging grounds in the southeastern United States, Mexico, and the Caribbean where they stay until March, with the majority of individuals leaving Canada by early September (COSEWIC, 2013; ECCC, 2021).

Piping plovers migrate from their breeding habitats within three hours after sunset and travel at night to their wintering grounds, which is suspected to be due to advantageous reductions in turbulence, evaporative water loss, and predation risks (Kerlinger & Moore, 1989; Loring et al., 2020). However, as global surface temperature increases, wind patterns affected by warmer waters are becoming altered by climate change and can divert avian migratory routes the species depend on for their survival (NABCIC, 2019; Ellis et al., 2021; Nature Canada, 2022). Researchers have predicted the piping plover will lose over 87% of its current breeding habitat and 31% of its wintering habitat in North America if the global surface temperature increases to 3ºC above current levels (National Audubon Society, 2022). Further, this increased surface temperature of the Earth will lead to hurricanes in the Atlantic Basin forming earlier and potentially hitting areas where piping plovers are actively using during the breeding season, which has the potential to threaten the species directly through the flooding of nesting sites (Galbraith et al., 2014; Camelo et al., 2020; Ellis et al., 2021; Zeigler et al., 2022). Therefore, the potential impacts of storms on adult survival rate and reproductive success should be further investigated in future studies as the Earth approaches warmer surface temperatures.

4.2.2 Sea-Level Rise, Severe Storm Impacts, and Other Climate Change Impacts

The combined climate impacts from increasing frequency and severity of storms and SLR potentially exacerbate issues associated with climate change and Piping Plover. With increasing global SLR, it is estimated that storm surges will become more severe during extreme weather events in the North Atlantic, which would accelerate coastal erosion on low-lying beaches and potentially drown coastal landforms (Sallenger et al., 2012; Cazenave et al., 2014; Ezer, 2014). Within the next century, it is predicted future SLR will devastate coastal ecosystems and result in widespread losses of sandy coastline in North America (Seavey et al., 2011; Cazenave et al., 2014). The Atlantic region, including the province of NS, is at an increased risk of future SLR due to land subsidence caused by glacial isostatic adjustment, which will result in a higher SLR than the global rate as the region is estimated to be sinking ~1mm/year (Greenan et al., 2018). Low-lying sandy beaches of the North Atlantic coast with minimal vegetation, such as those preferred by Piping Plovers, are susceptible to the risk of SLR and associated coastal erosion and flooding (Seavey et al., 2011; Boyne et al., 2014; Greenan et al., 2015).

Based on three tidal gauge stations (North Sydney, Bedford Institute, Yarmouth), this thesis estimated a historical SLR increase rate of 0.50cm/year from 1991 to 2020. Sand area was observed to decrease on Piping Plover habitats between the years 2011 and 2020, as did overall Piping Plover abundance within this period, during which 14 storms occurred in NS. It is important to note that in non-storm circumstances, when habitat creation does not occur in response to storms, the beach may become altered by other climate change processes, such as erosion due to SLR, to a point where the habitat would no longer be suitable for Piping Plovers (Boyne et al., 2014). Regardless, such observed changes cannot be solely attributed to either SLR or storms due to the various other environmental factors present at each site. Further, a cluster of habitats in this thesis exhibited minimal to no visible changes in habitat structure between 2011 and 2020. Explanations for this occurrence may be due to the habitats' resilience to storms and SLR, which may be attributed to previously discussed parameters, such as orientation, shoreline, beach type, and region. However, due to time constraints, this thesis did not investigate relationships between SLR and those characteristics. In addition, previous research encountered the issue of predictive SLR modelling yielding uncertainty in determining if SLR will definitively deteriorate breeding shorebird habitat due to factors such as nest relocation and migration (Zeigler et al., 2022).

The Canadian Extreme Water Level Adaptation tool [CAN-EWLAT] projects that relative SLR, which accounts for land subsidence of ~1mm/year in NS, will increase at a predicted rate of approximately 0.83cm/year in NS from 2020 to 2100 (BIO, 2021). This thesis predicted that approximately 82% of Piping Plover habitat sites in NS will be below sea-level (0m) by 2100 due to future SLR based on the projected rate. Barrier islands, mainland beaches, and habitats within the Atlantic region were more at-risk of future flooding by SLR by 2100. Seavey et al. (2011) predicted that a majority of habitat for Piping Plovers would be lost to SLR over the next one hundred years and would lead to a loss of population density along the Atlantic coast, indicating SLR as a threat to the species' future survival. In cases of future SLR, it is suggested that despite habitat loss of Piping Plovers, the species may be minimally impacted if individuals can migrate to different habitats (Seavey et al., 2011). If Piping Plovers could migrate from these submerged habitats, the impacts may not be as severe (Seavey et al., 2011). However, the major risk of this migration due to future SLR would be that it would lead to more species interactions between Piping Plovers and humans on beaches (Seavey et al., 2011; Sims et al., 2013). Reduced beach area for recreational activities due to SLR may push humans and plovers closer to what remains of the sandy shores (Sims et al., 2013).

4.2.3 Potential Influence of Anthropogenic Factors

An understanding of anthropogenic factors impacting Piping Plovers is needed to assess how they might interact with climate change impacts. A visual assessment of aerial imagery revealed that some of the study sample beaches exhibit human activity and influences on or near the habitat. Features observed include boardwalks, seawalls, paths, and ATV trails. Some beaches within the province were observed to have decreased in sand coverage between 2011 and 2020, potentially due to the combination of SLR, storms and the potential stresses and pressures from human influence. For example, Dominion Beach in Cape Breton Regional Municipality is a provincial park that has been hardened against the coast through initiatives by local and federal governments, including a boardwalk system which intersects a majority of the barrier beach and tidal marsh and seawalls to serve as protection from storm surge waves. Previous studies have shown that shoreline hardening through the construction of artificial structures such as seawalls, jetties, and artificial dunes accelerates coastal erosion (Finck, 2006; Zeigler et al., 2019). In addition, engineered systems on beaches alter coastal circulation patterns and sediment transport, dramatically affecting coastal erosion and reducing the beach's ability to mitigate flooding (Pontee, 2013; NRCAN, 2016). These findings suggest that beaches artificially hardened by anthropogenic developments may be more susceptible to the impacts of SLR, which could potentially harm Piping Plover populations in the region.

Piping Plovers are threatened by human activities, one of which is coastal development in or near their habitats (Cohen et al., 2009; Seavey et al., 2011). Human infrastructure developments on beaches reduce the amount of available sand for foraging and nesting and bring an influx of humans to the area, which can cause further disturbances and interruptions to the species (Cohen et al., 2009; Robinson, 2020).

Coastal engineering systems, such as seawalls, designed to harden the shoreline from climate change accelerate the rate of erosion through the artificial alteration of sediment transport and water circulation patterns, which increases the risk of inland flooding, deteriorates local ecosystems, and lowers the diversity of the food web (Gittman et al., 2016; Zeigler et al., 2019). Human presence near Piping Plover habitat stresses breeding pairs and their chicks and sometimes results in direct harm or injury (DeRose-Wilson et al., 2018). Recreational activities we may perceive as minimal risk to Piping Plovers such as walking on the dry sand portion of a beach (Burger et al., 2004) may become more consequential with reduced sand area due to SLR or storm damage. Reduced beach size may bring humans into closer contact with nesting plovers. Because Piping Plover eggs and nests are well-camouflaged, they are sometimes trampled by unsuspecting beachgoers (COSEWIC, 2013). Another threat humans pose to Piping Plovers and shorebirds is predator introduction through their pets, such as dog-walking, especially when dogs are not leashed by their owners, which causes distress to plovers as the birds may be injured or killed by wayward aggressive dogs (Burger et al., 1986; Rutter, 2016). Further, the incidence of ATV trails near Piping Plover habitats directly affects breeding pairs and chicks through the destruction of dune grasses, the compression of sand, and the risk of injury or death of adults and chicks (Wolcott & Wolcott, 1999; Schlacher et al., 2016). Motorized vehicles degrade habitat for foraging and shelter and cause shorebirds great distress because they expend most of their energy towards avoiding these perceived threats (Schlacher et al., 2016). The impact of all these activities may be exacerbated by reduced sand area and/or beaches that are pushed back closer to houses or other anthropogenic development along coastal areas as a result of SLR and storm damage.

Targeted educational outreach programs emphasize the importance of avoiding dry sandy portions of the beach and advise beachgoers to walk on wet sand instead, which helps to mitigate potential nest destruction and chick mortality by pedestrians, as well as through encouraging pedestrians to leash their dogs and refrain from using motorized vehicles when at the beach (ECCC, 2021). Despite these potential influences, the degree of human disturbance on the sample sites was not a focus of this study and thus not thoroughly examined but instead anecdotally observed during the aerial imagery analysis. However, the importance of human disturbance on Piping Plovers and other shorebirds cannot be discounted and should be investigated in future studies when examining the effects of storms and SLR. From this thesis, it can be concluded that the relationships between storms, SLR, and Piping Plover abundance are rather complicated and may involve additional factors. However, future SLR and storms will inevitably push the imperilled shorebird closer to humans as habitat availability grows scarce in the decades to come due to climate change.

4.2.4 Limitations

As with all research on species-at-risk, there were limitations throughout the study. Firstly, this study did not examine breeding adult dispersal or chick survival of Piping Plover within the GLMER modelling due to constraints with the available regional data and the time necessary to perform the analyses. The combined GLMER model of NS and NB used fledgling success as a metric based on an annual overall reproduction output per breeding site. Due to this study not including fieldwork, this research did not employ banded studies of Piping Plover individuals to track survival longitudinally over the chosen time series (i.e., 1994-2020, 2019-2020). Regarding habitat sampling, only a subset of habitats for NS and NB were input into the model to test for Piping Plover response to storms due to data availability. As a result, only six sites were selected each for both NS and NB. The sites selected for NB were the same sample as Bourque et al. (2015) and were chosen based on consistency for replication. However, because of this small sample size, the entire scope of Piping Plover response to storms was not captured. The presence of missing entries in the raw data from ECCC for 1991-2020 may have been an error by surveyors who may not have entered '0's when plovers were not present and instead left the section blank, or this could also be an indication of missing records of sites pre-1994. One significant limitation of this thesis study was that storm response analyses for breeding pairs and fledglings could only be carried out within one year of Hurricane Dorian, as data two to three years after the storm are not yet available for analysis. In addition, this study did not monitor the individual success of Piping Plovers at beaches more than one year post-Dorian, as it only examined year-end (annual breeding season) totals of breeding pairs and fledglings for both study years (2019-2020).

Further, this study did not examine backshore bathymetry or dune recovery after the storm, and the research did not utilize field observation studies of beach habitats to observe the potential changes in real-time. The geological dynamics of bedrock were observed at the surface level to determine which bedrock type lay beneath each beach. No specific research on bedrock was carried out. Additionally, the study relied on aerial satellite imagery, which is not always reliable because it is sometimes difficult to pinpoint certain land features (i.e., sand) due to poor image resolution (Warnasuriya et al., 2020). Another limitation this study encountered was tidal variations within the study area, as the use of aerial satellite imagery of beaches may yield potential errors for the land-water boundary due to the inconsistency of shorelines over differing periods (Chen & Chang, 2009). Tidal variation in imagery can lead to inaccurate findings of climate change impacts and influence, partly due to the change falsely implicated through shoreline variations (Chen & Chang, 2009; Hoang et al., 2017). To mitigate this potential error, aerial imagery was cross-referenced with tide charts obtained from DFO to ensure the satellite images for each year were of the same tide cycle (i.e., high tide, mid-tide, low tide) (DFO, 2019a; 2020).

This study used Hurricane Dorian as a case event but did not determine how the storm impacted seafloor topography or related complexities. Further, this study did not thoroughly investigate the ecological mechanisms differing between Gulf, SNS, and Atlantic region beaches. Although this study examined habitat remotely using aerial imagery comparisons and assessed for potential changes with SLR, human disturbance was not investigated, nor was it the focus of this study. Thus, evidence of human presence was only anecdotally observed through the imagery. These many and varied limitations indicate that results must be interpreted with caution. Nonetheless, the study contributes to an increased understanding of the impacts of SLR and storms on Piping Plover habitat and demographics by 1) the identification of a two-year lag in response from plovers to storm occurrences within the region, 2) the development of parameters utilizing beach characteristics (beach type, orientation, bedrock geology) in combination with change in sand coverage post-Dorian to determine which beaches may be resilient, induced, or vulnerable to climate changes and which types of habitats may experience abundance or decline in Piping Plovers, and 3) predicting which habitats may be submerged by future SLR increases in the region by 2030, 2050, 2080, and 2100. Together, conservation managers may use these outcomes in future studies to further investigate the ecological mechanisms at play and implement them within the species' recovery strategies.

4.2.5 Future Research

Recommendations for further research on Piping Plovers and how storms and SLR affect their breeding habitats and demographics were derived throughout the compilation of this research. Future research on potential responses of Piping Plovers to storm occurrences should investigate the effects storms and habitat creation may have on fledglings specifically to better understand the potential impact on their survival from fledged to adult stage (i.e., breeding maturity), as this was not explored in this study. In such studies, the potential impact of storms on invertebrate prey items should be examined, as little is known of their recolonization in Atlantic Canada in the context of extreme weather events and their shared relationship with Piping Plovers in the food web. Further, monitoring for the individual success of Piping Plovers (i.e., adult survival) using a combination of field studies and remote spatial analysis methodology should be considered, as field observations could give more depth to the questions surrounding Piping Plover responses to storms over time.

Future studies should consider the importance of bedrock geology when examining beaches for potential storm impacts. Backshore dynamics and dune recovery of sample beaches should also be investigated to better understand the environmental processes impacting potential habitat expansion and resilience. Future research concerning storm-induced habitat alteration should further consider the characteristics of prevailing beach orientation, along with wind direction, tide level, and shoreline bathymetry, in the respective region of each beach, to identify key factors for predicting potential outcomes of future storms on habitat.

When replicating this research, refinements should consider whether there are sequences of storms (i.e., multiple storms per season) within the study area during the chosen study period, as this thesis intentionally selected an isolated storm event, Hurricane Dorian, during the hurricane season and did not observe patterns in storm sequences over the time period. Storm sequences may lead to differing habitat resilience and deterioration outcomes than a single storm over time, as combined effects may be more severe (Cooper et al., 2004).

As this study did not investigate storm sequences over the 2011-2020 time period when examining SLR, future studies regarding Piping Plover habitat and SLR should consider storms and their potential influences on habitat structure longitudinally. Due to uncertainty surrounding the consequences and caveats of SLR on shorebird breeding habitats, SLR should be further investigated as a limiting factor for habitat size (e.g., beach area) in modelling for determining future habitat quantity and quality of nesting sites. Finally, future studies should consider the impacts human disturbances pose on Piping Plover habitats, particularly in combination with projected SLR, storms, and their associated effects.

4.3 Implications for Science and Management

The Piping Plover is a threatened shorebird species whose habitats may be at risk of the impacts of climate change and whose demographics may respond to habitat changes within one to three years after storms. When synthesized, the findings of this thesis reflect the complex issues surrounding climate change impacts on a threatened shorebird species. Firstly, increasing storm frequency and severity and SLR may threaten the quantity, quality and fidelity of their breeding habitats and future demographics. Although habitats appear resilient after a short-term change from Hurricane Dorian with minimal change in breeding pairs and fledglings one-year post-Dorian, such demographic changes may lag by two to three years post-storm. Conservation managers should consider this lag period when monitoring for Piping Plovers during the breeding season, as a broader understanding of how and why this lag occurs is needed to understand what ecological mechanisms underly their response to storms on their habitats.

Secondly, Hurricane Dorian was observed to cause only a minority of habitats to decrease in sand area one year following the storm. The majority were resilient to its impact, with a portion of habitats exhibiting expansion of sand area. Declines in fledglings were correlated with barrier island beaches with shale as the dominant bedrock; and, increases in sand area after Hurricane Dorian were correlated with barrier island beaches with a southern-facing profile. These findings indicate we may be able to predict which beaches are more vulnerable to declines in Piping Plovers and those which increase in sand area based on beach characteristics (beach type, orientation, bedrock geology). Further, these parameters and predictions may prove to be useful tools for conservation managers when determining which beaches may be more at-risk of losing sand area or Piping Plovers in the future.

Thirdly, when changes in sand coverage from pre- to post-Dorian were used to classify assessed sites as SI, SR, or SV, the highest number of sites (60.71%) were found to be resilient (SR) to the effects of the storm. This habitat classification system (SI, SR, SV), based on natural breaks in the results of the observed change in sand before and after Dorian, may be replicated by researchers and conservation managers in future studies when investigating losses of sand on beaches after a significant weather event. Furthermore, because the classification system was created in the context of the sample sites and species studied in this thesis, future research and modification is encouraged to best improve this tool for widespread use in classifying potentially critical habitat for coastal species more broadly within the Atlantic provinces.

Lastly, historical SLR in NS may have contributed to a decrease in Piping Plover habitat in the region due to the loss of sand area and width of beaches between 2011 and 2020. Further, this thesis predicted that ~82% of Piping Plover habitat in NS would be submerged by 2100 as a result of future SLR by utilizing a predicted rate increase of 0.83cm/year, based on projected relative SLR data (BIO, 2021). These predictions may be used in future studies concerning SLR impacts on Piping Plovers and other shorebird species when determining the scope of habitat loss imminent by rising water levels. Additionally, these predicted submerged habitats may provoke policy amendments to prevent further anthropogenic developments on what habitats currently remain in the region.

Although climate change has been identified as a threat to Piping Plovers by conservation managers in recovery strategies (COSEWIC, 2013; ECCC, 2021), it was not clear how much of a degree climate change impacted Piping Plovers in Atlantic Canada over the study period. From this research, we can conclude that Piping Plover and their habitats are impacted by climate change (i.e., storms, SLR) and that the results are not inherently negative, as some habitats appear to have exhibited expansion of the existing sand area, which may indicate those resilient to or induced by these pressures. Nonetheless, overall, Piping Plovers are declining in NS and NB. Thus, it may be surmised that other limiting factors may also be at play, such as human disturbance. Therefore, conservation managers should monitor and record Piping Plover demographics and storm events and assess these data against each other to determine whether demographic responses are observed over two to three years post-storm(s). These longer-term analyses are crucial to more accurately determine the scope of impact (i.e., recovery or decline) associated with storms. Further, emphasis should be given to assessing species' breeding habitats after a storm to determine future site fidelity of Piping Plovers and site vulnerability.

4.4 Conclusion

As a species-at-risk, the Piping Plover is a priority for protection due to the roles the species plays in the coastal ecosystem, as an indicator species, a predator of invertebrate biomass, and a potential regulator of coastal erosion (Haig, 1986; Booty et al., 2021), as well as for its inherent worth or intrinsic or existence value, regardless of its utility (Beazley, 2001). Ensuring that the breeding habitat for Piping Plovers in Atlantic Canada is protected from the negative impacts of storms and severe weather is listed as an ongoing recovery strategy implemented by ECCC (ECCC, 2021). Climate change impacts associated with the frequency and severity of storms and SLR need to be considered in order to produce potentially successful mitigation strategies for the species. This thesis gives some indication of what may need to be done to protect these habitats, and more research is needed to fully understand the potential impacts and develop effective mitigation strategies. As a flagship species, the Piping Plover brings attention to shoreline conservation due to its charismatic ecology and value for ecotourism (Stewart et al., 2015). Conserving the Piping Plover and their habitats is integral for the species' survival, other shorebirds, and the beaches where they breed and forage. Thus, conserving breeding habitats for Piping Plovers in the context of climate change impacts should be a priority for conservation managers and the government bodies which oversee their management and policy decisions.

Climate change is warming the waters within the Atlantic Basin, which will inevitably lead to hurricanes of increased severity reaching the coasts of Atlantic Canada (Camelo et al., 2020). Hurricane Dorian was the most powerful and damaging storm to reach the Maritimes until September 24, 2022, when Hurricane Fiona, a massive Category 2 hurricane, made landfall between Canso and Guysborough in NS with wind gusts exceeding 160km/h in coastal areas (The Canadian Press, 2022). Hurricane Fiona resulted in over $660 million in damages for the Maritimes from felled trees, broken power lines, and the destruction of infrastructure, with some homes swept into the sea by storm surge waves (The Canadian Press, 2022). Beaches were severely impacted by the storm, and some nearly lost their entire dune systems from the storm surge waves, which may make them more susceptible to future SLR impacts such as coastal erosion (Seavey et al., 2011; Sims et al., 2013; The Canadian Press, 2022). Storms such as Dorian and Fiona may become more frequent in the Atlantic provinces if surface temperatures continue to rise, which may impact breeding Piping Plover populations directly by flooding nests and destroying what habitat remains (Ellis et al., 2021).

In addition to the more proximate and localized insights gained, this thesis contributes to the fields of conservation biology, avian ecology, and management through 1) the examination of Piping Plover responses to storms of a long-term period which revealed a two-year lag, 2) determining the resiliency of habitats to Hurricane Dorian and classifying these habitats based on change in sand area caused by the storm, and 3) the investigation of historical SLR and the impacts it may have on Piping Plover habitats in the future. These findings help to address gaps in a nascent yet growing body of knowledge and literature on the impacts of climate change on a species-at-risk. This study homes in on the crucial questions at the interface of terrestrial and marine realms of the Atlantic coast, addressing key climate change impacts, including storm frequency and intensity and SLR. Specifically, it addresses an at-risk species in a geographical context in Canada, where few studies have been conducted that consider potentially positive effects of climate impacts and climate resilience or refugia. As such, these findings contribute to an increased understanding of interacting factors that affect Piping Plover demographics and their habitats and contribute to a knowledge base of diverse responses of specific species and populations in various geographical locations and contexts. As such, these findings may also be applicable when considering approaches to conduct similar studies related to other shorebirds of concern within the Atlantic region.

In conclusion, this thesis investigated Piping Plover demographics in NS and NB and their habitats through a perspective focused on climate change impacts and discovered methods which conservation managers may use when studying the species in the future. Findings from this study revealed how long it takes for Piping Plover demographics to respond to a storm, which habitats may be at risk of further vulnerability from climate change and SLR, and which may be resilient or induced. These findings can be replicated with studies of future storms in the context of Piping Plover recovery strategies to modify or enhance the identification of core and critical habitats, both new and currently protected for the species in NS and beyond.

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Appendix A: Supplementary Tables

Table A1 Characteristics of the 40 storm events in Nova Scotia, Canada, selected for this study, including water level (m), storm surge (m), wind direction, wind speed (km/h), wind gust (km/h), and incidence of landfall. Data was obtained from the Canadian Hurricane Centre, Historical Weather Data archive through Environment Climate Change Canada, and the National Oceanic Atmospheric Administration (CHC, 2021; ECCC, 2021; NOAA, 2019).

Day	Month	Year	Event Name	Water Level (m)	Surge (m)	Wind Direction	Wind Speed (km/h)	Wind Gust (km/h)	Landfall
1	November	1991	Unnamed Storm				74.08		No
8	June	1995	Hurricane Allison				37		Yes
9	July	1995	Hurricane Barry				41		Yes
13	July	1996	Hurricane Bertha				85		No
2	September	1996	Hurricane Eduoard		4		70		No
14	September	1996	Hurricane Hortense		1		120		Yes
30	August	1998	Hurricane Bonnie	1.56				93	No
16	September	1999	Hurricane Floyd	1.57	9			83	No
17	October	1999	Hurricane Irene	1.45	14.8			117	No
24	September	2000	Hurricane Helene	1.74	6	NE			No
7	October	2000	Hurricane Leslie	1.52		NE			No
18	October	2000	Hurricane Michael	1.77		N			No
13	October	2001	Hurricane Karen	1.77				104	Yes
12	September	2002	Hurricane Gustav	1.94					Yes
28	September	2003	Hurricane Juan	2.65	26			110-160	Yes
17	September	2005	Hurricane Ophelia	2.1				80	Yes
15	June	2006	Hurricane Alberto					119	No
21	July	2006	Hurricane Beryl					96	Yes
4	November	2007	Hurricane Noel			E		113	No

Day	Month	Year	Event Name	Water Level (m)	Surge (m)	Wind Direction	Wind Speed (km/h)	Wind Gust (km/h)	Landfall
22	July	2008	Hurricane Cristobal					90	No
7	September	2008	Hurricane Hanna					87	Yes
28	September	2008	Hurricane Kyle		0.46	E		91	Yes
23	August	2009	Hurricane Bill						No
23	August	2009	Hurricane Bill		0.64	E		82	No
4	September	2010	Hurricane Earl	1.86	1.16	E		120	Yes
21	September	2010	Hurricane Igor			E		59	No
28	August	2011	Hurricane Irene			E		83	No
16	September	2011	Hurricane Maria			E		56	No
2	October	2011	Hurricane Ophelia				130		No
10	September	2012	Hurricane Leslie				120		No
8	June	2013	Hurricane Andrea				65		Yes
13	September	2013	Hurricane Gabrielle			NE		70	No
5	July	2014	Hurricane Arthur			E		95	No
14	July	2015	Hurricane Claudette				65		No
8	June	2016	Hurricane Colin				83		No
10	October	2016	Hurricane Matthew			N		117	No
16	August	2017	Hurricane Gert						No
11	July	2018	Hurricane Chris						No
7	September	2019	Hurricane Dorian	2.89	1.42	NE		124	Yes
22	September	2020	Hurricane Teddy			NE		72	Yes

Table A2 Characteristics of the 18 storm events in New Brunswick, Canada, selected for this study, including water level (m), storm surge (m), wind direction, wind speed (km/h), wind gust (km/h), and incidence of landfall. Data was obtained from the Canadian Hurricane Centre, Historical Weather Data archive through Environment Climate Change Canada, and the National Oceanic Atmospheric Administration (CHC, 2021; ECCC, 2021; NOAA, 2019).

Day	Month	Year	Event Name	Water Level (m)	Surge (m)	Wind Direction	Wind Speed (km/h)	Wind Gust (km/h)	Landfall?
24-25	August	1991	Hurricane Bob				185		Yes
13	July	1996	Hurricane Bertha				85		Yes
8	October	1996	Hurricane Josephine						Yes
16	September	1999	Hurricane Floyd	1.57	9			83	No
29	October	2000	Unnamed Storm		1.5	NE	72		Yes
28-29	September	2003	Hurricane Juan	2.65	26			110-160	Yes
8	September	2004	Hurricane Frances						
12	July	2005	Hurricane Cindy						
4	November	2007	Hurricane Noel			E		113	No
7	September	2008	Hurricane Hanna					87	Yes
15	September	2008	Hurricane Ike						
28	September	2008	Hurricane Kyle		0.46	E		91	Yes
4	September	2010	Hurricane Earl	1.86	1.16	E		120	Yes
28	August	2011	Hurricane Irene			E		83	No
8	June	2013	Hurricane Andrea				65		Yes
5	July	2014	Hurricane Arthur			E		95	No
10	October	2017	Hurricane Nate						
7	September	2019	Hurricane Dorian	2.89	1.42	NE		124	Yes

Table A3 Model selection results based on second-order Akaike information criterion (AIC_c) on the number of Piping Plover (*Charadrius melodus melodus*) breeding pairs and fledglings in twelve sites in the Canadian provinces of Nova Scotia and New Brunswick between 1994 and 2020. Table design and modelling were based on previous research by Bourque et al. (2015).

Response Variable	Model	Estimated Parameters	AIC_c	ΔAIC_c	Akaike Weight	Log-likelihood
NS Breeding Pairs	Null model	2	507.31	1.71	0.18	-248.46
	Occurrence of storms one-year lag	3	506.77	1.17	0.24	-248.19
	Occurrence of storms two-year lag	3	505.60	0	0.42	-247.61
	Occurrence of storms three-year lag	3	507.53	1.93	0.16	-248.57
NS Fledglings	Null model	2	572.21	0.34	0.24	-280.81
	Occurrence of storms one-year lag	3	571.87	0	0.28	-280.64
	Occurrence of storms two-year lag	3	572.17	0.29	0.24	-280.79
	Occurrence of storms three-year lag	3	572.22	0.34	0.24	-280.81
NB Breeding Pairs	Null model	2	591.26	0	0.6	-290.41
	Occurrence of storms one-year lag	3	594.40	3.14	0.12	-291.98
	Occurrence of storms two-year lag	3	594.30	3.03	0.13	-291.93
	Occurrence of storms three-year lag	3	594.12	2.86	0.14	-291.84
NB Fledglings	Null model	2	678.86	0	0.33	-334.16
	Occurrence of storms one-year lag	3	679.92	1.06	0.19	-334.69
	Occurrence of storms two-year lag	3	679.63	0.77	0.22	-334.54
	Occurrence of storms three-year lag	3	679.33	0.48	0.26	-334.4

Response Variable	Model	Estimated Parameters	AIC_c	ΔAIC_c	Akaike Weight	Log-likelihood
NS-NB Fledgling Success	Null model	2	580.77	0	0.46	-281.99
	Occurrence of storms one-year lag	3	583.67	2.90	0.11	-283.44
	Occurrence of storms two-year lag	3	583.67	2.89	0.11	-283.43
	Occurrence of storms three-year lag	3	581.50	0.73	0.32	-282.35

** Note: ΔAIC_c represents the difference in AIC_c between a selected model and the top-ranked model, whereas Akaike weight is the probability that a model is the most parsimonious.*

Table A4 Beach type, orientation, shoreline composition, dominant bedrock geology, length (km), and distance from community (km) of selected beach sample sites ($N = 28$) in Nova Scotia, Canada.

Region	County	Beach	Beach Type	Orientation	Shoreline	Dominant Bedrock Geology	Length (km)	Distance from Community (km)
Gulf	Antigonish	Captains Pond	barrier	NE	sand	shale	2.75	2.5
		Dunns	barrier	NE	sand	shale	2.73	1.98
		Grahams Cove	mainland	NW	mixed sediment	sandstone	1.72	2.89
		Mahoneys	barrier island	N	sand	anhydrite	1.73	0.88
		Pomquet	barrier	NE	sand	sandstone	3.99	1.98
	Cumberland	Oak Island	barrier island	NE	sand	sandstone	2.17	1.22
	Inverness	South West Mabou	mainland	NW	sand	sandstone	2.66	0.4
	Pictou	Big Merigomish Island	barrier	N	mixed sediment	sandstone	3.29	3.84
		Bowen Island	barrier	N	sand	sandstone	0.73	1.37
		Melmerby	barrier	N	sand	sandstone	1.37	4.46
		Pictou Bar Spit	barrier	NE	mixed sediment	sandstone	1.4	0.83
SNS	Cape Breton	Dominion	barrier	NE	mixed sediment	shale	1.79	1.57
		Big Glace Bay	barrier	NE	mixed sediment	shale	3.1	1.7
	Victoria	South Harbour	barrier	NE	sand	sandstone	2.66	3.11
Atlantic	Halifax	Conrads (East and West)	mainland	SW	sand	sandstone	3.31	0.75
		Rainbow Haven	mainland	SE	sand	sandstone	1.62	0.92
		Stoney (Lawrencetown)	mainland	SW	mixed sediment	sandstone	1.4	0.64
	Lunenburg	Cape Bay	barrier island	S	mixed sediment	sandstone	1.11	6.32
	Queens	Carters & Wobamkek	mainland	NE	sand	sandstone	1.42	2.7
		Little Port Joli	barrier	SE	sand	sandstone	3.06	5.37
		St. Catherines River	barrier	SE	sand	sandstone	1.63	3.34
		Summerville	barrier	SE	sand	sandstone	1.27	1.24
	Shelburne	Daniels Head	mainland	SE	sand	sandstone	2.71	0.99
		Northeast Point	barrier	NE	sand	sandstone	0.74	0.59
		Sand Hills	barrier	SW	mixed sediment	sandstone	1.9	1.82
		Stoney Island	barrier	SE	sand	sandstone	2.67	1.41
		The Cape	barrier island	SW	sand	sandstone	9.07	2.17
		The Hawk	mainland	E	sand	sandstone	1.28	0.92

Table A5 Stepwise regression for percent change of sand of beaches (*N* = 28) following Hurricane Dorian in Nova Scotia, Canada.

Source	Degrees of Freedom	Adjusted Sum of Squares	Adjusted Mean Squares	F-Value	P-Value
Regression	4	14186.00	3546.50	3.74	0.019
Beach Type	2	8180.00	4090.10	4.32	0.027
Prevailing Orientation	2	6551.00	3275.50	3.46	0.050
Error	21	19897.00	947.50		
Total	25	34083.00			

Table A6 Stepwise regression for breeding pairs in relation to percent change of sand of beaches (*N* = 21)* following Hurricane Dorian in Nova Scotia, Canada.

Source	Degrees of Freedom	Adjusted Sum of Squares	Adjusted Mean Squares	F-Value	P-Value
Regression	1	0.79	0.79	2.57	0.125
Percent change of Sand (%)	1	0.79	0.79	2.57	0.125
Error	20	6.16	0.31		
Total	21	6.95			

**Note: Sample sites were reduced due to the presence of null data for breeding pairs.*

Table A7 Stepwise regression for fledglings in relation to percent change of sand of beaches (*N* = 25)* following Hurricane Dorian in Nova Scotia, Canada.

Source	Degrees of Freedom	Adjusted Sum of Square	Adjusted Mean Squares	F-Value	P-Value
Regression	5	9.13	1.83	16.16	0.000
Pre-storm Elevation (m)	1	0.28	0.28	2.51	0.129
Beach Type	2	8.76	4.38	38.77	0.000
Dominant Bedrock	2	5.06	2.53	22.40	0.000
Error	20	2.26	0.11		
Total	25	11.38			

**Note: Sample sites were reduced due to the presence of null data for fledglings.*

Table A8 Repeated Measures ANOVA for the interaction of habitat classification and time for breeding pairs in Nova Scotia, Canada, post-Hurricane Dorian.

	Degrees of Freedom	Adjusted Sum of Squares	Adjusted Mean Squares	F-Value	P-Value
Time	1	0.03	0.03	0.02	0.88
Habitat Classification	2	0.37	0.18	0.14	0.868
Habitat Classification*Time	2	0.66	0.33	0.26	0.776
Error	40	51.58	1.29		
Total	45	52.61			

Table A9 Repeated Measures ANOVA for the interaction of habitat classification and time for fledglings in Nova Scotia, Canada, post-Hurricane Dorian.

	Degrees of Freedom	Adjusted Sum of Squares	Adjusted Mean Squares	F-Value	P-Value
Time	1	0.13	0.13	0.03	0.855
Habitat Classification	2	2.48	1.24	0.32	0.725
Habitat Classification*Time	2	1.56	0.78	0.20	0.816
Error	40	153.08	3.83		
Total	45	157.33			

Appendix B: Supplementary Figures

Figure B1 Generalized Linear Model of Mixed-Effects [GLMER] for Piping Plover (*Charadrius melodus melodus*) breeding pairs in Nova Scotia, Canada, and two-year response lag to storm occurrences between 1994 and 2020. Breeding pairs increased two years after storms, but the relationship was not significant.

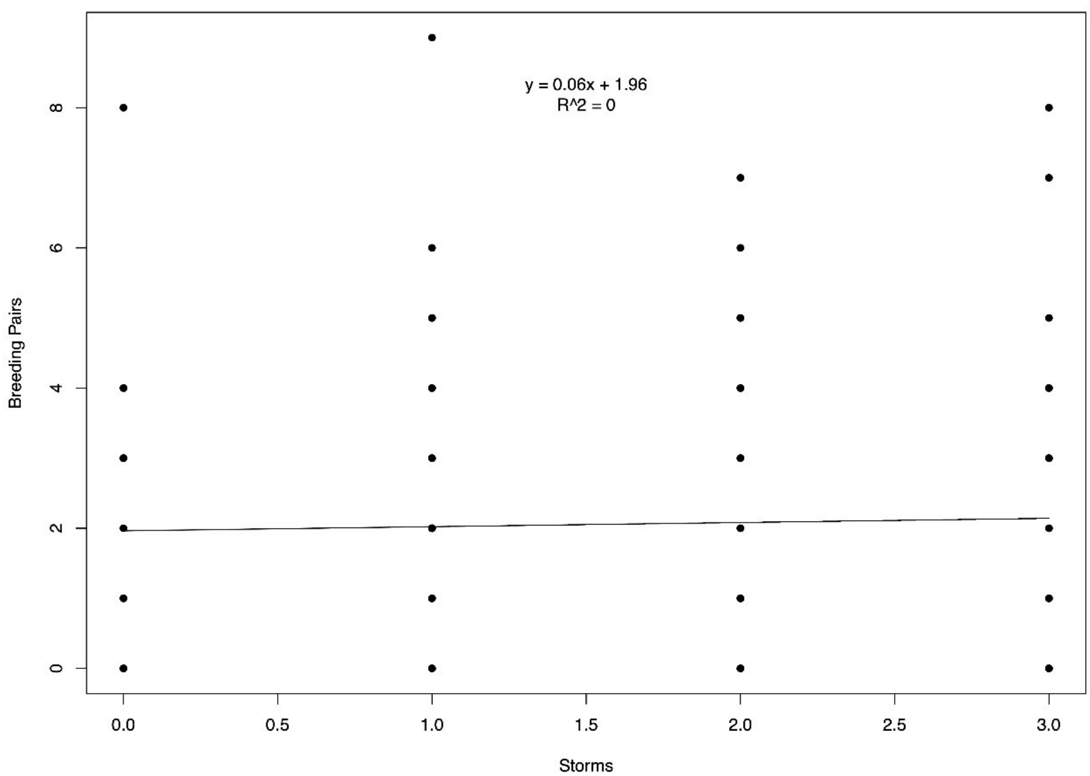


Figure B2 GLMER for Piping Plover (*Charadrius melodus melodus*) fledglings in Nova Scotia, Canada, and one-year response lag to storm occurrences between 1994 and 2020. Fledglings increased one year after storms, but the relationship was not significant.

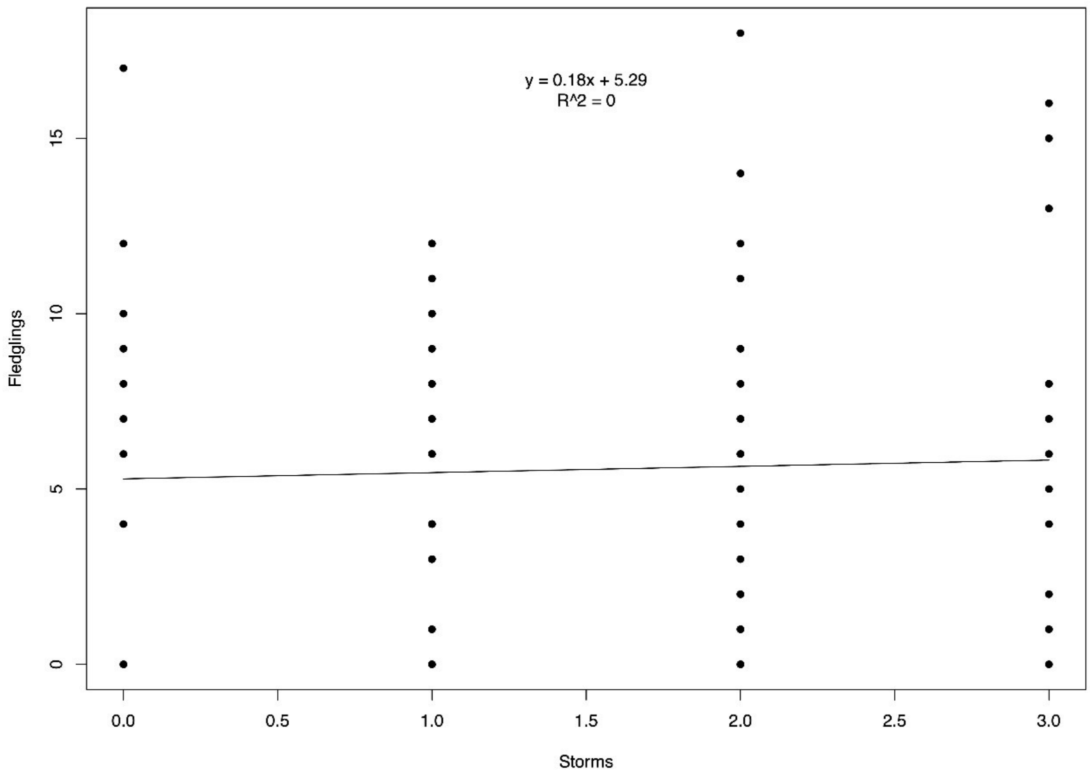


Figure B3 GLMER for Piping Plover (*Charadrius melodus melodus*) breeding pairs in New Brunswick, Canada, and response with no lag to storm occurrences between 1994 and 2020. Breeding pairs increased immediately after storms, but the relationship was not significant.

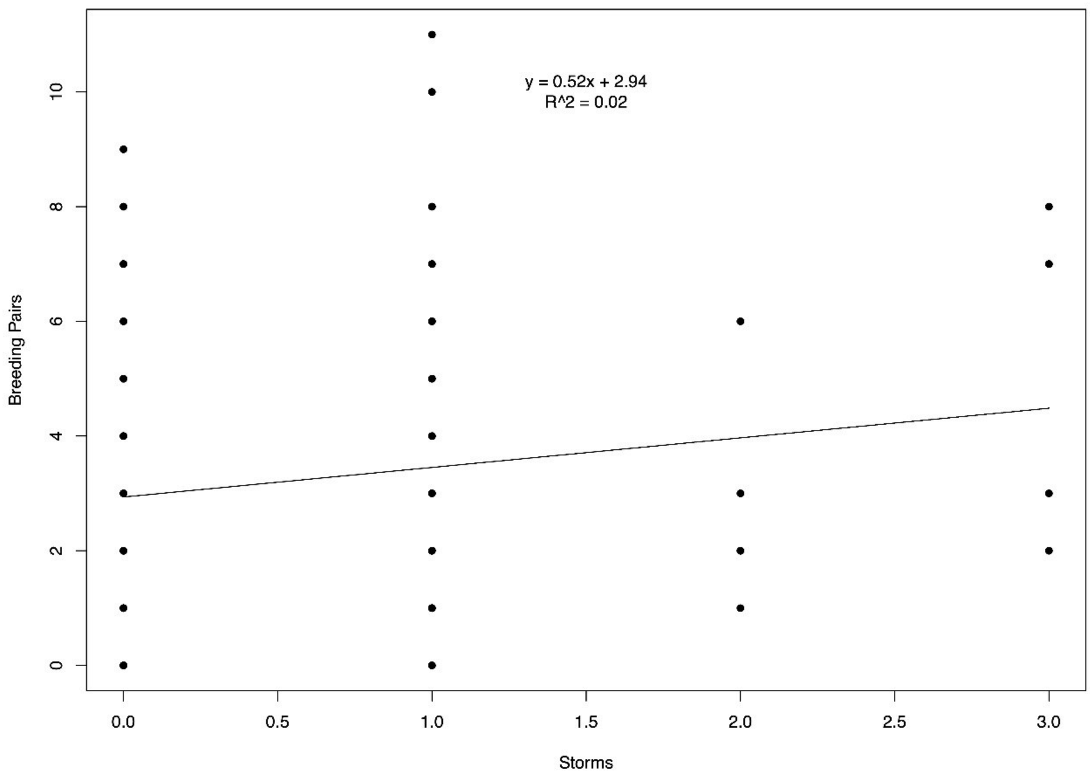


Figure B4 GLMER for Piping Plover (*Charadrius melodus melodus*) fledglings in New Brunswick, Canada, and response with no lag to storm occurrences between 1994 and 2020. Fledglings decreased immediately after storms, but the relationship was not significant.

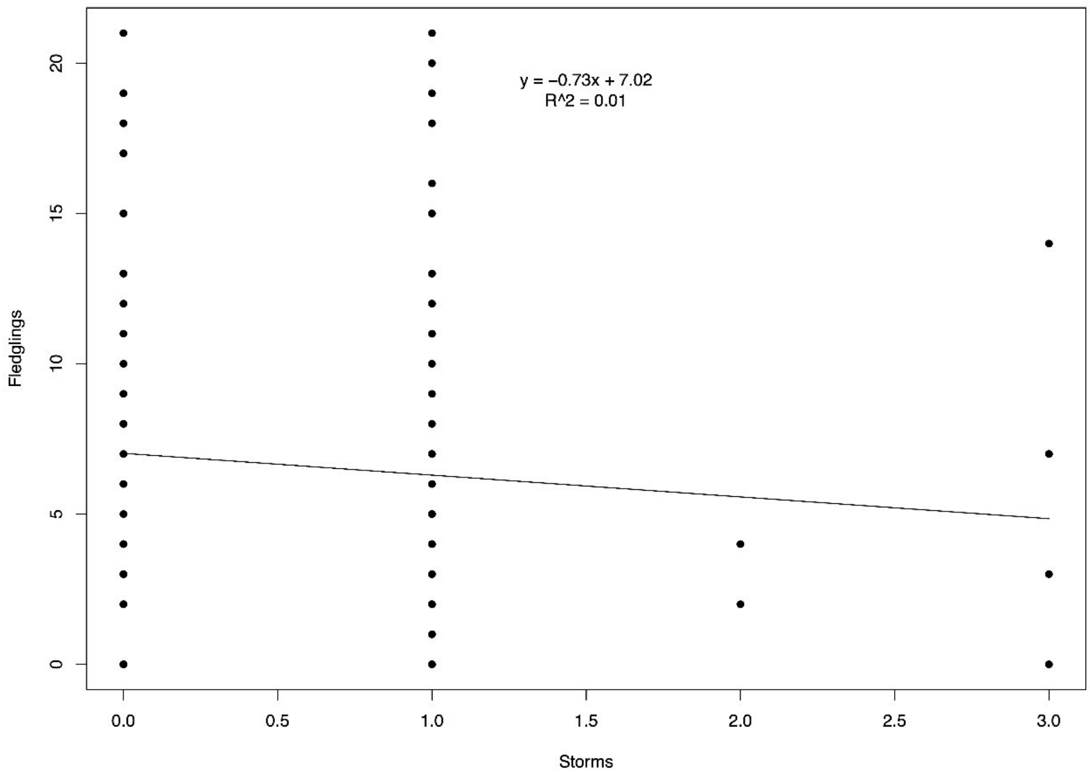
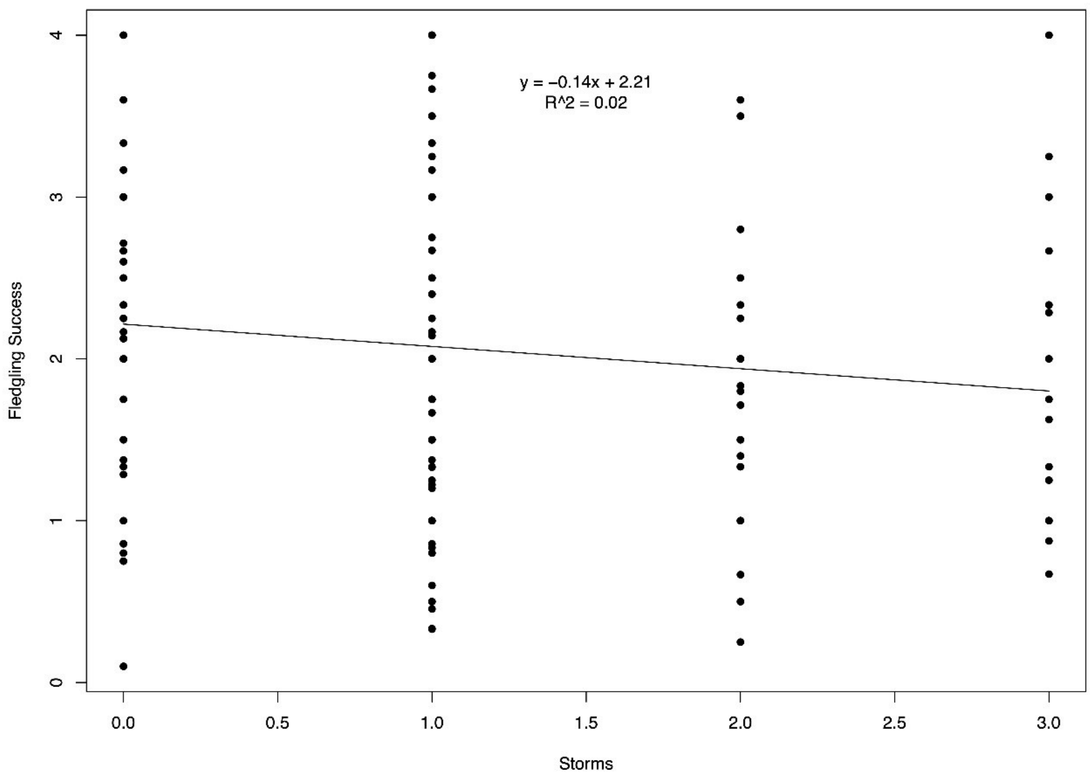


Figure B5 Combined GLMER model for Piping Plover (*Charadrius melodus melodus*) fledgling success for the provinces of Nova Scotia and New Brunswick, Canada, and response with no lag to storm occurrences between 1994 and 2020. Fledgling success decreased in both provinces immediately after storms, but the relationship was not significant.



Appendix C: Scripts for Generalized Linear Mixed-Effects Models

Script 1. Supplementary model code for GLMER modelling of Nova Scotia breeding pairs, 1994-2020.

```
#NS breeding pairs

#Made with assistance and guidance from Jeff Clements, PhD (Department of Fisheries and
Oceans Canada, Moncton, NB)
#Based on previous modelling by Bourque et al. (2015)

####################################################

#Load packages
library(lmerTest)
library(car)
library(blmeco)
library(AICcmodavg)

#File attachment
julia<-read.csv(file.choose())
attach(julia)
summary(julia)

#Build GLMER models for Poisson Distribution
#No Lag
nolag.mod<-
glmer(pairs~year_rescale+storms+(1|beach),family=poisson,data=julia,na.action=na.omit)
#Lag 1
oneyearlag.mod<-
glmer(pairs~year_rescale+storms_1.lag+(1|beach),family=poisson,data=julia,na.action=na.omit)
#Lag 2
twoyearlag.mod<-
glmer(pairs~year_rescale+storms_2.lag+(1|beach),family=poisson,data=julia,na.action=na.omit)
#Lag 3
threeyearlag.mod<-
glmer(pairs~year_rescale+storms_3.lag+(1|beach),family=poisson,data=julia,na.action=na.omit)

#Compare ANOVA
anova(nolag.mod,oneyearlag.mod,twoyearlag.mod,threeyearlag.mod)
#Two year lag was the best model

#Check for overdispersion
dispersion_glmer(twoyearlag.mod)
overdisp_fun <- function(twoyearlag.mod) {
  rdf <- df.residual(twoyearlag.mod)
  rp <- residuals(twoyearlag.mod,type="pearson")
  Pearson.chisq <- sum(rp^2)
  prat <- Pearson.chisq/rdf
```

```
  pval <- pchisq(Pearson.chisq, df=rdf, lower.tail=FALSE)
  c(chisq=Pearson.chisq,ratio=prat,rdf=rdf,p=pval)
}
overdisp_fun(twoyearlag.mod)
#Model is overdispersed (ratio > 1; p < 0.05)
#Since first model is overdispersed, can assume others likely are as well
#Shift to negative binomial models

#Build negative binomial GLMER models
#No Lag
nolag.nbmod<-glmer.nb(pairs~year_rescale+storms+(1|beach),data=julia,na.action=na.omit)
#Lag 1
oneyearlag.nbmod<-
glmer.nb(pairs~year_rescale+storms_1.lag+(1|beach),data=julia,na.action=na.omit)
#Lag 2
twoyearlag.nbmod<-
glmer.nb(pairs~year_rescale+storms_2.lag+(1|beach),data=julia,na.action=na.omit)
#Lag 3
threeyearlag.nbmod<-
glmer.nb(pairs~year_rescale+storms_3.lag+(1|beach),data=julia,na.action=na.omit)

#Compare models using AIC
anova(nolag.nbmod,oneyearlag.nbmod,twoyearlag.nbmod,threeyearlag.nbmod)
#Two year lag model is best (lowest AIC value and highest log likelihood value)

#Run ANOVA on two year lag model to test for significance of fixed effects
Anova(twoyearlag.nbmod,type=3)
#Non. sig.

#Define list of models
models <- list(nolag.nbmod, oneyearlag.nbmod, twoyearlag.nbmod, threeyearlag.nbmod)

#Specify model names
mod.names <- c('no.lagyear', 'one.year', 'two.year', 'three.year')

#Calculate AIC of each model
aictab(cand.set = models, modnames = mod.names)

###
```

Script 2. Supplementary model code for GLMER modelling of Nova Scotia fledglings, 1994-2020.

```
#NS fledglings

#Made with assistance and guidance from Jeff Clements, PhD (Department of Fisheries and
Oceans Canada, Moncton, NB)
#Based on previous modelling by Bourque et al. (2015)

##################################################

#Load packages
library(lmerTest)
library(car)
library(blmeco)
library(AICcmodavg)

#File attachment
NSfledge <- read.csv(file.choose())
attach(NSfledge)
summary(NSfledge)

#Classify variables
NSfledge$storms<-as.numeric(NSfledge$storms)
NSfledge$year_rescale<-as.factor(NSfledge$year)

#Build GLMER models for Poisson Distribution
#No Lag
nolag<-
glmer(fledglings~year_rescale+storms+(1|beach),family=poisson,data=NSfledge,na.action=na.o
mit)
summary(nolag)
#Lag 1
lag1<-
glmer(fledglings~year_rescale+storms_1.lag+(1|beach),family=poisson,data=NSfledge,na.action
=na.omit)
summary(lag1)
#Lag 2
lag2<-
glmer(fledglings~year_rescale+storms_2.lag+(1|beach),family=poisson,data=NSfledge,na.action
=na.omit)
summary(lag2)
#Lag 3
lag3<-
glmer(fledglings~year_rescale+storms_3.lag+(1|beach),family=poisson,data=NSfledge,na.action
=na.omit)
summary(lag3)

#Run ANOVA
anova(nolag,lag1,lag2,lag3)
#One year lag was best-fitted model
```

```
#Check for overdispersion
overdisp_fun <- function(lag1)
{
  rdf <- df.residual(nolag)
  rp <- residuals(lag1,type="pearson")
  Pearson.chisq <- sum(rp^2)
  prat <- Pearson.chisq/rdf
  pval <- pchisq(Pearson.chisq, df=rdf, lower.tail=FALSE)
  c(chisq=Pearson.chisq,ratio=prat,rdf=rdf,p=pval)
}
overdisp_fun(lag1)
#Model is overdispersed (ratio > 1; p < 0.05)
#Since first model is overdispresed, can assume others likely are as well
#Shift to negative binomial models

#Build negative binomial GLMER models
#No Lag
nolagb <- glmer.nb(fledglings~year_rescale+storms+(1|beach),data=NSfledge,na.action=na.omit)
summary(nolagb)
Anova(nolagb, type = 3)
#Lag 1
lag1b <-
glmer.nb(fledglings~year_rescale+storms_1.lag+(1|beach),data=NSfledge,na.action=na.omit)
summary(lag1b)
Anova(lag1b, type = 3)
#Lag 2
lag2b <-
glmer.nb(fledglings~year_rescale+storms_2.lag+(1|beach),data=NSfledge,na.action=na.omit)
summary(lag2b)
Anova(lag2b, type = 3)
#Lag 3
lag3b <-
glmer.nb(fledglings~year_rescale+storms_3.lag+(1|beach),data=NSfledge,na.action=na.omit)
summary(lag3b)
Anova(lag3b, type = 3)

#Compare models using AIC
anova(nolagb, lag1b, lag2b, lag3b)
#One year lag is best fitted model

#Run ANOVA on one-year lag model to test for significance of fixed effects
Anova(lag1b,type = 3)
#Non. sig.

#Define list of models
models <- list(nolagb, lag1b, lag2b, lag3b)

#Specify model names
mod.names <- c('no.lagyear', 'one.year', 'two.year', 'three.year')

#Calculate AIC of each model
aictab(cand.set = models, modnames = mod.names)

###
```

Script 3. Supplementary model code for GLMER modelling of New Brunswick breeding pairs, 1994-2020.

```
#NB breeding pairs

#Made with assistance and guidance from Jeff Clements, PhD (Department of Fisheries and
Oceans Canada, Moncton, NB)
#Based on previous modelling by Bourque et al. (2015)

###################################################

#Load packages
library(lmerTest)
library(car)
library(blmeco)
library(AICcmodavg)

#File attachment
julia<-read.csv(file.choose())
attach(julia)
summary(julia)

#Build GLMER models for Poisson Distribution
#No Lag
nolag.mod<-
glmer(pairs~year_rescale+storms+(1|beach),family=poisson,data=julia,na.action=na.omit)
#Lag 1
oneyearlag.mod<-
glmer(pairs~year_rescale+storms_1.lag+(1|beach),family=poisson,data=julia,na.action=na.omit)
#Lag 2
twoyearlag.mod<-
glmer(pairs~year_rescale+storms_2.lag+(1|beach),family=poisson,data=julia,na.action=na.omit)
#Lag 3
threeyearlag.mod<-
glmer(pairs~year_rescale+storms_3.lag+(1|beach),family=poisson,data=julia,na.action=na.omit)

#Compare ANOVA
anova(nolag.mod,oneyearlag.mod,twoyearlag.mod,threeyearlag.mod)
#NoLag was best fitted model

#Test for Overdispersion
dispersion_glmer(nolag.mod)
overdisp_fun <- function(nolag.mod) {
  rdf <- df.residual(nolag.mod)
  rp <- residuals(nolag.mod,type="pearson")
  Pearson.chisq <- sum(rp^2)
  prat <- Pearson.chisq/rdf
  pval <- pchisq(Pearson.chisq, df=rdf, lower.tail=FALSE)
  c(chisq=Pearson.chisq,ratio=prat,rdf=rdf,p=pval)
}
overdisp_fun(nolag.mod)
#Model is overdispersed (ratio > 1; p < 0.05)
```

```
#Since first model is overdispersed, can assume others likely are as well
#Shift to negative binomial models

#Build negative binomial GLMER models
#No Lag
nolag.nbmod<-glmer.nb(pairs~year_rescale+storms+(1|beach),data=julia,na.action=na.omit)
#Lag 1
oneyearlag.nbmod<-
glmer.nb(pairs~year_rescale+storms_1.lag+(1|beach),data=julia,na.action=na.omit)
#Lag 2
twoyearlag.nbmod<-
glmer.nb(pairs~year_rescale+storms_2.lag+(1|beach),data=julia,na.action=na.omit)
#Lag 3
threeyearlag.nbmod<-
glmer.nb(pairs~year_rescale+storms_3.lag+(1|beach),data=julia,na.action=na.omit)

#Compare models using AIC
anova(nolag.nbmod,oneyearlag.nbmod,twoyearlag.nbmod,threeyearlag.nbmod)
#NoLag was best fitted model

#Define list of models
models <- list(nolag.nbmod, oneyearlag.nbmod, twoyearlag.nbmod, threeyearlag.nbmod)

#Specify model names
mod.names <- c('no.lagyear', 'one.year', 'two.year', 'three.year')

#Calculate AIC of each model
aictab(cand.set = models, modnames = mod.names)

#NoLag model is best (lowest AIC value and highest log likelihood value)
#Run Anova on NoLag model to test for significance of fixed effects
Anova(nolag.nbmod,type=3)
#Non. sig.

###
```

Script 4. Supplementary model code for GLMER modelling of New Brunswick fledglings, 1994-2020.

```
#NB fledglings

#Made with assistance and guidance from Jeff Clements, PhD (Department of Fisheries and
Oceans Canada)
#Based on previous modelling by Bourque et al. (2015)

##################################################

#Load packages
library(lmerTest)
library(car)
library(blmeco)
library(AICcmodavg)

#File attachment
julia<-read.csv(file.choose())
attach(julia)
summary(julia)

#Build GLMER models for Poisson Distribution
#No Lag
nolag.mod<-
glmer(fledglings~year_rescale+storms+(1|beach),family=poisson,data=julia,na.action=na.omit)
#Lag 1
oneyearlag.mod<-
glmer(fledglings~year_rescale+storms_1.lag+(1|beach),family=poisson,data=julia,na.action=na.o
mit)
#Lag 2
twoyearlag.mod<-
glmer(fledglings~year_rescale+storms_2.lag+(1|beach),family=poisson,data=julia,na.action=na.o
mit)
#Lag 3
threeyearlag.mod<-
glmer(fledglings~year_rescale+storms_3.lag+(1|beach),family=poisson,data=julia,na.action=na.o
mit)

#Compare ANOVA
anova(nolag.mod,oneyearlag.mod,twoyearlag.mod,threeyearlag.mod)
#NoLag was best fitted model

#Test for Overdispersion
dispersion_glmer(nolag.mod)
overdisp_fun <- function(nolag.mod) {
  rdf <- df.residual(nolag.mod)
  rp <- residuals(nolag.mod,type="pearson")
  Pearson.chisq <- sum(rp^2)
  prat <- Pearson.chisq/rdf
  pval <- pchisq(Pearson.chisq, df=rdf, lower.tail=FALSE)
  c(chisq=Pearson.chisq,ratio=prat,rdf=rdf,p=pval)
```

```
}
overdisp_fun(nolag.mod)
#Model is overdispersed (ratio > 1; p < 0.05)
#since first model is overdispersed, can assume others likely are as well
#shift to negative binomial models

#Build negative binomial GLMER models
#No Lag
nolag.nbmod<-glmer.nb(fledglings~year_rescale+storms+(1|beach),data=julia,na.action=na.omit)
#Lag 1
oneyearlag.nbmod<-
glmer.nb(fledglings~year_rescale+storms_1.lag+(1|beach),data=julia,na.action=na.omit)
#Lag 2
twoyearlag.nbmod<-
glmer.nb(fledglings~year_rescale+storms_2.lag+(1|beach),data=julia,na.action=na.omit)
#Lag 3
threeyearlag.nbmod<-
glmer.nb(fledglings~year_rescale+storms_3.lag+(1|beach),data=julia,na.action=na.omit)

#Compare models using AIC
anova(nolag.nbmod,oneyearlag.nbmod,twoyearlag.nbmod,threeyearlag.nbmod)
#NoLag model is best (lowest AIC value and highest log likelihood value)

#Run ANOVA on NoLag model to test for significance of fixed effects
Anova(nolag.nbmod,type=3)
#Non. sig.

#Define list of models
models <- list(nolag.nbmod, oneyearlag.nbmod, twoyearlag.nbmod, threeyearlag.nbmod)

#Specify model names
mod.names <- c('no.lagyear', 'one.year', 'two.year', 'three.year')

#Calculate AIC of each model
aictab(cand.set = models, modnames = mod.names)

###
```

Script 5. Supplementary model code for GLMER modelling of New Brunswick and Nova Scotia combined fledgling success, 1994-2020.

```
#NB and NS Fledgling Success, combined model

#Made with assistance and guidance from Jeff Clements, PhD (Department of Fisheries and
Oceans Canada. Moncton, NB)
#Based on previous modelling by Bourque et al. (2015)

####################################################

#Load packages
library(lmerTest)
library(car)
library(blmeco)
library(AICcmodavg)

#File attachment
combo<-read.csv(file.choose())
attach(combo)
summary(combo)

#Omit rows containing null data
combin <- na.omit(combo)
summary(combin)

#Include NS and NB in same dataset and test for effect of province
#No Lag
nolag.provmod<-
glmer(fledgling_success~year_rescale+province*storms+(1|beach/province),family=Gamma,data
=combin,na.action=na.omit)
#Lag 1
oneyearlag.provmod<-
glmer(fledgling_success~year_rescale+province*storms_1.lag+(1|beach/province),family=Gamm
a,data=combin,na.action=na.omit)
#Lag 2
twoyearlag.provmod<-
glmer(fledgling_success~year_rescale+province*storms_2.lag+(1|beach/province),family=Gamm
a,data=combin,na.action=na.omit)
#Lag 3
threeyearlag.provmod<-
glmer(fledgling_success~year_rescale+province*storms_3.lag+(1|beach/province),family=Gamm
a,data=combin,na.action=na.omit)
#Anova test
anova(nolag.provmod,oneyearlag.provmod,twoyearlag.provmod,threeyearlag.provmod)
#No lag is best model

#Check for overdispersion
dispersion_glmer(nolag.provmod)
overdisp_fun <- function(nolag.provmod) {
  rdf <- df.residual(nolag.provmod)
  rp <- residuals(nolag.provmod,type="pearson")
```

```
  Pearson.chisq <- sum(rp^2)
  prat <- Pearson.chisq/rdf
  pval <- pchisq(Pearson.chisq, df=rdf, lower.tail=FALSE)
  c(chisq=Pearson.chisq,ratio=prat,rdf=rdf,p=pval)
}
overdisp_fun(nolag.provmod)
#Model is overdispersed (ratio > 1; p < 0.05)
#Since first model is overdispresed, can assume others likely are as well
#Shift to negative binomial models

#Build negative binomial GLMER models
#No Lag
nolag.nbprov<-
glmer.nb(fledgling_success~year_rescale+province*storms+(1|beach/province),data=combin,na.
action=na.omit)
#Lag 1
oneyearlag.nbprov<-
glmer.nb(fledgling_success~year_rescale+province*storms_1.lag+(1|beach/province),data=comb
in,na.action=na.omit)
#Lag 2
twoyearlag.nbprov<-
glmer.nb(fledgling_success~year_rescale+province*storms_2.lag+(1|beach/province),data=comb
in,na.action=na.omit)
#Lag 3
threeyearlag.nbprov<-
glmer.nb(fledgling_success~year_rescale+province*storms_3.lag+(1|beach/province),data=comb
in,na.action=na.omit)

#Compare models using AIC
anova(nolag.nbprov,oneyearlag.nbprov,twoyearlag.nbprov,threeyearlag.nbprov)
#no lag model is best (lowest AIC value and highest log likelihood value)

#Run ANOVA on no lag model to test for significance of fixed effects
Anova(nolag.nbprov,type=3)
#Non. significant

#Define list of models
models <- list(nolag.nbprov, oneyearlag.nbprov, twoyearlag.nbprov, threeyearlag.nbprov)

#Specify model names
mod.names <- c('no.lagyear', 'one.year', 'two.year', 'three.year')

#Calculate AIC of each model
aictab(cand.set = models, modnames = mod.names)

###
```

Appendix D: Hurricane Dorian Supplementary Maps

Figure D1 Aerial imagery map displaying sand coverage of Captains Pond and Monks Head beach in Antigonish County, Nova Scotia, 1:12,000. Pre-Dorian photo: July 19, 2019; post-Dorian photo: September 4, 2020. Minimal change in sand coverage was observed between conditions. Imagery was obtained with Google Earth Pro and ESRI World Imagery Wayback (Google, 2022; ESRI, 2021b).

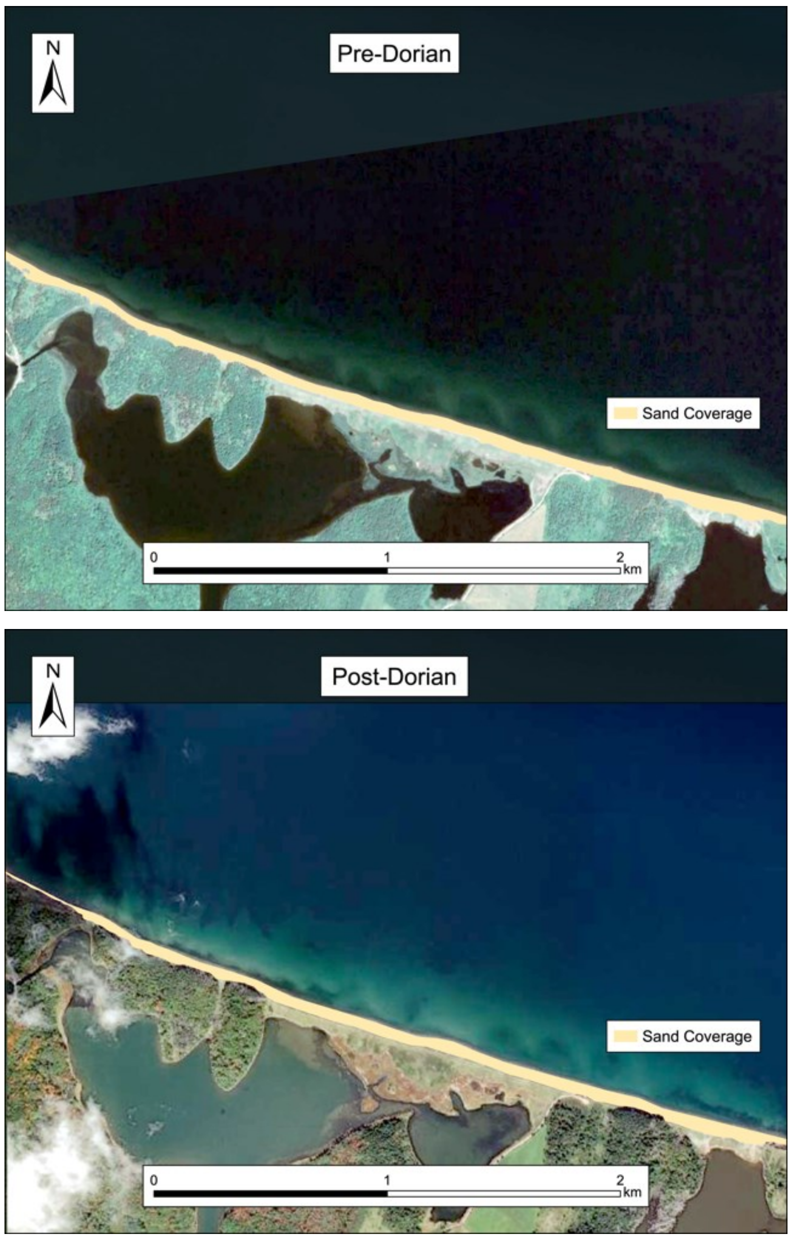


Figure D2	Aerial imagery map displaying sand coverage of Dunns beach in Antigonish County, Nova Scotia, 1:10,000. Pre-Dorian photo: July 19, 2019; post-Dorian photo: October 1, 2020. Minimal change in sand coverage was observed between conditions. Imagery was obtained with Google Earth Pro and ESRI World Imagery Wayback (Google, 2022; ESRI, 2021b).

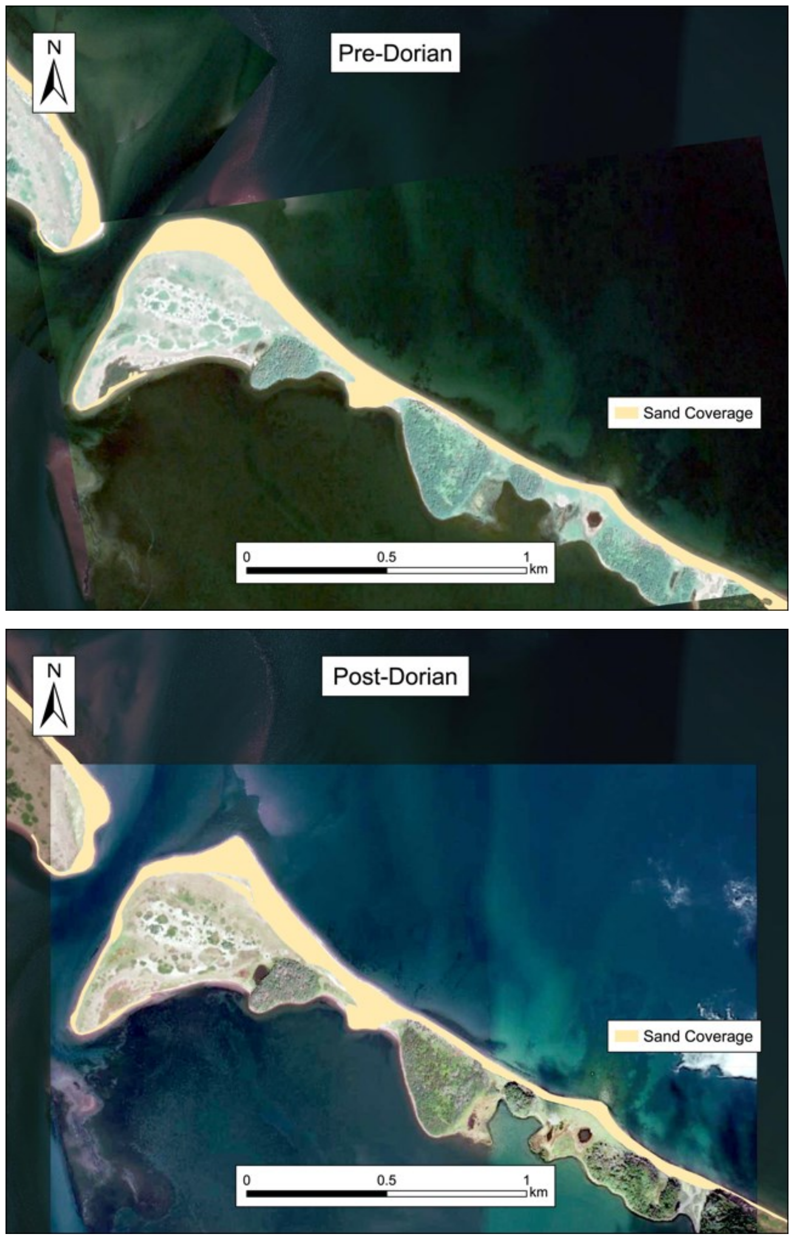


Figure D3 Aerial imagery map displaying sand coverage of Grahams Cove beach in Antigonish County, Nova Scotia, 1:6,000. Pre-Dorian photo: June 24, 2019; post-Dorian photo: October 1, 2020. Minimal change in sand coverage was observed between conditions. Imagery was obtained with Google Earth Pro and ESRI World Imagery Wayback (Google, 2022; ESRI, 2021b).

Figure D4 Aerial imagery map displaying sand coverage of Mahoneys beach in Antigonish County, Nova Scotia, 1:8,750. Pre-Dorian photo: July 19, 2019; post-Dorian photo: September 4, 2020. There was an expansion of sand within one-year following Hurricane Dorian from storm surge waves. Imagery was obtained with Google Earth Pro (Google, 2022).

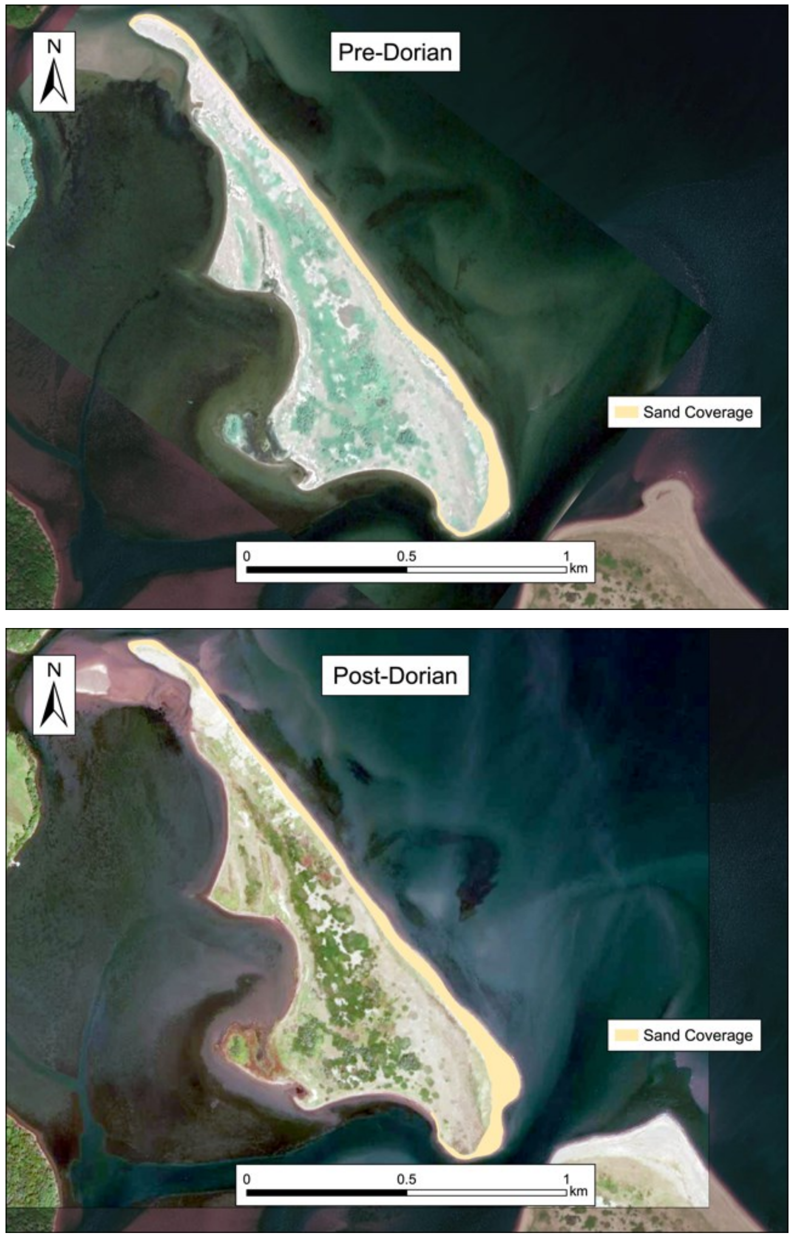


Figure D5 Aerial imagery map displaying sand coverage of Pomquet beach and provincial park in Antigonish County, Nova Scotia, 1:16,000. Pre-Dorian photo: June 24, 2019; post-Dorian photo: October 1, 2020. Minimal change in sand coverage was observed between conditions. Imagery was obtained with Google Earth Pro and ESRI World Imagery Wayback (Google, 2022; ESRI, 2021b).

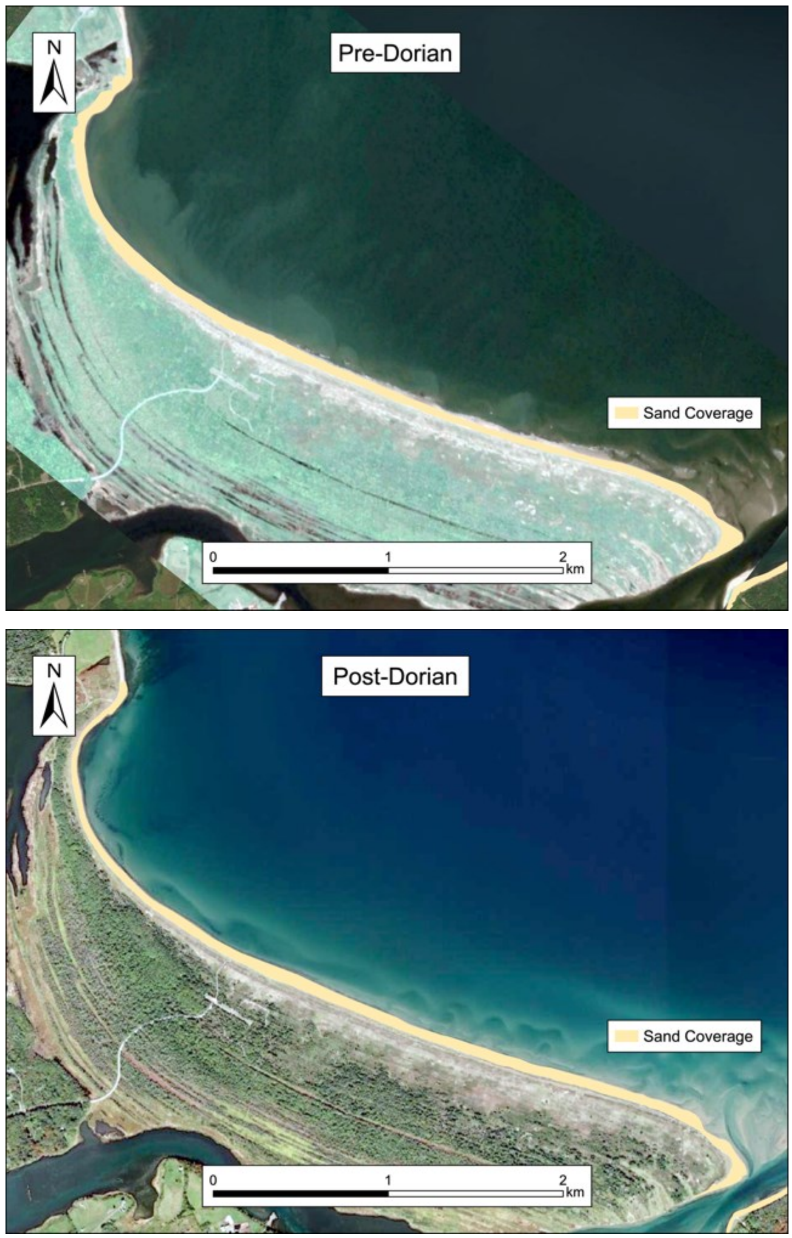


Figure D6 Aerial imagery map displaying sand coverage of Dominion beach and provincial park in Cape Breton Regional Municipality, Nova Scotia, 1:12,000. Pre-Dorian photo: June 9, 2019; post-Dorian photo: July 24, 2020. Minimal change in sand coverage was observed between conditions. Imagery was obtained with Google Earth Pro (Google, 2022).

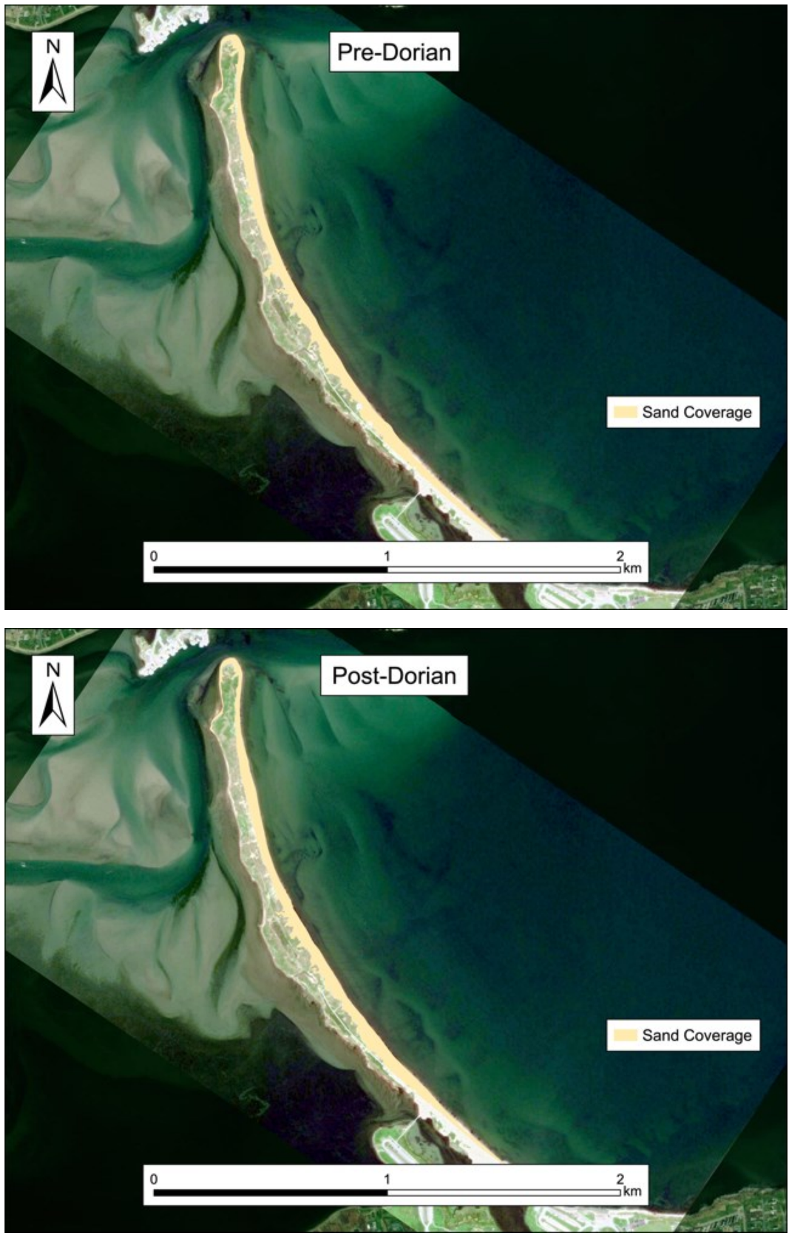


Figure D7 Aerial imagery map displaying sand coverage of Big Glace Bay Bar beach and national wildlife area in Cape Breton Regional Municipality, Nova Scotia, 1:10,000. Pre-Dorian photo: June 19, 2019; post-Dorian photo: July 24, 2020. There was a decrease in sand area after Hurricane Dorian. Imagery was obtained with Google Earth Pro (Google, 2022).

Figure D8 Aerial imagery map displaying sand coverage of South West Mabou beach in Inverness County, Nova Scotia, 1:7,000. Pre-Dorian photo: June 24, 2019; post-Dorian photo: July 27, 2020. There was an expansion of sand within one-year following Hurricane Dorian. Imagery was obtained with Google Earth Pro (Google, 2022).

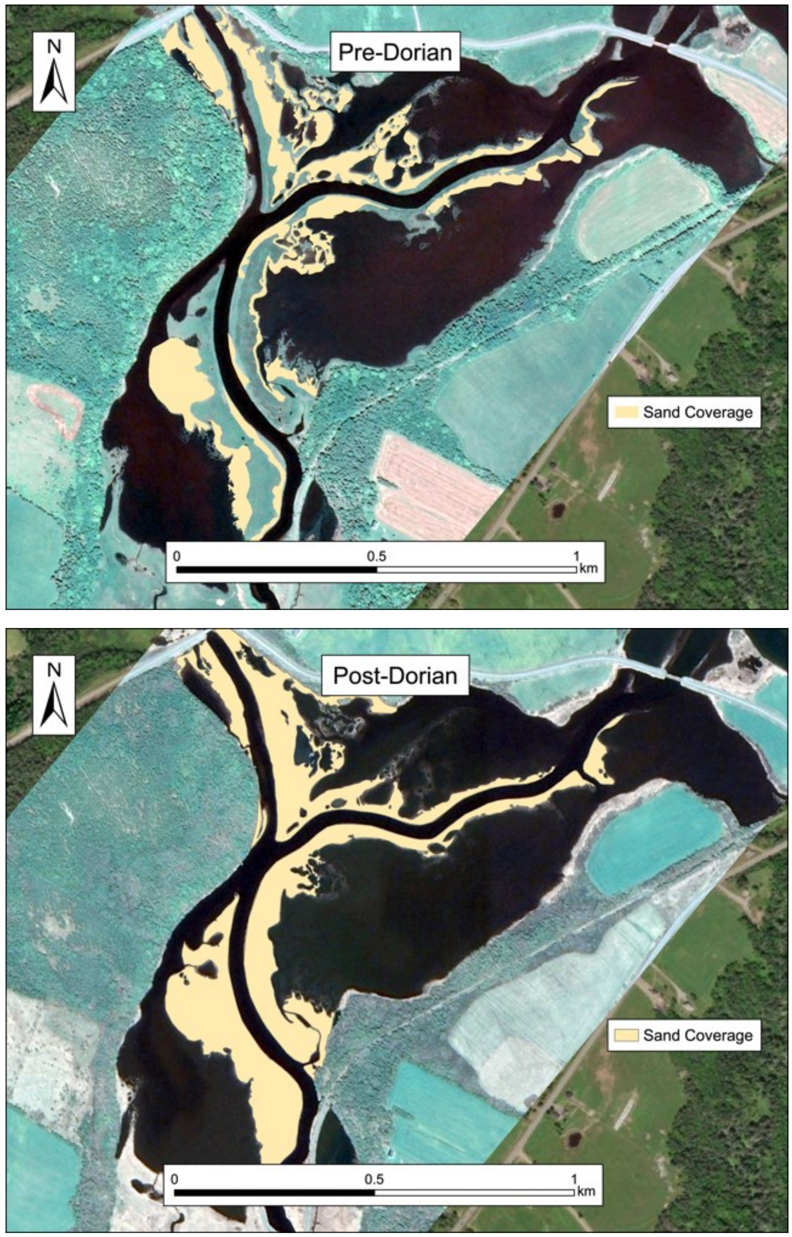
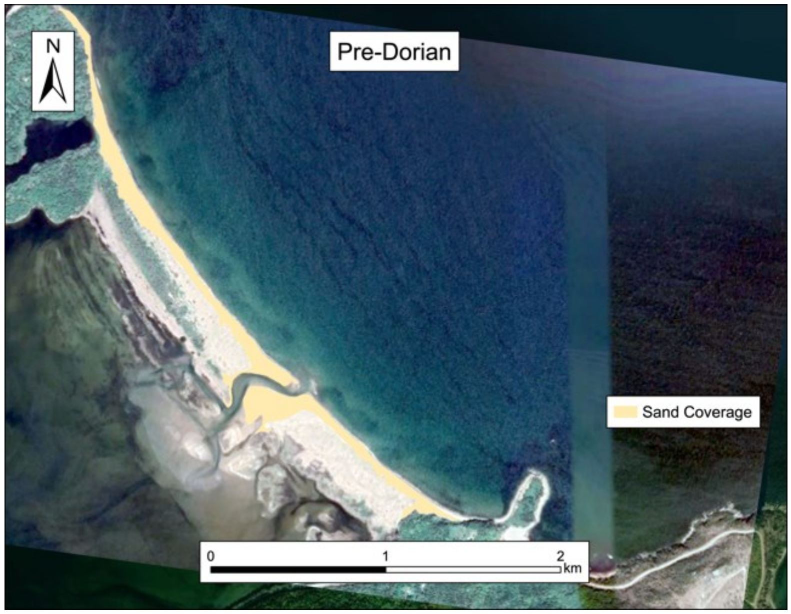


Figure D9 Aerial imagery map displaying sand coverage of South Harbour beach in Cape Breton Regional Municipality, Nova Scotia, 1:16,000. Pre-Dorian photo: June 17, 2019; post-Dorian photo: July 15, 2020. Sand coverage and beach structure remained largely the same between conditions. Imagery was obtained with Google Earth Pro (Google, 2022).



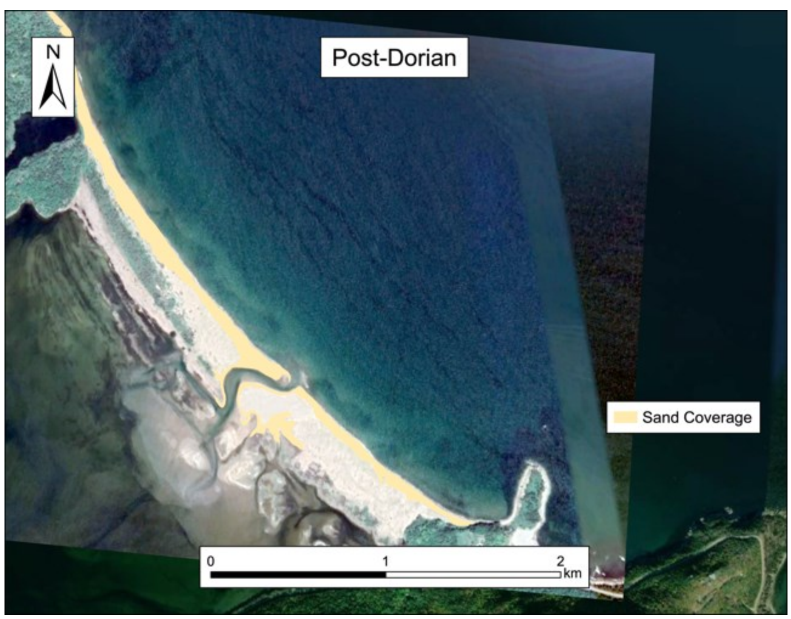


Figure D10	Aerial imagery map displaying sand coverage of Big Merigomish Island beach in Pictou County, Nova Scotia, 1:20,000. Pre-Dorian photo: June 6, 2019; post-Dorian photo: September 11, 2020. Minimal change in sand coverage was observed between conditions. Imagery was obtained with Google Earth Pro and ESRI World Imagery Wayback (Google, 2022; ESRI, 2021b).

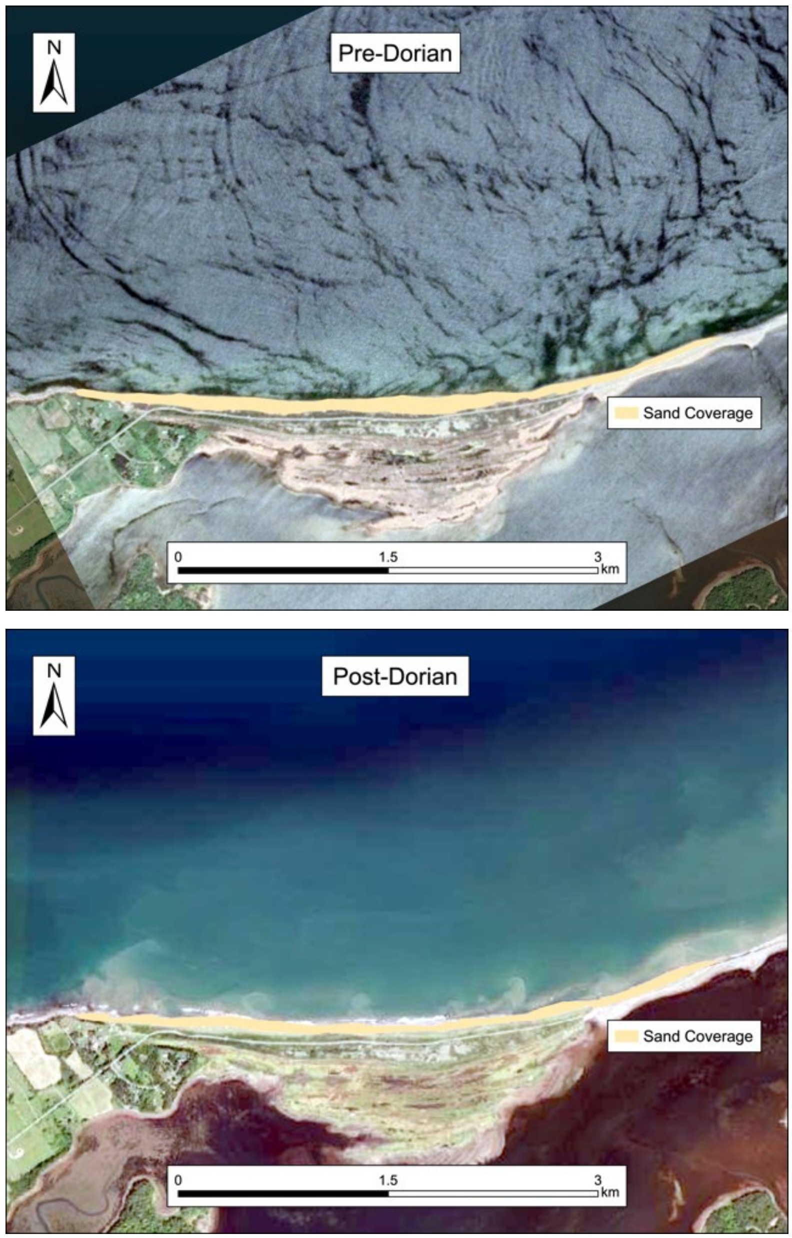


Figure D11 Aerial imagery map displaying sand coverage of Bowen Island beach in Pictou County, Nova Scotia, 1:7,000. Pre-Dorian photo: June 6, 2019; post-Dorian photo: September 12, 2020. There was a shifting of sand to create a sandbar within one-year following Hurricane Dorian from storm surge waves. There was an expansion of sand within one-year following Hurricane Dorian from storm surge waves. Imagery was obtained with Google Earth Pro (Google, 2022).

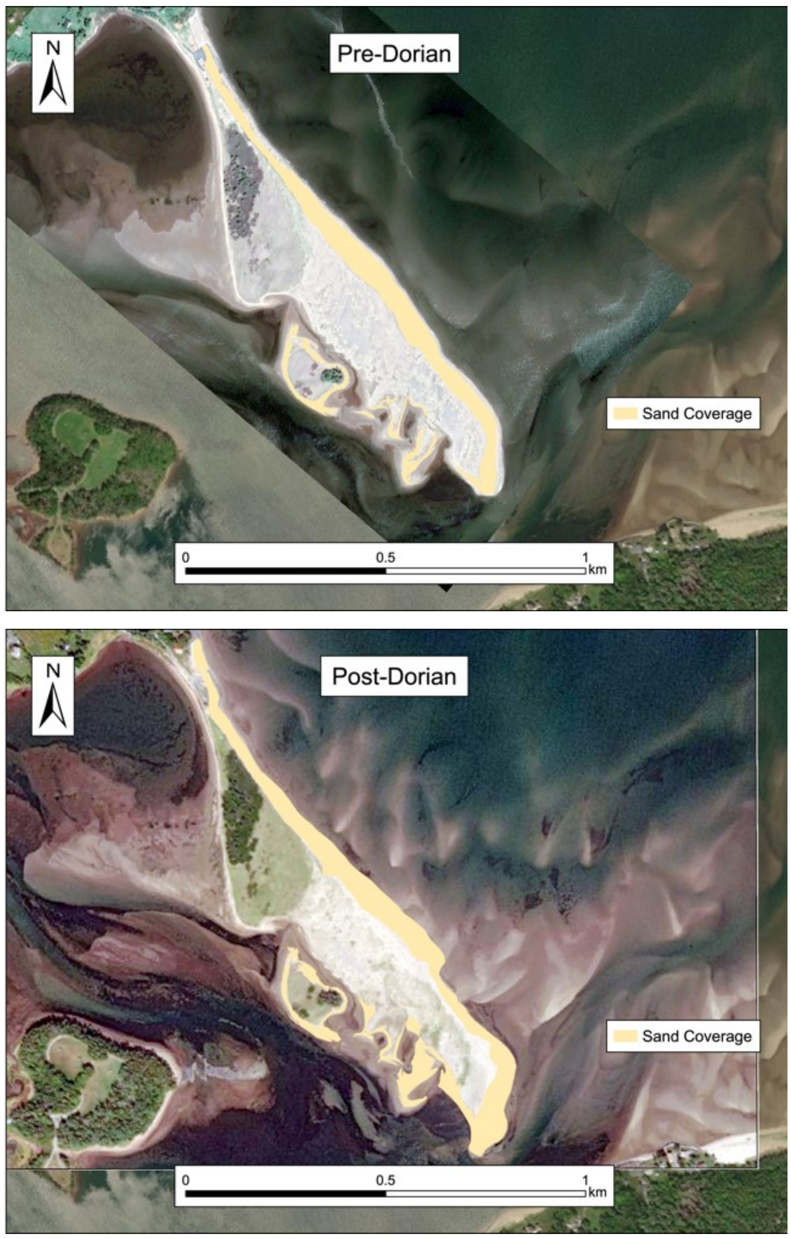


Figure D12 Aerial imagery map displaying sand coverage of Lighthouse Bar beach in Pictou County, Nova Scotia, 1:8,000. Pre-Dorian photo: June 9, 2019; post-Dorian photo: September 6, 2020. Minimal change in sand coverage was observed between conditions. Imagery was obtained with Google Earth Pro (Google, 2022).

Figure D13 Aerial imagery map displaying sand coverage of Melmerby beach in Pictou County, Nova Scotia, 1:16,000. Pre-Dorian photo: June 9, 2019; post-Dorian photo: September 12, 2020. Minimal change in sand coverage was observed between conditions. Imagery was obtained with Google Earth Pro (Google, 2022).

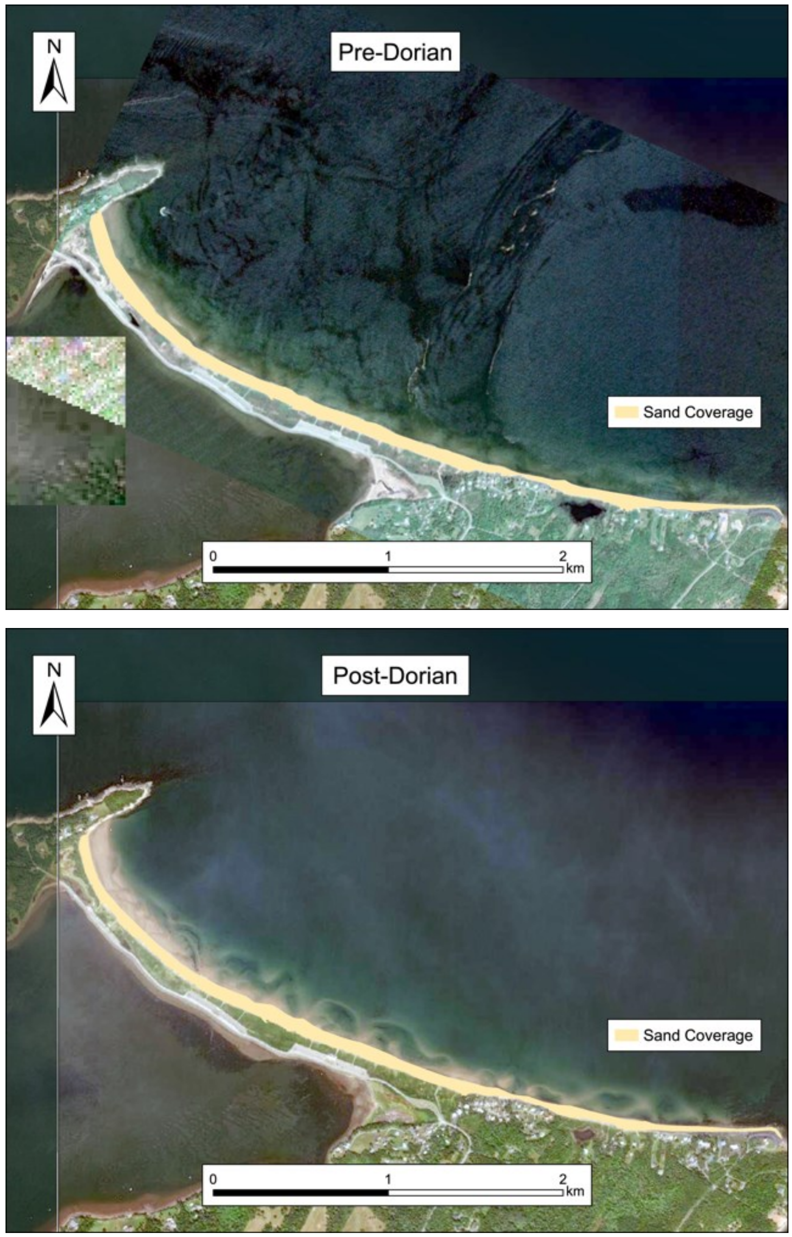


Figure D14	Aerial imagery map displaying sand coverage of Oak Island beach in Cumberland County, Nova Scotia, 1:10,000. Pre-Dorian photo: August 1, 2019; post-Dorian photo: September 30, 2020. Minimal change in sand coverage was observed between conditions. Imagery was obtained with Google Earth Pro (Google, 2022).

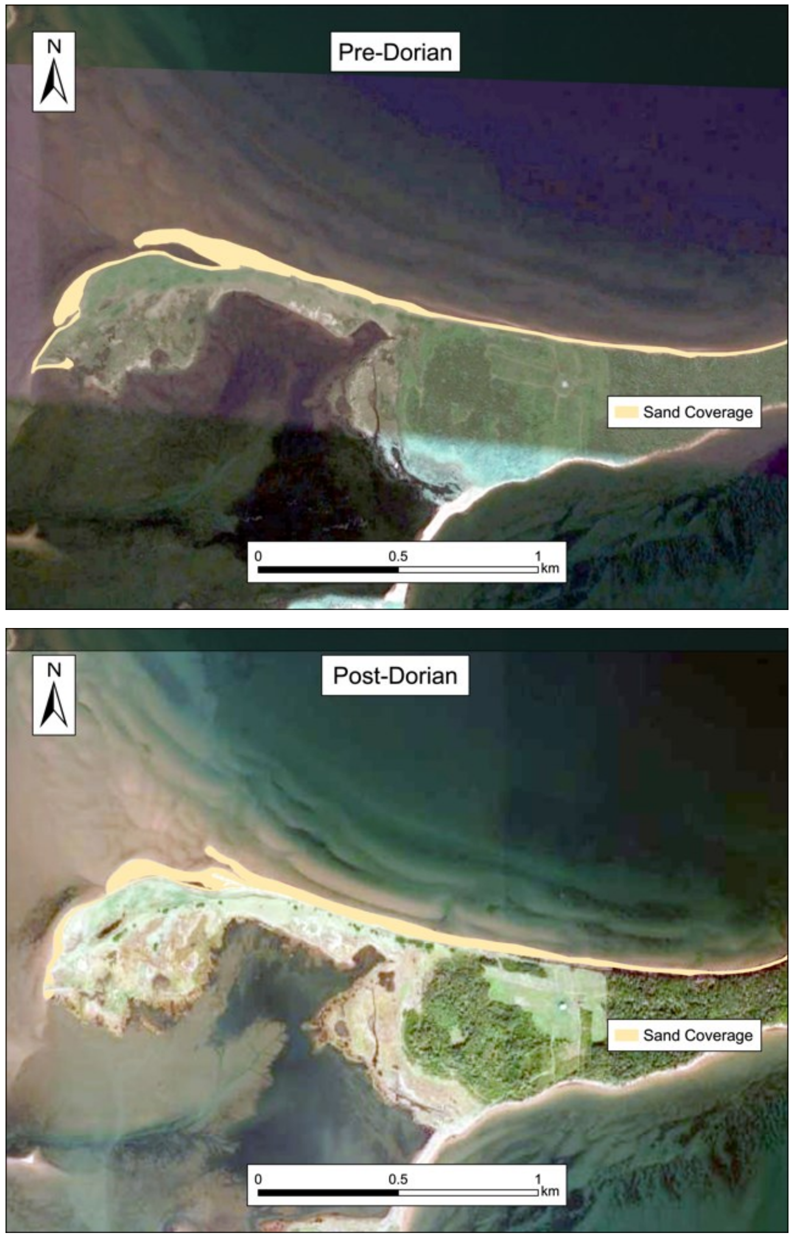


Figure D15 Aerial imagery map displaying sand coverage of Conrads East-West beach in Halifax Regional Municipality, Nova Scotia, 1:10,000. Pre-Dorian photo: April 25, 2019; post-Dorian photo: April 18, 2020. There was a shifting of sand to create a sandbar within one-year following Hurricane Dorian from storm surge waves. Imagery was obtained with Google Earth Pro (Google, 2022).

Figure D16 Aerial imagery map displaying sand coverage of Rainbow Haven beach and provincial park in Halifax Regional Municipality, Nova Scotia, 1:12,000. Pre-Dorian photo: April 25, 2019; post-Dorian photo: April 18, 2020. There was an expansion of sand within one-year following Hurricane Dorian from storm surge waves. Imagery was obtained with Google Earth Pro (Google, 2022).

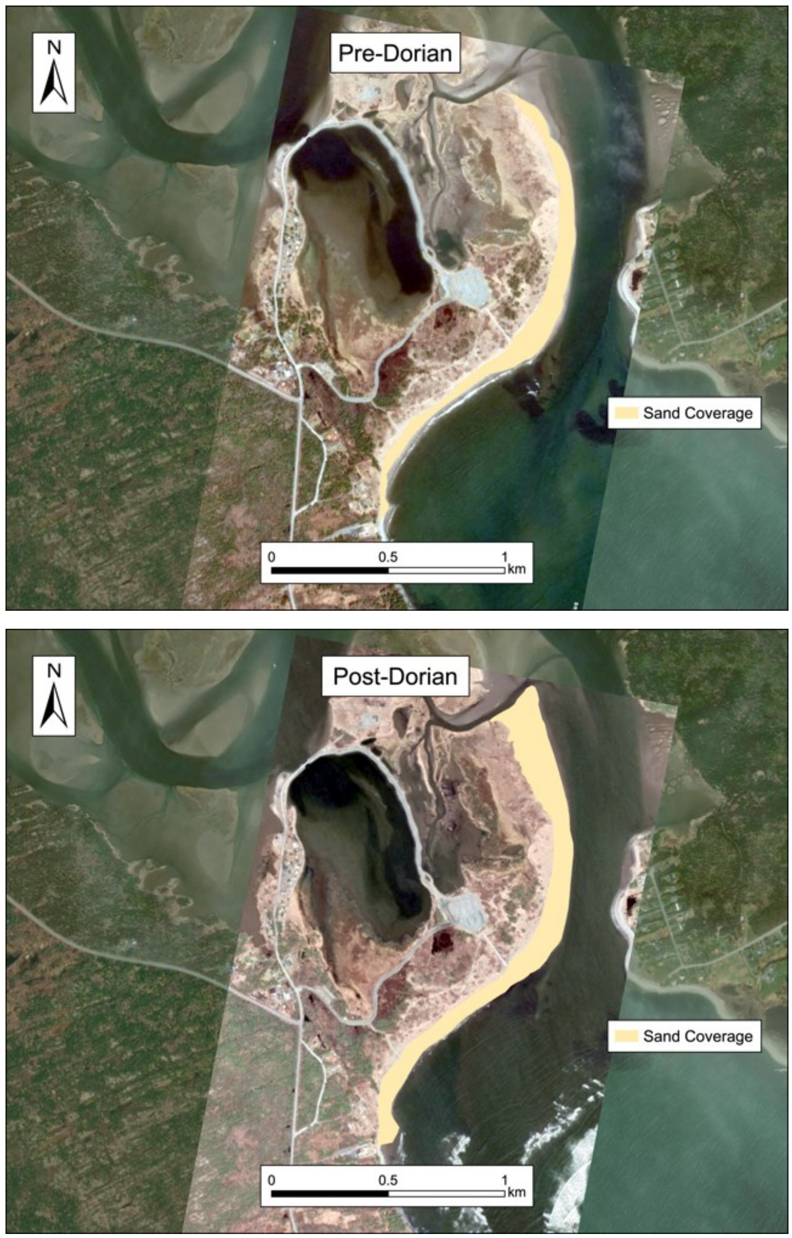


Figure D17 Aerial imagery map displaying sand coverage of Stoney (Lawrencetown) Beach in Halifax Regional Municipality, Nova Scotia, 1:5,000. Pre-Dorian photo: April 25, 2019; post-Dorian photo: April 18, 2020. There was a shifting of sand to create a sandbar within one-year following Hurricane Dorian from storm surge waves. Imagery was obtained with Google Earth Pro and ESRI World Imagery Wayback (Google, 2022).

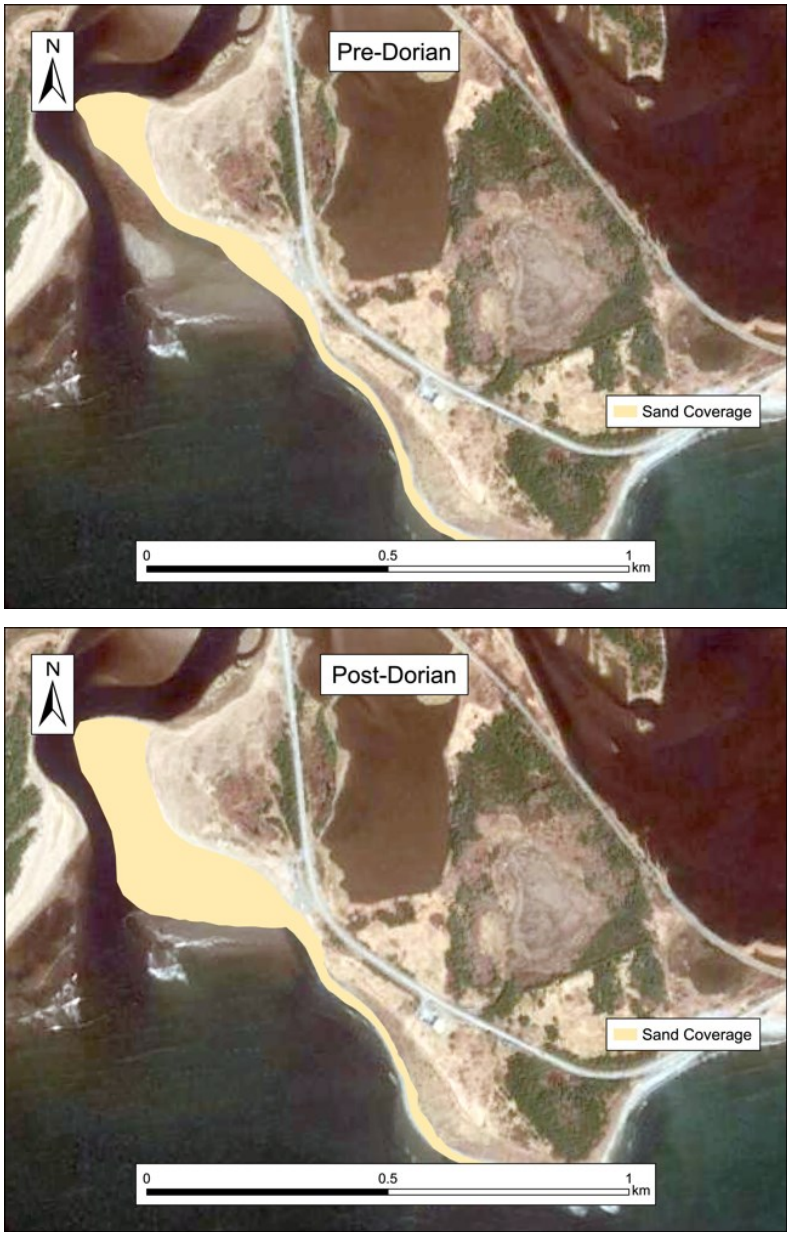


Figure D18 Aerial imagery map displaying sand coverage of Cape Bay, LaHave Island in Lunenburg County, Nova Scotia, 1:6,000. Pre-Dorian photo: August 1, 2019; post-Dorian photo: September 18, 2020. Imagery was obtained with Google Earth Pro and ESRI World Imagery Wayback (Google, 2022; ESRI, 2021b).

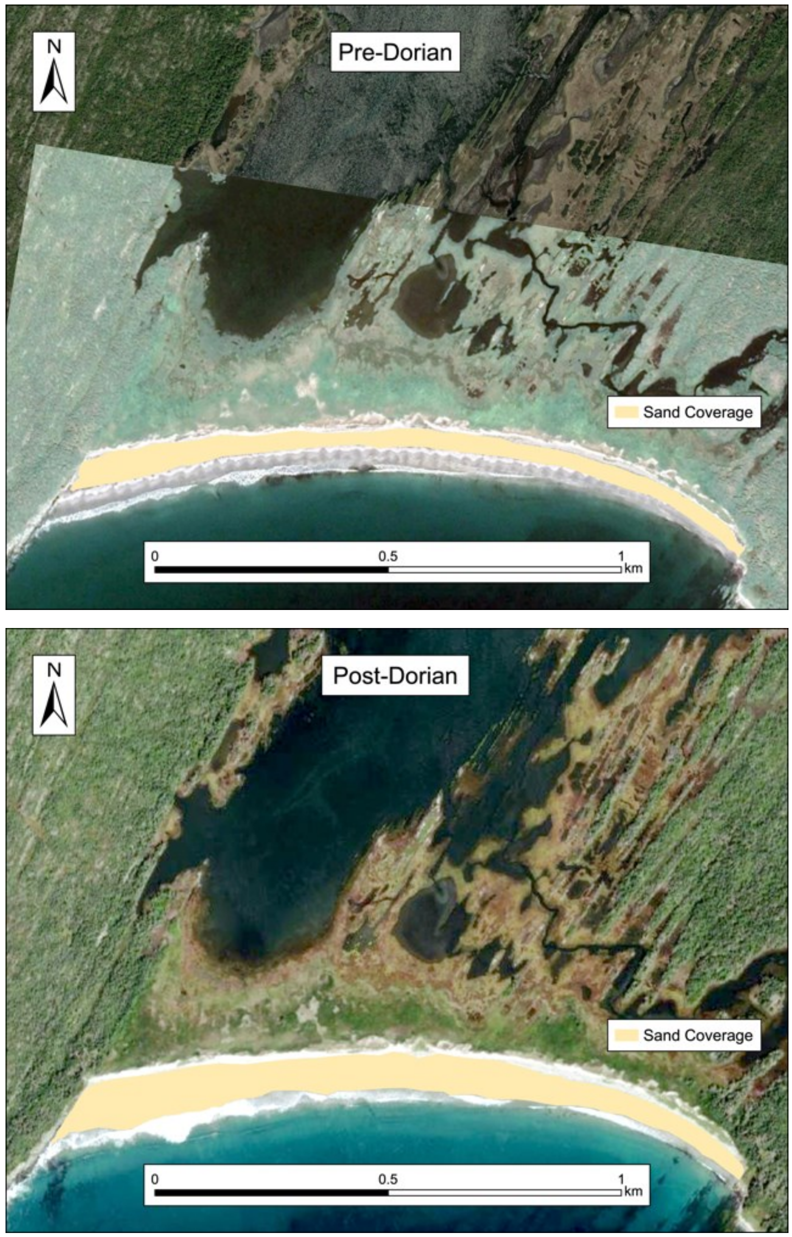


Figure D19 Aerial imagery map displaying sand coverage of Carters & Wobamkek beach in Queens County, Nova Scotia, 1:6,000. Pre-Dorian photo: September 7, 2019; post-Dorian photo: April 8, 2020. Minimal change in sand coverage was observed between conditions. Imagery was obtained with Google Earth Pro (Google, 2022).

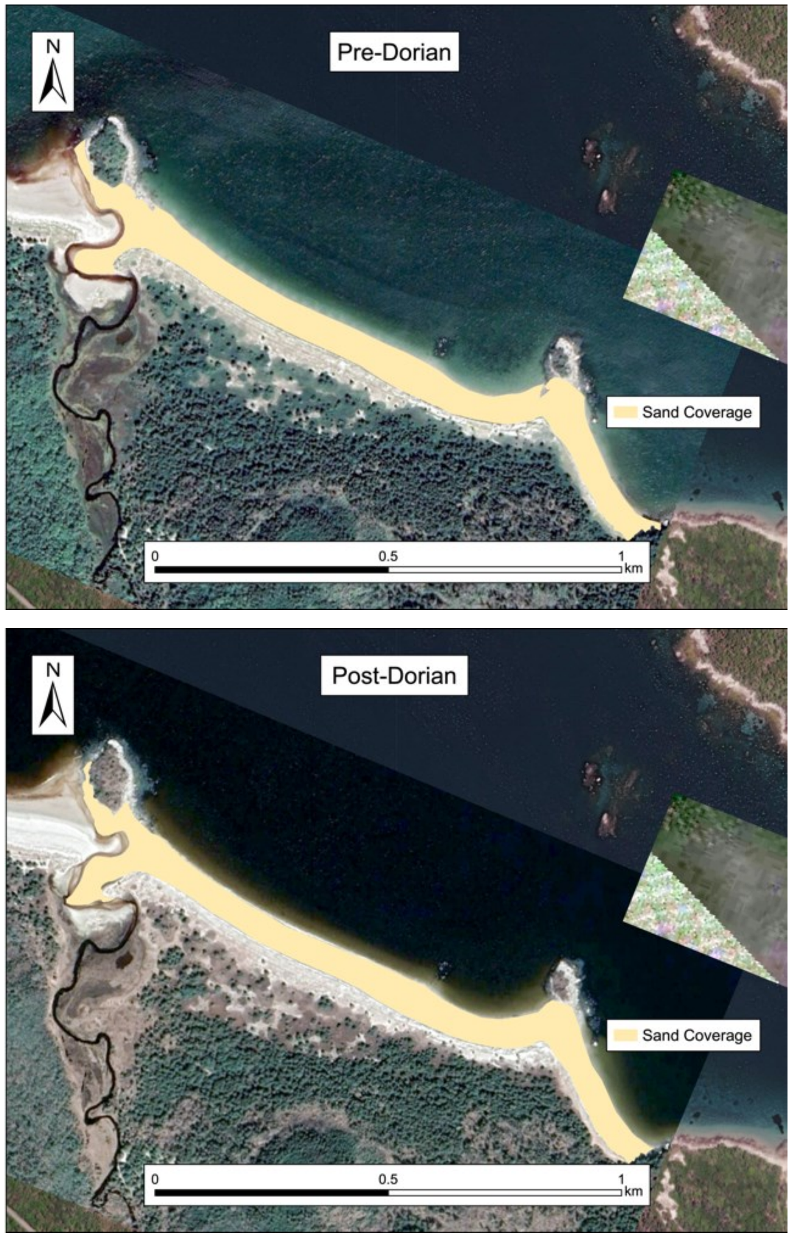


Figure D20	Aerial imagery map displaying sand coverage of Little Port Joli beach of Kejimkujik National Park-Seaside in Queens County, Nova Scotia, 1:8,000. Pre-Dorian photo: August 6, 2019; post-Dorian photo: April 14, 2020. Minimal change in sand coverage was observed between conditions. Imagery was obtained with Google Earth Pro (Google, 2022).

Figure D21 Aerial imagery map displaying sand coverage of St. Catherine's River beach of Kejimkujik National Park-Seaside in Queens County, Nova Scotia, 1:14,000. Pre-Dorian photo: August 6, 2019; post-Dorian photo: April 14, 2020. Minimal change in sand coverage was observed between conditions. Imagery was obtained with Google Earth Pro (Google, 2022).

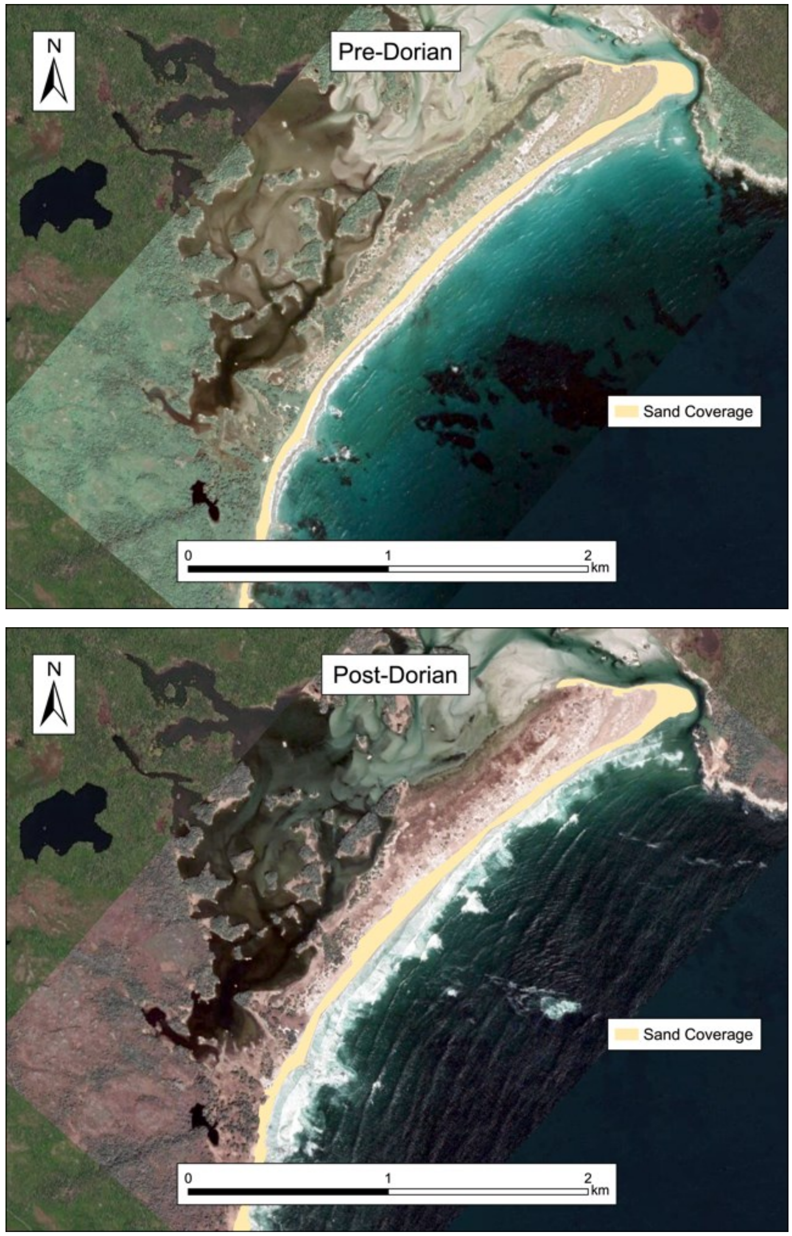


Figure D22 Aerial imagery map displaying sand coverage of Summerville beach in Queens County, Nova Scotia, 1:7,000. Pre-Dorian photo: September 7, 2019; post-Dorian photo: April 8, 2020. There was a shifting of sand to create an expansion of sand area within one-year following Hurricane Dorian from storm surge waves. Imagery was obtained with Google Earth Pro (Google, 2022).

Figure D23 Aerial imagery map displaying sand coverage of Daniels Head (Southside) beach in Shelburne County, Nova Scotia, 1:12,000. Pre-Dorian photo: August 6, 2019; post-Dorian photo: May 10, 2020. There was a decrease in sand area after Hurricane Dorian. Imagery was obtained with Google Earth Pro Google, 2022).

Figure D24 Aerial imagery map displaying sand coverage of Northeast Point beach in Shelburne, Nova Scotia, 1:3,000. Pre-Dorian photo: Pre-Dorian photo: August 30, 2019; post-Dorian photo: May 10, 2020. There was an expansion of sand area within one-year following Hurricane Dorian from storm surge waves. Imagery was obtained with Google Earth Pro (Google, 2022).

Figure D25 Aerial imagery map displaying sand coverage of Sand Hills beach and provincial park in Shelburne, Nova Scotia, 1:3,000. Pre-Dorian photo: August 6, 2019; post-Dorian photo: May 10, 2020. There was a shifting of sand to create a sandbar within one-year following Hurricane Dorian from storm surge waves. Imagery was obtained with Google Earth Pro (Google, 2022).

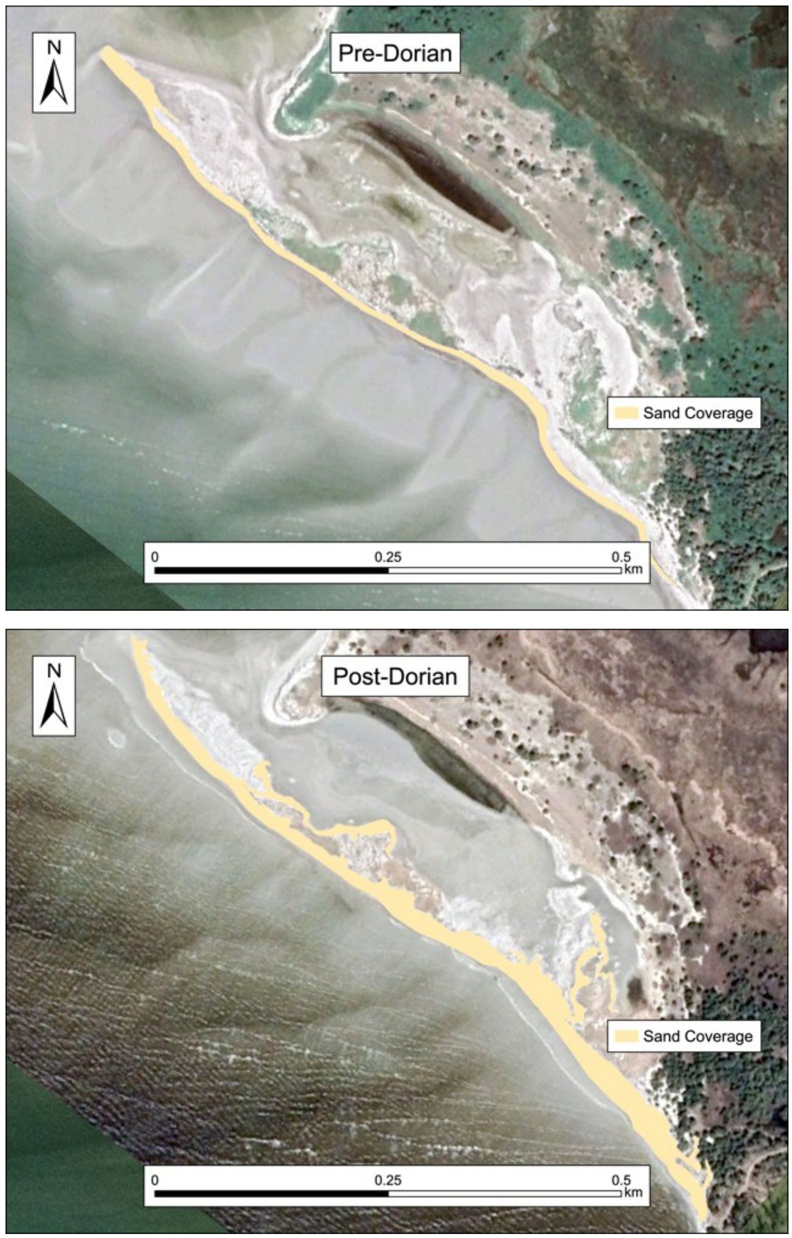


Figure D26 Aerial imagery map displaying sand coverage of Stoney Island beach in Shelburne County, Nova Scotia, 1:10,000. Pre-Dorian photo: August 9, 2019; post-Dorian photo: May 10, 2020. There was a decrease in sand area after Hurricane Dorian. Imagery was obtained with Google Earth Pro (Google, 2022).

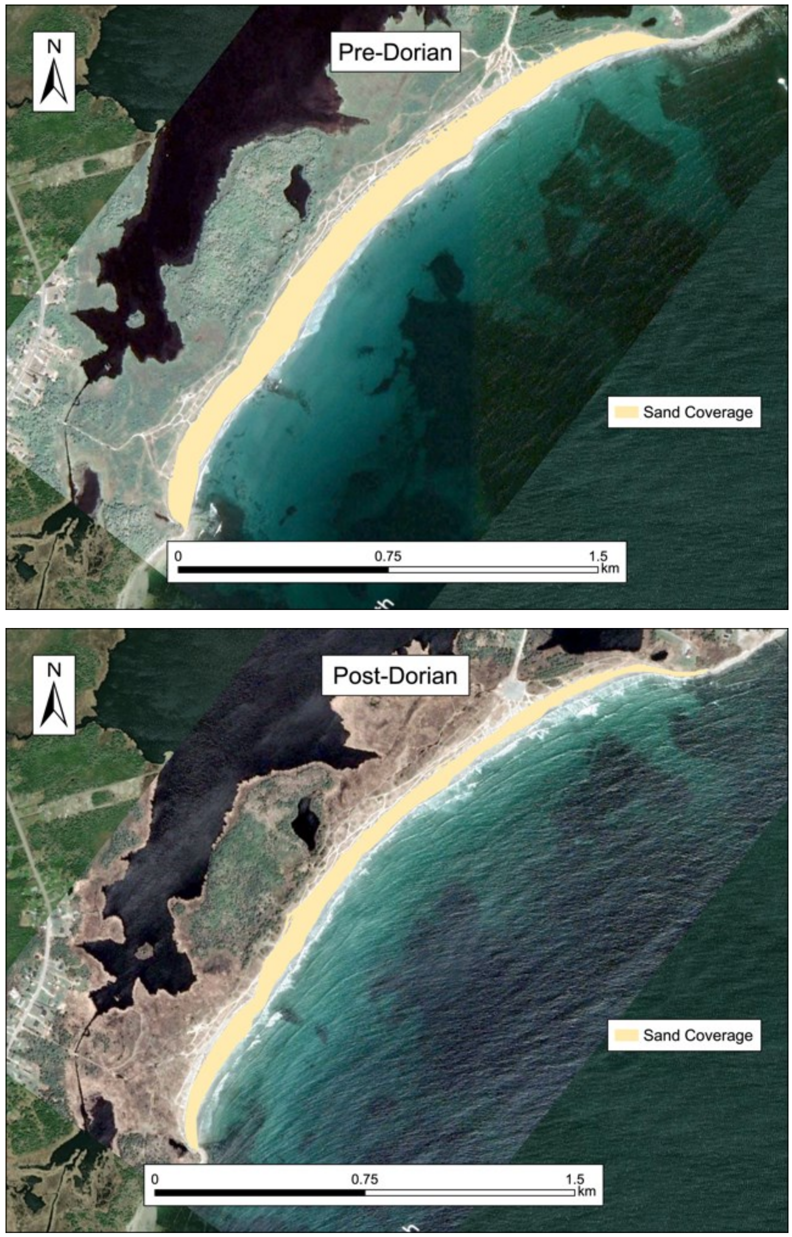
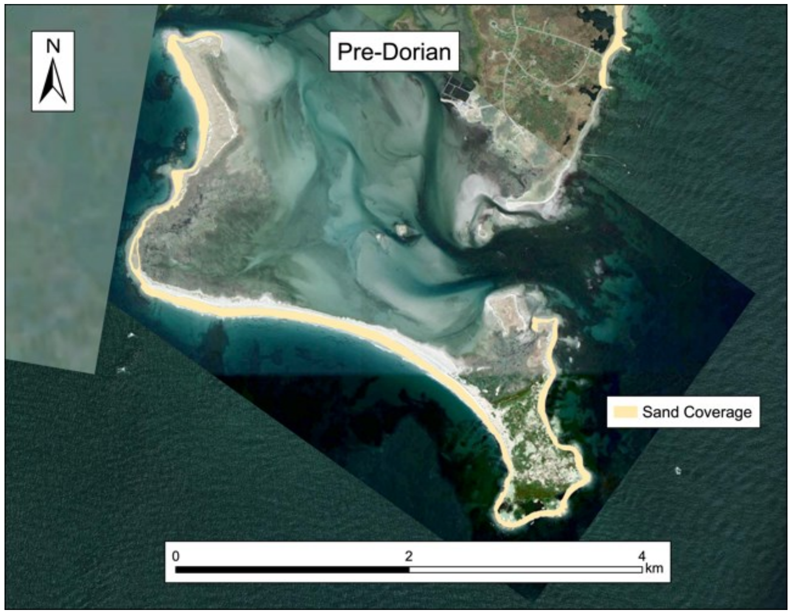


Figure D27 Aerial imagery map displaying sand coverage of The Cape beach in Shelburne, Nova Scotia, 1:24,000. Pre-Dorian photo: August 6, 2019; post-Dorian photo: May 10, 2020. Minimal change in sand coverage was observed between conditions. Imagery was obtained with Google Earth Pro (Google, 2022).



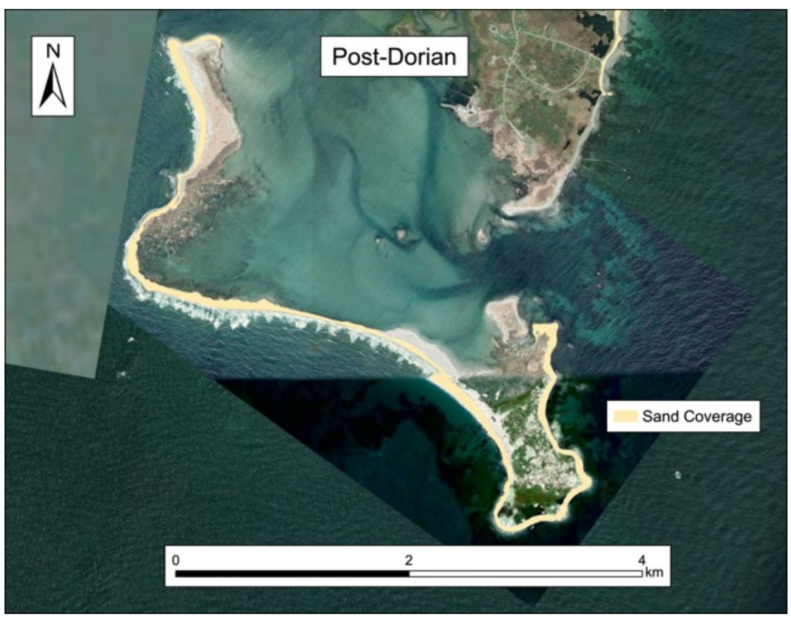
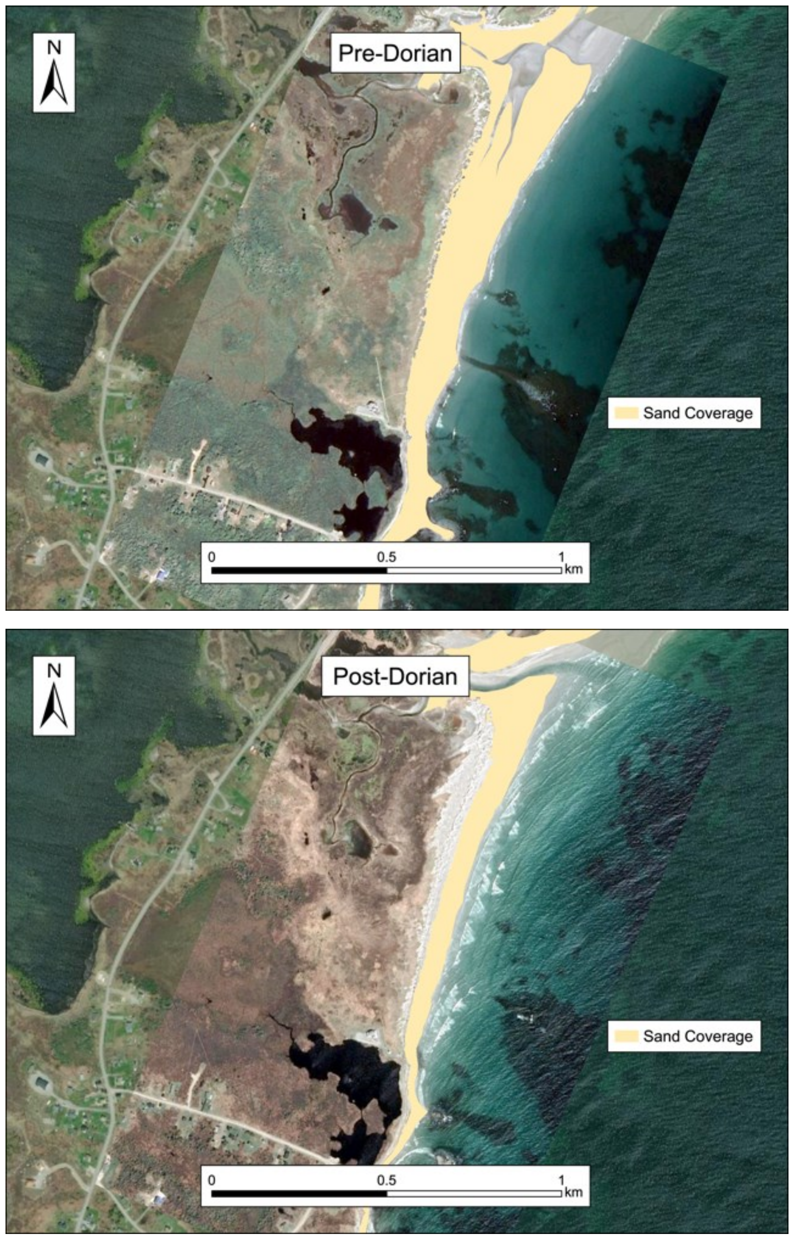


Figure D28 Aerial imagery map displaying sand coverage of The Hawk beach in Shelburne County, Nova Scotia, 1:8,000. Pre-Dorian photo: August 6, 2019; post-Dorian photo: May 10, 2020. There was a decrease in sand coverage in the area preceding the foredune of the backshore where the vegetation begins. Imagery was obtained with Google Earth Pro (Google, 2022).



Appendix E: Sea-level Rise Supplementary Maps

Figure E1 Aerial imagery map displaying sand coverage of Captains Pond and Monks Head beach in Antigonish County, Nova Scotia, 1:12,000. 2011 photo: June 22, 2011; 2020 photo: September 4, 2020. Minimal change in sand coverage was observed between conditions. Imagery was obtained with Google Earth Pro and ESRI World Imagery Wayback (Google, 2022; ESRI, 2021b).

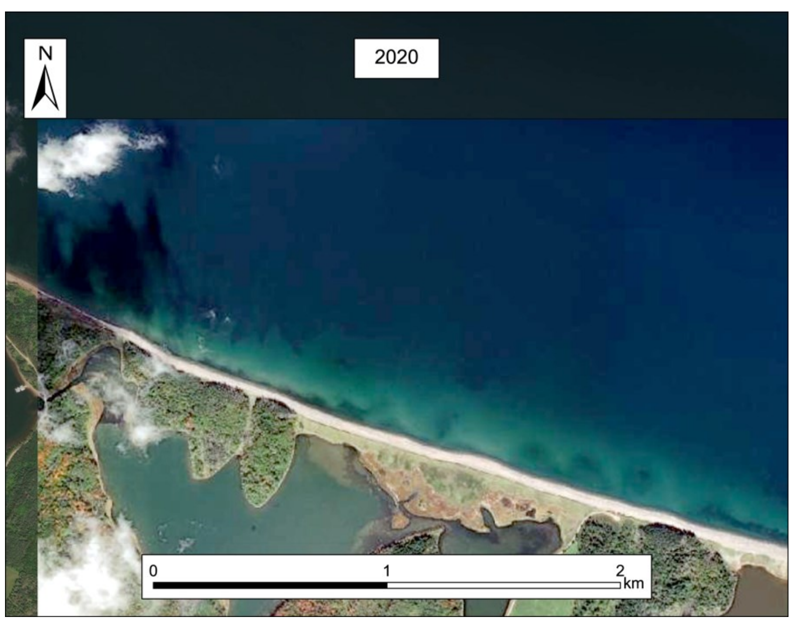


Figure E2 Aerial imagery map displaying sand coverage of Dunns beach in Antigonish County, Nova Scotia, 1:10,000. 2011 photo: June 22, 2011; 2020 photo: October 1, 2020. Sand was pushed by shifting waves to form a sandbar. Imagery was obtained with Google Earth Pro and ESRI World Imagery Wayback (Google, 2022; ESRI, 2021b).

Figure E3 Aerial imagery map displaying sand coverage of Grahams Cove beach in Antigonish County, Nova Scotia, 1:6,000. 2011 photo: June 11, 2011; 2020 photo: October 1, 2020. Sand was shifted slightly to form a sandbar. Imagery was obtained with Google Earth Pro and ESRI World Imagery Wayback (Google, 2022; ESRI, 2021b).

Figure E4 Aerial imagery map displaying sand coverage of Mahoneys beach in Antigonish County, Nova Scotia, 1:8,750. 2011 photo: June 22, 2011; 2020 photo: September 4, 2020. Sand decreased in area between conditions. Imagery was obtained with Google Earth Pro and ESRI World Imagery Wayback (Google, 2022; ESRI, 2021b).

Figure E5 Aerial imagery map displaying sand coverage of Pomquet beach and provincial park in Antigonish County, Nova Scotia, 1:16,000. 2011 photo: June 22, 2011; 2020 photo: October 1, 2020. Slight decrease in sand area was observed between conditions. Imagery was obtained with Google Earth Pro and ESRI World Imagery Wayback (Google, 2022; ESRI, 2021b).

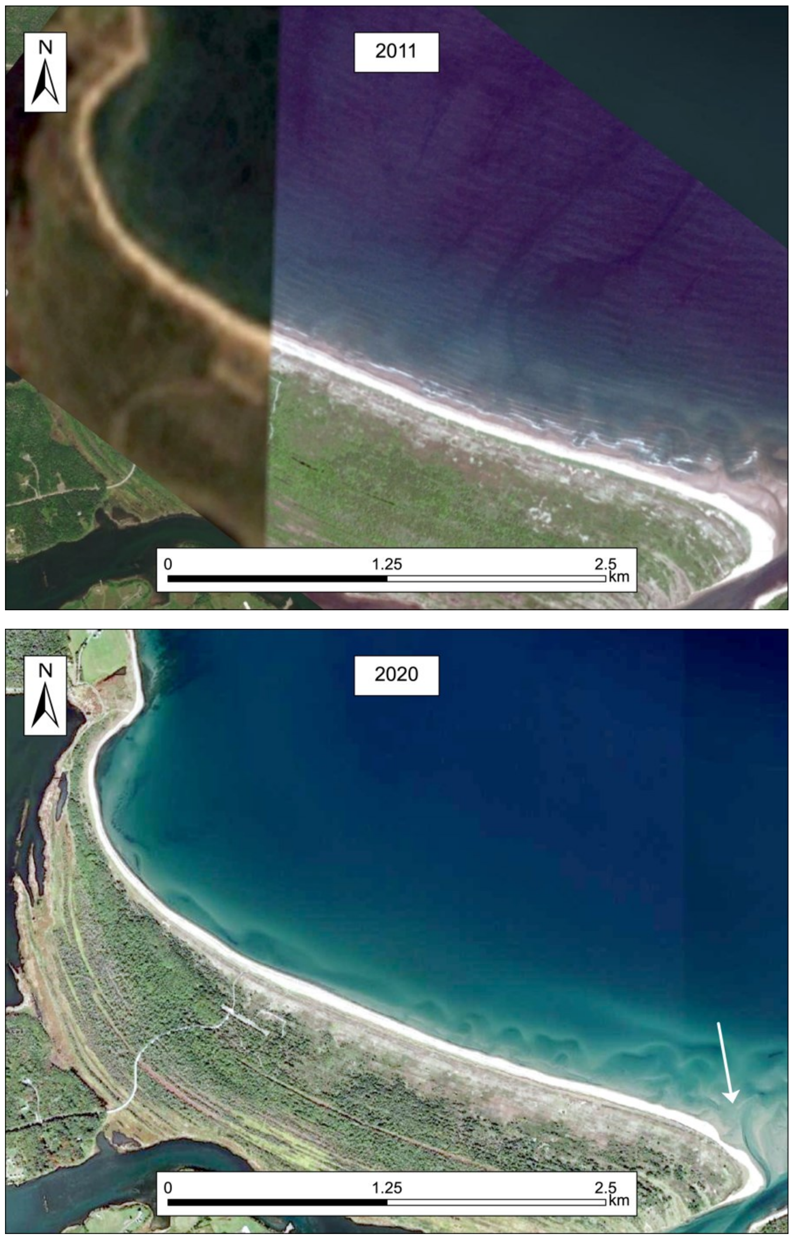


Figure E6 Aerial imagery map displaying sand coverage of Dominion beach and provincial park in Cape Breton Regional Municipality, Nova Scotia, 1:12,000. 2011 photo: April 15, 2011; 2020 photo: July 24, 2020. Minimal change in sand coverage was observed between conditions. Boardwalk intersects with the majority of beach area. Imagery was obtained with Google Earth Pro (Google, 2022).

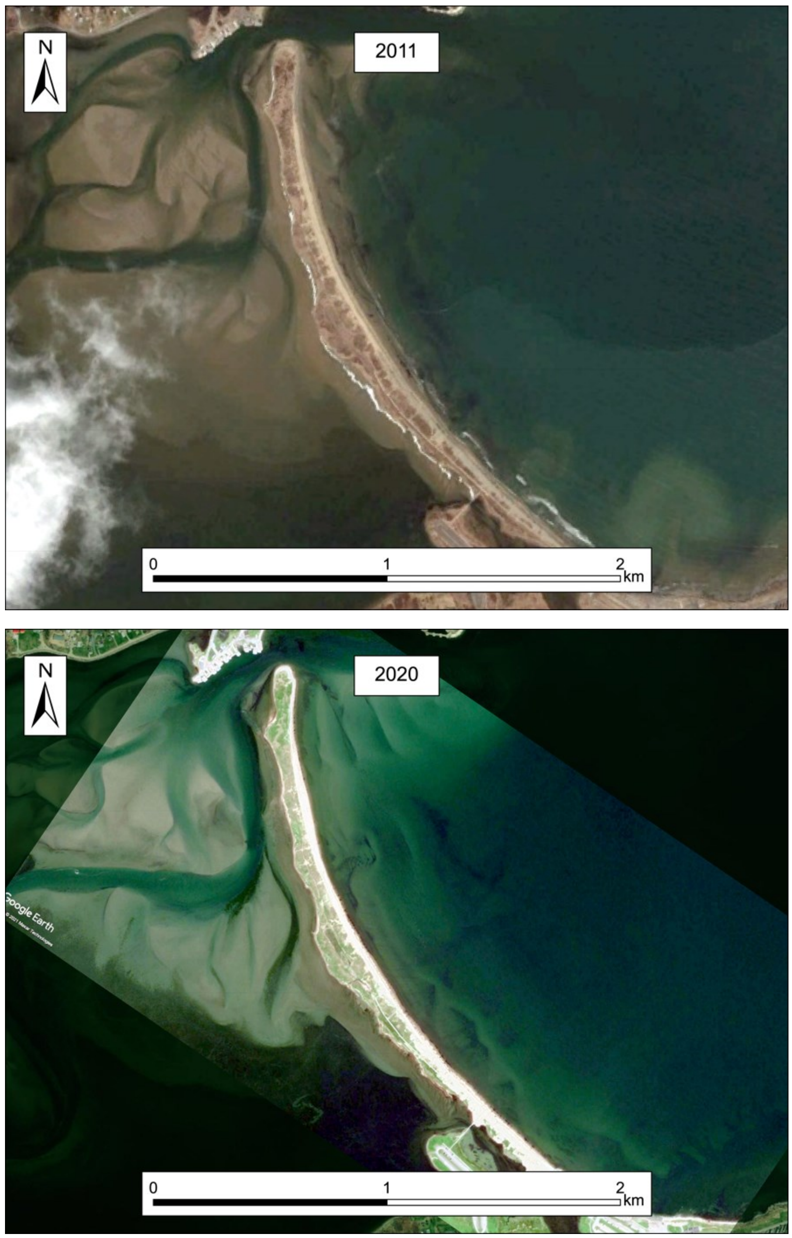


Figure E7 Aerial imagery map displaying sand coverage of Big Glace Bay Bar beach and national wildlife area in Cape Breton Regional Municipality, Nova Scotia, 1:10,000. 2011 photo: April 12, 2011; 2020 photo: July 24, 2020. Sand area increased between conditions in the tidal marsh. Imagery was obtained with Google Earth Pro (Google, 2022).

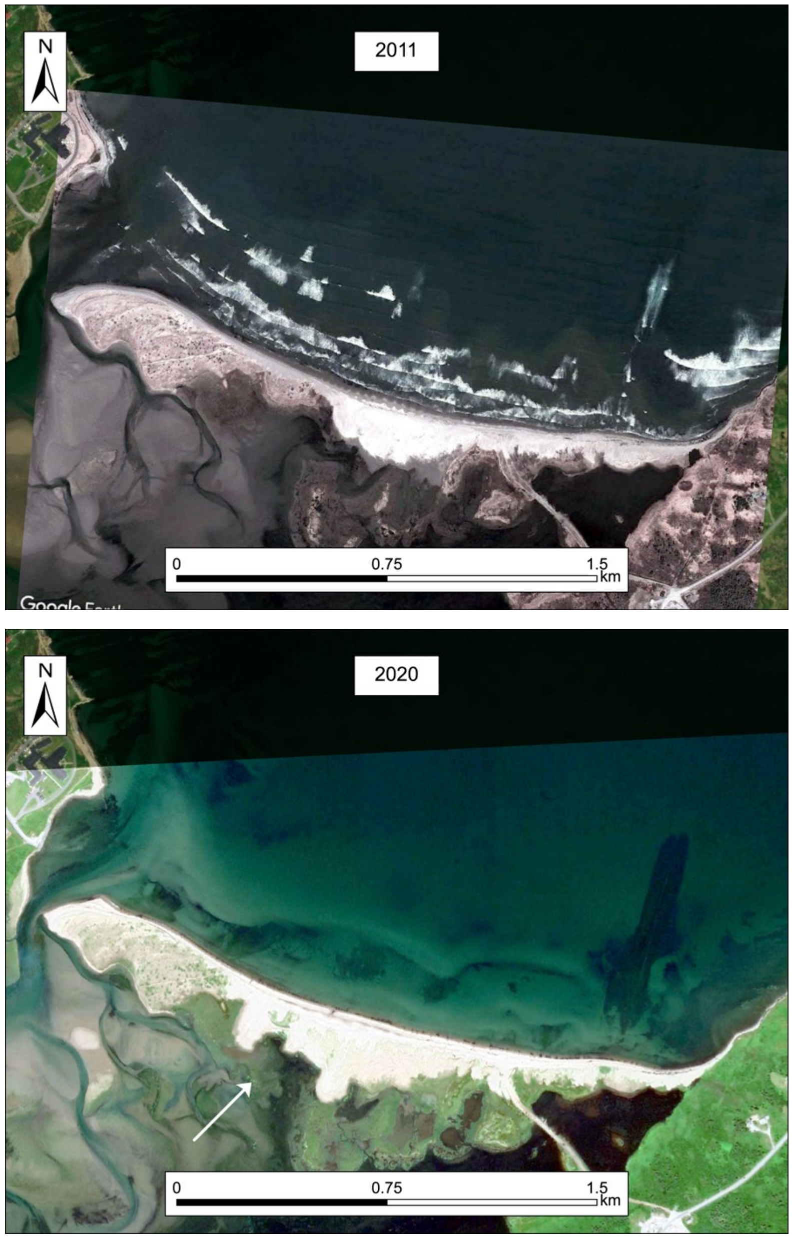


Figure E8 Aerial imagery map displaying sand coverage of Conrads East-West beach in Halifax Regional Municipality, Nova Scotia, 1:10,000. 2011 photo: July 9, 2011; 2020 photo: April 18, 2020. There was a shifting of sand to expand the sandbar connecting to an offshore island. Imagery was obtained with Google Earth Pro (Google, 2022).

Figure E9 Aerial imagery map displaying sand coverage of Rainbow Haven beach and provincial park in Halifax Regional Municipality, Nova Scotia, 1:12,000. 2011 photo: July 9, 2011; 2020 photo: April 18, 2020. Expansion in sand area was observed. Imagery was obtained with Google Earth Pro (Google, 2022).

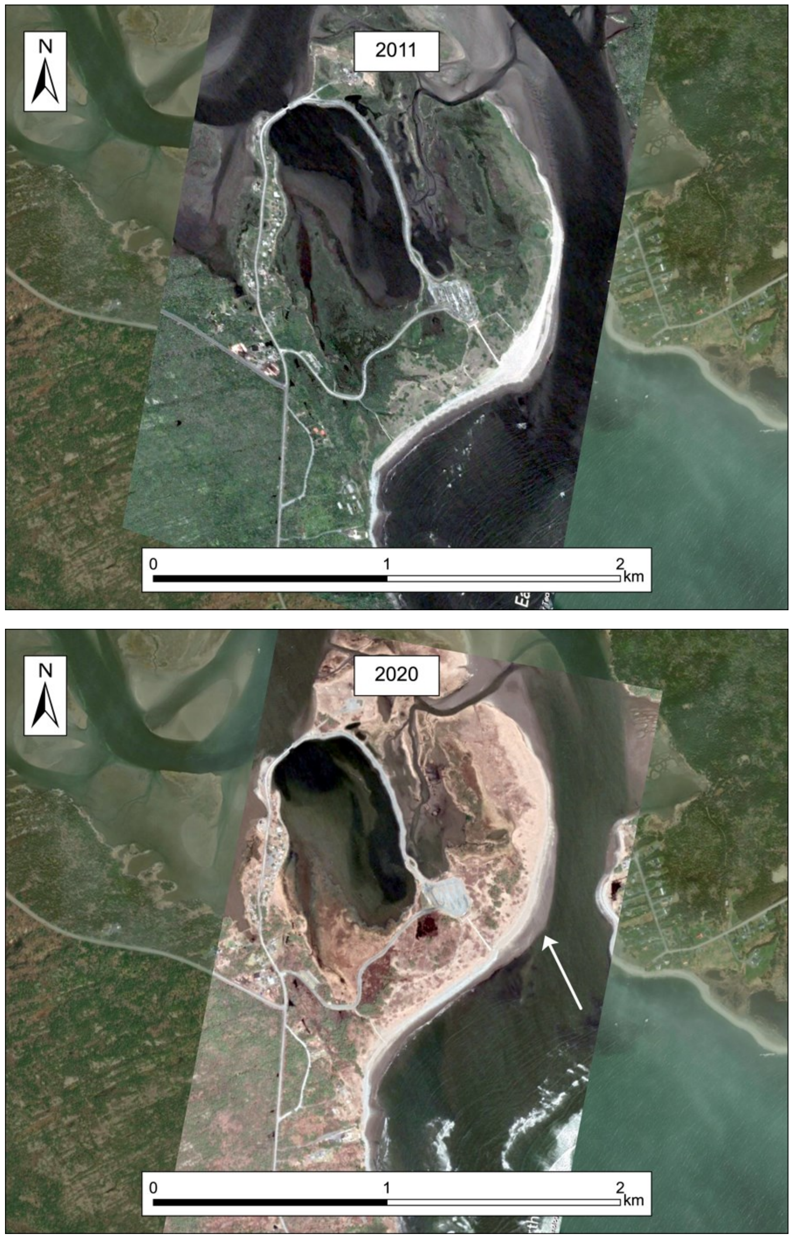


Figure E10 Aerial imagery map displaying sand coverage of Stoney (Lawrencetown) Beach in Halifax Regional Municipality, Nova Scotia, 1:5,000. 2011 photo: July 9, 2011; 2020 photo: April 18, 2020. Expansion of sand area occurred between conditions. Imagery was obtained with Google Earth Pro (Google, 2022).

Figure E11 Aerial imagery map displaying sand coverage of Cape Bay, LaHave Island in Lunenburg County, Nova Scotia, 1:6,000. 2019 photo: April 30, 2011; 2020 photo: September 18, 2020. There was a slight increase in sand area between conditions. Imagery was obtained with Google Earth Pro (Google, 2022).

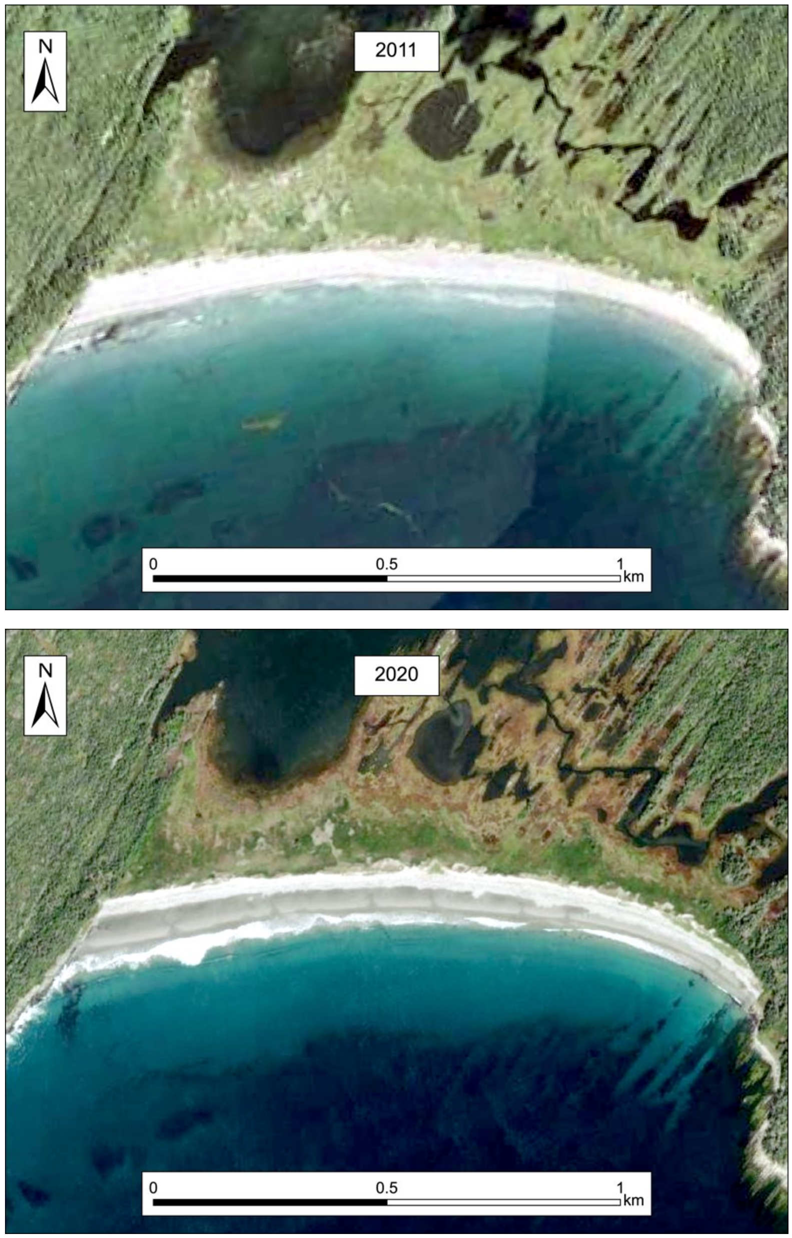


Figure E12 Aerial imagery map displaying sand coverage of Daniels Head (Southside) beach in Shelburne County, Nova Scotia, 1:12,000. 2011 photo: April 30, 2011; 2020 photo: May 10, 2020. A slight increase of sand occurred. In 2020, ATV trails and desired paths became more evident in the dunes. Imagery was obtained with Google Earth Pro (Google, 2022).

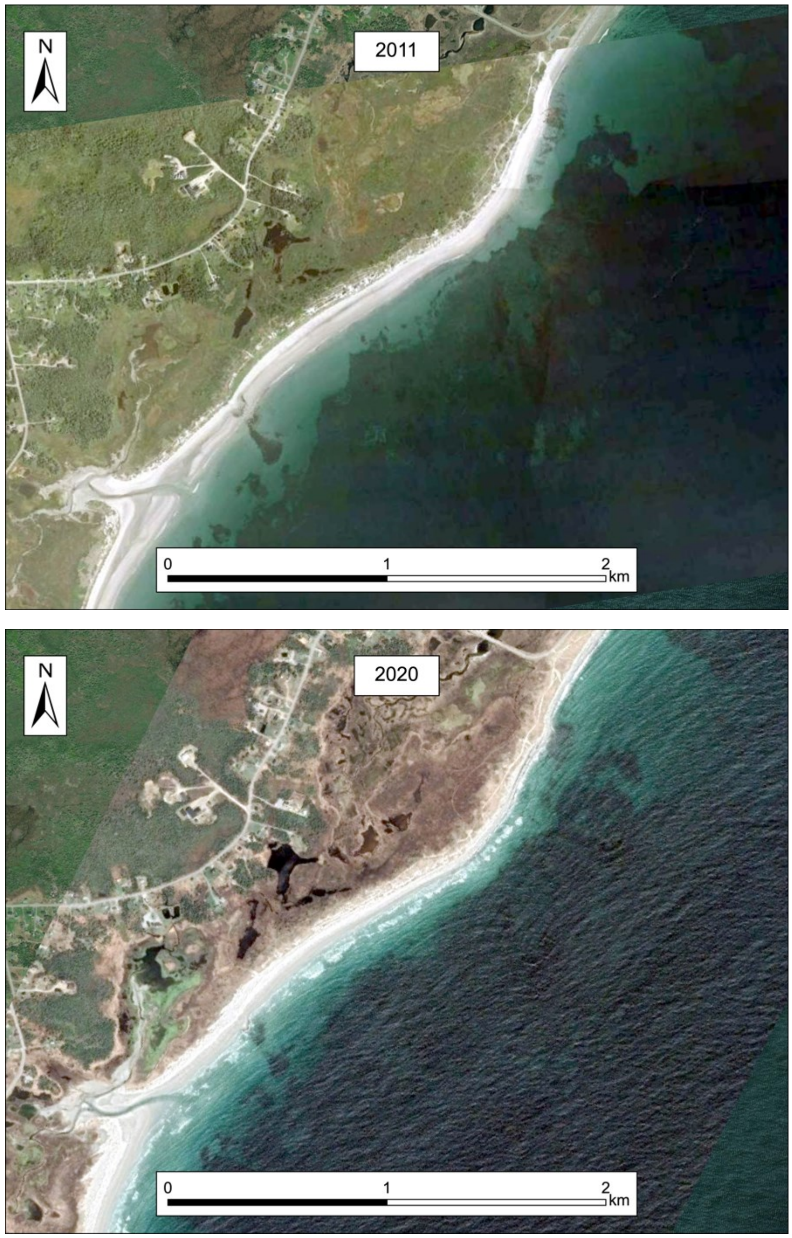
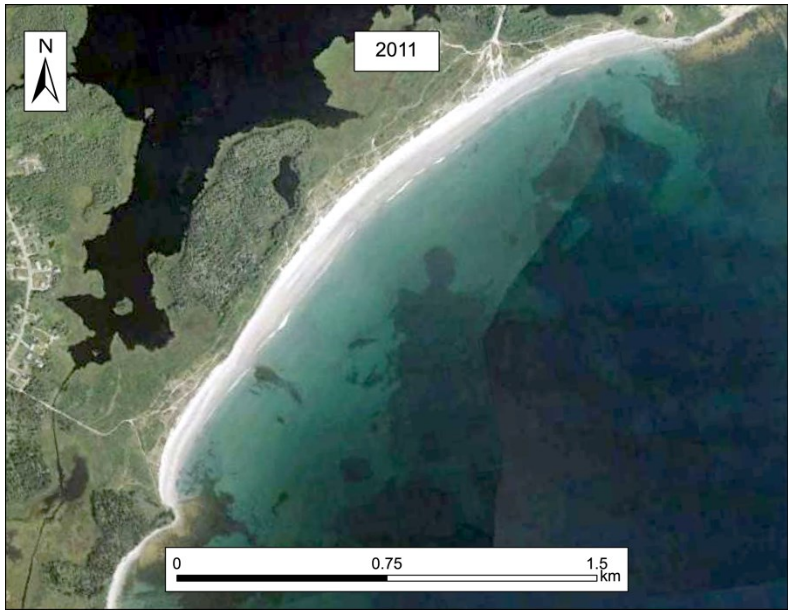


Figure E13 Aerial imagery map displaying sand coverage of Northeast Point beach in Shelburne, Nova Scotia, 1:3,000. 2011 photo: April 30, 2011; 2020 photo: May 10, 2020. A slight decrease in sand area occurred between conditions and structure was altered by wave action. Imagery was obtained with Google Earth Pro (Google, 2022).

Figure E14 Aerial imagery map displaying sand coverage of Sand Hills beach and provincial park in Shelburne, Nova Scotia, 1:3,000. 2011 photo: April 30, 2011; 2020 photo: May 10, 2020. Decrease in sand area occurred between conditions, and a breach occurred sometime between 2011 and 2020, separating the sand bar. Imagery was obtained with Google Earth Pro (Google, 2022).

Figure E15 Aerial imagery map displaying sand coverage of Stoney Island beach in Shelburne County, Nova Scotia, 1:10,000. 2011 photo: April 30, 2011; 2020 photo: May 10, 2020. Sand area decreased between conditions, and ATV trails appear more pronounced in 2020 than in 2011. Imagery was obtained with Google Earth Pro (Google, 2022).



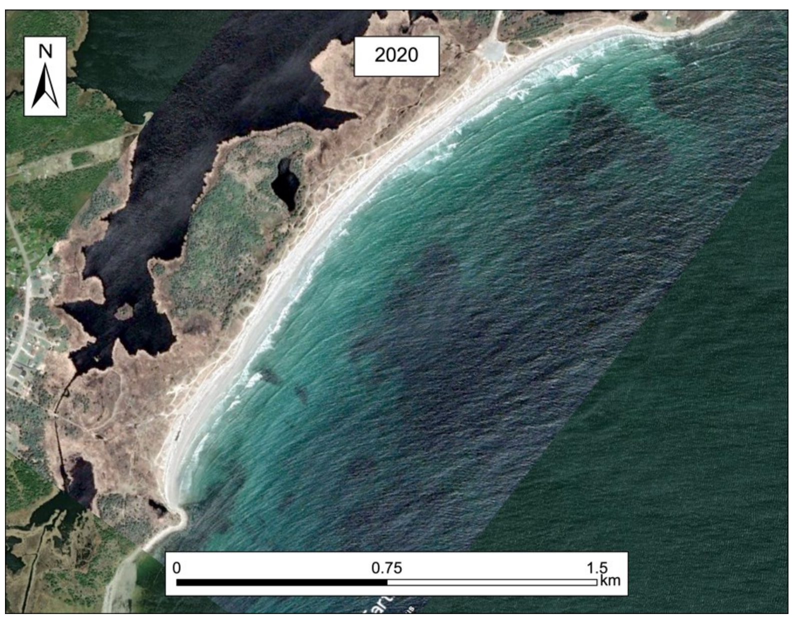


Figure E16 Aerial imagery map displaying sand coverage of The Cape beach in Shelburne, Nova Scotia, 1:24,000. 2011 photo: April 30, 2011; 2020 photo: May 10, 2020. Minimal decrease in sand coverage was observed between conditions, and the beach was narrower in 2020 than in 2011. Imagery was obtained with Google Earth Pro (Google, 2022).

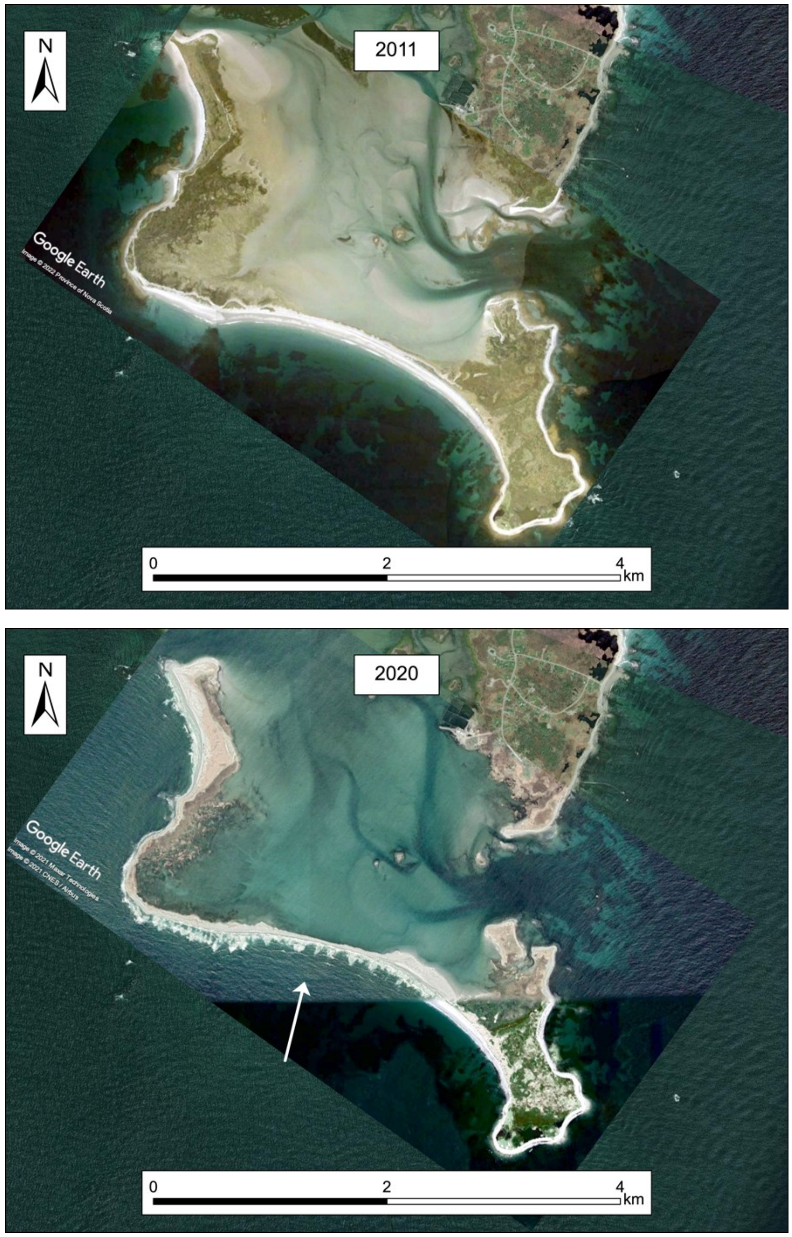


Figure E17 Aerial imagery map displaying sand coverage of The Hawk beach in Shelburne County, Nova Scotia, 1:8,000. 2011 photo: April 30, 2011; 2020 photo: May 10, 2020. Decrease in sand coverage occurred between conditions. River separating the beach widened sometime between 2011 and 2020. Imagery was obtained with Google Earth Pro (Google, 2022).