Development and Application of a Geo-temporal Atlas for Climate Change Adaptation in Bay of Fundy Dykelands

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ABSTRACT

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Globally, dykelands are of strategic importance for climate change adaptation. In the Bay of Fundy, these were originally designed to protect agricultural land, yet now protect valuable infrastructure. The purpose of this project was to develop a comprehensive digital atlas incorporating historical marsh plans, shore protection, coastal geomorphology, LiDAR and topographic dyke surveys to serve as a basis for climate change adaptation. 110 paper plans were scanned, geo-referenced and features such as current and historical dykes, aboiteaux, armouring, ditches, creeks, property boundaries, foreshore marsh, and geodetic elevations were digitized using ArcGIS. Attributes included age of structure, material, dimensions, and ownership. Dyke elevations were surveyed using an RTK GPS, and individual sections were identified as being vulnerable to storm surge and sea level rise. Erosion rates and width of foreshore marsh were calculated per dyke segment. At present, 55% of dykes within Nova Scotia are within 0.5 m of critical elevations established in the 1960s, 2% are more than 0.5 m below critical and all are below the predicted rates of SLR by 2055. There is also a strong relationship between the placement of armouring along the dyke toe and foreshore erosion. Conversely, timely placement of armouring along the foreshore marsh decreased rates of erosion. This was most effective in areas with the largest fetch; less effective where erosion was driven by tidal currents. All data were integrated into ArcReader for use by Agriculture personnel and have been essential for cost effective climate change adaptation including dyke topping, education and planning.

ADDITIONAL INDEX WORDS: *LiDAR, sea level rise, storm surge, erosion, marsh, macrotidal*.

INTRODUCTION

Globally, dykes protecting low-lying coastal areas, collectively known as dykelands (Brown et al. 2011), are of strategic importance for climate change adaptation (Rupp and Nicholls, 2007; van Proosdij and Page, 2012). In some areas, dykes are used to reclaim and protect agricultural land and in others, their primary function is to minimize flooding of city centers with high population densities and large economic production. Management strategies in part then reflect the value of land that these dykes protect and the protection mandate of the regulatory bodies. For example, in the Netherlands, China, France as well as the province of British Columbia in Canada, the function of sea dykes is to protect land and assets behind dykes against the effects of flooding and inundation (Paskoff, 2004; Hoekstra and DeKok, 2008; Cheng, 2009; BC Ministry of Environment, 2011). In the Netherlands, dyke crest elevations are mandated by law to be reviewed every 5 years and adjusted according to the new probability curves generated (Hoeskstra and DeKok, 2008). In the provinces of Nova Scotia and New Brunswick, the Department of Agriculture, Agriculture and Food Advisory Service (formerly Resource Stewardship), Land Protection section (NSDA) is mandated through the *Marshlands Reclamation Act (1989), Agricultural Marshland Conservation Act c.22.s1(2004)* to protect agricultural land. Regulatory *'marsh bodies'* were established in the 1940s and 50s by the federal Maritime Marshland Rehabilitation Administration (MMRA) based on the high water line at that time (Milligan, 1987). Over the next 20 years, the MMRA ensured the protection of 18,000 hectares of tidal farmland in Nova Scotia and approximately 15,000 ha in New Brunswick by building 373 km of dykes (Milligan, 1987). Responsibility was then transferred to the Provinces around 1967-1970. Large tidal dams and causeways were built across most major tidal rivers to promote movement between towns as well as dyke protection by way of reducing tidal oscillations. At present, there is approximately 32,350 hectares of tidal land that is protected from tidal waters. While development is restricted within the marsh bodies themselves in Nova Scotia, variances can and have been granted for infrastructure construction. Over time residential, public and commercial development has taken place on adjacent lands which are now vulnerable to dyke overtopping or breaching. This includes private homes, municipal sewage lagoons, public roads, rail and utilities including the Trans-Canada Highway and CN Rail between Nova Scotia and New Brunswick. It is estimated that temporary delays caused by flooding between NS and NB will halt more than $50M/day of trade (Webster et al. 2012). This vulnerability will only increase with rising sea levels and storm surge.

As with most coastal areas of the world, the Bay of Fundy will feel the effects of global sea level rise, local subsidence and tidal expansion and the Upper Bay was identified by Shaw et al. 1998 as being highly vulnerable to climate change. New estimates of relative sea level rise in the region range in order from 0.45 m ± 0.15 m (Richards and Daigle, 2011) to 0.79 m (Greenburg et al., 2012) by 2055 and 1.2 to 1.73 m for 2100. These figures are sufficient to overtop all of the dykes in the Upper Bay. The higher water levels will result in more flooding, potential damages to coastal infrastructure and property loss, potential loss of life, coastal erosion as well as freshwater flooding and dam failure (van Proosdij and Page, 2012). Effective planning and adaptive management for climate change has been shown to depend on accurate, accessible and comprehensive spatial digital data (e.g. Brown et al., 2011; Environmental Agency, 2011; Barron et al., 2012). However, until recently, all marsh plan surveys within the Department of Agriculture were in analogue form and did not include recent additions of dyke armouring, or topping. In addition, aboiteau superintendents did not have easy access to the most recent dyke elevation surveys nor any visual mechanism by which to demonstrate flooding risk to local landowners or emergency officials.

The purpose of this project was therefore to develop a comprehensive digital atlas incorporating historical marsh plans, shore protection, coastal geomorphology, LiDAR and topographic dyke surveys to serve as a basis for climate change adaptation. The introduction of historical maps and data into the GIS environment is advantageous, as it not only preserves such information, but also enables the enhancement of current data. Moreover, it permits the opportunity for comparative analysis of both spatial and temporal data and their associated attributes. A secondary objective was to begin to assess the effects of dyke maintenance practices on ecomorphodynamic processes within the estuary. Cumulative and synergistic effects of engineering projects and natural processes are often ignored, or there are not enough empirical data for detailed analyses and understanding is based on anecdotal evidence; and sediment transport and the littoral cell are not considered (Eurosian, 2004; Brown et al., 2011). Dyking and associated land claims will cause an alteration in tidal prism, hydrodynamics and sedimentary processes within an estuary as they can displace a significant volume of water and decrease accommodation space (French, 2001). This decreased accommodation space can enhance sedimentation in estuaries strongly dominated by fine sediments and fluid mud such as in the Petitcodiac River (van Proosdij et al., 2009). However, dyke land claims can cause estuaries to switch from flood to ebb dominated systems, thereby enhancing seaward sediment transport, erosion and increases with depth (Friedrichs et al. 1992) as is seen in the relatively sandy Avon River. This switch is dictated by the shape of the estuary, grain size (e.g. sand versus fines), depth of main thalweg and presence of additional tributary rivers (van Proosdij et al., 2009).

METHODS

Study Area

The Bay of Fundy is a large macrotidal estuary that forms the north-eastern extension of the Gulf of Maine, and splits into two inner-bay systems: Chignecto Bay and the Minas Basin. It is characterized by a semi-diurnal tidal regime with a maximum tidal range of 16.4 m in the Upper Bay, high suspended sediment concentrations and the presence of ice and snow for at least three months of the year. Extensive intertidal flats and salt marshes are exposed at low tide. In addition this region has an extensive dyking history which has restricted tidal flooding into low lying regions since the 1700s (Desplanque and Mossman, 2004; van Proosdij, 2012). This research focuses on dykelands managed by the Nova Scotia Department of Agriculture, Land Protection section which occupy the majority of former salt marsh habitat in both the upper (Figure 1) and lower Bay and do not include dykes constructed by private landowners.

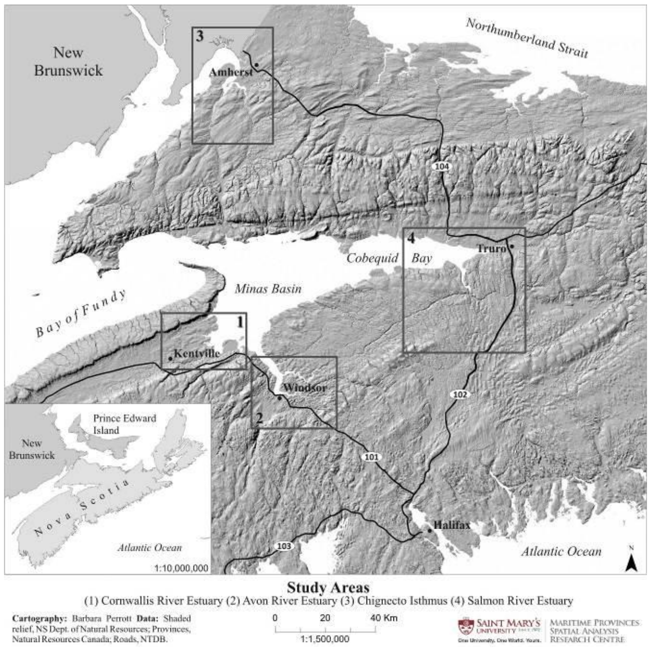

Figure 1. Areas of low lying marshlands incorporated into the atlas in the Upper Bay of Fundy. Shaded relief from the Nova Scotia Department of Natural Resources.

Digital Database Development

A total of 110 paper plans were scanned at 400 dpi and rectified using the 1:10,000 Nova Scotia digital topographic map series, satellite imagery and GPS coordinates of dyke centerlines as well as aboiteau structures provided by the NSDA in ArcGIS 9.3. All data were transformed from the Average Terrestrial System of 1977 (ATS77), North American Datum of 1927 (NAD27) or the World Geodetic System (WGS84) to the North American Datum of 1983 (NAD83) UTM zone 20, Canadian Spatial Reference System (CSRS98). This resulted in a mean cumulative horizontal position error of 5.8 m (Tibbetts, 2012). A number of vector features of these historical marsh surveys were digitized on-screen including: marsh body boundaries, dykes, aboiteaux, inner dykes, old dykes, ditches, creeks, dyke right of way, shoreline protection, toe of marsh, ditch elevations, marsh elevations and property boundaries. As well, present day vector data such as building footprints, property boundaries and surveyed features such as dyke center lines and aboiteaux were added to the GIS. Each feature's attribute table was populated by data gleaned from the original marsh plans, NSDA personnel or field observations such as age of structure or date of survey, construction materials, geodetic elevation, dimensions, number of gates, ownership, date of construction or abandonment, etc. In the case of marsh body boundaries, the date of incorporation was provided as well as the high water line used for boundary delineation by the MMRA. The sequence and location of placement of shore protection (e.g. dyke toe or foreshore marsh) as well as dyke topping was recorded based on NSDA field logbooks and interviews. LIDAR data, high resolution satellite imagery (IKONOS, QuickBird) and historical aerial photography were also added where available.

These data were then supplemented by field observations obtained during a companion project focused on shore zone characterization for climate change adaptation (Perrott and van Proosdij, 2012). The classification was loosely based on the

Figure 2: Geotagged photograph taken with the Trimble YUMA tablet during the ACAS shorezone characterization survey in 2011 at a) eroding dyke at Amherst Point, Cumberland Basin and b) extensive foreshore marsh protecting dyke at Kingsport, Cornwallis Estuary, Minas Basin.

Canadian Coastal Information System (Jenner et al, 2003) however where the CCIS uses one line, Perrott and van Proosdij used five lines to reflect the hyper-tidal conditions (>14m tides) and the highly dynamic intertidal zone. The use of one single shoreline would ignore important habitats occurring seaward of this line. This approach has the significant advantage of being able to quantify the amount of (and change in) foreshore salt marsh seaward of dyke infrastructure. In addition, a Trimble Yuma tablet computer with integrated GPS and a geotag enabled camera were used to document shoreline changes. The Yuma tablet attaches GPS coordinates to each photograph which allows for the photographs to be displayed within a GIS environment with the horizontal positional accuracy of 2-5 m. These photos were then integrated within the marshlands atlas and used to assess shoreline stability (observed erodibility) (Figure 2) and document anthropogenic structures such as armouring, non-agriculture culverts and aboiteaux and wharfs. Each aboiteau structure managed by the NSDA were integrated within the aboiteau geodatabase (Figure 3).

Figure 3: Modern one-way tide gate or aboiteau structure along the Grand Pre dyke in the Cornwallis Estuary.

Analysis

The GIS database was used to assess the vulnerability of current dyke elevations, the accuracy of existing marshbody boundaries and the width of foreshore marsh. Historically dykes were topped to maintain a minimum critical elevation, unique to each marshbody, the level of which was set in the 1950s without any consideration for climate change (van Proosdij and Page, 2012). Historically these have been determined by the MMRA primarily based on tidal heights in the 1950s and position of the marshbody within the estuary (exposed versus up river). Construction elevations were then established as being above this elevation at an average of two feet (0.61 m) for exposed dykes and less for dykes upriver. A set storm surge elevation based on return period was not added however the critical elevation of an individual dyke could be raised based on observed overtopping (van Proosdij and Page, 2012). Each dyke elevation point was assessed relative to critical elevation using an equation within the attribute table. These points were then symbolized and incorporated within the atlas. Additional fields were added and recommended elevations determined incorporating storm surge return periods for 1:10, 1:25, 1:50 and 1:100 year events based on Richards and Daigle (2011) and relative sea level rise for 2025, 2055, 2085 and 2100 (van Proosdij and Page, 2012). The percentage of dyke segments less than current critical elevations were quantified.

The presence and condition of foreshore marsh can offer significant erosion protection to the toe of the dyke mostly through the dissipation of wave energy (e.g. Möller and Spencer, 2002). Width of foreshore values were determined using foreshore polygons and transects cast to the backshore every 250 m by Analysis of Moving Boundaries Using R (AMBUR), which is a relatively new tool developed by Jackson (2010) (Tibbetts, 2012). This effectively provides a measure of the amount of protection that is currently being offered to individual dykes. This analysis was only performed for dykes likely to be exposed to significant wave energy (e.g. Cornwallis and Cumberland estuaries) and where foreshore data were available.

As mentioned previously, the jurisdictional boundaries for marsh bodies were determined based on high water levels from the 1950s using basic survey equipment. In order to examine the accuracy of these boundaries, the HWL from each marsh body was applied to the LiDAR digital elevation model to generate a boundary polygon and then compared to the historical boundary (van Proosdij and Page, 2012) (Figure 4).

Individual map templates for each marsh body were developed for use within the freely available ArcReader for use by the NSDA (Perrott and van Proosdij, 2012).

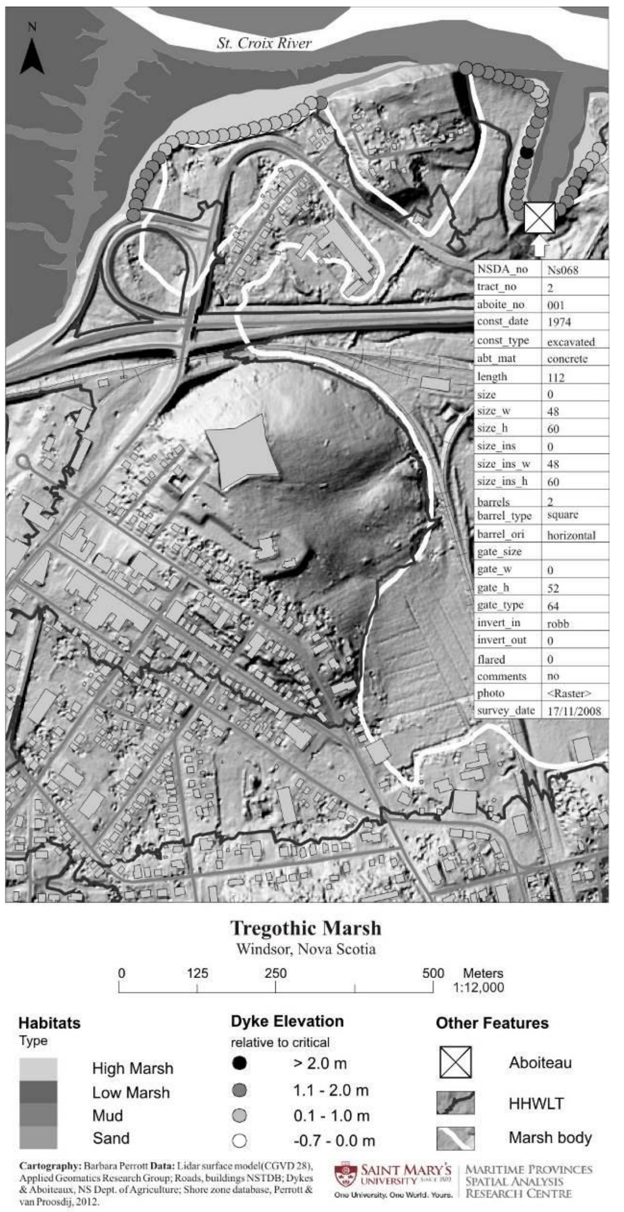

Figure 4: Example of the marshlands atlas for Tregothic Marsh (NS68) in the Avon River Estuary depicting aboiteaux attributes and marsh boundaries determined by the MMRA and by applying the marshbody HWL to the 2007 LIDAR data digital elevation model.

RESULTS

This project has succeeded in creating a comprehensive database that can be queried to identify specific areas of concern (e.g. dyke segments below critical elevation or foreshore marsh less than a particular width), assist in planning for climate change adaptation or assess the implications of dyke maintenance procedures such as abandonment of aboiteaux structures, placement of shore protection or dyke footprint modification. The most complete datasets are available for study areas 1-3(Figure 1) which were the focus of the ACAS climate change project (Perrott and van Proosdij, 2012).

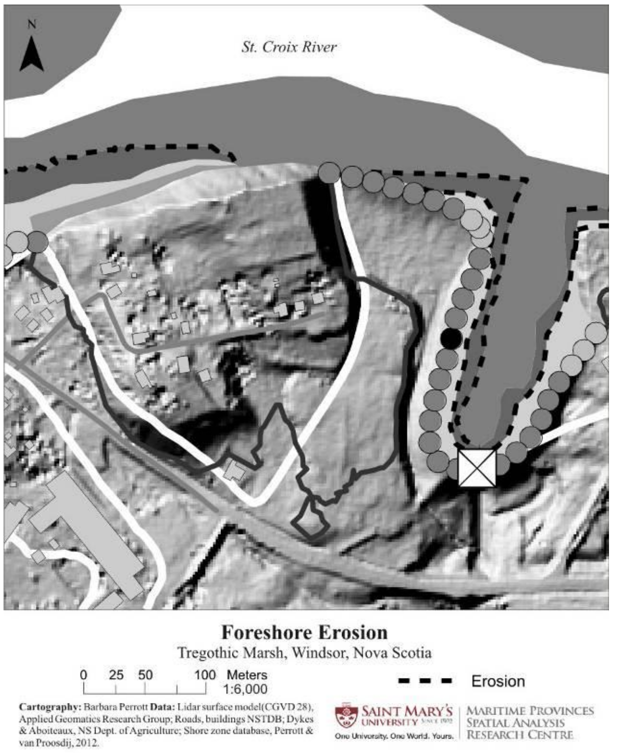

Figure 5: Example of foreshore erosion at the Tregothic Marsh, Windsor, Nova Scotia based on 2007 Ikonos imagery and field observations.

Individual dyke segments (~15 m intervals) were assessed relative to critical elevation (Figure 4) and most sections were above this elevation, particularly in Hants County. Marshbodies with dyke sections greater than 200 m in length that are below critical include Centre Burlington (NS48), Grand Pre (NS8), Bishop Beckwith (NS65), Belcher Street (NS91), Avonport (NS92), John Lusby (NS 53) and Minudie (NS 54) which had the longest segment at 825 m. These dykes are at imminent risk of overtopping for a 1:10 year storm event. Some of these dykes have a good mean width of foreshore fronting them (> 200m) (e.g. NS8, NS65, NS53 and NS54) while others such as NS91 and NS92 have limited foreshore. However, since these are mean values for the entire length of the marsh body, it does not preclude any particular subsection to have smaller amounts of foreshore (e.g. west side of Minudie).

The incorporated marshbody boundaries were originally determined by the MMRA in the 1950s corresponding to observed high water levels within each individual marsh. ArcGIS 9.3 was used to compare the spatial extent of these boundaries (using the same historical HWL) using the more accurate modern LiDAR data in the Southern Bight (Cornwallis and Avon River estuaries). In many areas there was good agreement, however, in some notable areas, the historical boundaries markedly underestimated (delineated) the ‘true’ flood boundary. Since these jurisdictional boundaries are tied to legislation restricting development within these areas (unless a variance is granted), non-inclusion of potential flood areas within these boundaries leads to a false sense of security. This was particularly notable in the Town of Windsor (Tregothic marsh NS68) where a section of downtown is within the floodplain boundary however historically would not have been included since it was not suitable agriculture land (Figure 4). In addition, in areas such as the Wolfville (Bishop Beckwith and Grand Pre), Windsor (Tregothic, Elderkin) and Amherst (Amherst Point, John Lusby) where variances have been granted (Figure 6), the value of the land being protected has increased significantly while the percent of which is agriculture has decreased.

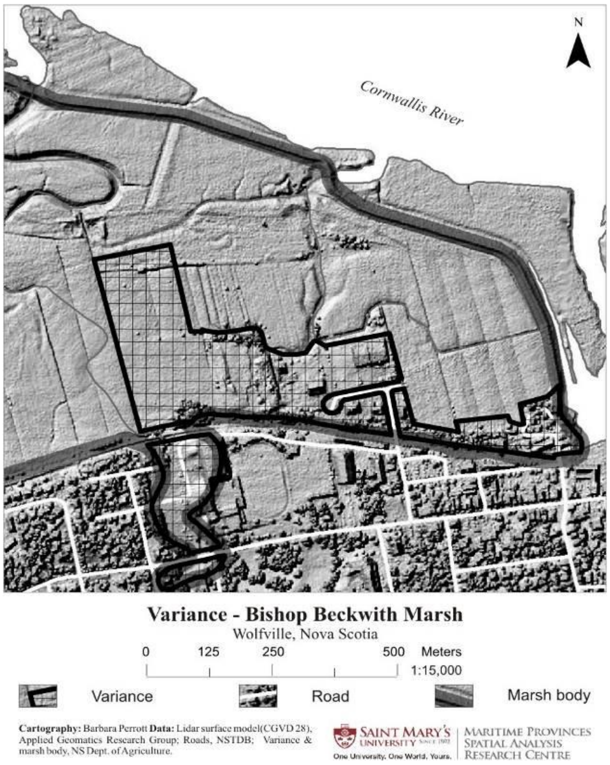

Figure 6: Variance granted within the Bishop Beckwith Marsh body adjacent to the town of Wolfville in the Cornwallis River Estuary.

Throughout the Cornwallis estuary the AMBUR analysis has shown that the average net change is -3m (± 5.8m), between 1977 and 2008. Most of the estuary saw less than 40 m or no change during this time period with some areas seeing as much as 150 m in marsh progradation (Tibbetts, 2012) AMBUR was also used to determine the width of foreshore marsh every 250 m. Based on data from SE England from Lindham and Nicholls, 2010 as well as analysis from Spencer and Moeller, 2002, with a 1 m water depth over the marsh surface, most of wave energy is dissipated within the first 80 m and this also results in the lowest cost of dyke maintenance. Therefore, for the purpose of this study, a foreshore marsh width greater than 200 m will provide adequate protection and efforts should be concentrated on protecting foreshore where widths are less than 100 m. In general, it is clear that the Cumberland Basin has less foreshore marsh than the Cornwallis Estuary. With the exception of NS54 (Minudie) all of the marsh bodies included in this assessment have more than 75% of their foreshore with a width less than 100m which places them at increased risk for long term consequences. Those at greatest risk include NS55 (Seaman marsh), NS44 (Converse marsh) and NS115 (Nappan-Maccan marsh). It should be noted that some of these are a result of river bank erosion from the La Planche and Maccan Rivers. Efforts should be made to protect what foreshore remains in these areas. The placement of armour stone on the foreshore marsh rather than dyke toe has been shown to be more effective in mitigating dyke failure.

In the Cornwallis estuary, the two main marsh bodies with the lowest amount of foreshore are NS56 (Wellington) and NS65 (Bishop Beckwith). Both NS80 and NS41 are well protected. Grand Pre (NS8) has 21.2% of foreshore within the 100-200 m category and may be a good candidate for armour stone.

Figure 7: Freshwater floodwater trapped behind dykes in Truro, Minas Basin. Photo from the Canadian Press, Sept. 20, 2012.

DISCUSSION

The Marshlands Atlas has become a valuable tool for both climate change adaptation planning as well as day-to-day management. To date, the digital database has been used to develop appropriate base (e.g. aboiteau geometry, land use, etc..) and boundary conditions for hydrodynamic flood modelling of dyke overtopping and breach within the town of Windsor in the Avon River estuary (Fedak, 2012); assess coastal vulnerability in the Cornwallis estuary (Tibbetts, 2012) and prioritize dyke segments at immediate risk of overtopping. It has also been used to respond to contemporary flood events when heavy rainfall is prevented from discharging through the aboiteaux at high tide (Figure 7).

The Atlas has also become a valuable tool for day to day operations of the dykelands. For example NSDA personnel have used the Atlas to plan the placement of rock protection along dykes and foreshore areas. Within a GIS they are quickly able to show contractors where rock should be placed and they can plan the safest route using the road data included in the Atlas. With ArcReader's measurement tools they can also estimate the length and area of protection required. Employees are also able to query property data and determine ownership of properties that fall under the mandate of the Agricultural Marshland Conservation Act; this becomes important for potential development projects happening in these sensitive areas. With the addition of LiDAR data, employees can click on a point and instantly know the associated elevation of that point. Dykes have also been symbolized using critical and construction elevations supplied by the NSDA and therefore employees can quickly determine where dykes may be in need of repair and potentially vulnerable to storm events. "*This project has also begun to address the current knowledge gap (incomplete and inaccurate data) presented by a paper based dyke mapping system. Employees now have access to pertinent data needed to make informed management decisions*" (pers communication, M. MacAulay, NSDA manager, 2012).

The structure of the atlas permits multiple spatial and temporal queries to be performed, including sequence of placement of shore protection or replacement/abandonment of aboiteaux structures. The response of the foreshore marsh over time can then be examined (e.g. erosion versus progradation) however at the present time one cannot distinguish between natural versus anthropogenic drivers of chance as discussed in Brown et al., 2011. However, one can observe sequences of erosion at the ends of lines of armour stone and subsequent extension of defenses. Although more detailed analysis of these responses is on-going, a shift in management strategy to protect foreshore marsh through the placement of armour stone in the late 1990s rather than immediately at the toe of the dyke has resulted in a decrease in dyke erosion in exposed areas. Areas within the relatively narrow Avon River estuary or upper portion of the Cumberland Basin, where erosion is driven by patterns of strong tidal currents rather than wave action, the role of foreshore marsh is not as evident.

CONCLUSIONS

The development of a geospatial marshlands atlas in the Bay of Fundy has facilitated effective planning for both day to day operations and planning for climate change impacts and adaptation. The majority of dykes within the Upper Bay of Fundy are at immediate risk of overtopping with a 1:10 year event, even without sea level rise. The preservation of foreshore marsh is essential to decrease rates of erosion along existing dyke infrastructure. In addition, the boundaries of marsh bodies set by the MMRA in the 1940s should be re-evaluated to reflect the current and future extent of the high water line. Furthermore, the atlas can be used as a visualization tool to assist planners and municipal officials to examine the consequences of non-action. Future research will include more in-depth analysis of the relationship between natural and anthropogenic drivers of change in intertidal ecosystems. Options are also being explored on how best to update and manage the data with the potential to serve it online.

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