water

MDPI

Article

Highwater Mark Collection after Post Tropical Storm Dorian and Implications for Prince Edward Island, Canada

Donald E. Jardine [1,*], Xiuquan Wang [2,3,*] and Adam L. Fenech [1,2,3]

1 Climate Research Lab, University of Prince Edward Island, Charlottetown, PE C1A 0P3, Canada; afenech@upei.ca
2 Canadian Centre for Climate Change and Adaptation, University of Prince Edward Island, Charlottetown, PE C0A 2A0, Canada
3 School of Climate Change and Adaptation, University of Prince Edward Island, Charlottetown, PE C0A 2A0, Canada
* Correspondence: dejardine@upei.ca (D.E.J.); xxwang@upei.ca (X.W.)

Abstract: Prince Edward Island (PEI), Canada has been experiencing the consequences of a rising sea level and intense storms on its coasts in recent years. The most recent severe event, Post Tropical Storm Dorian (Dorian), began impacting Prince Edward Island on 7 September 2019 and lasted for over 20 h until the morning of 8 September 2019. The measurement of highwater marks (HWM) from the storm was conducted between 25 September and 25 October 2019 using a high precision, survey grade methodology. The HWM measured included vegetation lines, wrack lines, beach, cliff, and dune morphological features, and tide gauge data at 53 locations in the Province along coastal areas that are exposed to high tides, storm surge, high winds, and wave runup. Photos were taken to provide evidence on the nature of the HWM data locations. The data reveal that Dorian caused extensive coastal floods in many areas along the North and South Coast of Prince, Queens and Western Kings Counties of Prince Edward Island. The floods reached elevations in excess of 3.4 m at some locations, posing threats to local infrastructure and causing damage to natural features such as sand dunes in these areas. The HWM data can provide useful information for community and emergency response organizations as plans are developed to cope with the rising sea level and increased frequency of highwater events as predicted by researchers. As Dorian has caused significant damage in several coastal areas in PEI, better planning using an enhanced storm forecasting and coastal flood warning system, in conjunction with flood stage values, could possibly have reduced the impacts of the storm in the impacted areas. This could help enhance public understanding of the potential impacts in local areas and how they can prepare and adapt for these events in the future.

Keywords: Dorian; Prince Edward Island; high water marks; storm surge; flooding; wave run-up

Citation: Jardine, D.E.; Wang, X.; Fenech, A.L. Highwater Mark Collection after Post Tropical Storm Dorian and Implications for Prince Edward Island, Canada. *Water* **2021**, *13*, 3201. https://doi.org/10.3390/w13223201

Academic Editor: Francisco Javier Gracia Prieto

Received: 20 August 2021
Accepted: 6 November 2021
Published: 12 November 2021

1. Introduction

Prince Edward Island is located on the Atlantic Coast of Canada in the Gulf of the St. Lawrence River as shown on Figure 1. The Canadian province has 3300 km of coastline that is exposed to coastal surges, and the sedimentary bedrock and glacial surficial deposits make it very vulnerable to coastal processes [1].

Hurricane Dorian (see Figure 2), a storm originating in the south-central Atlantic Ocean near the Lesser Antilles, started tracking toward North America as a category 5 Hurricane when it hit the Bahamas as the most powerful tropical cyclone on record to ever strike. As one of the most powerful hurricanes recorded in the Atlantic Ocean with 1 min sustained winds peaking at 295 km/h (185 mph), Hurricane Dorian's resultant damage was catastrophic, flattening most structures or sweeping them to sea, causing 70 fatalities and leaving at least 70,000 people homeless. Hurricane Dorian slowly made its way from the Bahamas, along the eastern seaboard of the USA, and made landfall in Nova Scotia at suppertime on 7 September, being reclassified from a category 2 Hurricane to a post tropical storm. Dorian continued to track in a north-easterly direction across Nova Scotia and brushed the eastern part of Kings County, PEI before making its way to the Magdalene Islands and eventually Newfoundland and Labrador.

Figure 1. Prince Edward Island Location. (PEI Government Map).

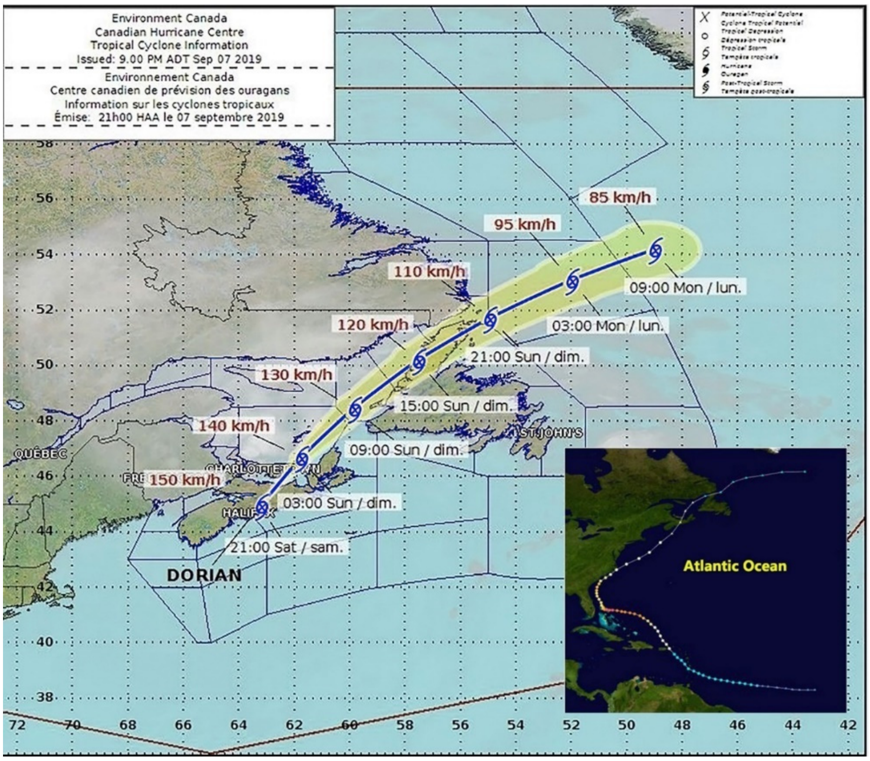

Figure 2. Path of Hurricane Dorian in Atlantic Canada provided by Environment Canada with NASA Inset Map of Storm Track.

Previous studies by Webster et al. [2] and US Army Corps [3] describe the value of having highwater mark (HWM) data for some areas in Province of Prince Edward Island (PEI) which are not near a tide gauge. These studies suggest that individual storms can cause major coastal damage in areas most exposed to the wind, wave and water conditions which develop during storms. It is important to collect accurate data after storms such as Dorian, as they can provide supplementary data to time series data provided by tide gauges. Conventional tide gauges only measure "still water level" information and do not reflect the full impacts caused by storm waves, which rise above still water levels and reach areas of higher elevation than shown by a tide gauge record. In PEI, there has been a tide gauge at Charlottetown since 1911 with some periodic tide level data from other locations. As shown in Figure 3, the Charlottetown tide gauge station shows a 36 cm rise in sea level since 1911. Figure 4 reveals the most pronounced rate of rise in average decadal sea level is in the most recent decade (2010s). The rate of sea level rise is expected to increase in the coming decades and needs to be considered when planning for future storm events.

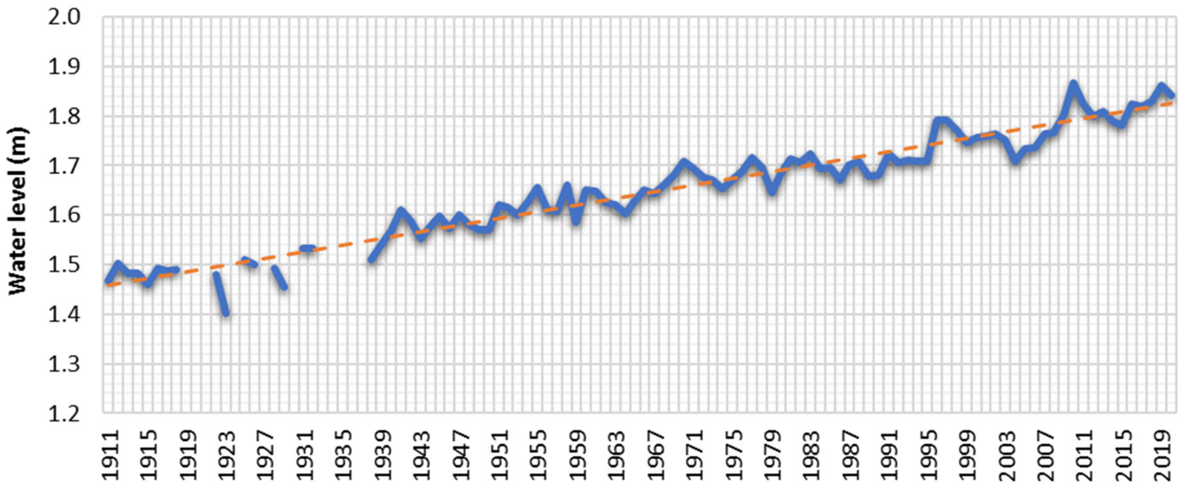

Figure 3. Sea level rise at Charlottetown, PEI from 1911 to 2019.

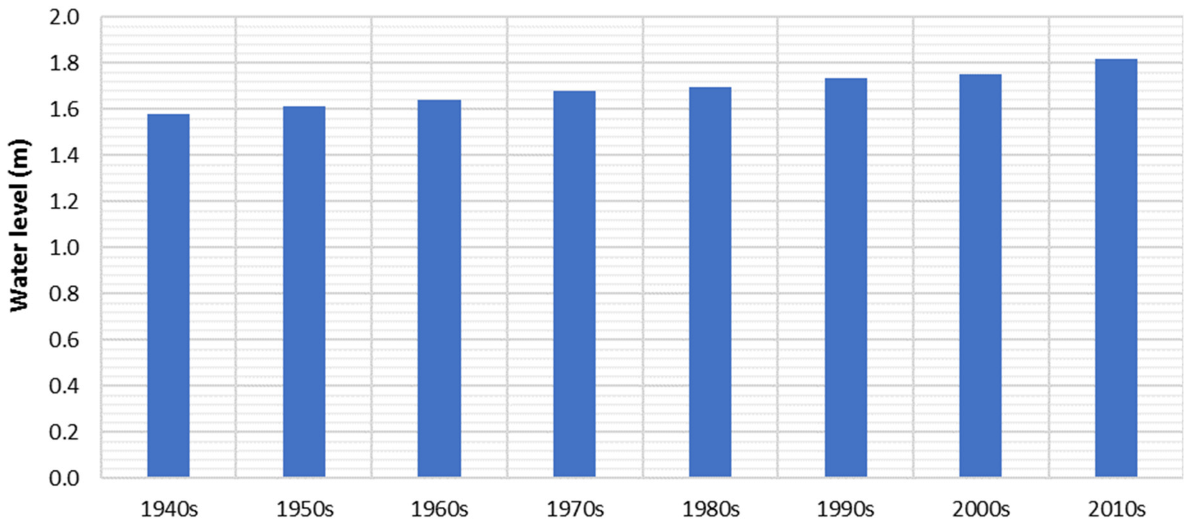

Figure 4. Average decadal sea level at Charlottetown, PEI.

Beginning in late 2018, the PEI Emergency Measures Organization sponsored the installation of four additional tide level monitoring locations including Tignish, Summerside, North Lake, and Souris. The Kensington North Watershed Group and the University of Prince Edward Island (UPEI) Climate Research Lab installed a tide gauge at Lower Darnley Wharf in late 2015. These gauges provide wider coverage of sea levels around the coast including three locations on the Gulf of St. Lawrence Coast of the Province.

Ascertaining high precision vertical watermarks provides useful information for community planning, design of coastal structures, and development of appropriate emergency response plans. As stated in Webster [2], the HWM measurements can be useful for:

(1) identification of high-risk areas, (2) development of return periods and probabilities of exceedance of future storm events, (3) providing documentation for an inventory of coastal vulnerability, and (4) production of inundation maps using tools such as CLIVE to enable visualization of the extent of previous and future climate change events [4]. Another study in the Chaleur Bay area of Eastern Quebec found that flood hazard assessment needs to include procurement of in situ HWM data to enable accurate planning for proper flood hazard assessment [5]. Most importantly, field data must be ascertained in a timely manner after the storm event to ensure accuracy for provision of high-quality information for risk management and policy decision making and planning [6]. Therefore, the objective of this study is to collect the most accurate measurements of HWMs across PEI through field visits and investigations right after Dorian. The collected dataset can help enhance public understanding of the potential impacts in local areas and how they can prepare and adapt for similar storm events in the future. It can also provide useful information for community and emergency response organizations to develop effective plans in order to cope with the rising sea level and increased frequency of highwater events in the context of climate change.

The data collected during this study can be used for numerical model validations for future storm events and to assist with planning responses to future events. It is very useful in areas where real-time monitoring records are not available so that areas where dangerous flooding and washouts might occur can be identified. Documentation of peak water levels attained during flooding events is important for historical purposes and for planning future development in flood prone areas. [7]. The methodology requires collection of the highwater mark data immediately after an event to ensure these marks are not altered or destroyed by anthropogenic activities or wave action. The relative low cost of procuring these measurements makes them very feasible for assessing coastal hazards from storms.

This extreme climate event was selected due to the presence of five processes that can alter water level [8]. when a storm is passing through an area, including: (1) the effect of barometric pressure, (2) the effect of direct winds, (3) the effect of the earth's rotation, (4) the effect of waves, and (5) the effect of heavy rainfall.

These effects were all present during the Dorian event, with wind gusts of up to 146 km/h and rainfall amounts of 138 mm reported [9]. The barometric pressure dropped to a low of 962 mbar on 7 September 2019 at 22 h at Charlottetown Airport from a high of 1014 mbar just 24 h earlier. This was the lowest pressure measured at any meteorological station in the province during the storm.

According to Lefaivre and Tesier, [10] of the Federal Department of Fisheries and Ocean Canada (DFO) a low-pressure system in the range of 960 mbar in the Gulf of St. Lawrence is a relatively rare occurrence. This caused a storm surge of 1.6 m over predicted tide in the Magdalene Islands of Quebec (approximately 80 km to the north of Prince Edward Island) due to the sudden drop in atmospheric pressure.

2. Materials and Methods

Field visits were made to the 53 locations (as listed in Appendix A and shown in Figure 5) beginning on 8 September 2019 and the measurement of HWMs for the storm began on 15 September and continued until 25 October 2019. These were established by performing field investigations at all the listed sites, examining the shoreline for evidence of watermarks, and by communication with local individuals who had firsthand knowledge of the maximum water height experienced during the storm.

Watermarks were measured with a Trimble Geo7X survey grade dual frequency receiver connected to a Networked Real Time Kinematic (NRTK) GPS tracking system with integrated 3G cellular modem to enable connection to Cansel's Can-Net Network of base stations to provide real time corrections with vertical accuracies in the 2 to 15 cm range, which is dependent on satellite connections and configuration [11]. Should cell connection be lost, differential correction is applied in the post processing stage. The collected data was then downloaded using Trimble Pathfinder Office correction software. The elevations reported utilize geoid HT2 and are referenced to the Canadian Geodetic Vertical Datum of 1928 (CGVD28) [12].

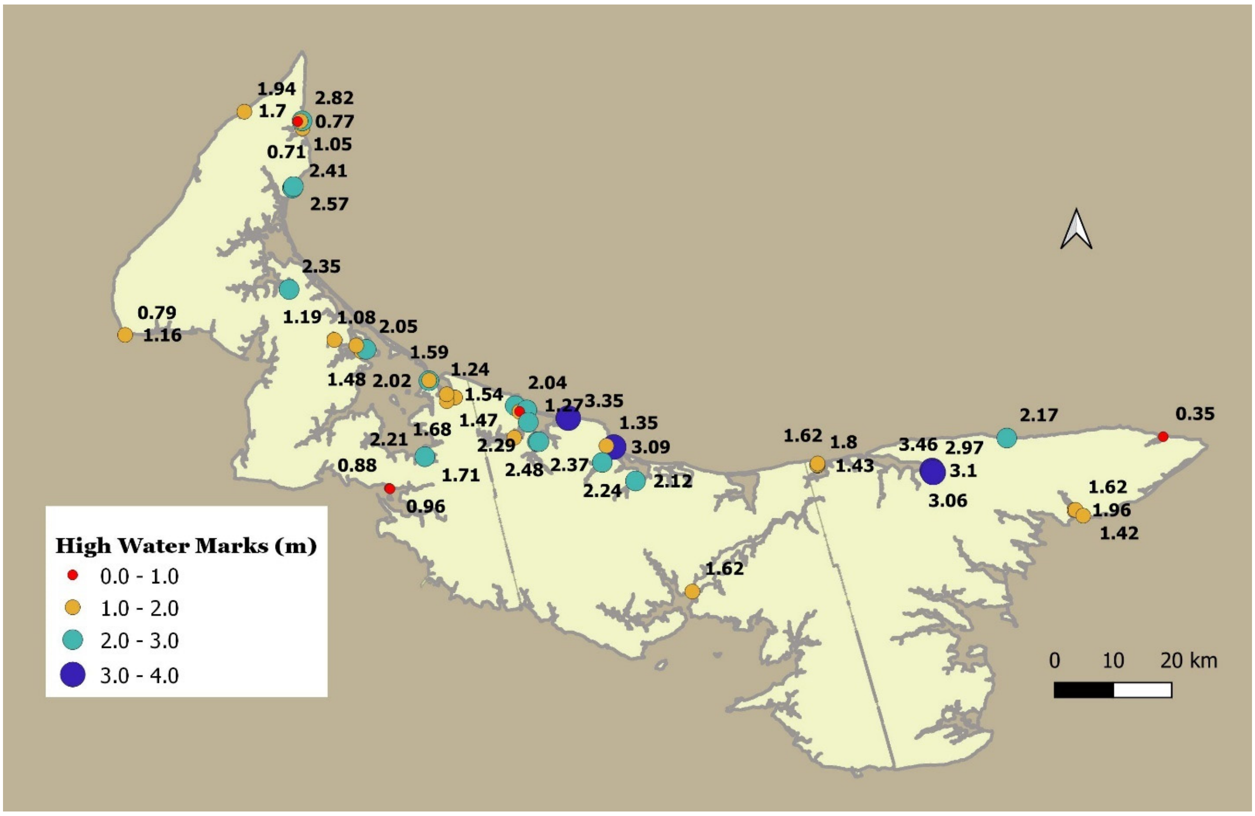

Figure 5. The measured HWMs in PEI after Dorian between 15 September and 25 October 2019.

According to a US Federal Emergency Management Agency (FEMA) report by URS Group Inc. on Hurricane Katrina in 2006, there are several types of flooding when coastal waters are driven inland by waves and high winds. The three basic types of HWM created during coastal flooding events reported in the FEMA report include surge only, wave height, and wave runup. These can have different elevations depending on local conditions such as topography, bathymetry, location of sand dunes or barrier bars, sloped water surface, over wash, or breaching. It is important that these conditions are evaluated properly when measuring HWMs [13].

The surge-only type of flooding occurs only when the area affected is protected from wave action. During Dorian, some of these areas were identified on PEI, such as the inner harbor area in North Rustico. In some locations, a strong onshore wind can force water inland up estuaries causing flooding of low-lying lands including marshes and other wetlands, where wave action is not a factor.

In wave-height type of flooding, the crest of waves may ride on the top of the surge, thus impacting areas higher than reported in a stilling well at a tide gauge location. Near-shore wave heights can impact elevations of a few meters above sea level. If there is a building in the path of storm waves, an HWM can be identified on the outside of the structure, as shown in Figure 6.

The wave-runup type of water mark is caused by wave action runup from a surf zone on the beach slope. As the wave breaks on the top of the surf zone, the energy of the wave resulting in the wave being carried up the slope of the beach, as shown on the left side of Figure 6. This will often result in a wrack line or vegetation line at the highest reach of the water from the wave runup. According to Liu et al., 2014 [14], the vegetation line may appear in two positions: a dense inland vegetation and the other a sparse vegetation lying on the back shore.

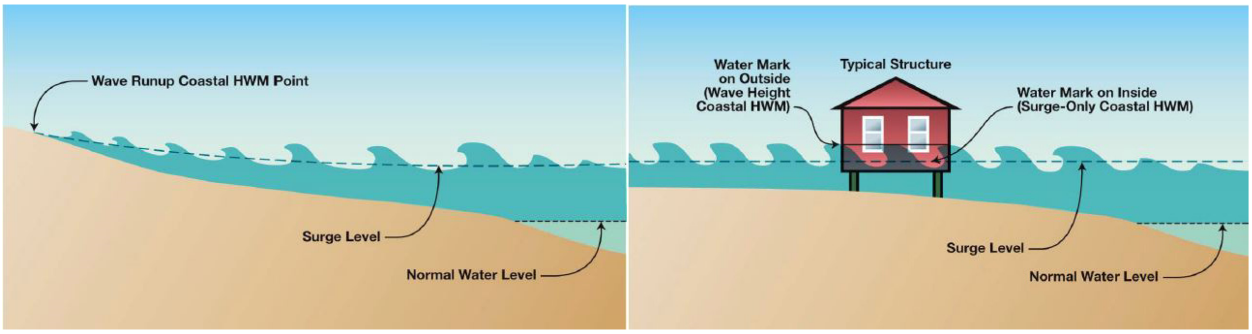

Figure 6. Types of high-water events (URS Group, 2006).

Sand dunes can be impacted by coastal flooding events during storms. Waves can flow across the beach and flow through gaps on the dunes or overtop the dunes leaving surge water on the inner side of the dune when the tide goes down. Hurricanes and tropical storms can cause changes to the shape of dunes and other natural features due to erosion. When this occurs, the level of coastal protection can be significantly jeopardized and result in inland inundation and flooding. During Dorian, several dunes were impacted resulting in sand being transported to areas, such as the parking lot at the Tignish Coop where over 600 m^3 of sand was deposited on a paved parking lot.

3. Results and Discussion

The locations visited during this study revealed that a variety of highwater events occurred during Dorian, as shown on Figure 6. In some cases, it is difficult to distinguish between wave height and wave runup events, and it is suspected, in some cases such as the Cavendish Beach dune, that both were factors. The surge only events were easier to identify due to these sites not being exposed to direct wave action impacts. As expected, the peak water levels observed in the stilling wells at the five tide gauge locations were the lowest of the investigated sites. This confirms that stilling well water levels do not accurately reflect the areas that are impacted during a high-water event during a sub-tropical storm such as Dorian. The stilling well at Tignish recorded a peak water level of 1.05 m whereas areas exposed to wave action such as the north side of the dune at Tignish revealed a peak water mark at 2.82 m, which was 2.5 times higher than reported by the tide gauge. This is an important consideration in the preparation and planning for similar events.

Figure 7 provides the locations of some of the key impact areas from the storm surge from Dorian. The Cavendish Beach Dune site and the St. Peter's Bay Bridge site both showed a wave runup in excess of 3.3 m, suggesting that wave heights in these two areas were significant resulting in the HWM reported in Appendix A. There is significant road, bridge, recreational, and trail infrastructure at the St. Peter's location, whereas at Cavendish, a new boardwalk and beach access was slightly damaged, and the sand dunes were severely eroded. An artificial sand dune constructed at West Point near the Lighthouse in June 2019 was completed destroyed by the wave action from the storm and sand was deposited in the nearby Cedar Dunes Campground. The Crystal Beach Campground at Lower New Annan, PEI was severely impacted by the storm surge and wave height, resulting in 20 campers requiring rescue during the peak of the storm and substantial damage to campground infrastructure and trees in the park.

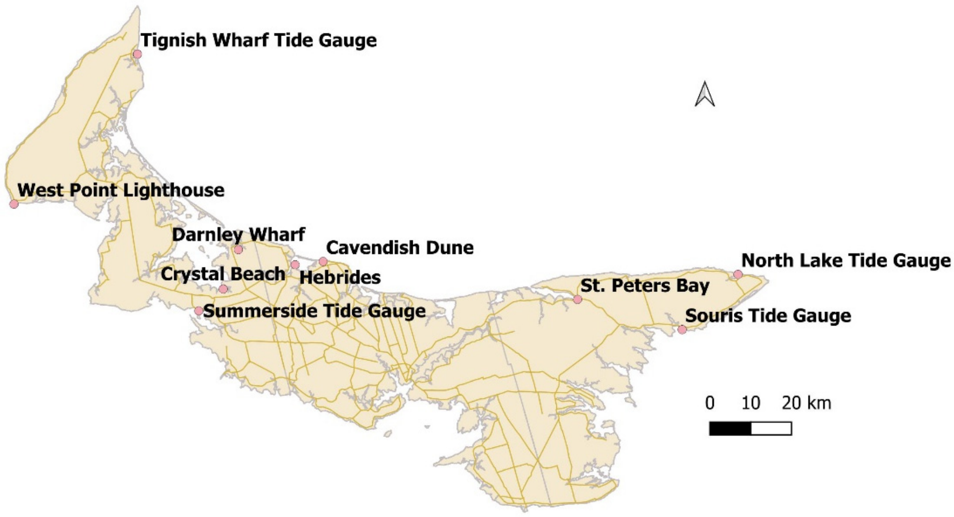

Figure 7. Select Dorian impact locations mentioned in the text.

Comparison of HWM data from Dorian to previous data reported in Webster et al. [15] demonstrates that the reach of the storm waves and wave run-up during Dorian was slightly higher at any comparable site reported from the storm events between 2000 and 2010 listed in the earlier report.

Figure 8 is a photo of storm surge flooding at West Point near the lighthouse at Cedar Dunes Provincial Campground on 9 September 2019, over 24 h after the peak water level occurred. The saline surge water overtopped a low-lying dune and was trapped when the storm waves subsided.

Figure 8. Storm Surge Flooding West Point, PEI.

The tide gauge records at Tignish measured between 6 and 12 September 2019 are shown on Figure 9 and the peak water level was reported at 04:00 on 8 September, which was 1.05 m geodetic. The water height remained above normal tide levels for over 10 h.

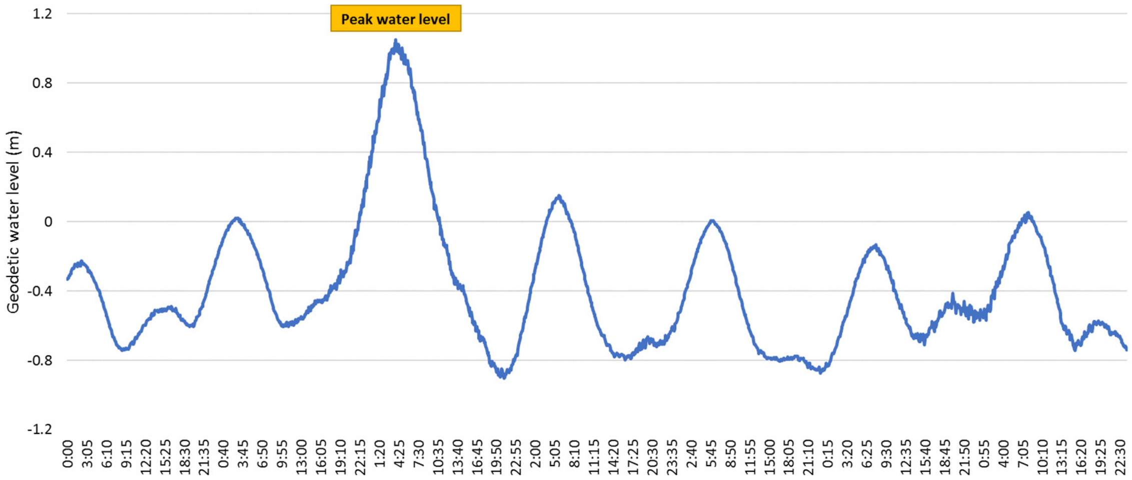

Figure 9. Observed tide gauge water levels in Tignish from 6 to 12 September 2019.

The tide gauge records for Darnley (shown in Figure 10) show a peak water level of 1.68 m geodetic at 00:30 on 8 September, indicating that the peak at this location was reached 3.5 h before Tignish. This figure reveals the extremity of the storm surge, which was experienced during the Dorian event, compared to the six previous months and the subsequent month. According to local observers on the northern coast of the province at French River, Malpeque, Foxley River, and Tignish, this storm exceeded the extreme water level from the most recent high-water event on 21 December 2010.

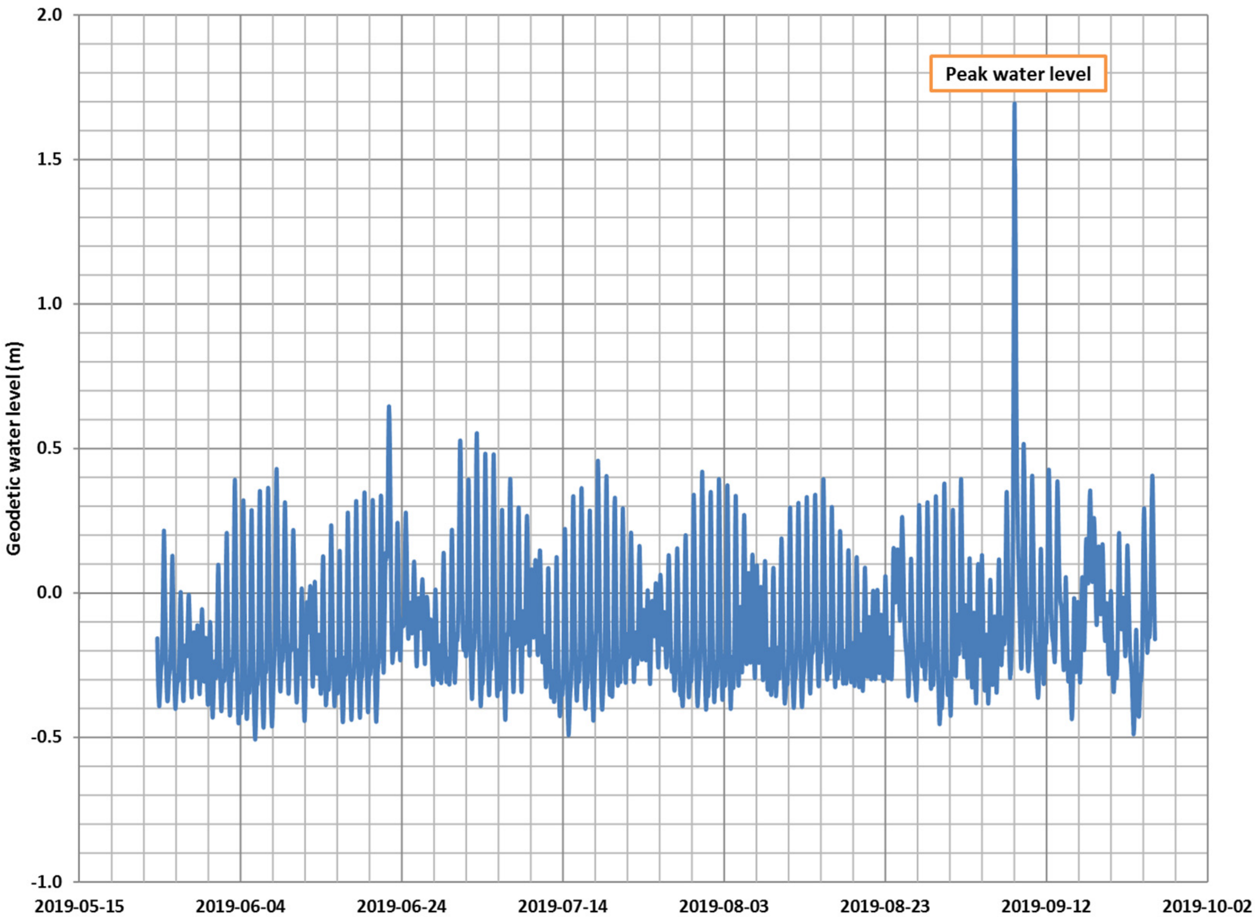

Figure 10. Observed tide gauge water levels in Darnley from 15 May to 2 October 2019.

The storm surge hit the Hebrides subdivision at McEwen's Island, PEI on the night of 7 September and the early morning of 8 September 2019 and did some damage to cottages. The tide rose to a height of 20 cm above the floor of one cottage located on the isthmus to McEwen's Island (see Figure 11) ripping away the front entryway stairs from the frame, carrying it across the small tidal inlet of New London Bay to the opposite southwest shore by the water and waves. Water rose on the trees outside the cottage to a depth of 91 cm with sea moss debris deposited on the trees, as shown in Figure 11.

Figure 11. Seaweed wrack line on trees on MacEwen's Island after Dorian with Inset Map Showing Sea Plant Piles.

There were piles of sea moss and sea plants all along the lower sections of Hebrides Lane and Skye Lane as shown on Figure 11. The geographic location of cottage on the low-lying isthmus to MacEwen's Island is provided in Figure 12. This area is very vulnerable to storm surges during events such as Dorian.

There has been an upward trend in deep cyclone counts in the northern hemisphere between 1958 and 2010 [16], indicating more storm events similar to or more intense than Dorian may occur. Another study by Bender et al. [17] using dynamic models forecasts that the frequency of category 4 and 5 storms will double by the end of the 21st century especially north of latitude 20 N in the Western Atlantic Ocean. Dorian was classified as a category five hurricane when it passed over the Bahamas in early September 2019.

The causeway road to the other part of MacEwen's Island was also flooded during the storm. Figure 13 shows the visual impact of the area inundated by the storm surge which reached 2.17 m geodetic (CGVD28). These visualizations are created using the CLIVE tool developed by Fenech et al. [4].

Figure 12. Provides the Cottage Location on MacEwen's Island in New London Bay, PEI.

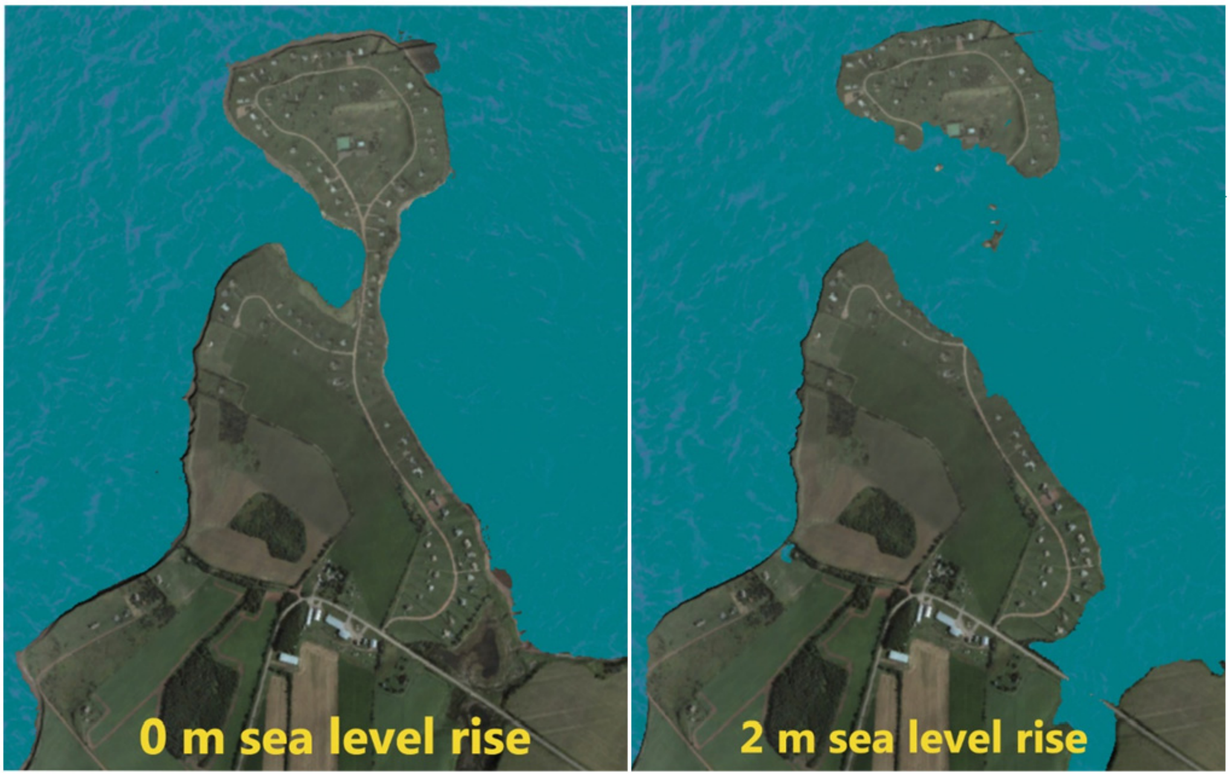

Figure 13. Visualization of areas impacted by 2 m storm surge on MacEwen's Island.

4. Conclusions

There is a paucity of HWM data available in published data for the Province of Prince Edward Island, Canada, revealing a potential gap in data available for planners, engineers, designers, and other practitioners in the field of coastal design and protection. Information on the historical extent of previous storm events would be an important consideration in the location, design, and construction of any infrastructure at elevations below 5 m in coastal areas. The peak high watermark measured from Dorian was 3.46 m geodetic at St. Peters Bay Bridge, as shown in Figure 5, and as listed in Appendix A. The projections of more intense cyclone events in the North Atlantic Ocean towards the end of the 21st century and the projection of a 1-meter rise in sea level by the year 2100, emphasizes the need for planning for more such events in coastal areas at elevations under 5 m.

The highwater mark data presented in Appendix A outlines that storms such as Dorian can have a varied impact on coastal areas due to exposure from direct or indirect wave action or storm surge components. Areas on the northern coast of Prince Edward Island were more vulnerable to the extremely high-water levels resulting from the storm, and this provides valuable information in preparing for future such events.

Dependence on water level data from stilling well tide gauges will underestimate the coastal flood hazard posed during storms and this stresses the need for in situ measurements to be taken after storm events. Prince Edward Island could benefit from a program for obtaining such measurements within a few weeks of the termination of each major storm. The collection of such data would enable production of high-resolution maps and visualization tools to help with public education about the impacts of storm events such as Dorian on infrastructure and natural features such as sand dunes and wetlands.

Prince Edward Island could also benefit from a system of coastal flood categories such as the US National Weather Service's Advanced Hydrologic Prediction Service [18] for forecast flood events that can cause local impacts. Flood stage values measured in imperial feet are established for the three flooding categories of minor flooding, moderate flooding, and major flooding for the five datapoints currently set for the City of Boston [19]. A similar system could be developed for Prince Edward Island coastal areas with flood stage values established for high-risk areas in the province. The existing PEI storm surge early warning system (available at: https://pssews.peiclimate.ca, accessed 9 November 2021) could form a foundation for this network.

Author Contributions: Conceptualization, D.E.J., X.W. and A.L.F.; methodology, D.E.J.; software, D.E.J.; validation, D.E.J., X.W. and A.L.F.; formal analysis, D.E.J. and X.W.; investigation, D.E.J.; resources, D.E.J. and A.L.F.; data curation, D.E.J.; writing—original draft preparation, D.E.J.; writing—review and editing, D.E.J., X.W. and A.L.F.; visualization, D.E.J. and A.L.F.; supervision, X.W.; project administration, X.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data for this study is contained in Appendix A.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Measured HWMs along PEI Coast after Dorian.

Location	Longitude	Latitude	Geodetic High-Water Level (CGVD28) (m)	Vertical * Precision (m)	Category (as Defined by URS Group, 2006)
Baltic River at Cousins field	−63.6459	46.5299	1.24	0.10	Surge only
Bideford Wharf	−63.9165	46.6165	1.19	0.07	Surge only
Cavendish Beach at dune wrack line	−63.3934	46.4993	3.35	0.03	Wave Runup on dune, Wave Height
Charlottetown −1700 tide gauge	−63.1167	46.2333	1.62	-	Stilling well

Table A1. *Cont.*

Location	Longitude	Latitude	Geodetic High-Water Level (CGVD28) (m)	Vertical * Precision (m)	Category (as Defined by URS Group, 2006)
Crystal Beach, Lower New Annan—field	−63.7117	46.4370	1.71	0.04	Surge only
Crystal Beach, Lower New Annan—Shore area	−63.7122	46.4384	2.21	0.05	Wave runup onto shallow cliff
Darnley Wharf Tide Gauge	−63.6645	46.5242	1.68	-	Stilling well
Darnley Wharf Wrack line	−63.6647	46.5347	1.54	0.04	Wave height.
Foxley River—Phillips	−64.0190	46.6933	2.35	0.04	Surge only
French River Wharf Road	−63.5118	46.5179	2.04	0.05	Wave height
French River Cannery Wrack Line at Road	−63.5025	46.5088	1.27	0.12	Wave height
French River Lighthouse at Dune	−63.4859	46.5115	2.73	0.04	Wave runup onto dune.
French River Cannery Wharf—Blackett Bldg.	−63.5021	46.5092	1.47	0.15	Wave height
Hebrides—Hood Cottage	−63.4826	46.4918	2.17	0.03	Wave height
Hebrides—Park	−63.4823	46.4925	2.29	0.04	Wave height wrack line.
Kildare Jacques Cartier Swings	−64.0144	46.8493	2.41	0.02	Wave height wrack line over cliff.
Kildare N or park at beach access	−64.0122	46.8517	2.57	0.02	Wave height wrack line
Kildare Rte. 12 roadside	−64.0123	46.8517	3.31	0.02	Reference Elevation
Lennox Island Wharf-steps	−63.8562	46.5996	1.48	0.05	Wave height. Wrack line on stairs
Lennox Island Tuplin Bldg.	−63.8454	46.6026	2.05	0.05	Wave height. Wrack line on grass above cliff.
Lennox Island Causeway	−63.8676	46.6083	1.08	0.07	Surge only. Wrack line On N side of causeway
Malpeque Harbour at Road	−63.7047	46.5553	2.02	0.04	Wave height. Wrack line on road
Malpeque Harbour—Coop Bldg.	−63.7041	46.5560	1.59	0.08	Wave height.
Naufrage Harbour Wrack Line on Dune	−62.4169	46.4679	2.17	0.05	Wave runup onto dune
New London Wharf	−63.5136	46.4688	1.47	0.03	Wave height, wrack line.
North Lake Wharf Tide Gauge	−62.0686	46.4677	0.35	0.05	Stilling well
North Rustico Inner	−63.2921	46.4552	1.72	0.03	Surge only
North Rustico Lighthouse Outer	−63.2919	46.4552	3.09	0.03	Wave runup on dune and wooden cribwork
North Rustico Wharf Buote	−63.3082	46.4570	1.35	0.02	Surge only
Oyster Bed Bridge—Gillis Wharf	−63.2432	46.4031	2.12	0.03	Wave runup
Rusticoville Bridge	−63.3174	46.4314	2.24	0.02	Wave runup
Savage Harbour Wharf Deck near boats	−62.8382	46.4268	1.43	0.06	Reference elevation on top of wharf
Savage Harbour Wharf east end	−62.8395	46.4276	1.80	0.04	Wave height, Wrack line
Savage Harbour Road near civic number 453	−62.8382	46.4301	1.62	0.05	Surge only. Wrack Line on field
Skinner's Pond Harbour Dune	−64.1247	46.9656	1.94	0.04	Wave runup on dune.
Souris Causeway West Seawall	−62.2679	46.3563	1.96	0.02	Wrack line on Seawall
Souris Causeway East Stairs	−62.2654	46.3565	1.62	0.02	Wrack line on 5th step of stairs
Souris Harbour Tide Gauge	−62.2485	46.3475	1.42	0.03	Stilling well on side of wharf

Table A1. *Cont.*

Location	Longitude	Latitude	Geodetic High-Water Level (CGVD28) (m)	Vertical * Precision (m)	Category (as Defined by URS Group, 2006)
St. Peters Bay Park N end 1	−62.5836	46.4186	3.10	0.04	Wave runup. Wrack Line near top of cliff
St. Peters Bay Park N end 2 (Figure A1)	−62.5834	46.4184	2.97	0.04	Wave runup, Wrack line
St. Peters Bay Bridge wrack	−62.5812	46.4157	3.46	0.05	Wave runup
St. Peters Bay Bridge Blowout	−62.5812	46.4157	3.06	0.04	Wave runup
Stanley Bridge Campbellton Rd. Intersection	−63.4620	46.4626	2.37	0.03	Wave runup
Stanley Bridge Wharf	−63.4586	46.4628	2.48	0.03	Wave runup
Summerside Arsenault Fish Mart	−63.7950	46.3894	0.88	0.03	Surge only
Summerside Wharf	−63.7889	46.3884	0.92	0.05	Stilling well
Tignish Shore East end near 210 Cottage Rd	−63.9935	46.9413	1.70	0.04	Wave height onto cliff evidenced by wrack line.
Tignish Shore 14 Cottage Road	−63.9957	46.9484	0.71	0.04	Surge only
Tignish Wharf N side Dune	−63.9948	46.9527	2.82	0.11	Wave runup onto outer dune
Tignish Wharf N side Tide gauge	−63.9983	46.9523	1.05	0.05	Stilling well
Tignish Jude's Point S Side by COOP	−64.0045	46.9516	0.77	0.05	Wave Height. Wrack line. Dune erosion
West Point Cedar Dunes	−64.3839	46.6182	0.79	0.15	Wave height. Dune erosion
West Point Lighthouse Road	−64.3837	46.6194	1.16	0.05	Wave height.

* Note that the vertical precision can vary depending on the strength of the satellite signal to the receiver of the measuring instrument which may be impeded by nearby obstacles such as trees or buildings. Further information on vertical precision of this methodology is provided in Section 2 of this paper. "-" indicates that vertical precision is not available for this site.

Figure A1 shows the extent of flooding from the storm surge and wave runup at St. Peter's Bay as evidenced by the HWM wrack line in the photo.

Figure A1. HWM from Wave Runup Wrack Line at St Peters Bay.

References

1. Atlantic Climate Adaptation Solutions Association (ACASA). Coastal Climate Change in Prince Edward Island: Shoreline Protection. 2021. Available online: http://www.gov.pe.ca/photos/original/cle_ShoreProtec.pdf (accessed on 15 October 2021).
2. Webster, T. *Community High-Water Storm Surge Mapping Network*; NS Department of Environment: Halifax, NS, Canada, 2011.
3. US Army Corps of Engineers, Dames & Moore. *Hurricane Floyd High Water Marks and Inundation Mapping for Eastern North Carolina*; FEMA District IV: Atlanta, GA, USA, 2000.
4. Fenech, A.; Hedley, N.; Chen, A.; Clark, A. Building a Tool for Visualizing the Impacts of Climate Change on Prince Edward Island, Canada. In *Climate Change Adaptation in North America*; Filho, W.L., Keenan, J.M., Eds.; Springer Science + Business Media LLC: New York, NY, USA, 2017; pp. 225–238.
5. Didier, D.; Bernatchez, P.; Boucher-Brossard, G.; Lambert, A.; Fraser, C.; Barnett, R.L.; Van-Wierts, S. Coastal Flood Assessment Based on Field Debris Measurements and Wave Runup Empirical Model. *J. Mar. Sci. Eng.* **2015**, *3*, 560–590. [CrossRef]
6. Duo, E.; Trembanis, A.C.; Dohner, S.; Grottoli, E.; Ciavola, P. Local-scale post-event assessments with GPS and UAV-based quick-response surveys: A pilot case from the Emilia-Romagna (Italy) coast. *Nat. Hazards Earth Syst. Sci.* **2018**, *18*, 2969–2989. [CrossRef]
7. Koenig, T.A.; Bruce, J.L.; O'Connor, J.; McGee, B.D.; Holmes, R.R., Jr.; Hollins, R.; Forbes, B.T.; Kohn, M.S.; Schellekens, M.F.; Martin, Z.W.; et al. *Identifying and Preserving High-Water Mark Data*; Techniques and Methods; No. 3-A24; United States Geological Survey: Reston, VA, USA, 2016.
8. Harris, D.L. *Characteristics of the Hurricane Storm Surge*; Technical Paper No. 48.; US. Department of Commerce, US. Government Printing Office: Washington, DC, USA, 1963.
9. Jardine, D.E.; University of Prince Edward Island, Charlottetown, PE, Canana. Personal communication, 2019.
10. LeFaivre, D.; Tessier, B. *Unusual Water Level Variations in the St. Lawrence Associated with Hurrican Dorian*; Fisheries and Oceans Canada; 19 December 2019. Available online: https://www.qc.dfo-mpo.gc.ca/infoceans/en/infocean/unusual-water-level-variations-st-lawrence-associated-hurricane-dorian (accessed on 9 November 2021).
11. Clark, A. A Comparitive Analyis of Conventional and Emerging Methods for Characterizing Coastal Morphology and Change. Master's Thesis, University of Prince Edward Island, Charlottetown, PE, Canada, 2016.
12. NRCan. Height Reference System Modernization. 2019. Available online: https://www.nrcan.gc.ca/height-reference-system-modernization/9054#_Canadian_Geodetic_Vertical_1 (accessed on 15 October 2021).
13. URS Group, Inc. *Final Coastal and Riverine High-Water Mark Collection for Hurricane Katrina in Mississippi, FEMA-1604-DR-MS, Task Orders 413 and 420*; Federal Emergency Management Agency (FEMA): Atlanta, GA, USA, 2006.
14. Liu, X.; Arnold, S.; Xia, J. A state-of-the-art review on High Water Mark (HWM) determination. *Ocean. Coast. Manag.* **2014**, *102*, 178–190. [CrossRef]
15. Webster, T.; McGuigan, K.; Webster, C. Survey Grade GPS Storm Surge High Water Mapping. Atlantic Climate Adaptation Solutions Association. 2011. Available online: www.atlanticadaptation.ca (accessed on 15 October 2021).
16. Wang, X.L.; Feng, Y.; Chan, R.; Isaac, V. Inter-comparison of extra-tropical cyclone activity in nine reanalysis data sets. *Atmos. Res.* **2016**, *181*, 133–153. [CrossRef]
17. Bender, M.A.; Knutson, T.R.; Tuleya, R.E.; Sirutis, J.J.; Vecchi, G.A.; Garner, S.T.; Held, I.M. Modeled Impact of Anthropogenic Warming on the Frequency of Intense Atlantic Hurricanes. In *Science*; New Series; American Association for the Advancement of Science Stable, 2010; Volume 327, pp. 454–458. Available online: https://www.jstor.org/stable/40508597 (accessed on 15 October 2021).
18. Kriebel, D.L.; Geiman, J.D. A Coastal Flood Stage to Define Existing and Future Sea-Level Hazards. *J. Coast. Res.* **2014**, *30*, 1017–1024. [CrossRef]
19. Kruel, S. The Impacts of Sea-Level Rise on Tidal Flooding in Boston, Massachusetts. *J. Coast. Res.* **2016**, *32*, 1302–1309.