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Solutions d'adaptation aux changements climatiques pour l'Atlantique

Best Management Practices for Climate Change Adaptation in Dykelands: Recommendations for Fundy ACAS sites

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Executive Summary

Dykelands are of strategic importance for climate change adaptation in the Bay of Fundy region as well as globally. At the present time, in Nova Scotia (NS) and New Brunswick (NB) combined, there are 364 km of dykes protecting a total of 32,350 ha of agricultural land. Excluded in those numbers are dykes that were constructed by private landowners, industries and communities. At the present time, the primary mandate of the NS Department of Agriculture, Land Protection section, Agriculture and Food Advisory Services (formerly Land Protection) is to protect agricultural land behind the dykes. However, since the dykes were constructed and the marshbodies delineated, residential and commercial development has taken place on adjacent lands which are now vulnerable due 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. The marshlands themselves also provide a buffer to storm surge impacts, dissipating wave energy.

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. A number of dykes are at risk of overtopping with the next Saros peak of high tides in upcoming years and the majority are at significant risk to storm surge. However, determination of an appropriate critical elevation to deal with climate change is a challenge and may require re-engineering the existing Fundy dyke model.

The purpose of this project was to assess the vulnerability of dykes under provincial jurisdiction within the Upper Bay of Fundy to climate change impacts and provide mitigation and management recommendations for the future. This project will be of particular use to NS Department of Agriculture, Resource Stewardship, Land Protection personnel, municipal and district planners, emergency management officials in addition to local property owners. This project includes:

- An analysis of best practices using information from Nova Scotia, New Brunswick and British Columbia as well as other regions in the world where dykelands are present (e.g. United Kingdom, France, Netherlands).
- GIS assessment of individual dyke vulnerability with the Fundy ACAS communities
- Determination of new critical elevations and associated engineering modification.
- An assessment of current and potential future management practices (e.g. maintenance of foreshore, placement of armour rock, creek modifications)
- Recommendations of mitigation strategies and recommendations of coastal engineering practices to protect existing foreshore marsh.

Coastal erosion, tides and storm surge are natural processes which have always existed and have contributed throughout history to shape global coastal landscapes. Humans have used dykes and other barriers to prevent flooding and shoreline armouring to prevent erosion for centuries across the world, notably in Europe, Asia, United Kingdom and North America. Dykes have been used to a lesser extent in Australia and New Zealand. Dyke design standards evolved over time, mostly in response to severe flooding events in Europe and North America. The UK, Netherlands and British Columbia (Canada) have been particularly proactive in incorporating climate change adaptation into their planning decisions. In all three cases, dykes are also constructed to protect human life and property and as such, the design standards are greater than in Atlantic Canada. Generally the seaward side of a dyke is built with a vertical to horizontal ratio of 1:3 to 1:6 to dissipate wave energy and armoured, while the landward side is generally steeper with 1:2 or 1:3 to minimize the amount of land used. Fundy dykes were initially designed by the Maritime Marshland Rehabilitation Administration (MMRA) to have a 1:3 and 1:2 seaward and landward slope respectively. Over time however, repeated dyke topping with minimal adjustment of toe placement (at the expense of agricultural land) has resulted in a 1:1.5 seaward slope and 1:3 or 1:4 landward slope. Although the seaward toe of the dyke is typically armoured with rock, the steep slope does increase the potential for erosion through wave reflection and scour.

The parameters that are used to determine dyke crest elevation vary globally although most use the higher high water level or highest recorded tide level plus a freeboard elevation which is typically 0.5-0.6 m. In many areas, excluding Fundy, a potential storm surge elevation (return period varies depending on the value of land being protected) is added as well as an agreed upon rate of sea level rise for a typical planning horizon. The Netherlands balances the cost of the land being protected with the cost of optimal protection. At the present time, most of the dykes within the Fundy ACAS communities are below the critical elevation required to stop a 1:10 year storm (0.85 m) event. A detailed table is provided with recommended elevations for each marshbody to protect for either storm surge alone or sea level rise (SLR) or both scenarios combined. It will be important to recognize that increases in critical elevation will also require additional landtake for dyke heightening to maintain proper slope ratios. It will be up to provincial and local officials to determine the degree of risk they are willing to assume, which will ultimately depend on cost and the value of the land that is being protected.

Individual dyke segments (~15 m intervals) were assessed relative to critical elevation 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. In addition, in areas such as the Wolfville (Bishop Beckworth and Grand Pre), Windsor (Tregothic, Elderkin) and Amherst (Amherst Point, John Lusby) where variances have been granted, the value of the land being protected has increased significantly while the percent of which is agriculture has decreased.

A physical assessment was done for all of the dykes within the Fundy ACAS study areas, including field visits, wave exposure analysis and historical erosion rates (Cornwallis), foreshore width and observed erodibility as well as type and extent of shore protection applied. These observations were also tied to areas of concern identified by NS Department of Agriculture aboiteau superintendents and land surveyor. Critical areas were identified, photographed and action recommended for select areas. The primary goal will be to preserve foreshore marsh as much as possible which may involve dyke re-alignment, foreshore armouring or limiting the use of borrow pits in area of limited foreshore.

A comprehensive review of international best practices for climate change adaptation in dykeland areas is provided. Advantages, disadvantages and conditions are provided for the three main climate change adaptation approaches: hold the line (defend), re-align (retreat) or abandon. Adaptation can take the form of either engineering solutions or management approaches. Engineering solutions can include both hard (e.g. rock armouring) or soft (e.g. salt marsh restoration or terracing). It is recognized that Fundy dykelands no longer simply contain agricultural land and cooperation is required at federal, provincial and local levels to find funding for dyke heightening. A combination of both an engineering and management approach is recommended for the Fundy environment.

Based on an analysis of international best practices and existing conditions within the Fundy ACAS communities, the following recommendations are provided:

- Conduct a cost benefit analysis for marshbodies identified by Browning, 2011 as containing significant infrastructure using the methodology of van Alphen (2012) to balance the value of the land protected and cost of required infrastructure as well as degree of risk that the communities are willing to assume.

- Develop a differential determination of critical elevation incorporating sea level rise and storm surge for dykes protecting valuable infrastructure similar to Pilarcyk, 1998. For example, use a 1:100 year storm return period for high value areas (1.13 m) versus a 1:10 year storm (0.85 m) in primarily agricultural land. In these high value areas, a minimum of the predicted 2055 sea level rise estimate should be included.

- In areas where dykes are being topped, it is recommended that the proposed cross sectional profiles be carefully assessed and a decrease in slope (e.g. 1:2 or 1:3 ideally) be applied on the seaward side. Although this may come at the expense of some agricultural land as the dyke crest will need to shift landward, the tradeoff of a loss of 10 m of agricultural land versus the significant financial cost of dyke repair due to erosion is warranted.

- The allocation of variances should be significantly limited and flood proofing requirements should be mandatory. Applicants of proposed variances should be shown detailed maps of the extent (and depth) of potential inundation so that they are fully aware of the risk of building within this zone. Various products generated through ACAS are available to support these activities.

- Managed re-alignment should be considered in those areas that have less than 80 m of foreshore. In those cases, dykes should be re-aligned so as to provide a minimum of 100 m of foreshore and that foreshore be armoured. Efforts should be focused on proactive rather than reactive protection. However, not all foreshore should be armoured as sediments released through the erosion process will in turn nourish new marsh growth in other areas within the estuary.

- Small, underutilized tracts should be considered as candidates for salt marsh restoration if the cost of maintenance is significantly more than the value of the land that is being protected. However, large, intact tracts of agricultural land that are threatened yet underutilized should not necessarily be seen as immediate candidates for large scale restoration activities. Constrained managed realignment in areas of concern should be undertaken to prevent breaching and to protect fertile agricultural land for future generations.

- No additional salt marsh should be reclaimed even if there is significant growth of foreshore marsh seaward of an individual dyke structure. This foreshore marsh serves as a buffer for erosion and wave energy dissipation for future generations. Natural processes of erosion and progradation should be encouraged.

- In areas where communities benefit directly from the protection of dykes for their critical infrastructure, these communities should bear some of the costs of maintenance (e.g. 'protection tax' proportional to the amount of land at risk) in addition to the province and federal government. No one entity should bear the cost in its entirety.

Planning for flood risk requires collaboration and partnerships at all levels. This will include engaging provincial, municipal and community stakeholders in education and visioning activities to raise the understanding of current and future flood risks, use the products generated through ACAS to quantify this risk and decide as a community and a province, how best to address these risks. It is important to note that while this report provides an evaluation of dyke vulnerability and adaptation options that can be applied to non-ACAS areas (e.g. Truro and Annapolis), it does not negate the need to conduct site specific vulnerability assessments for other areas of the Province. Fundy communities can successfully adapt to climate change providing there is sufficient political will, community acceptance and financial resources.

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1 Background

1.1 Introduction

> "When we consider what many regard as the greatest threat to the contemporary coastline, sea level rise, we might gain an appreciation of how fruitless this battle may turn out to be."
> (French, 2001, pg.273)

Dykelands are of strategic importance for climate change adaptation in the Bay of Fundy region as well as globally. At the present time, in Nova Scotia and New Brunswick combined, there are 364 km of dykes protecting a total of 32,350 ha of agricultural land (van Proosdij, 2011). This does not include additional structures (e.g. dykes, levees, berms, seawalls) constructed by individuals, industries or communities. These are outside the jurisdiction of the Province. At the present time, the primary mandate of the NS Department of Agriculture, Agriculture and Food Advisory Services (formerly Resource Stewardship), Land Protection section is to protect agricultural land behind the dykes. Dykes are the second line of defence after coastal wetlands and are no longer simply protecting agricultural land. Since the dykes were constructed and the marshbodies delineated, residential and commercial development has taken place on adjacent lands which are now vulnerable due to dyke overtopping or breach. The marshlands themselves also provide a buffer to storm surge impacts, dissipating wave energy.

In addition, historically dykes were topped to maintain a minimum critical elevation, unique to each marshbody, the level of which was set in the 1950s and 1960s without any consideration for climate change. A number of dykes will likely overtop with the next Saros peak of high tides in 2013 and the majority are at significant risk to storm surge. However, determination of an appropriate critical elevation to deal with climate change is a challenge and may require re-engineering the existing Fundy dyke model.

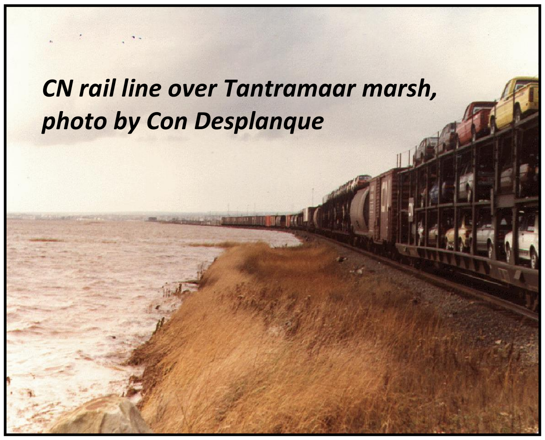
The purpose of this project is to assess the vulnerability of dykes under provincial jurisdiction within the Upper Bay of Fundy to climate change impacts and provide mitigation and management recommendations for the future. This project will be of particular use to NS Department of Agriculture, Resource Stewardship, Land Protection personnel, municipal and district planners, emergency management officials in addition to local property owners. The project will include the following:

- An analysis of best practices using information from Nova Scotia, New Brunswick and British Columbia as well as other regions in the world where dykelands are present (e.g. United Kingdom, France, Netherlands).
- GIS assessment of individual dyke vulnerability
- Determination of new critical elevations and associated engineering modification.
- An assessment of current and potential future management practices (e.g. maintenance of foreshore, placement of armour rock, creek modifications)
- Recommendations of mitigation strategies and recommendations of coastal engineering practices to protect existing foreshore marsh.

1.2 Climate Change Impacts in the Bay of Fundy

The Upper Bay of Fundy was identified in the Shaw et al., 1998 national coastal sensitivity to sea level rise assessment as being highly vulnerable. This is mostly associated with the extensive low lying regions of former marshland that are now restricted behind an extensive system of dykes. As with most coastal regions in the world, the Bay of Fundy will feel the effects of global sea level rise, local subsidence and tidal expansion. Refer to Webster et al., 2011 and Richards and Daigle 2011 for detailed discussions of sea level rise predictions for the region. These range in order from 0.45 ± 0.15 m (Richards and Daigle, 2011) to 0.79 m (Greenburg et al. in press) by 2055 and from 1.2 to 1.73 m for 2100. The latter of which is sufficient to overtop all of the dykes in the Upper Bay. The higher water levels will result in more flooding, potential damage to coastal infrastructure and property loss, potential loss of life, coastal erosion as well as freshwater flooding and dam failure.

One thing to remember is that climate change may not create new coastal hazards but it will almost certainly exacerbate existing coastal flooding and erosion problems.


CN rail line over Tantramaar marsh, photo by Con Desplanque

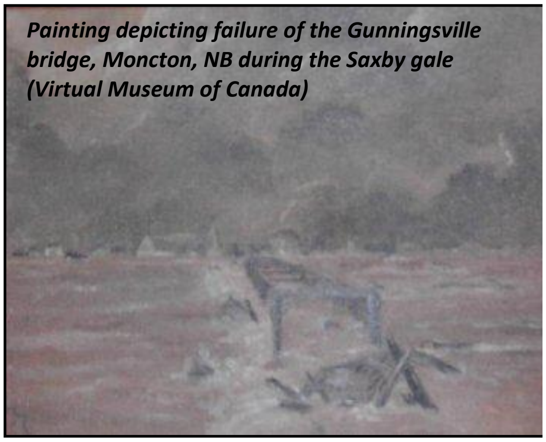
"Atlantic Canada will experience more storm events, increasing storm intensity, rising sea levels, storm surges, coastal erosion and flooding"
(Vasseur & Catto, 2008)

1.3 Strategic Importance of Dykelands for Climate Change Adaptation

Dykelands are of strategic importance for climate change adaptation in the Bay of Fundy region. They are the second line of defence after coastal wetlands and are no longer simply protecting agricultural land. Some considerable real estate value also depends on the protection provided by the earthen barrier infrastructure, including private homes, public roads and utilities. The Trans-Canada Highway through the Tantramaar marsh in Sackville provides a critical transportation and trade link between Nova Scotia and the rest of Canada and currently depends entirely on the protection provided by dyke infrastructure. Dykelands also protect other infrastructure such as the CBC international broadcast facility, CN Rail, streets, utilities, municipal sewage lagoons of the Town of Sackville, Windsor, Dieppe, Hillsbourough and Wolfville. The marshlands themselves also provide a buffer to storm surge impacts, dissipating wave energy. In other areas of the world such as the United Kingdom, efforts are underway to mitigate climate change impacts by practicing managed realignment, a management plan that roles back the dykes and lets the dykeland revert to tidal wetland habitat. The new influx of silt helps maintain the elevation of this now new foreshore, protecting the dykes and infrastructure behind.

Although the mandate of the Department of Agriculture in NS and NB is to protect agricultural land, over time there has been considerable infrastructure (e.g. homes, businesses, roads, utilities) that have been developed behind the dykes. For example, it is estimated that the NS dykes protect more than

2,200 Ha of land and approximately $70 M in assets within the Chignecto Isthmus (Webster and Pett, 2012). Temporary delays caused by flooding between NS and NB will halt more than $50 M/ day of trade (based on $10s B/yr) (Webster and Pett, 2012). In addition, due to the nature of the soil and isolation from the tides, marshlands behind the dyke are subsiding, creating a situation of impeded drainage if dykes were overtopped. During the Saxby Gale in 1868, all of the dykes in the Upper Bay were overtopped by at least 0.9 m and resulted in extensive flooding (Desplanque and Mossman, 2004). If such an event were to occur in the present day, it would result in billions of dollars of damaged infrastructure and potentially loss of life, given the amount of development which has occurred behind the dykes (Shaw et al., 1994). Webster et al., 2011 provides an overview of the extent of flooding through the Tantramaar region in the event of a storm of similar magnitude. Although a complete flooding of a dyked area by flood water is not desirable for agricultural purposes it is not nearly as serious as when buildings become inundated with salt water. Despite the fact that the frequency of this occurring is not high, it is a definite risk that must be considered.



Painting depicting failure of the Gunningsville bridge, Moncton, NB during the Saxby gale (Virtual Museum of Canada)

> *"Since the Saxby Tide more than seven 'Saros' ago, sea level has risen eustatically nearly 25 cm. Added to the minimum 1.5 m by which the Saxby Tide exceeded high astronomical tides, a height is calculated that is more than sufficient to overtop the present dyke system"*
>
> (Desplanque and Mossman, 2004)

1.4 Overview of Coastal Processes

In order to fully appreciate the potential risk to the region, it is important to have a basic understanding of the geographical setting, mechanics of tidal processes, historical storm activity and climate change.

1.4.1 *Geographical Setting*

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 (Davidson-Arnott et al., 2002; van Proosdij et al., 2000). 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 (indicated by pale green on the IKONOS satellite image in Figures 1 & 2). These dykes now protect significant amounts of infrastructure. The region also has a history of construction of tidal barriers, particularly in the 1960s. Large causeways were constructed across the main large tidal rivers in the area in order to decrease maintenance costs associated with protecting large expanses of agricultural land upstream. These aboiteaux, culverts, causeways and dykes have altered the hydrodynamics and sedimentary processes within the estuary, decreasing fish habitat, causing increased siltation in some areas (e.g. Petitcodiac and Avon Rivers) or erosion in others as well as influencing the development of foreshore marsh (seaward of dyke).

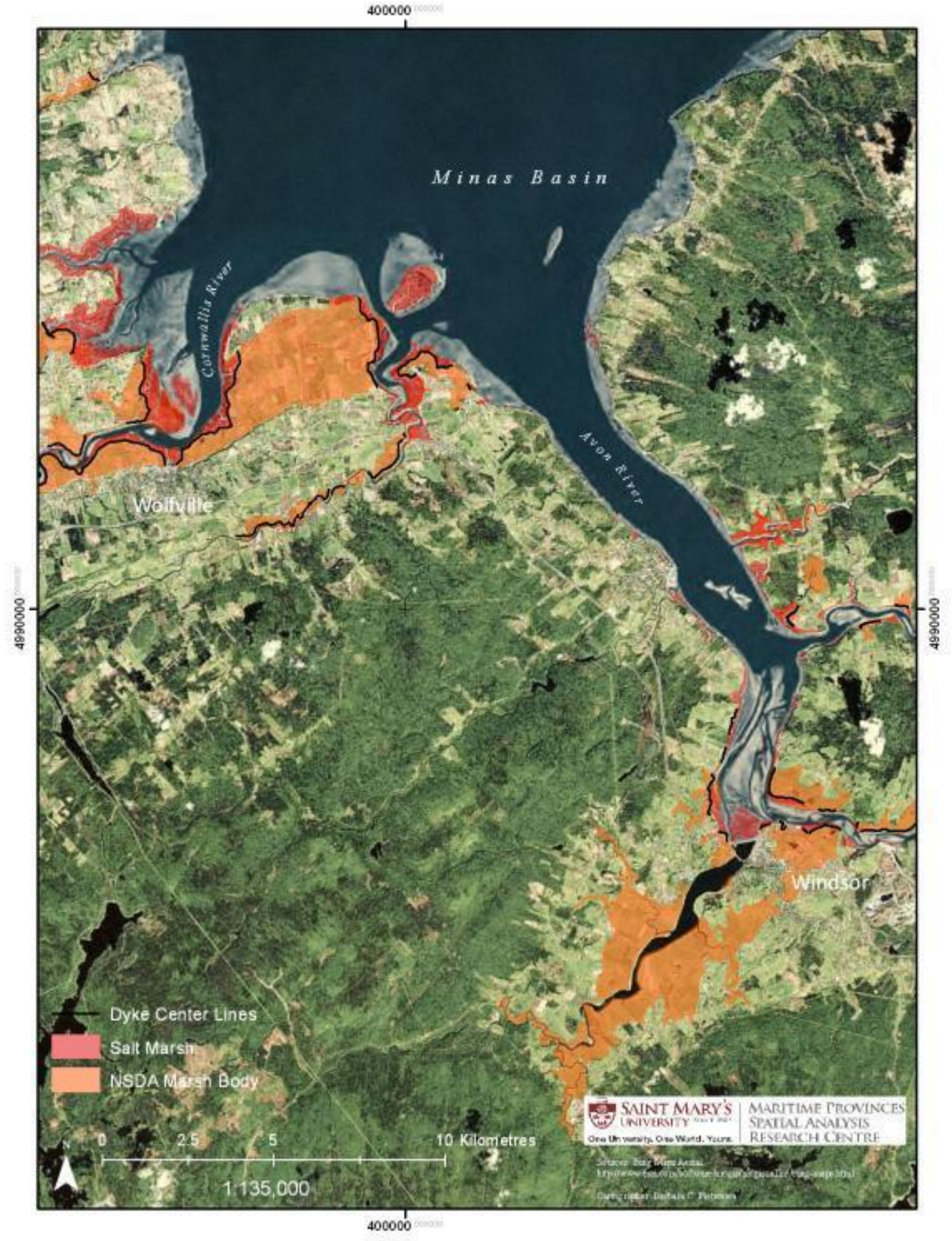


Figure 1: Salt marsh and NSDA Marsh Bodies in the Southern Bight of the Minas Estuary as of 2007. Pale green color on IKONOS satellite image indicates expanse of former salt marsh and associated low lying areas prior to historical dyking

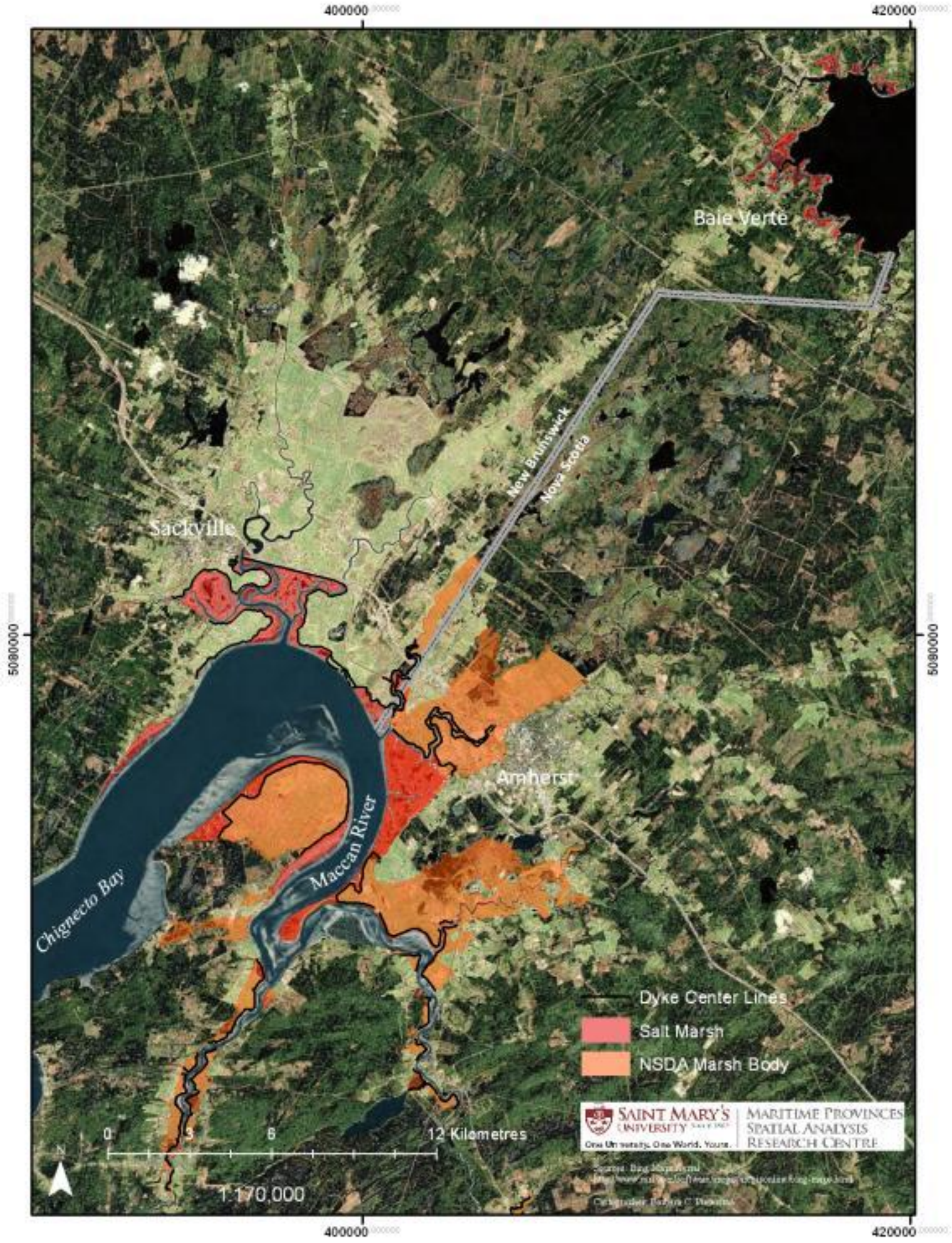


Figure 2: Salt marsh and NSDA Marsh Bodies in Chignecto Bay. Marsh body boundaries were not available for NB.

1.4.2 *Tides, Currents and Waves*

The Bay of Fundy is renowned for its large tidal range, which reaches a maximum of 16.3 m at Burntcoat Head in the Minas Basin. Tidal range in the Avon River estuary varies from 8.2 m Chart Datum at neap tide and 15.6 m CD at lunar perigee spring tide (CHS 1976, predictions for Hantsport). The Higher High Water Large Tide (HHWLT) level for Cumberland (Joggins predictions) is set at 13.4 m Chart Datum (Webster et al., 2011). Tides are strongly semidiurnal (twice a day) with a diurnal inequality that is almost always less than 0.6 m (Lambiase, 1980).

Tides produce strong currents which are the main agents of transportation and deposition of sedimentary material in the Bay, effectively transporting, creating, and remolding surface and geological features. A recent publication by Desplanque and Mossman (2004) provides a comprehensive overview of the mechanics and impacts of Fundy tidal processes on the geology of the region. Due to the relatively shallow nature of the Avon and Cornwallis River Estuaries, the rising limb of the tide will be compacted within a shorter period, whereas the period of the falling tide will increase.

> *"The highest tide recorded by the MMRA at the Windsor Bridge was 26.96 ft geodetic on April 4th, 1958, when the tide height predicted (tide table) for Saint John, New Brunswick was 29.1 low water datum. Note that this was the highest predicted tide for the region at least since 1932. The actual height reached at Saint John on this occasion was 29.0. The tide in the upper end of the Falmouth Great Dyke, above the Windsor Bridge, reached 26.85 geodetic, approximately one-tenth of a foot lower than the Windsor bridge peak.*
>
> *Many of the dykes constructed by this Administration around the inner perimeter of the Bay of Fundy were overtopped in sections by this tide which was sufficiently above our predictions to puzzle us. There were meteorological conditions favouring this particular occurrence and subsequent tides of the same predicted magnitude verified this as having been unusually severe.*
>
> *These tides, of 1958 and 1959, as peaks of the very definite cycle of approximately 18 years proved to us the adequacy of our dyke construction grades. It may be of interest to note that marshland owners at Falmouth were of the opinion dyke grades were too high when construction was in progress. It is believed that this 18 year cycle is not generally realized and that past occurrences are attributed to other factors or are forgotten."*
>
> Portion of letter from J.D. Conlon, Chief Engineer, Dept of Agriculture,
> MMRA to
> Mr. J.A. Brown, District Engineer, Habours & Rivers Engineering Branch,
> Department of Public Works on Oct 12, 1961in response to file No. 1411-11

However, this process will vary depending on the lunar cycle. At neap tide, the tidal curve is generally symmetrical with both the ebb and the flood flow lasting around 6.5 hours. In contrast, the tidal curve for spring tides is slightly asymmetric at the mouth of the estuary with ebb flows lasting 0.5 hours longer than flood. This asymmetry increases as one travels up the estuary, where there can be as much as 8.5

h of ebb flow with only 4 h of flood flow (Lambiase, 1980). As mentioned previously, the tidal prism is the volume of water flowing in and out of the estuary with the rise and fall of the tide. Because tides are variable in strength, the tidal volume and tidal prism are variable, as is the wetted cross sectional area. This results in variable pressure and erosive forces on the banks of foreshore marshes and toe of the dykes. In addition, during low water, sections of the estuary south of Hantsport and within the nearshore in the Cornwallis estuary are completely drained since bottom elevations are higher than the lower tidal limit. The Cumberland Basin however is deeper and has a less extensive lower intertidal zone.

Cycle	Period	~ Tidal range
Diurnal cycle due to relation of moon to earth	0.517 days (12 hr 25 min)	11.0 m
Spring/neap cycle	14.77 days	13.5 m
Perigee (high) / apogee (low)	27.55 days	14.5 m
206 day cycle due to spring/neap and perigee/apogee cycles	206 days	15.5 m
Saros cycle (last peaked in 1994-95 predicted peak in 2012-2013 AD)	18.03 years	16.0 m

Table 1: Summary of characteristics of major constituents of tidal cycles in upper sections of the Bay of Fundy (Desplanque & Mossman, 2004).

In general, higher water levels are recorded during spring tides and lower water levels are recorded during neap tides although, due to the tidal asymmetry in the Bay of Fundy, this is not always the case. In addition, the absolute elevation of the tide will vary depending on the relative position of the sun and the moon and orbital cycles (Table 1). The most favorable combination of factors to produce strong tides in the Bay of Fundy occurs when the perigee coincides with a spring tide and other cycles to produce Saros tides every 18.03 years (Desplanque & Mossman, 2004). Based on Desplanque & Mossman's (2004) calculations, the peaks of the Saros cycles within the last century occurred in 1904-1905, 1922-1923, 1940-1941, 1958-1959, 1976-1977, 1994-1995, and the next will occur in 2012-2013. In addition, detailed tidal records over several decades show that there will be slightly higher maximum monthly high water marks in a 4.5 cycle year, examples being the peaks in 1998 and 2002 (Desplanque & Mossman, 2004).

The only permanent tide gauge operated by Canadian Hydrographic Service is located in St. John, New Brunswick; therefore one must depend on predicted tides at Hantsport or Joggins for most historical calculations. However, detailed tide records have been maintained by Maritime Marshland Rehabilitation Administration (MMRA) and Department of Agriculture personnel at the Windsor Tide gate from the mid 1980s. In addition, MMRA and NSDA personnel routinely recorded tides at select marsh bodies throughout the region for short time periods. These data provide an idea of the difference in water level elevations between different marsh bodies. For example, a large tide on April 4, 1958 was recorded as 8.23 m CGVD28 (26.96 ft) at the Windsor bridge and 8.18 m at Burlington marsh (across from Hantsport), but 8.23 m at Herbert River and Chambers. Fortunately, the MMRA had recently increased the height of dykes in the region but this had not received extensive support at the time.

To date, the highest tides recorded at the causeway tide gate were 8.87 m (29.1 ft) (date unknown) (pers com. K. Carroll, 2007) and 8.6 m CGVD28 (28.2 ft) on January 10, 1997. These tide levels reflect the Saros cycle or the 4.5 yr cycle mentioned previously. Examining the digital record between April 2002 and September 2007, a total of 121 tides exceeded the HHWLT elevation (7.57 m CGVD28). Eleven of these dates were greater than 8.0 m (Table 2) with the highest recorded tide on February 1, 2006 (8.2 m) which overtopped dykes in many areas. Additional analysis of the tide record and comparison with predicted tides are recommended for the Cornwallis and Avon River Estuaries to develop an appropriate conversion. Refer to Ollerhead, 2011 for analysis of predicted versus observed water levels for the Tantramar dykelands.

Date	**Recorded Tide Height (m CGVD28)**
Feb 1, 2006	**8.211**
Nov 25, 2003	**8.206**
Feb 09. 2005	**8.170**
Feb 10, 2005	**8.129**
Feb 11, 2005	**8.129**
Dec 25, 2003	**8.082**
Dec 13, 2004	**8.046**
Dec 24, 2003	**8.040**
Sept 28, 2007	**8.024**
Dec 12, 2002	**8.004**
Aug 21, 2005	**8.004**
Feb 28, 2006	**8.004**

Table 2: Record of tides greater than 8 m geodetic at the Windsor tide gate between April 2002 and Sept. 2007

Due to the large tidal range, the time period during which waves can exert a significant influence is limited. Lambiase (1980) reports that waves are not an important hydraulic process on intertidal sand bodies in the Avon River estuary since waves tend to be small due to the limited fetch. These waves are believed to be the cause of small-scale slumps observed on sand bodies in the Avon and Cobequid bay (Darlrymple, 1979). Observed wave heights did not exceed 1.3 m in Lambiase's (1980) study and most ranged between 0.3 and 0.6 m. However, during high water the foreshore is covered with a significant amount of water, and a much larger percentage of wave energy reaches the shoreline than when the tide is at low water. The influence of wave action is much greater in the Cumberland Basin which has a much longer fetch and deeper intertidal zone. Waves can exert a significant influence in exposed areas on the edges of marsh cliffs and foreshore, causing erosion and local re-suspension of sedimentary material. In addition, it can cause considerable damage to dykes in exposed areas that are not protected by a vegetated foreshore. This was evidenced on August 23, 2009 when Hurricane Bill passed offshore Nova Scotia. Waves caused significant damage to the dyke at Noel despite the presence of shoreline armouring (Figure 3). Some of this rock material was transported over the top of the dyke into the low lying region behind (Figure 3). It is likely that another storm would have completely breached the dyke at the eroded location if it had not been rapidly repaired. The section of dyke protected by a section of marsh received minimal damage since once waves travelled over the marsh surface their energy was rapidly dissipated (e.g. Möller & Spencer, 2002). Therefore marshes can serve as natural forms of coastal defence. The extensive marsh which has developed downstream of the Windsor causeway offers a natural form of shore protection for the causeway, although limited protection is provided in the tide gate channel itself. In other areas such as along the outer bend of river channels, strong tidal currents will be the primary forces causing foreshore and marsh erosion.

Storm surges are a large rise in water level, which can accompany a coastal storm, and are caused by strong winds and low atmospheric pressure. Conversely, a negative storm tide can result from higher atmospheric pressure producing lower water levels than predicted. Compared to the Atlantic coast, storm surges exert less of an influence on the intertidal zone in the Upper Bay of Fundy due to the large tidal range. For example, a hurricane in July 1975 (recorded speeds of 130 $km \cdot h^{-1}$) only generated waves around 1.25 m in height and caused minimal changes to the morphology of sand waves in the Avon River Estuary (Lambiase, 1980). However, when a storm tide coincides with an exceptionally high astronomical tide (e.g. perigeen or Saros tide) the results can be significant, causing extensive coastal flooding and damage to infrastructure.

Figure 3: Impacts of Hurricane Bill on dyke at Noel (NS24) in August 2009. a) erosion and undercutting of earthen dyke structure and removal of shoreline armouring, b) armouring rocks transported to the landward side of the dyke by wave action and overtopping.

The heavy rainfall accompanying such an event can also cause extensive overland, freshwater flooding since the numerous aboiteaux and tide gates cannot discharge water at high tide (**Figure 4**). This has been seen in Truro, Nova Scotia on a number of occasions, most notably March 31, 2003 (**Figure 5**).

Figure 4: Modern aboiteau structure Grand Pre Marsh Summer, 2011

Historically, a number of significant storm events have occurred in the Bay of Fundy. Desplanque and Mossman (2004) provide a detailed account of the events surrounding them. One of the most notable storms was the Saxby Gale (or "Saxby Tide") which occurred on October 4th, 1869. Severe coastal flooding and wind damage occurred all along the North American seaboard. By 1:00 am on October 5th, the Saxby tide overtopped dykes by at least 0.9 m. In the Cumberland Basin, the tides were such that two fishing vessels were lifted over the dykes bordering the Tantramar marshes and deposited 5 km from the shoreline. At Moncton, the water level rose about 2 m higher than the next highest tide on record (Desplanque & Mossman, 2004). While damage in the Minas Basin was less severe, dykes were breached throughout the region, cattle and sheep drowned, and in many areas travel become impossible since the transportation lines (e.g. rail and road) were washed away. Desplanque and Mossman (2004) estimate that the Saxby Tide was at least 1.5 m higher than astronomically caused high tides at that time.

Figure 5 :Flooding in Truro March 31, 2003 as heavy precipitation run-off during high tide prevented freshwater discharge from dyke aboiteaux. Photo by Claude Barbeau

The 'Groundhog's Day' storm (February 2nd, 1976) is a classic example of the difference in impact due to timing with tide levels. Significant damage and coastal flooding were reported in Maine where water levels rose more than 2.5 m above the predicted level, heavily eroding the shoreline (Desplanque & Mossman, 2004). The strong SSE winds which had been blowing for five to six hours over the open water resulted in a storm surge up Penobscott Bay, and much of Bangor, Maine was flooded. Water levels rose to 3.2 m above predicted tides in fifteen minutes (Desplanque & Mossman, 2004). Fortunately for those in the Bay of Fundy, the tide was an apogean (e.g. lower) spring tide, therefore, although there was a recorded surge of 1.46 m, the damage was limited. If the storm had occurred during the perigean spring (sixteen days later on February 18th), the damage would have been significant (Desplanque & Mossman, 2004). It is estimated that if the Goundhog's Day storm had occurred on April 16th, 1976 it would have had the potential of "*causing calamity on the scale of the Saxby Tide*" (Desplanque & Mossman, 2004 p. 102).

If such an event were to occur in the present day, it would result in billions of dollars of damaged infrastructure and potentially loss of life, given the amount of development which has occurred behind the dykes (Shaw et al., 1994). Desplanque & Mossman (2004) suggest that the probability that a 'Saros' tide would coincide with an astronomically high spring tide is about 3%. However, postglacial sea-level rise significantly influences this probability. With every repeat of the 'Saros', an increase of the high tide mark of at least 3.6 cm (2 mm/yr for 18 yrs) can be expected (Desplanque & Mossman, 2004).

1.4.3 *Erosion, Accretion and Progradation*

Tides produce strong currents which are the main agents of transportation and deposition of sedimentary material in the Bay, effectively transporting, creating, and remolding surface and geological features. A recent publication by Desplanque and Mossman (2004) provides a comprehensive overview of the mechanics and impacts of Fundy tidal processes on the geology of the region.

Coastal erosion is a natural phenomenon which has always existed and has contributed throughout history to shape global coastal landscapes (Eurosian, 2004). Erosion processes, or the removal of sedimentary material from a cliff or bank, are essential to natural functioning of the coastal environment. The eroded material is re-distributed, allowing for the formation of intertidal flats, bars, beaches, and salt marshes in more sheltered areas. This influx of sediment helps to maintain a balanced sediment budget within the coastal system. Salt marshes and intertidal flats depend on the ability to accrete vertically within the tidal frame to allow for the colonization of salt tolerant vegetation. These features are also able to prograde horizontally, often balancing foreshore marsh erosion on the opposite shore and contributing to marsh cycles reported in the literature (e.g. Ollerhead et al. 2006; van der Wal and Pye, 2004; Cox et al., 2003; Pringle, 1995; van der Wal and Pye, 2008). Coastal systems within most estuaries try to maintain an equilibrium state with a net balance in import and export of sediment, controlled primarily by the tidal prism. Placement of armouring along the shoreline, land reclamation through dyking, or causeway construction will alter the natural processes of erosion and deposition, potentially leading to a dis-equilibrium state. As in other parts of the world, dyking decreases the accommodation space for sediment accumulation (Slagle et al. 2006) and causes a decrease in the tidal prism which enhances sedimentation (Healy and Hickey, 2002; van der Wal and Pye, 2003). This leads to initial development of foreshore marsh seaward of the dyke and has been observed within the Fundy region (van Proosdij and Baker, 2007). Tidal barriers such as causeways cause a decrease in the tidal prism and can lead to rapid accumulation of sediment immediately downstream of the structure. The extent of this accumulation however can vary significantly between estuaries (e.g. Petitcodiac versus

Avon River) (van Proosdij et al., 2009). Over time this can promote the colonization of low marsh vegetation (van Proosdij and Townsend, 2006; van Proosdij et al. 2009). However, as the estuary seeks to establish equilibrium, this deposition is offset by erosion mostly in the main channel through bed lowering as tidal currents are constrained between emergent bar features (van Proosdij and Baker, 2007).

1.4.4 *Salt marshes and Mudflats*

Due to its macrotidal nature, the upper Bay of Fundy has an extensive intertidal zone which primarily contains sand or mudflat and salt marsh ecosystems. These ecosystems form an important component of the estuarine food web contributing nutrients and organic matter (e.g. Daborn et al., 2003; Gordon and Cranford, 1994; Gordon et al., 1985). Salt marshes may be categorized as either high marsh (e.g. *Spartina patens*) or low marsh (e.g. *Spartina alterniflora*) species. In general, high marsh occurs above the mean high water level while the low marsh occupies the zone between mean high water and the high water level of neap tides (Daborn et al., 2003a). Cycles of erosion and progradation are marked by the presence of a low cliff between the high and low marsh zones.

1.4.5 *Meteorological and Seasonal Conditions*

A comprehensive description of the Avon estuary and surrounding region, as well as a summary of previous research in the area can be found in Daborn et al., 2003. Large ice blocks can also develop during the in the winter months and be rafted significant distances, transporting sediment, plant and animal material (Figure 6). Dominant winds are from the WSW and SW with the strongest winds during the winter months (Figure 7). In 2004 a metrological station was installed near the Windsor Tide Gate to provide local measures of temperature, precipitation, barometric pressure, and wind speed and direction. Comparison of wind speed and direction data with Kentville over the same time period suggests that strong NNE winds do occur at the Windsor site during the winter months (van Proosdij, 2007) (Figure 8). This has implications for wave hindcast modelling, and it could potentially cause some water set-up within the estuary, as this time frame coincides with the dominant fetch (distance 6.5 km) for the southern reach. The Cumberland basin area is much more exposed with a SW fetch almost the entire length of the Bay of Fundy which allows for the development of larger waves than in the Southern Bight.

Figure 6: Approximately 2.5 m high by 4 m block of ice blocking creek channel near southeast corner of Windsor marsh adjacent to causeway. Meter stick for scale. Photo by D. van Proosdij, Feb 25, 2005.

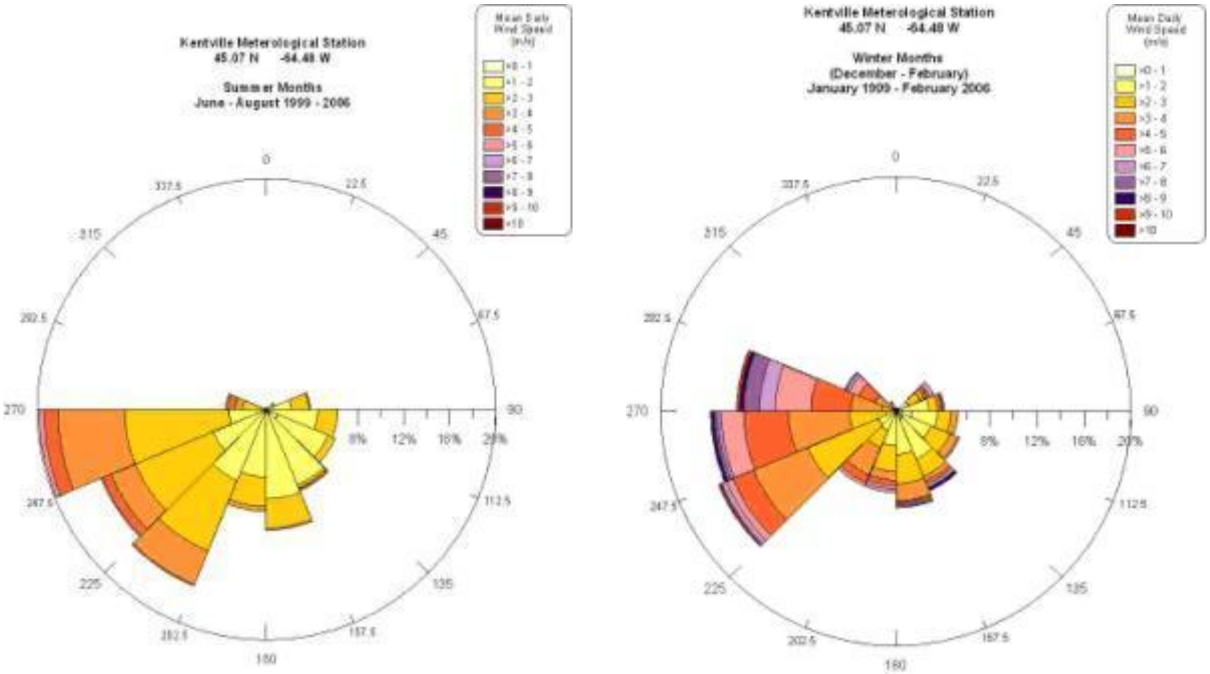


Figure 7: Wind rose diagrams derived from available wind speed and direction data from the Kentville meteorological station from 1996 to 2006 . Data are divided into a) summer and b) winter months (van Proosdij, 2007)

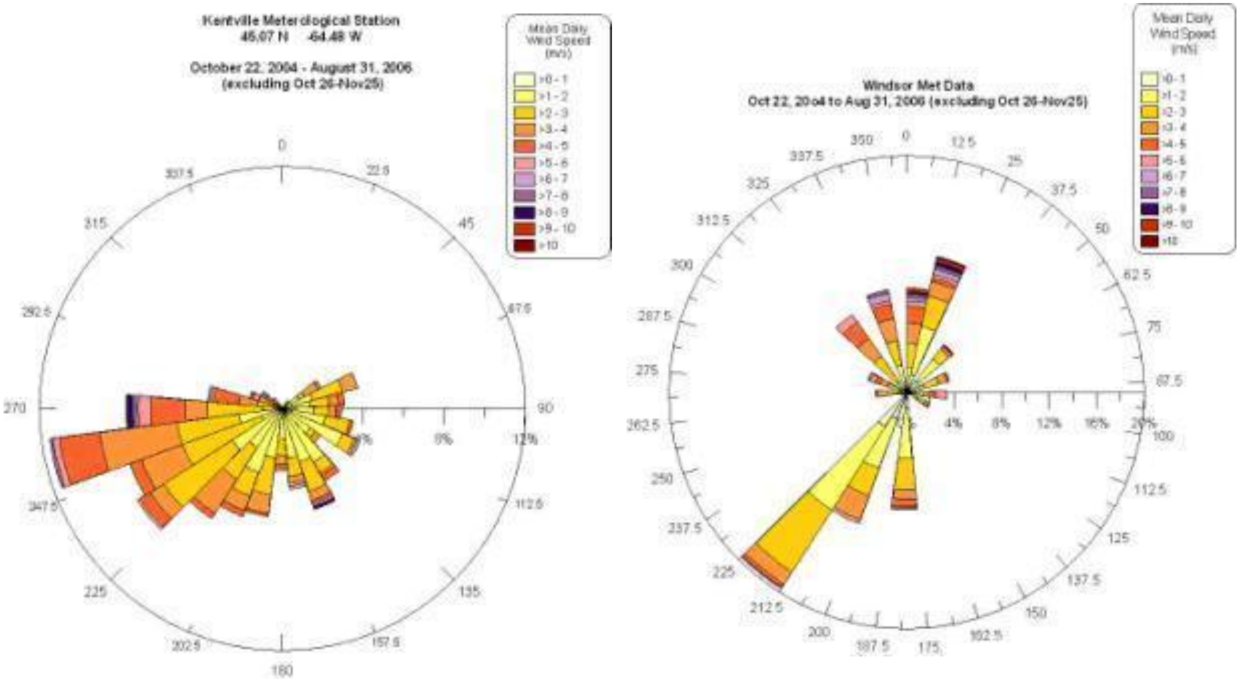


Figure 8: Comparison of wind speed and direction between a) the Kentville meteorological station (45.07N, -4.48W) from Oct 22, 2004 to August 31, 2006 and b) Windsor for the same time period recorded at a Weatherhawk^{tm} meteorological station (44.99 N, -64.15 W) (van Proosdij and Baker, 2007).

1.5 Dykes, Tidal Barriers and Climate Change

1.5.1 *Terminology*

In coastal defence literature, there are often many different terms used to describe similar coastal structures. The following definitions aim to provide a general understanding of dyke terminology. Although all terms are acceptable, for this report we will use the terms dyke and dykelands.

Dyke (Dike): an earthen structure that prevents flooding of the land it protects (Robins et al., 2004)
Dykelands: an area of land that is protected from flooding by a dyke (Robins et al., 2004)
Dike Ring: an area that is protected against flooding by a system of dykes. Dyke rings are most common in the Netherlands (Jorritsma-Lebbink, 1996)
Sea Dike System: see definition of Dyke Ring. Sea Dyke System is a term used in British Columbia (BC Ministry of Environment, 2011a)
Embankment: see definition of dyke
Levee: American synonym for dyke (Hillen et al., 2010)
Levee Ring: American synonym for dyke ring (Hillen et al., 2010)
Polder: an area of low-lying land that has been reclaimed from a body of water and is protected by dykes (Verbessem et al., 2007) (Very similar to dykelands)
Revetments: a structure made of concrete, stone or asphalt that protects the shoreline from erosion. Revetments are commonly used to armour sloping natural shorelines. (United States Army Corps of Engineers, 2006)
Seawall: a structure made of concrete or stone that alleviates overtopping and flooding of land and structures such as roads and houses and limits erosion of the coastline. (Linham & Nicholls, 2010)

1.5.2 Overview of Bay of Fundy Dykelands

The evolution of dykelands within the Bay of Fundy can be attributed to the arrival of French settlers, or Acadians, in the 1600s that were skilled in converting salt marsh to fertile marshlands by constructing dykes and aboiteux. Slowly over time the Acadians built new dykes, gradually extending farmland towards the seaward extent of high salt marsh hay (*Spartina patens*). This continued until the expulsion of the Acadians in 1755 followed by German, Yorkshiremen and Loyalist immigrants in the 1800s. This all changed in the 1920s when fossil-fuel engines replaced horsepower as North America's main source of energy. As a result, many hay fields that were brought into the boom were abandoned and dyke and aboiteau maintenance fell to the marshbody owners that remained. Government intervention was ultimately needed in the 1930s because of the socio-economic, ecological and political importance of the dyked areas. It was during this time that mechanization techniques, such as the use of tractors, were first employed to maintain and build new dykes which resulted in many old or original dykes being destroyed or were upgraded to newer and taller structures (Milligan 1987; Edwards 2001). Over the next 20 years, the MMRA ensured the protection of 18,000 hectares of tidal farmland in Nova Scotia and approximately 15,000 hectares in New Brunswick by building 373 km of dykes (Milligan, 1987). Over time there has been a continual cycle of maintenance and development. A detailed historic timeline is provided in van Proosdij (2012).

Between the years 1967-1970 the federal government turned the responsibility of dykes over to provincial managers. In the late 1960's to early 1970's, the provincial governments of Nova Scotia and

New Brunswick began the construction of causeways across important tidal waters to promote movement between towns as well as dyke protection by way of reducing tidal oscillations (Edwards 2001; Daborn et al. 2003). Large tidal dams were built near the mouths of the Shepody, Annapolis, Avon, Tantramar, Petitcodiac and Memramcook rivers. This eliminated the need for many kilometers of dyke and many smaller aboiteaux. For example, the Windsor causeway of Nova Scotia was first built between 1968-1970 and protects around 1300 hectares (ha) of agricultural land and 26 km of dykes (van Proosdij et al. 2009).

In 1970, the individual provinces took over all responsibility for the dyke infrastructure while the landowners were responsible for the lands behind the dykes. One of the aims of both the Nova Scotia and New Brunswick government was to increase the amount of land that could be farmed using modern machinery. At present, there is approximately 32,350 hectares of tidal land that is protected from tidal waters.

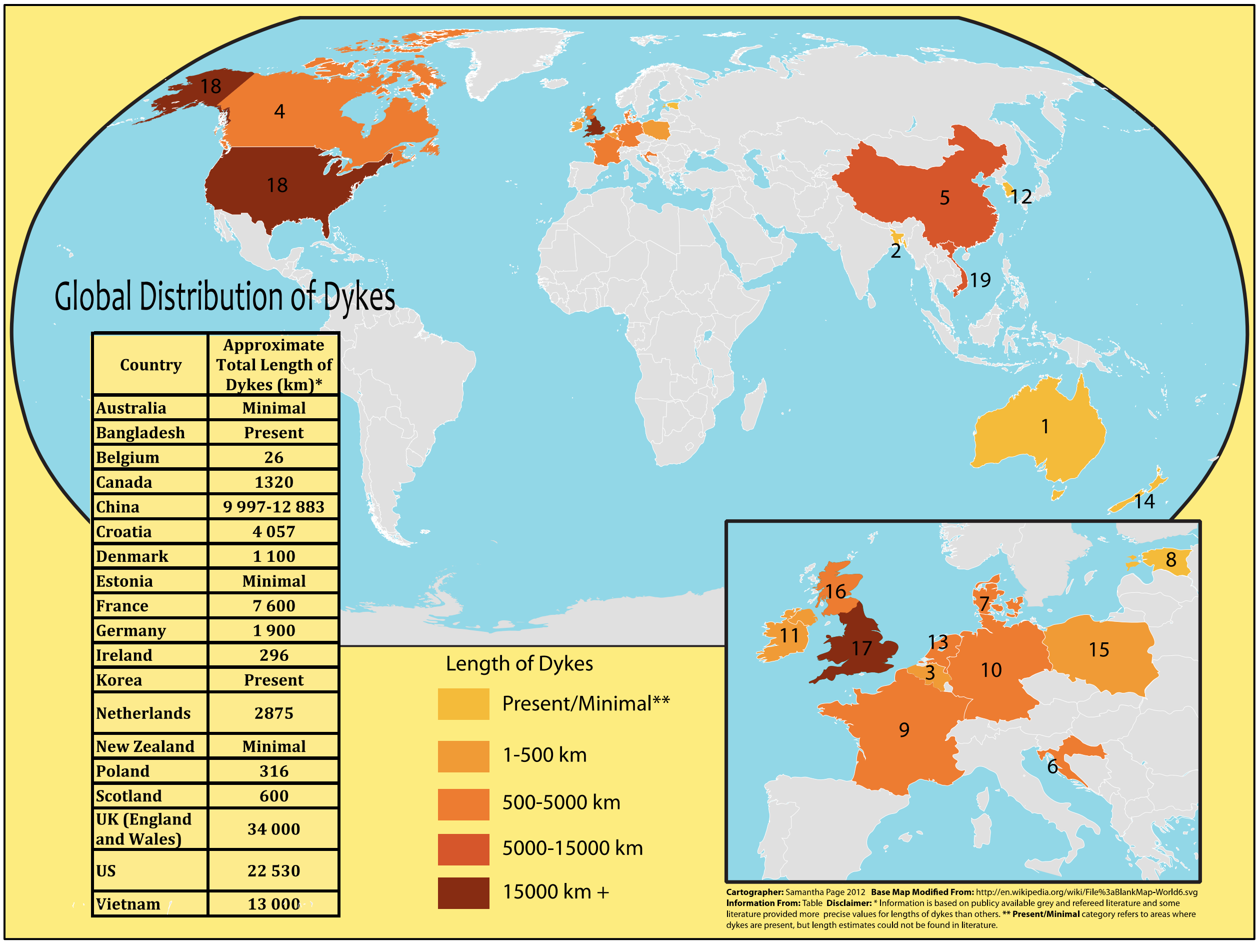
In Nova Scotia, the responsibility of dykelands is carried by the Nova Scotia Department of Agriculture (NSDA), Resource Stewardship Division, Land Protection Section and in New Brunswick this is carried by the New Brunswick Department of Agriculture, Fisheries and Aquaculture. Marshland staff monitor the integrity of the earthen dykes, dams and aboiteaux, and are responsible for their operation, maintenance and repair. Most of the mechanically operated tide gates now run on an automated system in association with the tides, however often must be manually operated by marshland staff in order to lower upstream water levels in response to a high precipitation event, to allow for fish passage, or for maintenance. Tidal dams are maintained for public safety, farming and fishing and can only be opened on the falling tide.

There is currently no Federal legislation regulating either dykelands or dykes. In Nova Scotia the marshlands are regulated according to the *Marshland Reclamation Act* from 1989 with numerous amendments through the *Agricultural Marshland Conservation Act* c.22,s.1 (amended 2004). It is explicitly stated that construction works (e.g. dykes, aboiteaux, breakwaters, etc…) are to be employed to protect agricultural land (hereby known as marshland). It dictates the incorporation of Marsh Bodies which clearly identifies the boundaries and size of the marshland section and the approximate amount of marshland owned by each owner in the marshland section. The owners may be constituted as a 'marsh body'. The marsh bodies have the power to acquire, sell and lease property, construct or repair construction works, enter into agreement with the Ministry for the construction, maintenance of these works, make by-laws and rules among others (Agricultural Marshland Conservation Act 2000, c.22, section 14). A permit for a variance is required for any development that takes place on a marshland section. This is granted by the Marshland Administrator and requires a supportive vote from two thirds of the marsh body members (Agricultural Marshland Conservation Act 2000, c.22, s.14). It is important to recognize that since agricultural land can tolerate some overtopping, the construction elevations and design of earthen dykes within the region are not designed to protect life and property. Municipalities located behind a dyke have no control over these activities nor are they financially responsible for repairs. This is different from the case in British Columbia where individual municipalities are financially responsible for maintenance and repair of flood structures (BC Minister of Environment, 2011) or in the Netherlands where design water levels were reviewed every 5 years by law (Hoekstra and DeKok, 2008) and are under federal jurisdiction. Those dykes are constructed to protect life and property.

Cumulative and synergistic effects of engineering projects and natural processes are often ignored or there are not enough empirical data for detailed analyses; and sediment transport and the littoral cell are not considered (Eurosian, 2004). 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, 1997). This decreased accommodation space can in 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).

1.6 Global Distribution of Dykes

Dykes are most commonly found in low-lying coastal areas, protecting land and communities from flooding. In the Netherlands, extensive dyke systems are also used to minimize the effects of river flooding. (Ross, 2011). 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. Needless to say, dykes play an important role in flood protection and are used in countries all around the world. (Figure 9 & Table 3).



Country	Approximate Total Length of Dykes (km)*
Australia	Minimal
Bangladesh	Present
Belgium	26
Canada	1320
China	9 997-12 883
Croatia	4 057
Denmark	1 100
Estonia	Minimal
France	7 600
Germany	1 900
Ireland	296
Korea	Present
Netherlands	2875
New Zealand	Minimal
Poland	316
Scotland	600
UK (England and Wales)	34 000
US	22 530
Vietnam	13 000

Cartographer: Samantha Page 2012 **Base Map Modified From:** http://en.wikipedia.org/wiki/File%3aBlankMap-World6.svg **Information From:** Table **Disclaimer:** * Information is based on publicy available grey and refereed literature and some literature provided more precise values for lengths of dykes than others. ** **Present/Minimal** category refers to areas where dykes are present, but length estimates could not be found in literature.

Figure 9: Global Distribution of Dykes

Country	Approximate Total Length of Dykes (km)*	Reference	Additional Comments
Australia	minimal	Abel et al., 2011	Dykes and embankments
Bangladesh	Present	Butzengeiger & Horstman, 2004	Dykes (earth) and embankments
Belgium	26	Wang et al., 1995	Artificial defence structures (mostly dykes)
Canada	1364	Mallin et al., 2007; BC Ministry of Environment, n.d.; van Proosdij, 2011	241 km in NS, 123 km in NB and 1000km in BC
China	9 997-12 883	Chen & Chen, 2001; Mazik et al., 2007	Dykes
Croatia	4 057	Baric et al., 2008; Petraš & Marušić	Dykes
Denmark	1 100	Fenger et al., 2008	Dykes
Estonia	minimal	Kont et al., 2008	Focused around Tallin
France	7 600	Ministère de l'Écologie, 2011	Dykes
Germany	1 900	Sterr, 2008	Baltic Sea (560km) + North Coast (1340km)
Ireland	296	Devoy, 2008	Includes Republic of Ireland and Northern Ireland
Korea	Present	Byun et al., 2004	Dykes, seawalls (Mokepo Coastal Zone)
Netherlands	2875	De Bake & Wolters, n.d.; Transport and Water Management Inspectorate, 2006	Dykes and dunes which provide direct protection against the sea, the major rivers and the Ijsselmeer and Markermeer lakes
New Zealand	Minimal	Butzengeiger & Horstman, 2004	Seawalls, dykes
Poland	316	Pruszak & Zawadzra, 2008	Polder dykes
Scotland	600	The Scottish Government, n.d.	Defended coastline
UK (England and Wales)	34 000	Hall et al., 2005	Flood defences
USA	22 530	United States Army Corps of Engineers, n.d.	22 530 dykes are in the Levee Safety Program, but there are estimates of 161 000 km of dykes in the US
Vietnam	13 000	Southern Institute for Water Resources Planning, n.d.	Embankments and dykes mainly in Red River and Mekong Delta

Table 3: Approximate total length of dykes in countries around the world

Some literature provided more precise values for lengths of dykes than others and accordingly the values given are only estimates of total lengths of dykes. In some cases, a qualitative description will be given for locations

where dykes are present, but length estimates could not be found in the literature. **Locations included in table are based on those found in publically available grey and refereed English and French literature.

2 Dyke vulnerability

2.1 Evolution of Design Standards

Dykes have been used for centuries for flood protection and land reclamation. Initially their design was based on observations and experience of local inhabitants and used local sources of material (e.g. brush, soil, sod, logs). Water levels were observed and dykes were constructed higher and seaward slopes armoured in areas known to be more susceptible to wave action. Standards were based on the highest recorded water level plus 0.5 to 1.0 m (Pilarczyk, 1998). Acadians in the Bay of Fundy invented the aboiteau or tide gate to permit freshwater drainage during low but also to permit 'tiding' and entry of nutrient rich silt into the agricultural land (Province of Nova Scotia, 1987). To keep labour and material costs to a minimum however, dykes were built as short and narrow as the tides would permit using marsh mud and sod from a borrow pit (Milligan, 1987). Generally these dykes were approximately 2 m in height with a 5 m base and a level top 0.6 m across resulting in a steep slope with a vertical to horizontal ratio of 1:1 (Province of Nova Scotia, 1987). Brush or plants were used to protect the dyke face from waves.

After a period of severe flooding from the North Sea in 1953 that resulted in massive dyke failures in the Netherlands, the Delta commission was created in Holland to shorten the coastline and implement a more scientific approach to flood defences (Pilarczyk, 1998; BC Ministry of Environment, 2011). The Delta commission recommended safety standards for individual 'dyke rings' based on weighing the costs of construction of flood defences and possible damages caused by floods (Pilarczyk, 1998). Statistics were used to define expected storm surge levels and associated wind and wave related set-up (BS Ministry of the Environment, 2011). Total water level included astronomic tides and storm surge with a defined return period or annual probability of being exceeded (AEP) and an additional freeboard for wave effects (BC Ministry of the Environment, 2011). The Netherlands then came up with a simplified standard based on design loads where the basic assumption was that every individual section of dyke had to be high enough to safely withstand a given extreme water level and associated wave impact. Each section had to have a maximum angle of inner slope and minimal strength of surface cover to assume sufficient safety based on a probabilistic flood return period. This was referred to as the "overload" or "probabilistic" approach (Pilarcyzk, 1998; Hoekstra and DeKok, 2008).

When designing a coastal structure, one needs to consider the function of the structure, physical environment, construction method and operation and maintenance (Pilarczyk, 1998). Particular attention needs to be paid to loading zones along the seaward edge of the dyke and the stability of the underlying substrate. In general, the degree of wave attack on a dyke during a storm depends on the angle of attack, the storm duration, strength of the wind, fetch (amount of open water in front of the dyke), presence or absence of foreshore marsh and bottom topography (Pilarczyk, 1998).

Design will also be affected by the mandate of the regulatory body. For example, in BC and the Netherlands, the function of sea dykes is to protect people and assets behind the dyke against the effects of flooding and inundation (BC Ministry of the 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 curve generated (Hoekstra and DeKok, 2008). In Nova Scotia, the NS Department of

Agriculture, Resource Stewardship, Land Protection Section is mandated through the Marshlands Act to protect agricultural land although often protects other public and private infrastructure (van Proosdij, 2012). In all areas dykes are not intended to protect the shoreline or adjacent seabed from erosion.

It has been explicitly recognized that some risk of flooding or inundation must be accepted and it is not economically practical to build defence structures large or safe enough to prevent all flooding (BC Ministry of the Environment, 2011). Additional limits include available land (e.g. to increase base of footprint of dyke), existing land uses, soil or foundation conditions, access, visibility over the dyke, available construction equipment and habitat issues (BC Ministry of Environment, 2011; BC Ministry of Water, Land and Air Protection, 2003)

2.2 Cross Sectional Profile

Dykes are earthen structures that prevent flooding of the land they protect. The components of a typical dyke include a sand core to allow water that enters the dyke to easily drain, an impermeable cover such as asphalt or clay to prevent water from entering the sand core, toe protection to minimize scour and undercutting, a drainage channel to allow water that enters the core to drain away, a steep or gentle seaward slope to reduce wave energy and a steep landward slope to minimize land take (Lindham & Nicholls, 2010). (Figure 10). Dyke slopes are often described by a ratio of vertical to horizontal measures (e.g. 1:3). The closer the values, the steeper the slope (e.g. 1:2 is steeper than 1:4). A 1:1 slope would have an angle of 45 degrees compared to 27 and 18^0 for 1:2 and 1:3 slopes.

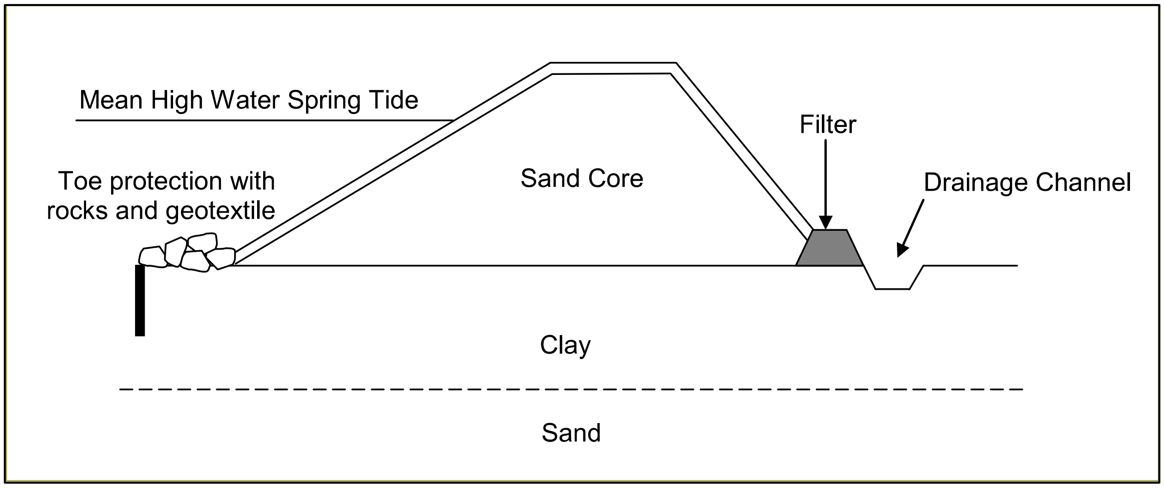


Figure 10: A typical dyke profile (Adapted from Lindham & Nicholls, 2010)

However, depending on the authority responsible for dyke construction, their cross sectional profiles and engineering specifications can vary from place to place. This section provides an overview of cross sectional profile examples from the United States, The Netherlands, British Columbia, Vietnam and the Bay of Fundy.

2.2.1 *United States*

The United States Army Corps of Engineers (USACE) are responsible for dyke construction in the United States and they use the following specifications when constructing sea dyke structures (Figure 11):
Function: protection of low-lying areas against flooding
Construction Material: sand, silty sand and clay

Seaward Slope: gentle slope, but a steeper slope results in the need of stronger armour

- ***Steep Slope (1:3, 1:5):*** asphalt armouring
- ***Gentle Slope (1:10):*** grass armouring

Landward Slope: steepness determined by risks of slip failures and erosion by piping

NOTE: when there is risk of erosion of the foreshore, it is recommended to design an embedded toe or a flexible toe

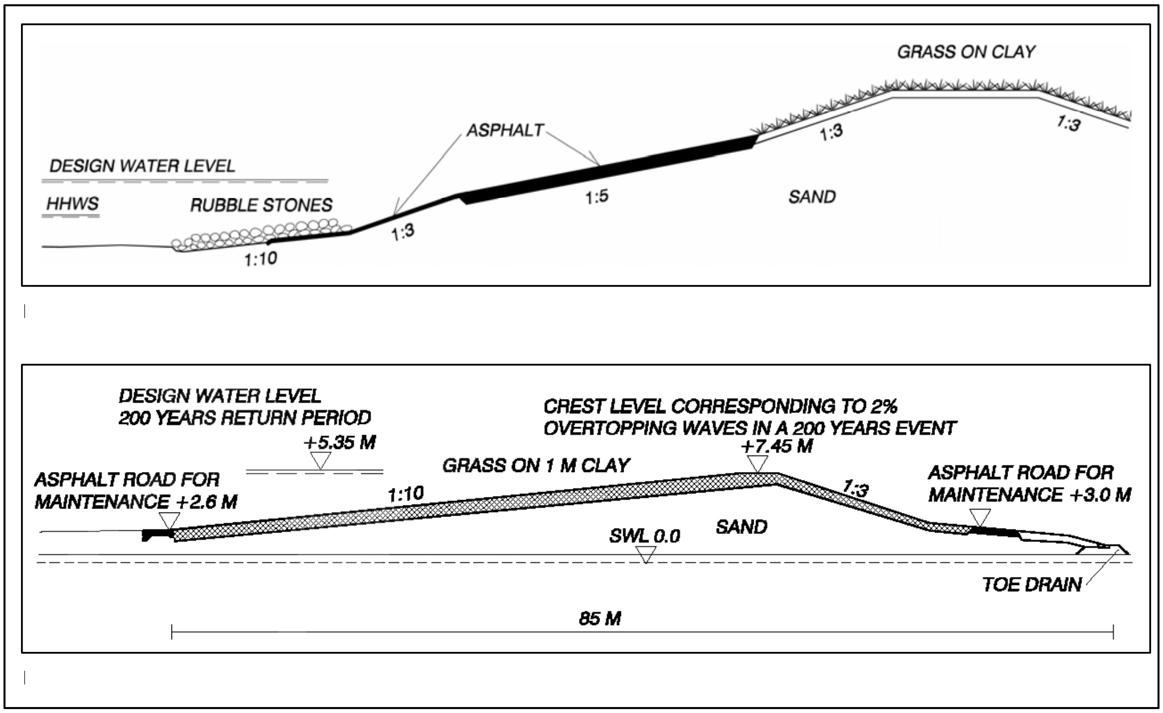


Figure 11: Selected dyke profiles from the United States Army Corps of Engineers (United States Army Corps of Engineers, 2006).

A typical levee cross section in New Orleans is presented below (Figure 12).

Construction Material: hydraulic till with asphalt armouring to provide structure flexibility in the case of settlement.

Seaward Slope: 1:6, which encourages wave energy dissipation

Landward Slope: 1:4, which has been determined as a safe value when taking overflow and soil mechanics into consideration (Hillen et al., 2010).

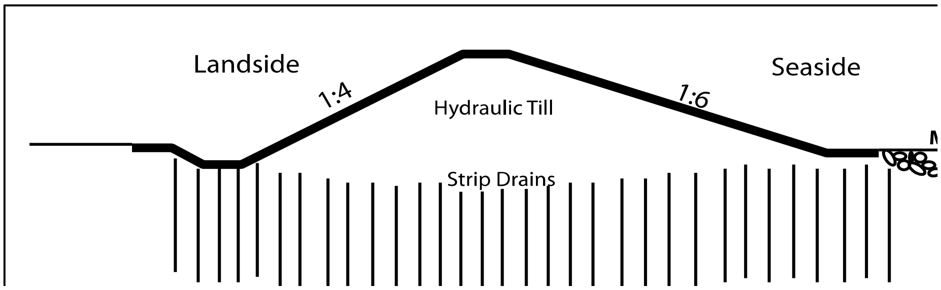


Figure 12: Profile of a New Orleans levee

2.2.2 *Netherlands*

The basic sea dyke design in the Netherlands includes a seaward face with a 1:3 to 1:6 slope (V:H) to decrease wave loading and a landward height to width ratio of 1:2 or 1:3 in order to minimize land take and maximize stability (Zhu et al., 2010). Typically there is a core of sand to allow water that enters the dyke to drain away as well as some form of impermeable cover layer to protect the sand core (Barends, 2003); some form of toe protection (e.g. armour stone) (Pilarczyk, 1998) and a drainage channel (Zhu et al., 2010).

In general, the design of coastal structures is based on a deterministic approach, which often does not account for uncertainties of the ocean boundary and the resistance of the structure (Mai van et al., 2007). In the Netherlands, a single weak spot determines the actual safety of an entire dyke ring (Mai van et al., 2007).

According to the Dutch, the following specifications pertain to sea dyke structures (Figure 13):
Function: to protect low-lying, coastal areas from inundation by the sea under extreme conditions
Seaward Slope: gradient between 1:3 and 1:6
Landward Slope: gradient between 1:2 and 1:3 (A steeper back slope minimizes the amount of land used)
Armour: can be composed of clay or asphalt with the purpose of protecting the sand core
Toe Protection: prevents waves from scouring and undercutting the structure
Construction Materials: mainly sand
Drainage Channel: allows water that has entered sand core to drain away

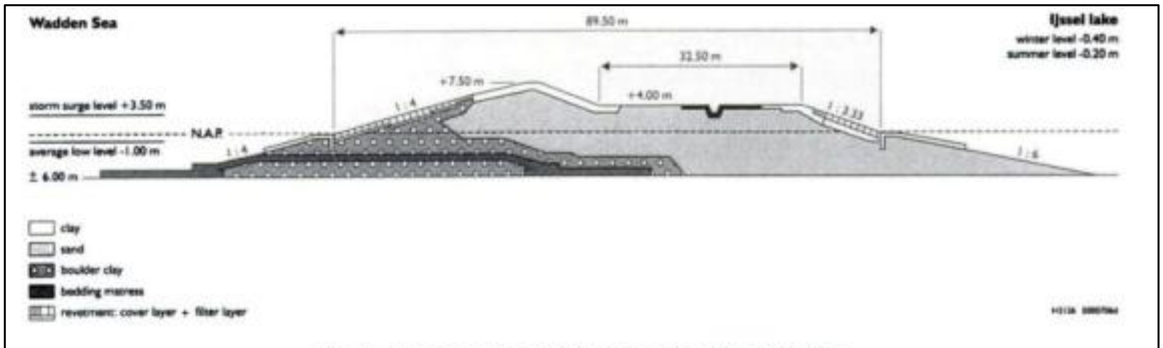


Fig. 2. Cross-section of Enclosure Dike/Barrier Dam.

Figure 13: Example of a dyke profile from the Netherlands (Chen et al., 2002).

2.2.3 *British Columbia*

For British Columbia, there are no general dyke specifications, as the procedures in "Sea Dyke Guidelines" are to be used to calculate specifications for each particular scenario. In British Columbia, dykes are designed for a 1 in 200 yr storm return period, coupled with high tide and freeboard however these design standards are increased for areas most at risk (BC Ministry of the Environment, 2011; BC Ministry of Water, Land and Air Protection, 2003). Freeboard refers to the vertical distance added to the designed flood level and is used to establish the flood construction level (BC Ministry of the Environment, 2011). At present, the minimum freeboard allowance is 0.6 m.

On the seaward side, the slope of the dyke typically is gentle (1:3 V:H) to reduce wave run-up and wave impact and will also be armoured. The steepness of the rear slope is determined by risks of slip failure and erosion by piping (USACE, 2006) and associated with materials used to construct the dyke. The following figures illustrate examples of simplified cross sectional profiles for existing and future dykes for two B.C. communities; Boundary Bay (Figure 14) and Richmond (Figure 15).

Boundary Bay
Function: protect low-lying agricultural land
Seaward Slope: 1:3, armoured with stone
Landward Slope: armoured with grass

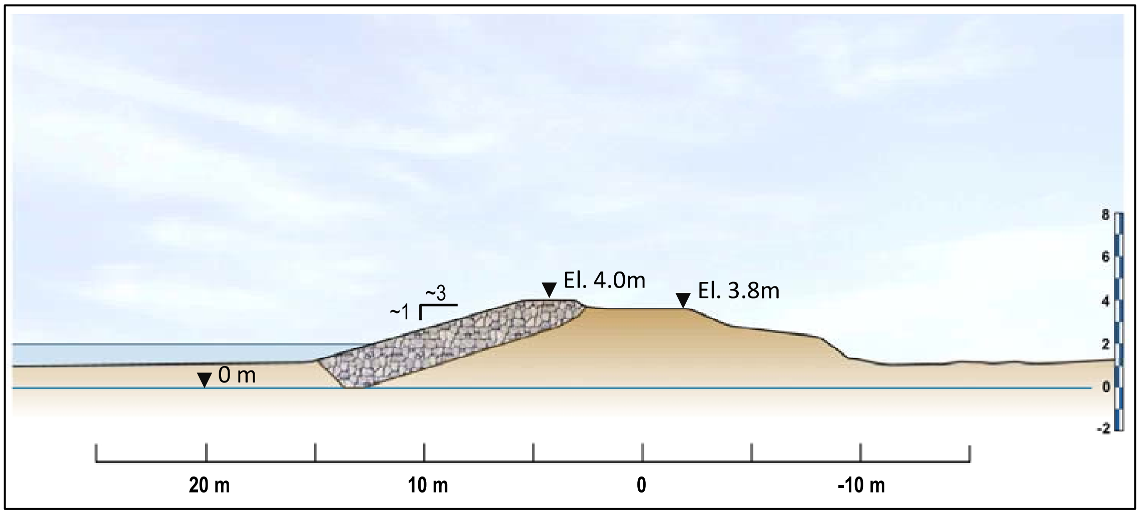


Figure 14: Cross sectional profile of existing dyke in Boundary Bay, BC (BC Ministry of Environment, 2011a).

Richmond
Function: protect large city as part of a larger dyke system
Seaward Slope: 1:5, armoured with grass
Landward Slope: steep slope, armoured with grass
Drainage Channel: present

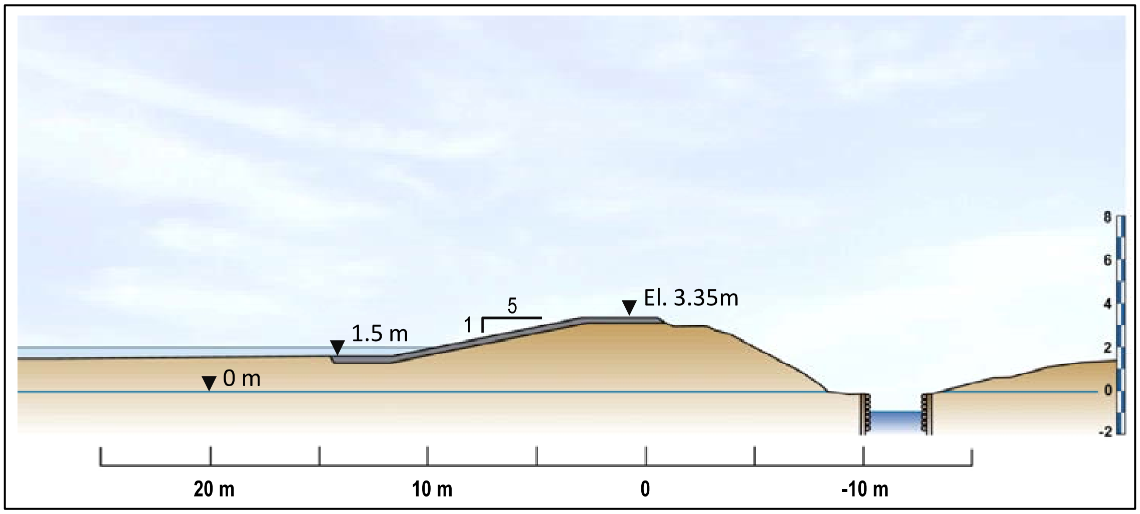


Figure 15: Cross sectional profile of existing dyke in Richmond, BC (BC Ministry of Environment, 2011a).

2.1.1. *Vietnam*

A typical cross section for sea dykes in the Nam Dinh Province of Vietnam is illustrated in Figure 16.
Function: protect large coastal population from flooding and protect low-lying agricultural land from flooding and erosion
Construction Materials: sand/clay body and rock revetments
Seaward Slope: 1:4 consisting of layers of loamy clay, gravel and coarse sand and a rock revetment
Landward Slope: 1:2
Dyke Height: dykes are constructed up to heights of 8 m

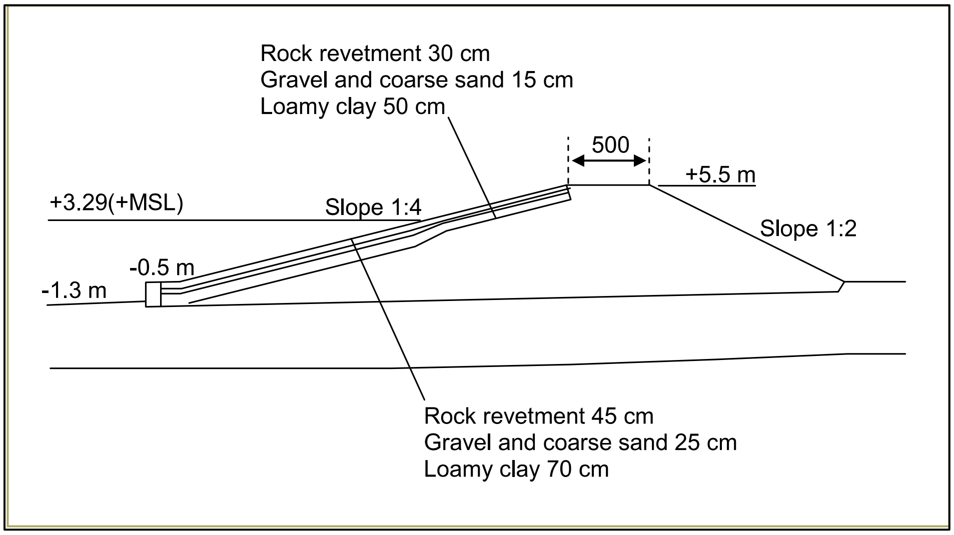


Figure 16: Typical cross sectional profile of a dyke in Nam Dinh Province, Vietnam (Lindham & Nicholls, 2010; Hillen et al., 2010).

2.2.4 *Atlantic Canada*

In the Atlantic Canadian RAC area, dykes primarily consist of marsh soil for fill, woven synthetic fabric to strengthen core and prevent erosion on dyke face, rock armour on the seaward slope (on exposed dykes only) and grass cover on the crest and landward slope to help protect the dyke from overtopping by tides and rain. (Province of Nova Scotia, 1987) (Figure 17). Brush matting is used in areas where reinforcement of the foundation was needed (Klassen, 2010). The 'working' design however may be modified due to lack of local suitable material along the construction corridor or restricted area to build the dyke (pers communication D. Hingley, April 6, 2012).

Construction Material: earth (van Proosdij, 2011).
Seaward Slope: 1:3, with vegetation and rock armour (where needed) at the toe
Landward Slope: 1:2, with vegetation

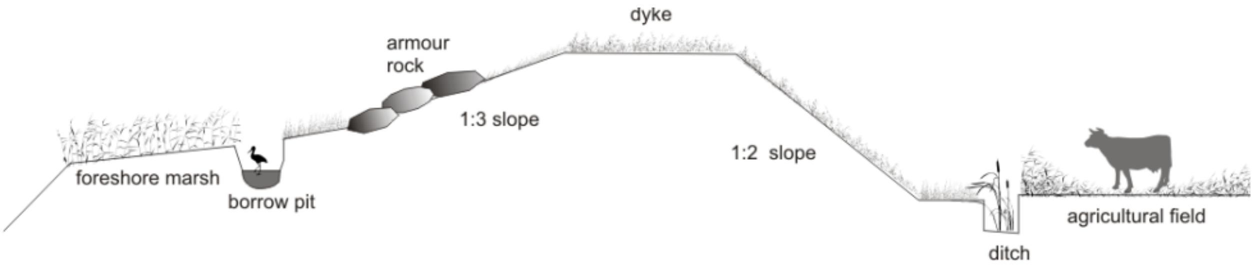


Figure 17: A typical cross sectional view of a dyke in the Maritimes based on a 1958 MMRA design (Adapted from: van Proosdij, 2011).

In Fundy, the Department of Agriculture uses the traditional method of using dyke fill from a foreshore borrow pit, however includes the addition of a synthetic carpet like backing (Province of Nova Scotia, 1987) and rock for shore protection. The use of salt marsh sediments as a natural renewal resource for dyke construction is also practiced in Europe (Karle and Bartholomä, 2008). The significant tidal range and unpredictable and spatially variable stability of marshland soils makes each construction project unique. A difference in soil conditions between different locations with an individual marshbody can contribute to the failure of an aboiteau that is being relocated, as seen in the failure of the La Planche (Amherst) aboiteau in 2008 (Klassen, 2010).

2.3 Dyke Failure Mechanisms

Dykes will fail as a result of a range of conditions. Failure 'mode' refers to the ways in which the structures fail where as failure 'mechanism' refers to the process at which the dykes are failed by a certain failure mode (Mai van et al., 2007). Failure mechanisms are summarized in Figure 18 and include: a) overtopping; b) instability of slope protection element; c) sliding of outer and/or inner slope; d) piping; e) erosion of outer and/or inner slope and f) dyke toe instability. These failure mechanisms can result in a dyke breach. A breach typically refers to the failure of a flood defence structure (Floodsite, 2009) and will occur via a series of stages.

Breach initiation occurs where water starts to erode material through the embankment body or from the surface. Surface erosion can take place on either the landward or seaward slope, typically in an area directly impacted by waves or where grass cover is of poor quality. Subsequent waves will continue the process of erosion until large holes have developed, rock armouring removed or, if the storm last a sufficiently long time, erosion may lead to a full breach. This erosion does not affect the crest elevation of the dyke, therefore the rate of overtopping water does not increase dramatically unless the water level rises further. Once the dyke crest starts to erode and more water can flow over it, then breach initiation ceases and breach formation begins (Floodsite, 2009). In addition, earthen dykes may permit high water levels to force water to seep into the through the embankment if water levels are high for a sufficient length of time.

Breach formation occurs after initiation and is where erosion of the dyke starts to allow more and more water over or through the embankment as the crest lowers or the hole increases in size. In turn, the increased flow of water results in an increased rate of breach formation and normally results in complete failure of the flood embankment or dyke since it is very difficult to stop once the erosion has started.

Breach growth or widening occurs once erosion has reached the base level of the embankment. Often at this point erosion will begin to remove material from the base of the structure and breach growth or widening occurs through the continued erosion of material from the sides of the breach similar to gully formation. While erosion does occur through increased flow of water due to storm conditions, equivalent or more erosion occurs on the ebb tide as the large prism of water contained within the marshbody drains through a relatively narrow opening. This process will be repeated with each incoming and outgoing tide.

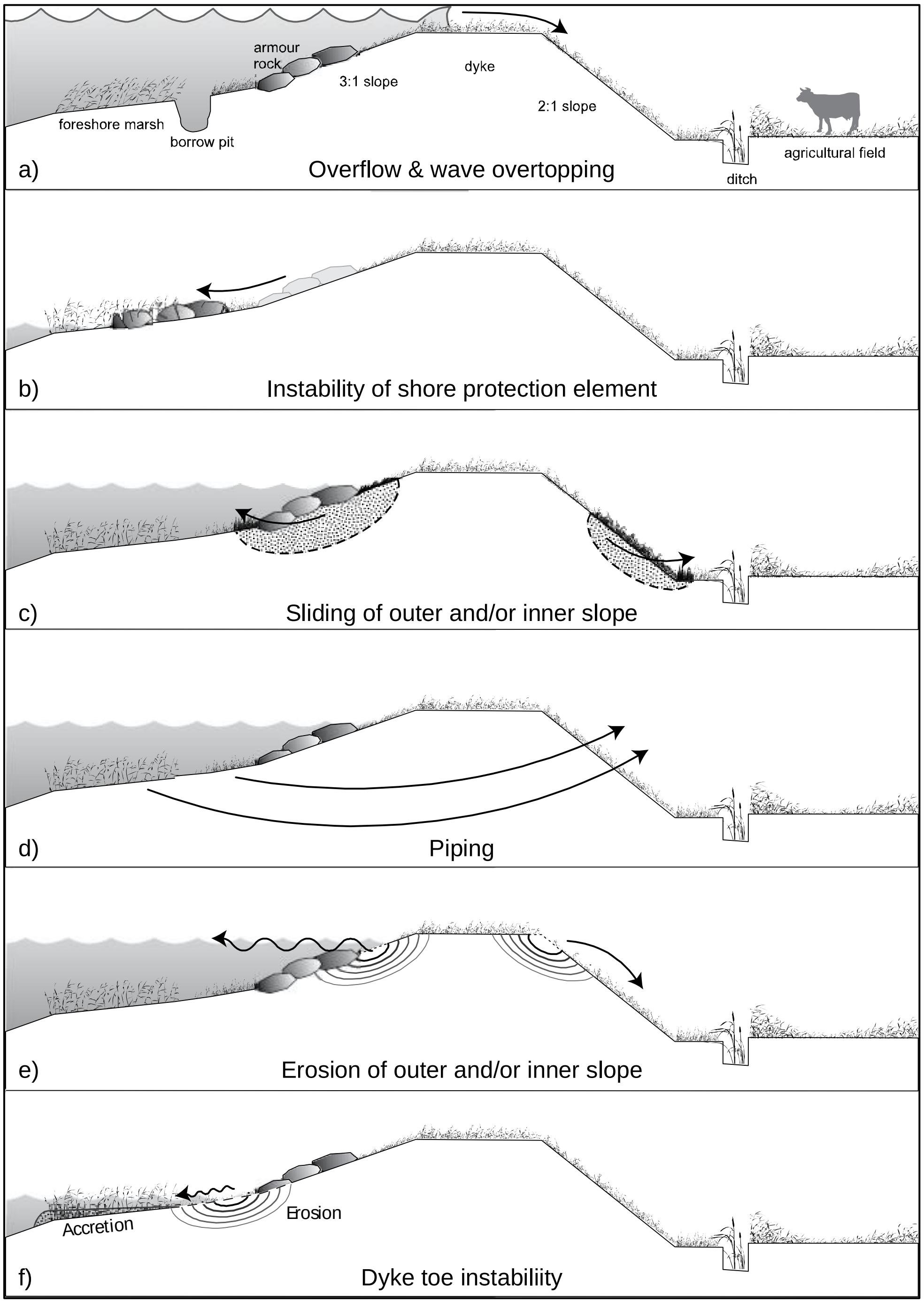


Figure 18: Types of mechanisms that can result in dyke failure (cartography by Will Flanagan, 2012)

2.4 Design Standards for Climate Change Adaptation

Although there are some general guidelines regarding climate change adaptation in dyked regions, the choice of an appropriate response option or adaptation measure is often very site specific (BC ministry of Environment, 2011). In Canada, a building code or standard does not exist for coastal engineering structures (BC Ministry of the Environment, 2011) however one can loosely ascribe the primary mandate of safety and security of people identified within the National Building Code of Canada to structural requirements of dykes.

Design uncertainties include those associated with climate change (e.g. future greenhouse gas emissions, rate of sea level rise, storminess, wave set-up and run-up), site condition (e.g. changes in bathymetry, relationship between mean sea level and datum used to describe the terrestrial elevation), surface and sub-surface soil conditions and variability in coastal erosion or settlement along the dyke or shoreline of interest (BC Ministry of Environment, 2011).

Barriers to implementation are high space requirements and cost (Zhu et al., 2010). Cost will likely increase in the future due to increased water depth and wave loading (Burgess and Townsend, 2004; Townsend and Burgess, 2004). In many cases coastal protective structures cannot be removed due to valuable infrastructure behind them that they protect therefore one needs to try and increase their value as habitat (Chapman and Underwood, 2011).

2.4.1 *Crest Elevation*

The parameters that are used to determine dyke crest elevation vary globally. However, most areas use the higher high water mean tides (Fundy) or the highest recorded water level (BC, Netherlands) upon which a freeboard (typically 0.6 m) is applied (Pilarczyk, 1998; BC Ministry of Environment, 2011; pers communication Ken Carroll, Dec 10, 2008) as a base level. In areas such as BC or the Netherlands, a potential storm surge level is then applied. In BC this is based on a 1:200 year storm return period (BC Ministry of Environment, 2011) whereas the Netherland's ranges from 1:1,250 to 1: 10,000 return periods depending on the value of land behind the dyke (Pilarczyk, 1998). Wave run-up and overtopping and resultant loading are also considered (Mai van et al., 2007). Pilarczyk (1998) suggests a general flooding frequency allowance for various types of properties (Table 4).

Type of Property	Suggested Flooding Frequency Allowance
High-yield agricultural land flooded by freshwater	1:10
High-yield agricultural land flooded by freshwater but with high investments	1:25
High-yield agricultural land flooded by salt water	1:50 – 1:100
Individual houses	1:50 – 1:100
Complete town	1:500
Big cities, industrial areas essential services (ie: airports railways)	1:1000

Table 4: Flooding allowance frequencies for various types of property (compiled from Pilarcyk, 1998)

Van Alphen (2012) undertook a comprehensive analysis to compare the investments necessary to improve the level of protection and the avoided damage of flooding. BC will also modify a dyke's critical elevation based on the value of infrastructure and population density behind the dyke.

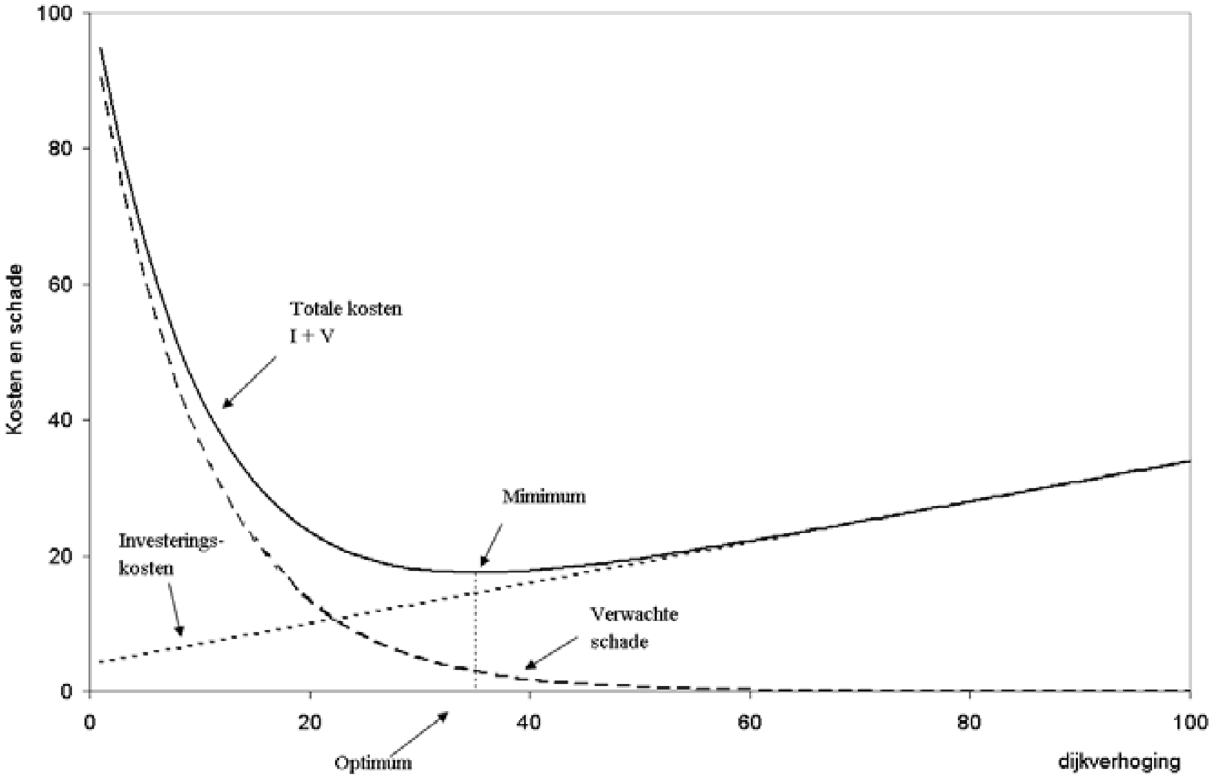


Figure 19: An illustration of the cost benefit analysis completed by the 1st Delta Commission for the area of Central Holland. In this figure, dijkverhoging = dyke heightening, kosten en schade = costs and damage, totale kosten = total cost, investerings-kosten = investment costs, verwachte schade = expected damage (Adapted from: van Alphen, 2012).

> *"The horizontal axis relates to dyke heightening (cm), the vertical axis relates to costs of dyke heightening or damage by flooding. Total costs of dyke heightening increase with height (continuously rising dotted line), while damage due to flooding decreases exponentially (hatched line). The economic optimum level of protection is where the sum of investments in dykes and residual damage (continuous line) shows a minimum, i.e. where further increase of dyke height doesn't outweigh the related avoided damage anymore."* (van Alphen, 2012).

The equation used to determine the optimal protection level is:

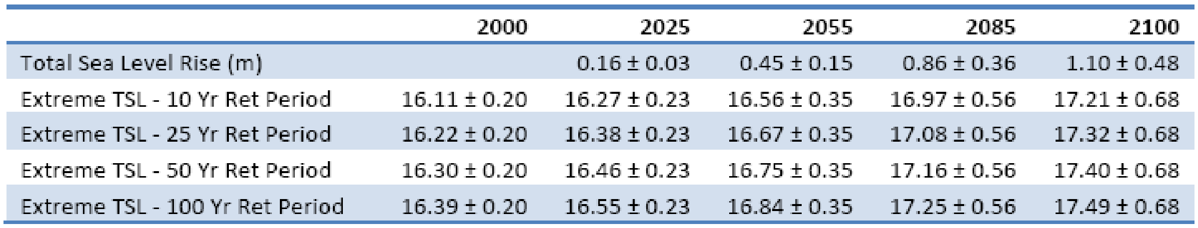
$$P_{opt} = (IrB)/D$$

Where: P_{opt}= optimal protection level (1:year)
I = costs per unit heightening/strengthening of the flood defence
r = net discount rate
B = constant related to the statistical distribution of the water levels
D = potential damage in case of flooding (Hillen et al., 2010).

Determination of a suitable crest elevation for climate change adaptation either involves the addition of global (determined by the IPCC) or a regional sea level rise estimate for the desired planning horizon (life of structure) which in most cases is 2100 (BC Ministry of the Environment, 2011) or resultant changes in the probabilistic storm wave return periods (Mai van et al., 2007) or a combination of both. It is important to recognize however that there are structural and financial limits for maximum dyke heights. In BC for example, the 'Designated Flood Level" (in m CGVD28) for climate change adaptation for 2100 in Boundary Bay (Figure 21) is equal to the elevation of the toe of the sea dyke (e.g. 1.6 m CGVD28) + regional SLR (1.2 m) + HHWLT (+1.8 CGVD28 m) + 1/500 yr storm surge (1.3 m) + local wind set-up (0.5 m). Note that the elevation of the toe of the sea dyke relative to CGVD28 is needed in order to calculate the existing difference between that elevation relative to datum and HHWLT (e.g. 1.8 – 1.6 = 0.2 m). Overall this translates to an elevation of 4.8 m CGVD28. This compares to 3.45 m CGVD28 for 2010 existing guidelines. Wave run-up is added as is an overtopping acceptance criteria of 10 L/s/m and finally a freeboard elevation (0.6 m) to allow for subsidence after construction.

Determination of critical elevations in the Bay of Fundy marshes have been historically based primarily on tidal heights and position of the marshbody within the estuary (exposed versus up river). The tidal height information was known from the Saint John station and could be accurately determined at various locations around the Bay of Fundy in the 1940s and 50s by the MMRA. Using spot tidal elevation checks and surveyed information from the existing dykes, a critical elevation based on the average high tide was established. 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 upriver dykes. There were studies carried out to determine the rate of dyke settlement for newly topped dykes at various sites and adjustments made accordingly to the construction elevation as well as surveyed tidal or rainfall events that occurred over the years. Construction elevations were then adjusted when dyke over topping occurred as the MMRA program proceeded. In 2002, the construction elevation was raised for all dykes in Nova Scotia by 0.30 m which raised the mid-point elevation for topping (pers. Communication K. Carroll, Dec 10, 2008). Critical elevations ranged from 7.6 to 8.1 m CGVD28 in Kings County and all were set at 8.2 m in Hants County. All were topped by 0.60 m to bring it up to construction elevations. 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.

Richard and Daigle (2011) identified total sea level rise for a series of stations in Atlantic Canada. Table 5 summarizes anticipated sea level rise for the Hantsport tide station in the Avon River. These values do not include the tidal expansion component mentioned in Greenberg et al. (in press) which is predicted to be 0.2 m by 2100, therefore are conservative estimates. All elevations are relative to chart datum and HHWLT is noted as 15.26 m chart datum at Hantsport. This translates to 8.03 m CGVD28. It should be noted that these storm surge values do not include the possibility of an extremely rare historic event such as the Saxby Gale (1869), Groundhog Day Storm (1976) or a direct hit by a hurricane (2003) (Richards and Daigle, 2011).



	2000	2025	2055	2085	2100
Total Sea Level Rise (m)		0.16 ± 0.03	0.45 ± 0.15	0.86 ± 0.36	1.10 ± 0.48
Extreme TSL - 10 Yr Ret Period	16.11 ± 0.20	16.27 ± 0.23	16.56 ± 0.35	16.97 ± 0.56	17.21 ± 0.68
Extreme TSL - 25 Yr Ret Period	16.22 ± 0.20	16.38 ± 0.23	16.67 ± 0.35	17.08 ± 0.56	17.32 ± 0.68
Extreme TSL - 50 Yr Ret Period	16.30 ± 0.20	16.46 ± 0.23	16.75 ± 0.35	17.16 ± 0.56	17.40 ± 0.68
Extreme TSL - 100 Yr Ret Period	16.39 ± 0.20	16.55 ± 0.23	16.84 ± 0.35	17.25 ± 0.56	17.49 ± 0.68

Table 5: Total relative sea level rise and storm surge height and return period for Hantsport CHS station (Richards and Daigle, 2011). Elevations are relative to chart datum. Richards and Daigle, 2011

Using the storm surge and sea level rise values provided by Richards and Daigle (2011), a range of new critical elevations are recommended for the Fundy ACAS marshbody dykes. These new elevations incorporate the position of the existing critical elevation relative to the observed HWL within each marsh body. Table 6 summarizes these recommended critical elevations. The choice of critical elevation will be up to the NS Department of Agriculture and will be influenced by the degree of risk willing to be assumed, value of land behind the dyke and presence of critical infrastructure as well as availability of construction material and cost. The HWL elevations identified within the table are derived from the HWL identified on individual marshbody plans within the Marshlands Atlas (Pietersma-Perrott and van Proosdij, 2012).

				Storm surge & return periods				Relative Sea Level Rise (m)				Combined (SLR + surge)		
	Hants County	HWL	Crit.	1:10	1:25	1:50	1:100	2025	2055	2085	2100	2055 &	2085 &	2100 &
NS #	Name	(m)	(m)	0.85	0.96	1.04	1.13	0.16	0.45	0.85	1.1	1:100	1:100	1:100
14	Elderkin	7.9	8.2	8.8	8.9	8.9	9.0	8.1	8.4	8.8	9.0	9.5	9.9	10.1
27	Newport Town	7.8	8.2	8.7	8.8	8.8	8.9	8.0	8.3	8.7	8.9	9.4	9.8	10.0
38	St. Croix*	7.9	8.2	8.8	8.9	8.9	9.0	8.1	8.4	8.8	9.0	9.5	9.9	10.1
48	Centre Burlington	7.6	8.2	8.5	8.6	8.6	8.7	7.8	8.1	8.5	8.7	9.2	9.6	9.8
49	Scotch Village	8.1	8.2	9.0	9.1	9.1	9.2	8.3	8.6	9.0	9.2	9.7	10.1	10.3
50	Hebert River	7.8	8.2	8.7	8.8	8.8	8.9	8.0	8.3	8.7	8.9	9.4	9.8	10.0
61	Kennetcook	8.1	8.2	9.0	9.1	9.1	9.2	8.3	8.6	9.0	9.2	9.7	10.1	10.3
68	Tregothic	8.4	8.2	9.3	9.4	9.4	9.5	8.6	8.9	9.3	9.5	10.0	10.4	10.6
79	Chambers	7.9	8.2	8.8	8.9	8.9	9.0	8.1	8.4	8.8	9.0	9.5	9.9	10.1
85	Mantua Poplar Grove	7.9	8.2	8.8	8.9	8.9	9.0	8.1	8.4	8.8	9.0	9.5	9.9	10.1
88	Burlington	8.1	8.2	9.0	9.1	9.1	9.2	8.3	8.6	9.0	9.2	9.7	10.1	10.3
93	Greenhill	8.2	8.2	9.1	9.2	9.2	9.3	8.4	8.7	9.1	9.3	9.8	10.2	10.4
100	Wentworth	8.1	8.2	9.0	9.1	9.1	9.2	8.3	8.6	9.0	9.2	9.7	10.1	10.3
105	Belmont	8.1	8.2	9.0	9.1	9.1	9.2	8.3	8.6	9.0	9.2	9.7	10.1	10.3

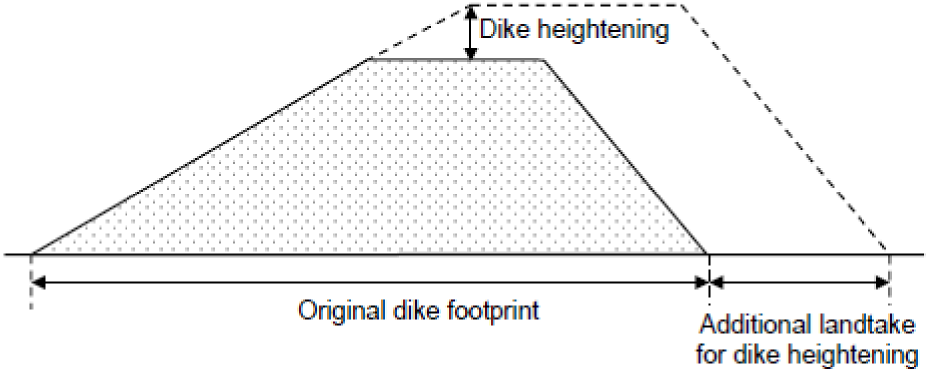
				Storm surge & return periods				Relative Sea Level Rise (m)				Combined (SLR + surge)		
	Kings County	HWL	Crit.	1:10	1:25	1:50	1:100	2025	2055	2085	2100	2055 &	2085 &	2100 &
NS #	Name	(m)	(m)	0.85	0.96	1.04	1.13	0.16	0.45	0.85	1.1	1:100	1:100	1:100
8	Grand Pre	7.9	8.2	8.8	8.9	8.9	9.0	8.1	8.4	8.8	9.0	9.5	9.9	10.1
41	Habitant	7.9	8.2	8.8	8.9	8.9	9.0	8.1	8.4	8.8	9.0	9.5	9.9	10.1
56	Wellington	7.9	8.2	8.8	8.9	8.9	9.0	8.1	8.4	8.8	9.0	9.5	9.9	10.1
57	New Minas	8.1	8.1	9.0	9.1	9.1	9.2	8.3	8.6	9.0	9.2	9.7	10.1	10.3
65	Bishop Beckwith	8.0	8.2	8.9	9.0	9.0	9.1	8.2	8.5	8.9	9.1	9.6	10.0	10.2
72	Hortons	7.7	8.1	8.6	8.7	8.7	8.8	7.9	8.2	8.6	8.8	9.3	9.7	9.9
76	Farnham	8.0	8.2	8.9	9.0	9.0	9.1	8.2	8.5	8.9	9.1	9.6	10.0	10.2
80	Starrs Point	8.0	8.2	8.9	9.0	9.0	9.1	8.2	8.5	8.9	9.1	9.6	10.0	10.2
82	Kentville	7.8	8.1	8.7	8.8	8.8	8.9	8.0	8.3	8.7	8.9	9.4	9.8	10.0
91	Belcher Street	7.8	8.2	8.7	8.8	8.8	8.9	8.0	8.3	8.7	8.9	9.4	9.8	10.0
92	Avonport	7.6	8.2	8.5	8.6	8.6	8.7	7.8	8.1	8.5	8.7	9.2	9.6	9.8
101	Pereau	7.6	7.9	8.5	8.6	8.6	8.7	7.8	8.1	8.5	8.7	9.2	9.6	9.8

				Storm surge & return periods				Relative Sea Level Rise (m)				Combined (SLR + surge)		
	Cumberland County	HWL	Crit.	1:10	1:25	1:50	1:100	2025	2055	2085	2100	2055 &	2085 &	2100 &
NS #	Name	(m)	(m)	0.85	0.96	1.04	1.13	0.15	0.42	0.82	1.05	1:100	1:100	1:100
42	Amherst Point	7.6	8.1	8.5	8.6	8.7	8.8	7.8	8.0	8.4	8.7	9.2	9.6	9.8
44	Converse	7.9	8.1	8.8	8.9	9.0	9.1	8.1	8.3	8.7	9.0	9.5	9.9	10.1
45	Barronsfield	8.1	8.1	8.9	9.0	9.1	9.2	8.2	8.5	8.9	9.1	9.6	10.0	10.3
46	River Herbert	8.0	8.1	8.9	9.0	9.0	9.1	8.2	8.4	8.8	9.1	9.6	10.0	10.2
53	John Lusby	7.8	8.1	8.6	8.7	8.8	8.9	7.9	8.2	8.6	8.8	9.3	9.7	10.0
54	Minudie	8.1	8.1	8.9	9.0	9.1	9.2	8.2	8.5	8.9	9.1	9.6	10.0	10.3
55	Seaman	8.1	8.1	9.0	9.1	9.2	9.3	8.3	8.6	9.0	9.2	9.7	10.1	10.3
63	Maccan	8.1	8.1	9.0	9.1	9.1	9.2	8.3	8.5	8.9	9.2	9.7	10.1	10.3
78	Athol	7.6	8.1	8.5	8.6	8.7	8.8	7.8	8.0	8.4	8.7	9.2	9.6	9.8
87	Chignecto	8.0	8.1	8.9	9.0	9.0	9.1	8.2	8.4	8.8	9.1	9.6	10.0	10.2
115	Nappan-Maccan	7.9	8.1	8.8	8.9	9.0	9.1	8.1	8.3	8.7	9.0	9.5	9.9	10.1
119	Upper-Maccan	8.1	8.1	9.0	9.1	9.1	9.2	8.3	8.5	8.9	9.2	9.7	10.1	10.3

Table 6: Recommended elevations relative to CGVD28 datum for Fundy ACAS marshbodies. Storm surge and sea level rise estimates derived from Richards and Daigle, 2011. HWL determined from NSDA marsh plans with the exception for Cumberland County where HWL value is based on HHWLT at CHS Joggins site and transformed to CGVD28 at Fort Beausejour by Ollerhead et al. 2011. Standard error for SLR estimates for 2025 and 2055 is 0.1 m, 2085 is 0.2 and 2100 is 0.4.

2.4.2 *Slope and Footprint*

As mentioned previously, dykes are designed for a particular slope with associated vertical to horizontal ratios. Typically these are 1:3 to 1:5 on the seaward edge to mitigate erosion effects and 1:2 to 1:3 on the landward edge. Therefore, in order to maintain these ratios when raising the height of the dyke for climate change adaptation, one must also increase the footprint of the base (Figure 20).



Schematic illustration of the large land areas required for dike construction and the additional land take required upon dike heightening

Figure 20: Schematic illustration of the large land areas required for dyke construction and the additional land take required upon dyke heightening (Adapted from: Lindham & Nicholls, 2010).

As an example, Figure 21 illustrates the new cross sectional plan for climate change adaptation for Boundary Bay in BC. The new crest elevation is 7.8 m CGVD28, which is 2.8 m higher than the 2010 existing guideline. The base increases in width by approximately 10 m on either side. This can provide a significant problem if land is not available or construction costs exceed the value of the land that the dyke is protecting. In the idealized Fundy example, a 1 m increase in elevation would translate into an additional 3 m of seaward expansion to maintain a 1:3 slope and 2 m for a 1:2 m ratio on the landward edge. A number of actual dyke cross sections from the Bay of Fundy will be examined in Section 3.2.

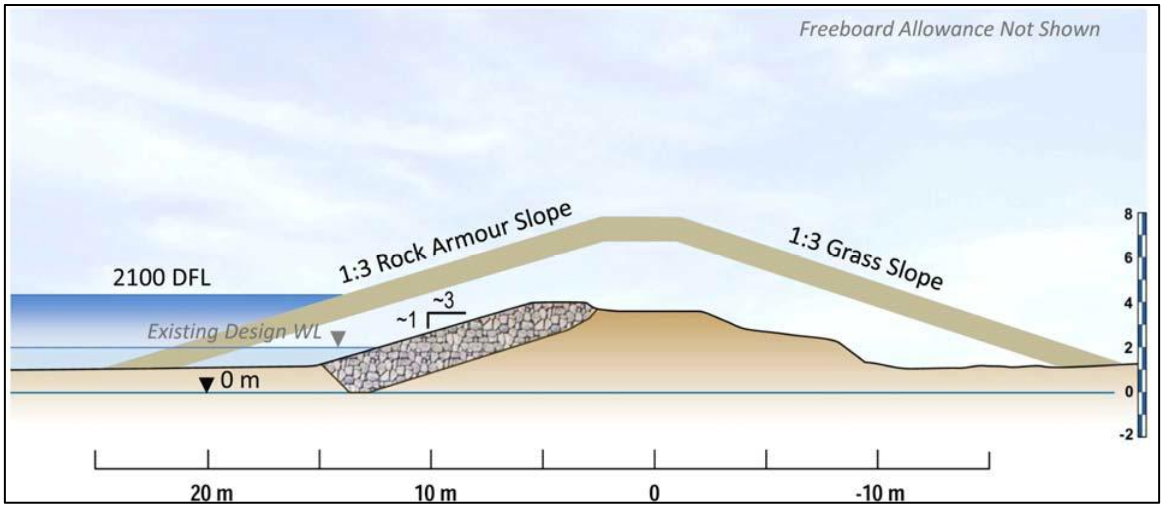


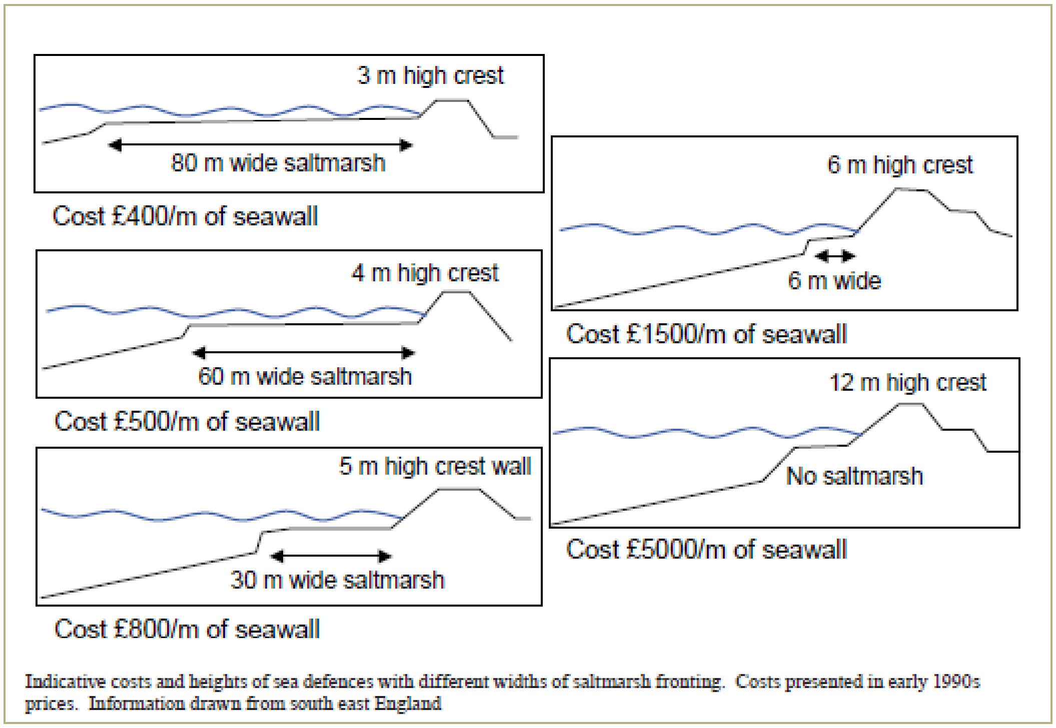
Figure 21: Cross sectional profile of dyke in Boundary Bay with recommended dimensions for climate change adaptation 2100 (BC Ministry of Environment, 2011a).

2.4.3 *Scour prevention*

All dykes typically have some form of material that is placed at the toe of the dyke for scour protection. In most instances this takes the form of rock armouring using local materials, rock revetments or brush matting. Two primary components of erosion can be distinguished: structural and acute (Eurosian, 2004). ‘Structural’ erosion is *“a continuing process of erosion due to adaptation of the coastal system to changed conditions”* (e.g. sea level rise) (Eurosian, 2004 p.35). This type of erosion is triggered or strengthened by human influence such as creation of a sediment deficit through dredging or interrupting longshore drift. ‘Acute’ erosion is mainly caused by storm events and erosion rates can be very high. However, if there is adequate sediment, the coastal feature can be rebuilt during intermediary calm conditions. Acute erosion however is a more serious problem at cliff coasts, including marsh cliffs. Preservation of an adequate width of foreshore marsh for energy dissipation is therefore one of the most cost effective and preferred options for shore protection. The advantages and disadvantages of hard (e.g. rock) versus soft (e.g. marsh) shore protection methods will be discussed in Section 4.

2.4.4 *Width of Foreshore*

Saltmarsh which developed seaward of the dyke structure is referred to a ‘foreshore marsh’ and studies have shown that they are capable of attenuating up to 97% of incoming wave energy depending on the width of the marsh (Doody, 2008). This is mostly effective with *Spartina sp.* due to their grass like structure and extensive root mat (Leonard and Reed, 2002; Moeller and Spencer 2002; Moeller 2003).



Indicative costs and heights of sea defences with different widths of saltmarsh fronting. Costs presented in early 1990s prices. Information drawn from south east England

Source: Adapted from Doody, 2008

Figure 22: Indicative costs and heights of sea defences with different widths of foreshore marsh. Cost presented in early 1990s prices and information is drawn from SE England (Lindham & Nicholls, 2010; Doody 2008).

Preservation and/or encouragement of foreshore marsh habitat may be seen as an example of ecological engineering which attempts to combine engineering principles with ecological processes to decrease the environmental impacts from built infrastructure (Chapman and Underwood, 2011). Different methods are used in order to encourage the development of foreshore marsh. For example, in Denmark, the practice of 'warping' is used, in which parallel lines of excavated ditches are enclosed by brushwood fences to encourage salt marsh development seaward of the seawall (Doody, 2008). This practice works in areas of limited fetch (< 200 m) and experiments in the UK have failed. 'Bay bottom terracing' has been used in the southern USA where terraces are built using material dredged from the bay bottom. These have proven successful in the microtidal Gulf of Mexico but are not suited for the creation of large expanses of salt marsh (Doody, 2008). Re-seeding or other forms of vegetative restoration depends on the availability of local species, elevation of the foreshore relative to the tidal frame (dredge spoil could be added), wave climate, suspended sediment supply and shoreline configuration (Doody, 2008; Williams and Orr, 2002).

In order for these efforts to be successful, one needs to look at the broad picture and consider the shorezone as a whole rather than per individual marsh body. Placement of rock armouring along a section of dyke will cause erosion of the adjacent foreshore. There is little experimental research on the outcomes of building or repairing coastal structures (Chapman and Underwood, 2011), let alone in a macrotidal area such as the Bay of Fundy. In the Bay of Fundy, management practices have been handed down through time by years of trial and error in the form of traditional knowledge of local conditions and processes. Efforts to create foreshore marsh in Fundy are limited due to the presence of steep high marsh cliffs along the main channel. The main way of creating foreshore is through limited retreated and re-alignment or encourage the formation of an intertidal flat seaward of the cliff. The best bet is to protect foreshore marsh as much as possible including limiting the creation of a borrow pit in areas of narrow foreshore (less than 50 m). It may be possible in some areas to incorporate offshore breakwater (Kamphius, 2010) or rip rap with vegetation within it (e.g. terraced) in areas that are mainly affected by wave action rather than tidal currents.

2.5 Cost Estimation

Factors affecting the unit cost of sea dyke construction are (Hillen et al, 2010; Zhu et al., 2010):

- ***Land availability and cost:*** dyke construction requires significant land since an increase in elevation requires an increase in the base footprint in order to main engineered ratios (e.g. 1:3). In addition, urban land is more expensive and less available (Hillen et al., 2010).

- ***Dyke design and safety margin***: this will affect the overall amount and type of materials that will be used in the construction. Ultimately it is the perception of risk by local populations that influences considerably the design of coastal defence solutions (Eurosion, 2004).

- ***Anticipated wave loading***: higher wave loadings will require stronger and expensive structures as well as affecting the amount of stone armouring required.

- ***Proximity to availability of raw materials:*** there is a significant cost difference if material to build the dyke is not available in the immediate area (e.g. no borrow pit possible due to small foreshore) or transportation of materials requires specialized equipment. This is completely dependent on each individual site.

- ***Availability and cost of human resources***: this includes the availability of personnel with experience in dyke construction and physical conditions (e.g. tides, soils, ice) and limitations of the local area.

- ***Single or multistage construction:*** According to Nicholls and Leatherman, 1995, aggregate costs are lower for single stage construction.

Maintenance costs are an on-going requirement for sea dykes to ensure that the structure continues to provide structural design levels of protection. Although detailed information on maintenance costs is limited, the literature does report figures ranging from US$0.03 million in Vietnam (Hillen, 2010) to US$0.14 million in the Netherlands (AFPM, 2006; Hillen et al., 2010) per linear km of dyke. These costs are presented in 2009 US dollars. The main factors that determine costs at a system level include measures and solution for individual reaches, accessibility, system length and any modification in the system's alignment (e.g. close off the estuary with a causeway to reduce its length) (Hillen et al., 2010). The latter approach was employed in the 1960s and early 1970s as causeways were constructed across a number of major rivers in the Bay of Fundy including, among others, the Petitcodiac, Avon and Memramcook Rivers. However, although this practice did reduce maintenance costs upstream of the causeway, it had significant consequences for fish passage and sediment transport, deposition processes; and is not viewed as a viable option in the present day.

Annual maintenance costs in Fundy can vary greatly on individual dykes, depending on what work is being done and the availability of local materials. Maintenance costs include dyke mowing and maintenance, topping, aboiteau repair / replacement and rock protection, and are highly spatially and temporally variable. It costs $4,550 on average (1996-2003) per linear km of dyke to maintain a Fundy dyke, excluding aboiteau replacement, significant topping or re-engineering (Pers communication K. Carroll, Dec 10, 2008). This translates to roughly $70 per hectare. These values are extremely low compared to IPCC or international standards and potentially reflect the historical mandate to protect agricultural land which can tolerate some overtopping. Hillen et al., 2010 produced a comprehensive analysis of coastal defence cost estimates for the Netherlands, New Orleans and Vietnam and compared these values to the IPCC summaries (1990). It is recommended that a similar study be undertaken for Fundy dykes in which in which graphs are produced to relate required dyke height increase to deal with sea level rise, versus cost per km. Maintenance costs will increase in the future due to increased water depth and wave loading (Burgess and Townsend, 2004; Townsend and Burgess, 2004). However significant barriers to implementation include the high space requirements and cost, especially for rip rap (Zhu et al., 2010).

3 Assessment of Dyke Vulnerability within Fundy ACAS Sites

The assessment of dyke vulnerability within the Nova Scotia ACAS study sites was conducted using analysis of historical marsh plans, satellite imagery, and historical aerial photography within ArcGIS in addition to shore surveys, key informant interviews and participatory mapping exercises with personnel within the Resource Stewardship, Land Protection Division of the Department of Agriculture. This assessment draws heavily from research reported in companion 2012 ACAS reports produced by Saint Mary's University: *Shore Zone Characterization for Climate Change Adaptation in the Bay of Fundy* by Pietersma-Perrot and van Proosdij; *A Relative Vulnerability Assessment Tool for Macrotidal*

Environments: a case study for the Cornwallis Estuary by Tibbetts and van Proosdij; *Dykelands: Climate Change Adaption Issues Paper* by van Proosdij and *Hydrodynamic Flood Modelling within Fundy Dykelands* by Fedak and van Proosdij. This assessment also incorporates data and analysis presented within the Marshlands Atlas project with NS Department of Agriculture (Pietersma-Perrott et al., 2012) and Avon Estuary evolution report with NS Department of Transportation and Infrastructure Renewal (van Proosdij, 2007). An overview of pertinent methods will precede each analysis section however readers are encouraged to view the companion documents for a more in-depth and detailed discussion.

3.1 Assessment of Crest Elevation

Every five years each dyke is profiled at 15.7 m (50 ft) intervals along the centre crest of the running dyke by the Land Protection's surveyor (Darrel Hingley) using an RTK Leica GPS unit (5 mm horizontal and 10 mm vertical accuracy) and the results are forwarded for processing to each Construction Superintendent. Each dyke has two elevations that are essential for determining whether to add more material to the height (topping). These profiles are required due to long term settlement that occurs on the dykes. These elevations are described as 'Critical' (the lowest elevation where action must be done) and 'Construction' elevations (the elevation desired when topping has been completed to allow for settling). Marsh bodies may have been assigned different critical and construction elevations since maximum water levels vary as a result of dominant wave orientation, wave set-up and position within the estuary (e.g. upriver versus main channel).

The Construction Superintendent then divides the difference between the Construction and Critical elevations and that number is used as an elevation for considering topping. By comparing the newly surveyed elevations with the critical and the mid-point elevations the Construction Superintendent can then determine which sections of the dyke are below the mi-point elevation. If there are individual sections that fall within the critical to mid-point range then raising the dyke is warranted. In 2002 the construction elevation was raised by 30 cm for all dykes in Nova Scotia which in effect raised the mid-point elevation for considering topping (K. Carroll, pers communication Dec. 2008). According to Ken Carroll (former Aboiteax Superintendent for Hants County), there are different considerations to be factored in when determining dyke topping and these are summarized within Table 7.

Category	Consideration
Location of the dyke	• Upriver sites may be flooded due to fresh water events & not salt water
	• Sites that are exposed to storm conditions
	• Land usage behind the running dyke
	• Material may have to be trucked in & onto the site
Length of topping	• Individual spot locations may warrant just repairing holes in the dyke top
	• Full dyke length topping may warrant spreading the topping over two years
Topping material	• Dykes upriver usually can be topped & seeded within one year
	• Dykes closer to the Bay may require two years or more for the salt to leach out and seeding to become established

Table 7: Factors to be considered when determining dyke topping.

The survey data were entered within ArcGIS and incorporated within the Marshlands Atlas GIS. The differences between surveyed elevation and the critical elevation were calculated and entered into a new field. Data were then binned into 0.5 m categories for additional analysis and visualization. It was important to maintain the individual survey points rather than the mean of the running dyke since different sections within a dyke may settle or be worn more than others. Each point then has a GPS coordinate that can be used by Land Protection personnel to strategically plan topping exercises and calculate the potential amount of material required. All data are summarized in Table 8.

	Hants County	Length of dyke		Construction		Critical		HWL	Area (ha)		Diff.	foreshore width	Dyke Length below critical	
NS #	Name	ft	m	ft	m	ft	m	(m)	NSDA	Lidar	(%)	(m)	(%)	(m)
14	Elderkin	6110	1862	29.0	8.8	27.0	8.2	7.9	79.3	63.3	-25.3	NA	0.0	0.0
27	Newport Town	7633	2327	29.0	8.8	27.0	8.2	7.8	138.7	147.7	6.1	NA	0.0	0.0
38	St. Croix*	26450	8062	29.0	8.8	27.0	8.2	7.9	97.5	111.2	12.3	NA	0.0	0.0
48	Centre Burlington	1200	366	29.0	8.8	27.0	8.2	7.6	69.6	75.8	8.2	NA	28.4	285.0
49	Scotch Village	1625	495	29.0	8.8	27.0	8.2	8.1	34.2	38.3	10.7	NA	0.0	0.0
50	Hebert River	6648	2026	29.0	8.8	27.0	8.2	7.8	27.0	27.8	2.9	NA	0.0	0.0
61	Kennetcook	8332	2540	29.0	8.8	27.0	8.2	8.1	67.6	78.0	13.3	NA	0.0	0.0
68	Tregothic	7046	2148	29.0	8.8	27.0	8.2	8.4	238.2	267.7	11.0	NA	0.0	0.0
79	Chambers	3648	1112	29.0	8.8	27.0	8.2	7.9	22.8	20.5	-11.2	NA	0.0	0.0
85	Mantua Poplar Grove	20110	6130	29.0	8.8	27.0	8.2	7.9	136.5	155.1	12.0	NA	0.0	0.0
88	Burlington	3613	1101	29.0	8.8	27.0	8.2	8.1	41.6	42.1	1.2	NA	1.4	15.0
93	Greenhill	4090	1247	29.0	8.8	27.0	8.2	8.2	19.1	23.9	20.1	NA	2.2	30.0
100	Wentworth	6400	1951	29.0	8.8	27.0	8.2	8.1	58.7	61.1	3.9	NA	0.0	0.0
105	Belmont	4094	1248	29.0	8.8	27.0	8.2	8.1	28.2	42.6	33.8	NA	0.0	0.0
	Kings County	Length of dyke		Construction		Critical		HWL	Area (ha)		Diff.	foreshore width	Dyke Length below critical	
NS #	Name	ft	m	ft	m	ft	m	(m)	NSDA	Lidar	(%)	(m)	(%)	(m)
8	Grand Pre	28454	8673	29.0	8.8	27.0	8.2	7.9	1207.7	1190.8	-1.4	397.2	2.8	255.0
41	Habitant	2400	732	29.0	8.8	27.0	8.2	7.9	265.4	295.0	10.0	177.7	0.0	0.0
56	Wellington	6000	1829	29.0	8.8	27.0	8.2	7.9	1240.1	1195.9	-3.7	239.7	0.0	0.0
57	New Minas	22618	6894	28.5	8.7	26.5	8.1	8.1	100.8	94.4	-6.8	NA	0.0	0.0
65	Bishop Beckwith	19421	5920	29.0	8.8	27.0	8.2	8.0	241.1	232.2	-3.8	220.7	3.7	210.0
72	Hortons	21577	6577	28.5	8.7	26.5	8.1	7.7	118.0	119.1	0.9	NA	0.0	0.0
76	Farnham	4760	1451	29.0	8.8	27.0	8.2	8.0	77.3	79.1	2.3	0.0	1.7	30.0
80	Starrs Point	8022	2445	29.0	8.8	27.0	8.2	8.0	120.7	109.8	-9.9	458.7	0.6	15.0
82	Kentville	6461	1969	28.5	8.7	26.5	8.1	7.8	22.7	18.3	-24.0	NA	0.0	0.0
91	Belcher Street	30641	9339	29.0	8.8	27.0	8.2	7.8	126.9	121.3	-4.6	NA	5.0	375.0
92	Avonport	10054	3064	29.0	8.8	27.0	8.2	7.6	100.0	101.5	1.5	NA	12.2	390.0
101	Pereau	1491	454	28.0	8.5	26.0	7.9	7.6	47.9	39.5	-21.3	NA	6.7	30.0
	Cumberland County	Length of dyke		Construction		Critical		HWL	Area (ha)		Diff.	foreshore width	Dyke Length below critical	
NS#	Name	ft	m	ft	m	ft	m	(m)	NSDA	Lidar	(%)	(m)	(%)	(m)
42	Amherst Point	26181	7980	28.5	8.7	26.5	8.1	7.6	900.8	NA	NA	107.3	0.0	0.0
44	Converse	26919	8205	28.5	8.7	26.5	8.1	7.9	335.2	NA	NA	87.6	0.0	0.0
45	Barronsfield	9793.3	2985	28.5	8.7	26.5	8.1	8.1	94.8	NA	NA	18.6	0.0	0.0
46	River Herbert	67323	20520	28.5	8.7	26.5	8.1	8.0	420.8	NA	NA	25.4	0.0	0.0
53	John Lusby	12943	3945	28.0	8.5	26.5	8.1	7.8	328.4	NA	NA	229.1	7.2	285.0
54	Minudie	33907	10335	28.0	8.5	26.5	8.1	8.1	1084.4	NA	NA	323.8	8.0	825.0
55	Seaman	3789.4	1155	28.5	8.7	26.5	8.1	8.1	176.4	NA	NA	79.7	0.0	0.0
63	Maccan	13337	4065	28.5	8.7	26.5	8.1	8.1	80.0	NA	NA	19.0	0.0	0.0
78	Athol	6545.3	1995	28.5	8.7	26.5	8.1	7.6	52.4	NA	NA	NA	0.0	0.0
87	Chignecto	3887.8	1185	28.5	8.7	26.5	8.1	8.0	217.6	NA	NA	17.6	0.0	0.0
115	Nappan-Maccan	10778	3285	28.5	8.7	26.5	8.1	7.9	155.2	NA	NA	13.3	0.0	0.0
119	Upper-Maccan	7431.1	2265	28.5	8.7	26.5	8.1	8.1	67.6	NA	NA	46.0	0.0	0.0

Table 8: Summary marshbody statistics from both the NSDA and GIS analysis. Mean foreshore width calculated by J. Tibbets (2012) based on widths calculated every 250 m segment and Lidar areas calculated by B. MacIssac (2011).

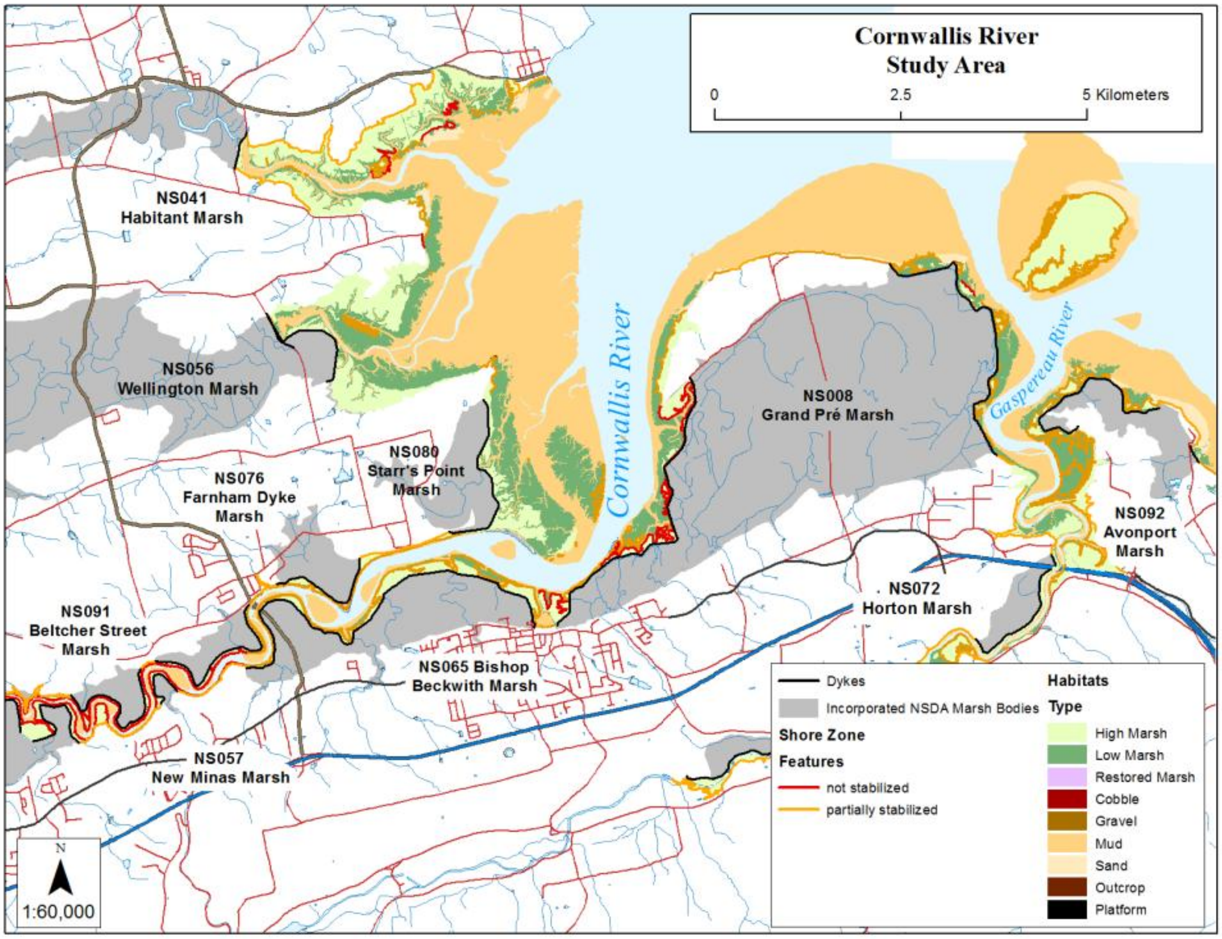


Figure 23: Incorporated marsh bodies within the RAC area of the Cornwallis Estuary in Kings County.

3.1.1 *Kings County*

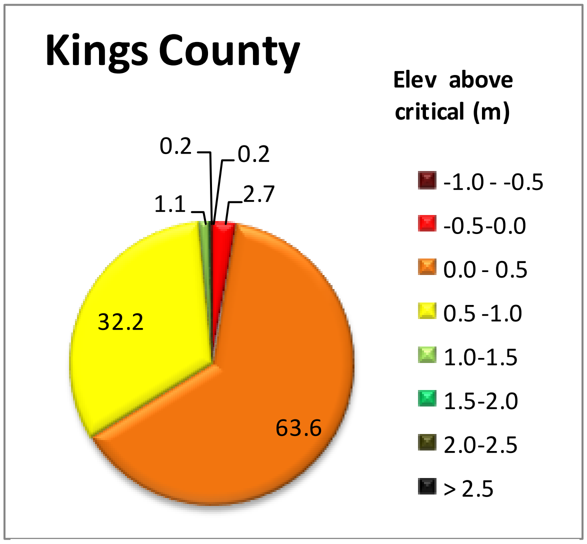


Figure 24: Proportion of dyke survey point elevations for all marsh bodies within Kings County relative to critical elevation.

Within Kings County, the majority (63.6%) of dyke points surveyed fall within 0.5 m of the critical elevation for each marsh body (Figure 24). Critical elevations in the County are around 8.23 m (27 ft) with construction elevations of 8.84 m (29 ft) (Table 8). However 2.7% of the points are lower than the critical elevation. This translates roughly to around 1.3 km of dyke section below critical elevation if we assume minimal variation within the 15 m between survey points. These points are located within two primary marsh bodies: NS8 (Grand Pré) and NS65 (Bishop Beckwich) in the Cornwallis Estuary. The primary area affected at Grand Pré is a 255 m segment on the northeast section, east of Evangeline Beach (Figure 23). This area is directly impacted by north east storms. NS65 is located adjacent to the town of Wolfville and the dyke is a popular walking/running trail. Excessive foot and trail bike traffic is known to cause accelerated compaction of the marsh soils and prevent grass growth. Approximately 210 m are affected. This area is of additional concern due to the number of variances that were granted for town expansion (e.g. Railtown Development, Home Hardware) and resultant development on former agricultural land which would be prone to flooding.

Twelve percent of the elevations (390 m segment) within NS92 (Avonport) are currently below critical (Figure 30). This marsh is exposed to the large fetch of the Minas Basin during Northeast storms and regularly overtops during those conditions (Figure 25). NS101 (Pereau) is located at the mouth of the Pereaux River and has 6.7 % of the points (375 m) below critical elevation with Jackson Barkhouse Rd passing to the west (Figure 30)

Figure 25: Storm impacts on Feb 1, 2006 at the Avonport Dyke. a) storm waves battering marsh; b) storm surge reached upper limits of dyke and dyke overtopped. Photo by T. Hamilton, 2006.

3.1.1 *Hants County*

Hants County is in much better condition for the most part with 58.7% of the dyke surveyed elevations falling within the 0.5 to 1m category. Only 1% of the dyke elevations or 375 m fall below critical (Figure 26). Critical elevations in the ACAS portion of the County stand at 8.23 m (27 ft) with constructed elevation of 8.84 m (29 ft) similar to Kings County. The primary marsh body at risk is NS48 (Centre Burlington) at the confluence of the Kennetcook and Avon Rivers (Figure 27). Approximately 30% of the surveyed elevations fall below critical representing 285 m of dyke (Figure 31). Greenhill Marsh (NS93) on the west shore of the Avon River south of Hantsport has around 2.2% of elevations below critical representing only 30 m of dyke. Burlington Marsh (NS88) along the Kennetcook River has an approximately 15 m

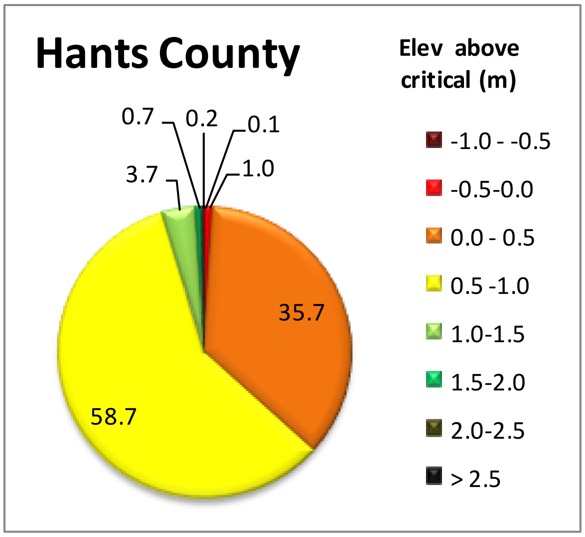


Figure 26: Proportion of dyke survey point elevations for all marsh bodies within Hants County relative to critical elevation.

long segment of dyke below critical. Surveyed elevations at Tregothic Marsh (NS68) incorporating parts of the Town of Windsor, ranged primarily within categories 0.5 m and above critical (Figure 32). Twenty-two percent of the elevations (465 m) do fall within 0.5 m of critical elevations and given the significant infrastructure that this dyke protects approximately 31M dollars worth of property with only 0.6% being zoned agriculture (Browning, 2011), the area should receive high priority for topping. The most vulnerable sections are along the Northeast edge along the St. Croix River (Figure 32).

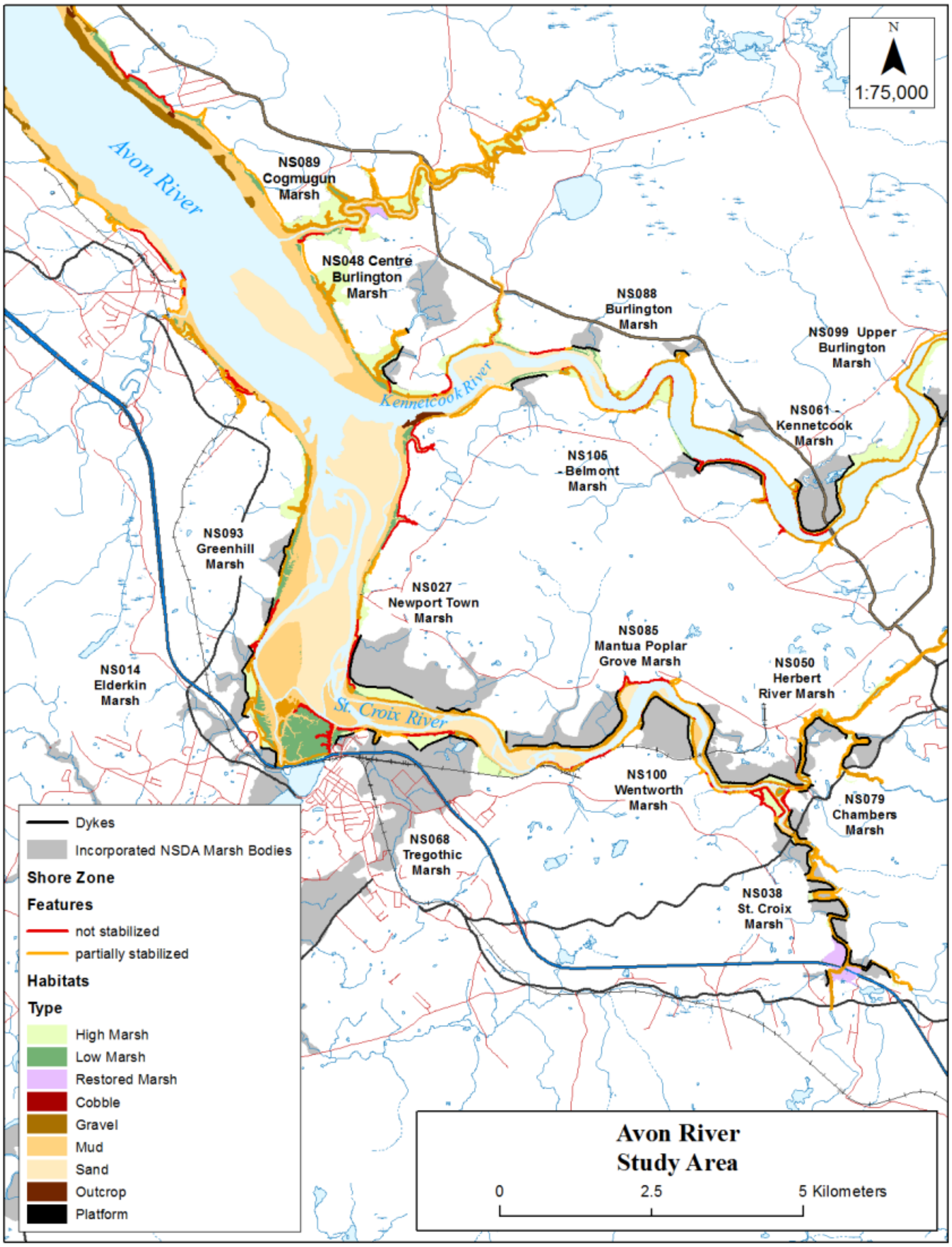
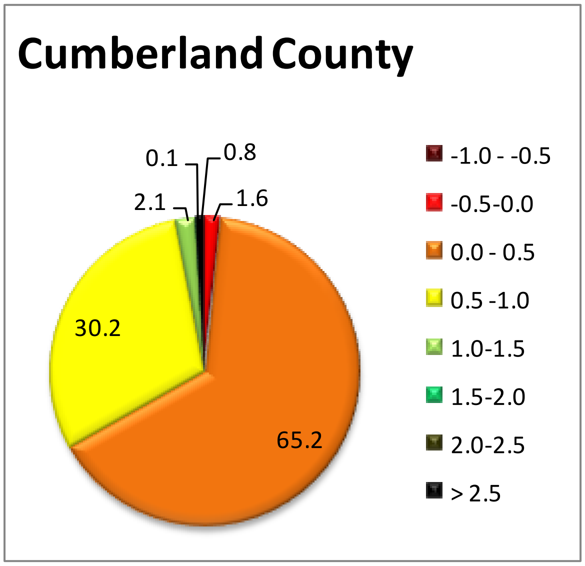


Figure 27: Incorporated marsh bodies within the Avon river estuary, Kings and Hants Counties

3.1.2 *Cumberland County*

Critical elevations within Cumberland County are slightly lower than in Kings or Hants at 8.1 m (26.5 ft) with a construction elevation of 8.69 m (28.5 ft). Only 1.6% of the surveyed elevations in the County fell below 8.1 m (Figure 28). The two primary marsh bodies that showed the highest proportion of points below this level were NS53 (John Lusby) and NS54 (Minudie) with 7.2% and 8.0% respectively (Figure 32). Approximately 285 m of dyke along the La Planche River are below critical, mostly associated with meander bends in the river at NS53. The largest section of dyke below critical within Cumberland County is Minudie (NS54). Approximately 825 m of dyke is currently below critical elevation along the west shore. This site is most directly impacted by wave action during storms coming up the Cumberland Basin (Figure 29).

Figure 28: Proportion of dyke survey point elevations for all marsh bodies within Cumberland County relative to critical elevation.



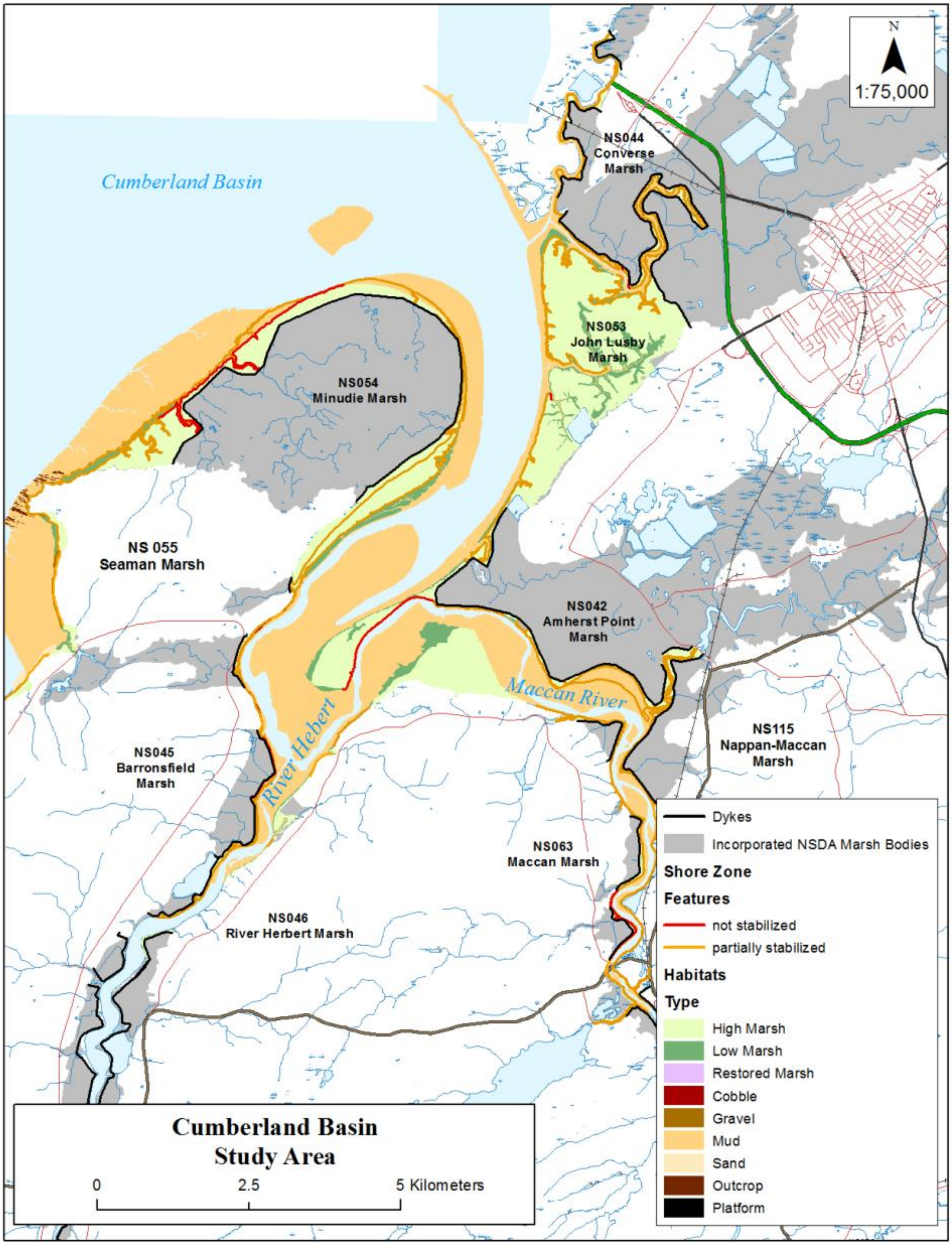


Figure 29: Incorporated marsh bodies within Cumberland County RAC.

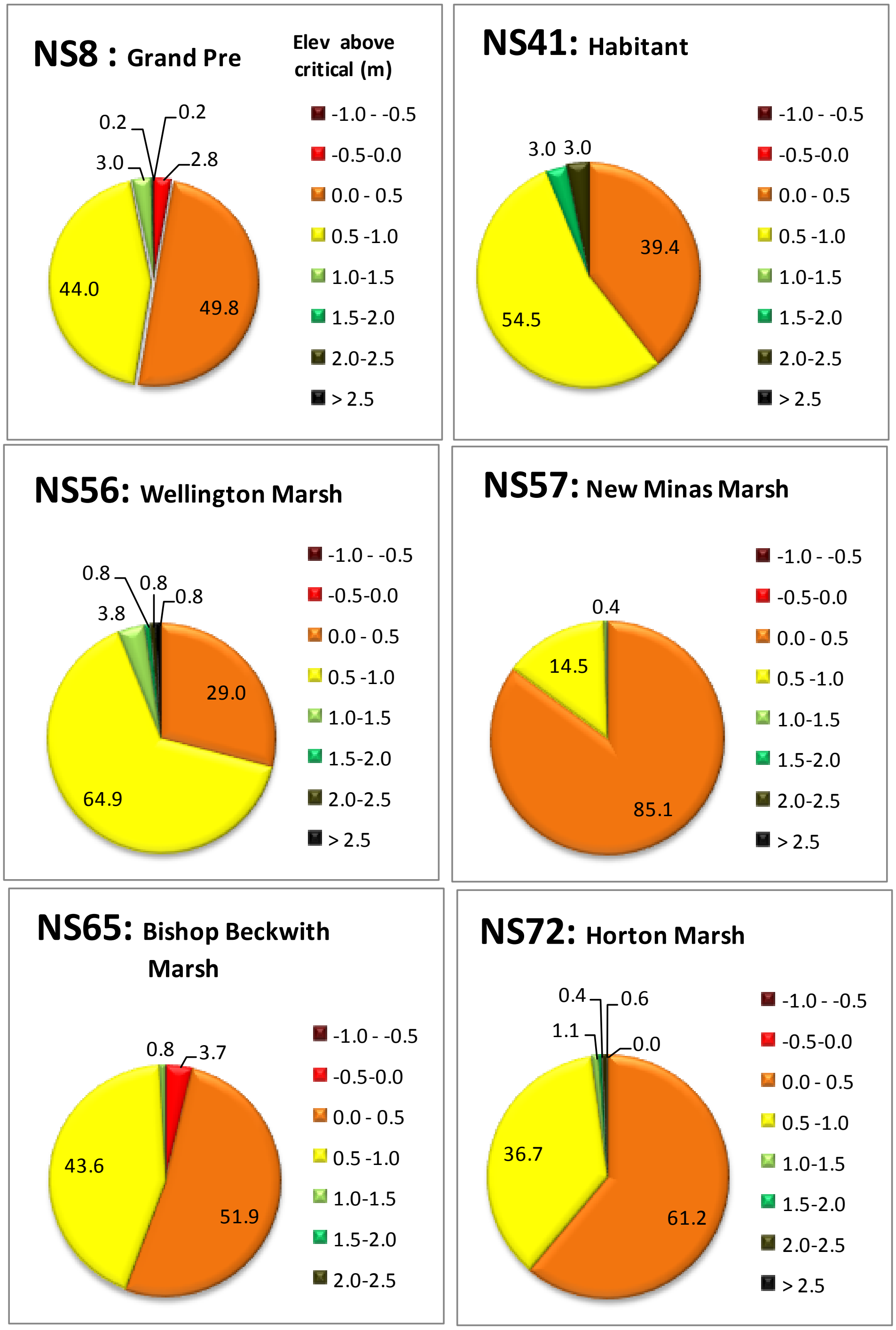


Figure 30: Proportion of dyke survey point elevations for marsh bodies (NS8,NS41,NS56, NS57,NS65, NS72) within Kings County relative to critical elevation.

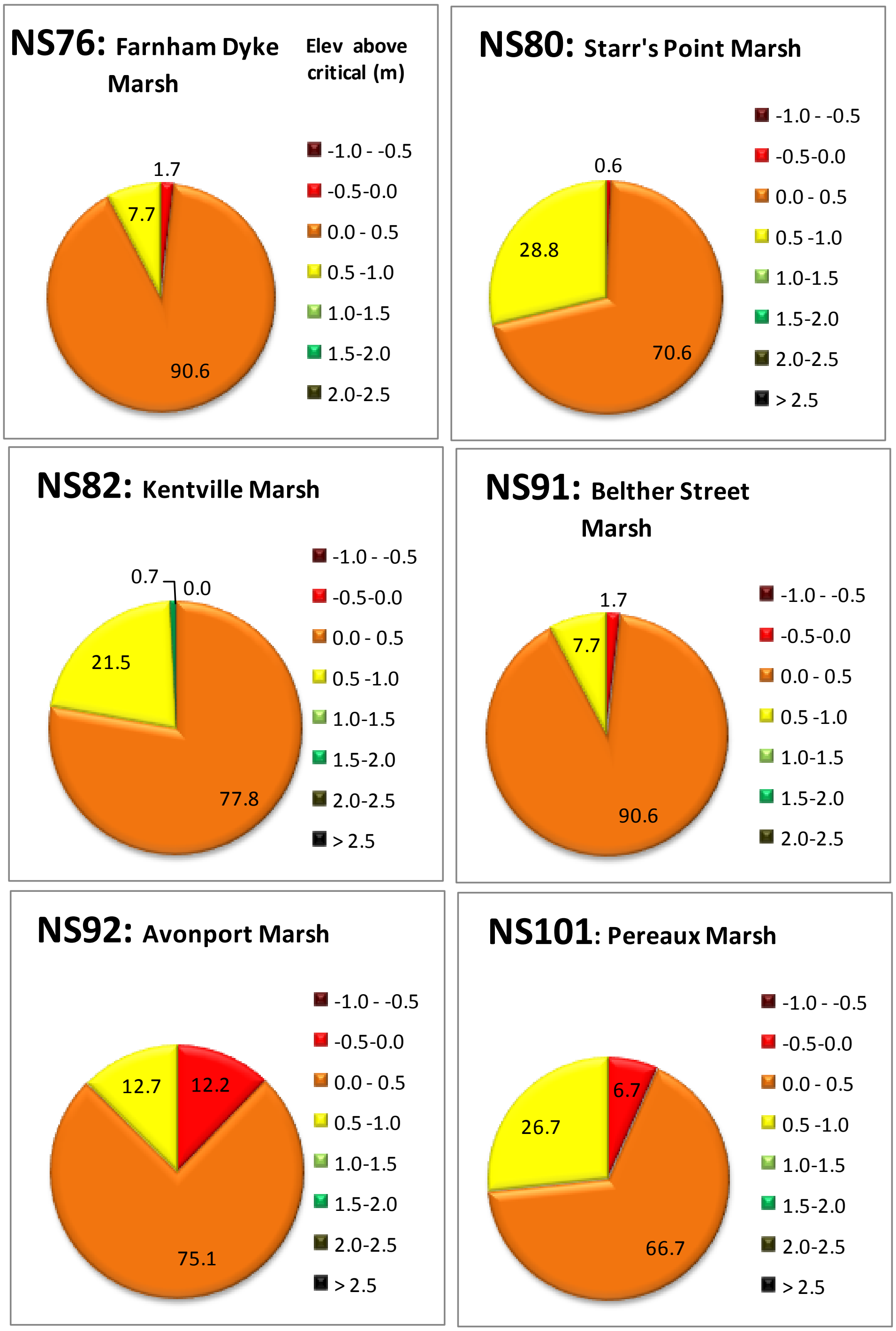


Figure 31: Proportion of dyke survey point elevations for marsh bodies (NS76,NS80,NS82,NS91,NS92,NS101) within Kings County relative to critical elevation.

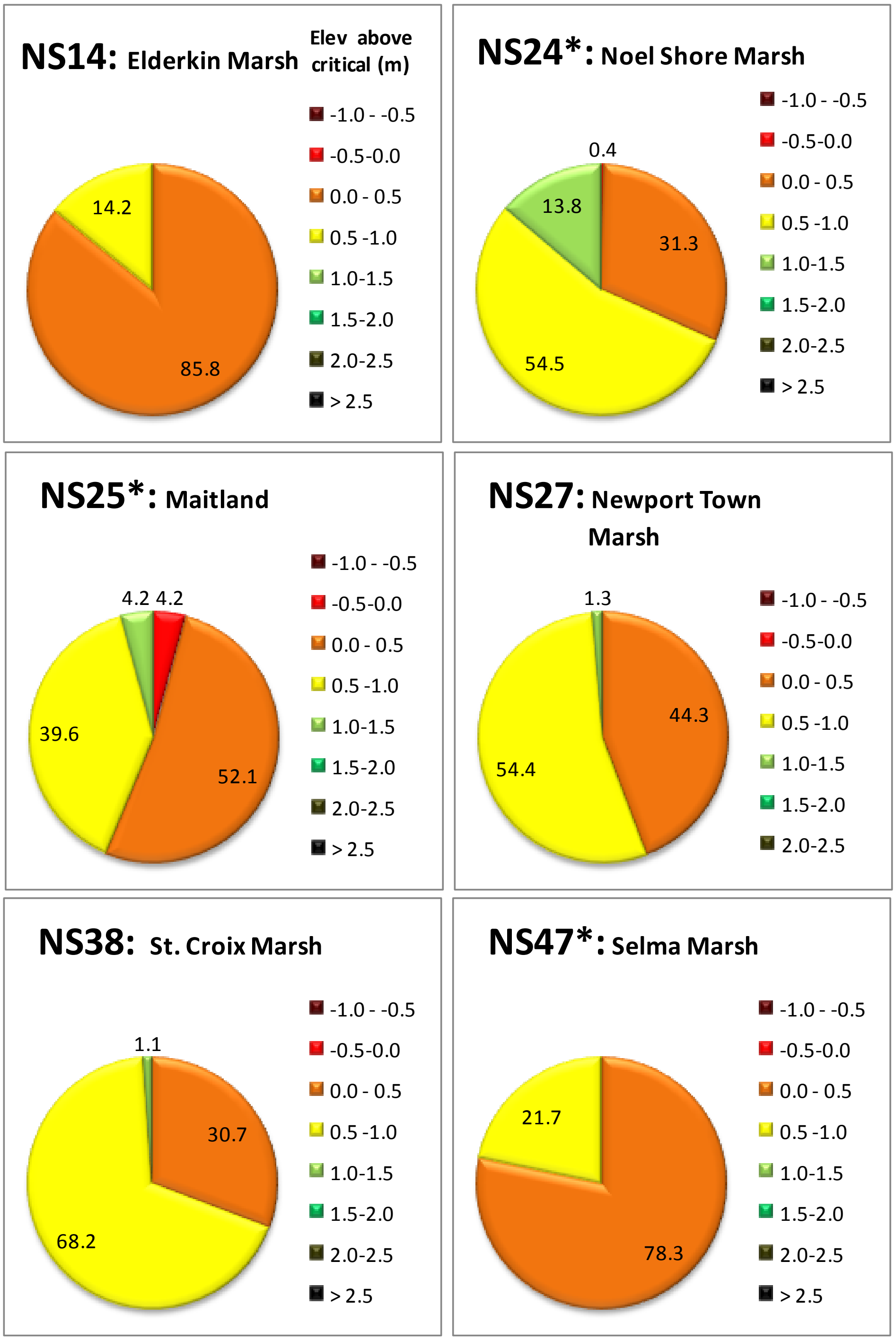


Figure 32: Proportion of dyke survey point elevations for marsh bodies (NS14, NS24*, NS25*, NS27, NS38 and NS47*) within Hants County relative to critical elevation. Marsh bodies indicated with an asterix are not within the ACAS study area and will not be analyze within this report.

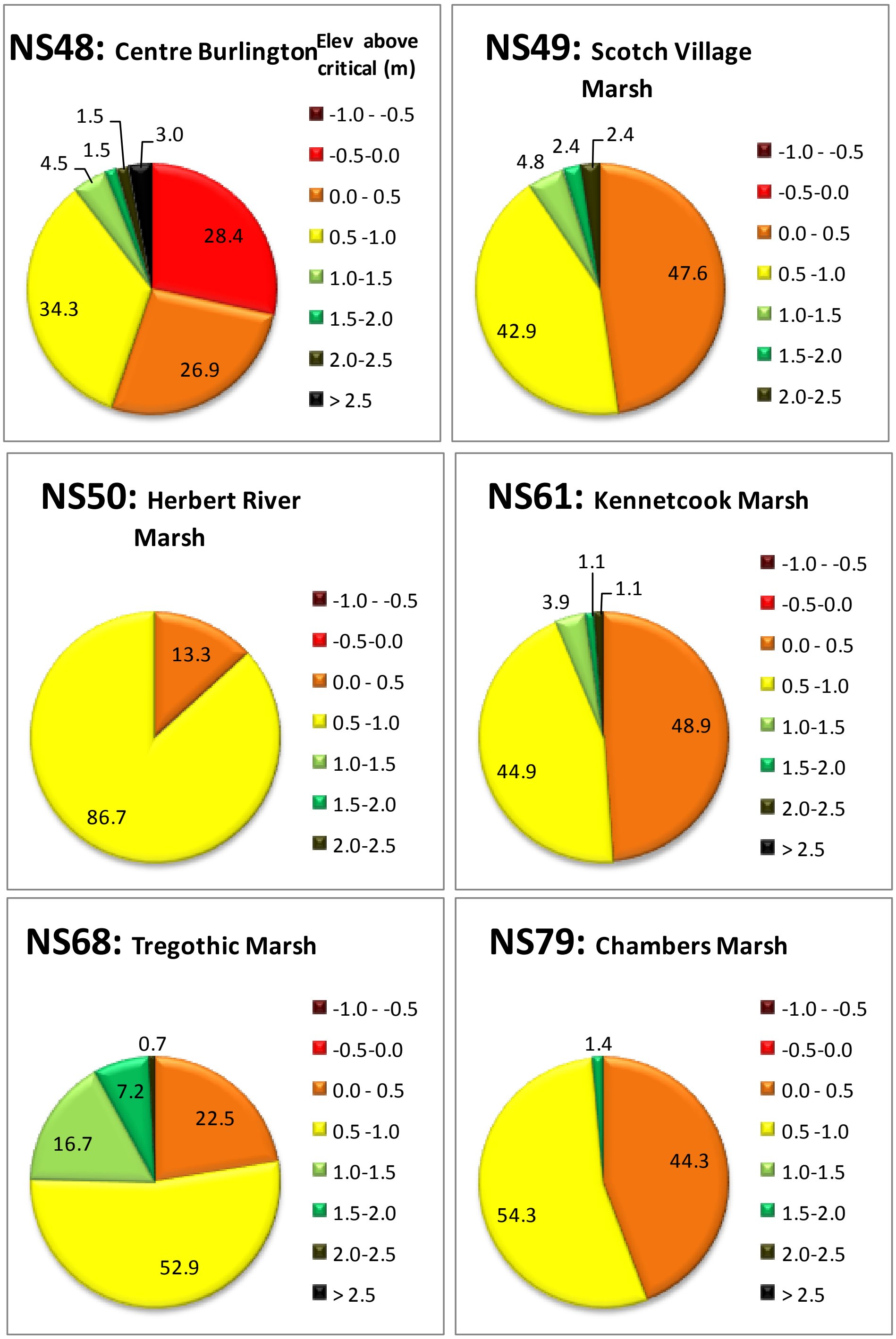


Figure 33: Proportion of dyke survey point elevations for marsh bodies (NS48,NS49,NS50,NS61,NS68,NS79) within Hants County relative to critical elevation. Marsh bodies indicated with an asterix are not within the ACAS study area and will not be analyzed within this report.

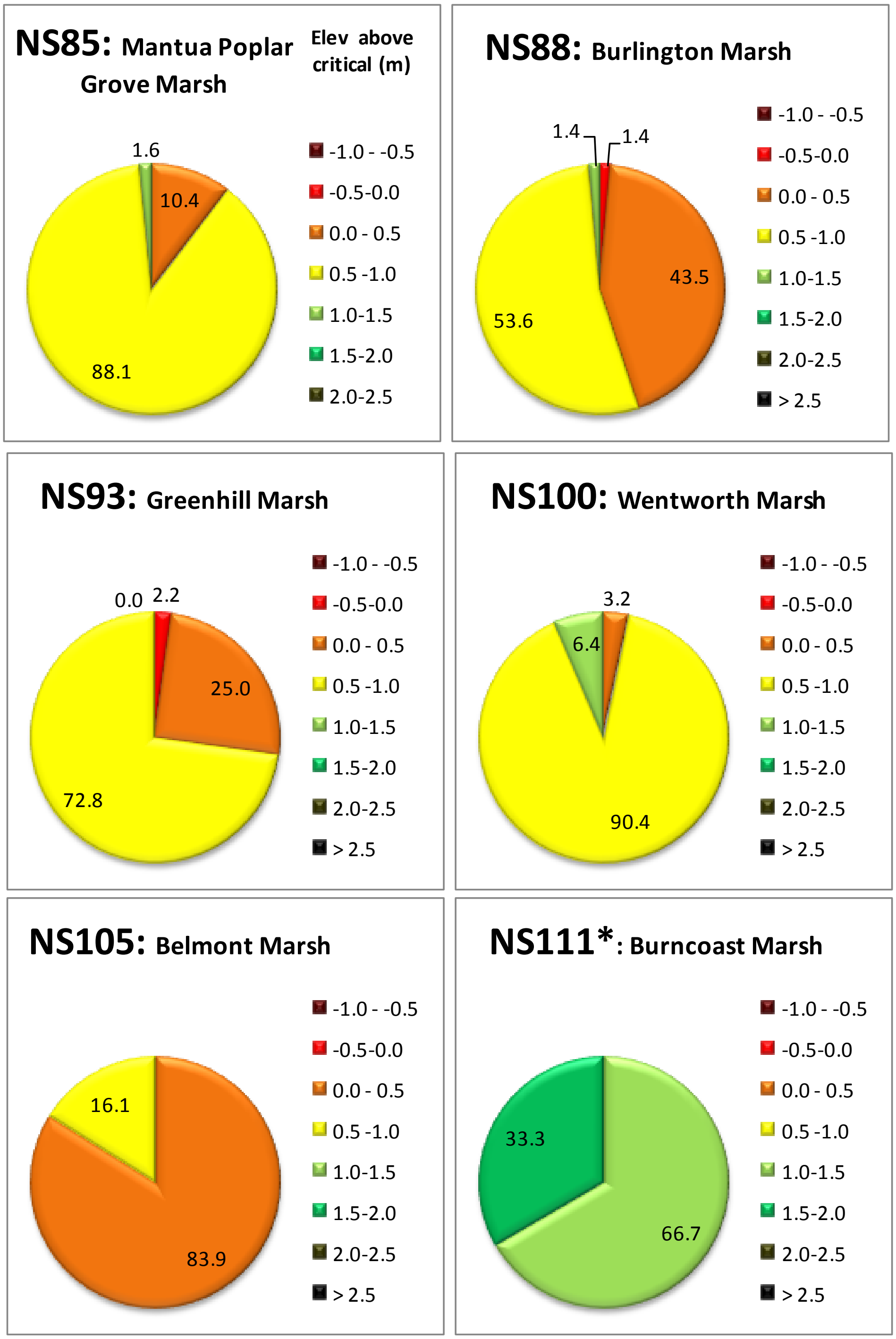


Figure 34: Proportion of dyke survey point elevations for marsh bodies (NS85, NS88, NS93, NS100, NS105 and NS111*) within Hants County relative to critical elevation. Marsh bodies indicated with an asterix are not within the ACAS study area and will not be analyzed

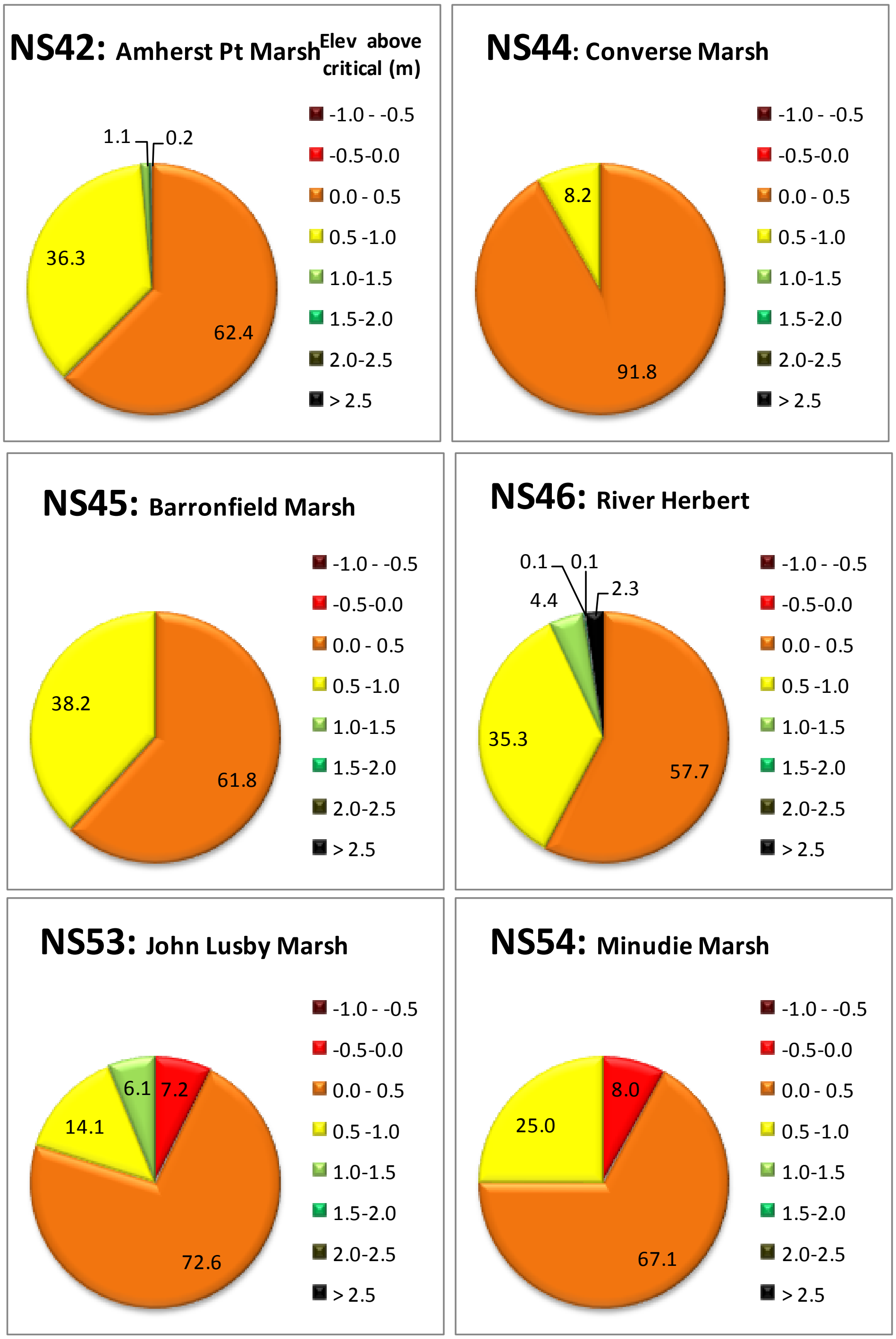


Figure 35: Proportion of dyke survey point elevations for marsh bodies (NS42, NS44, NS45, NS46, NS53, NS54) within Cumberland County relative to critical elevation.

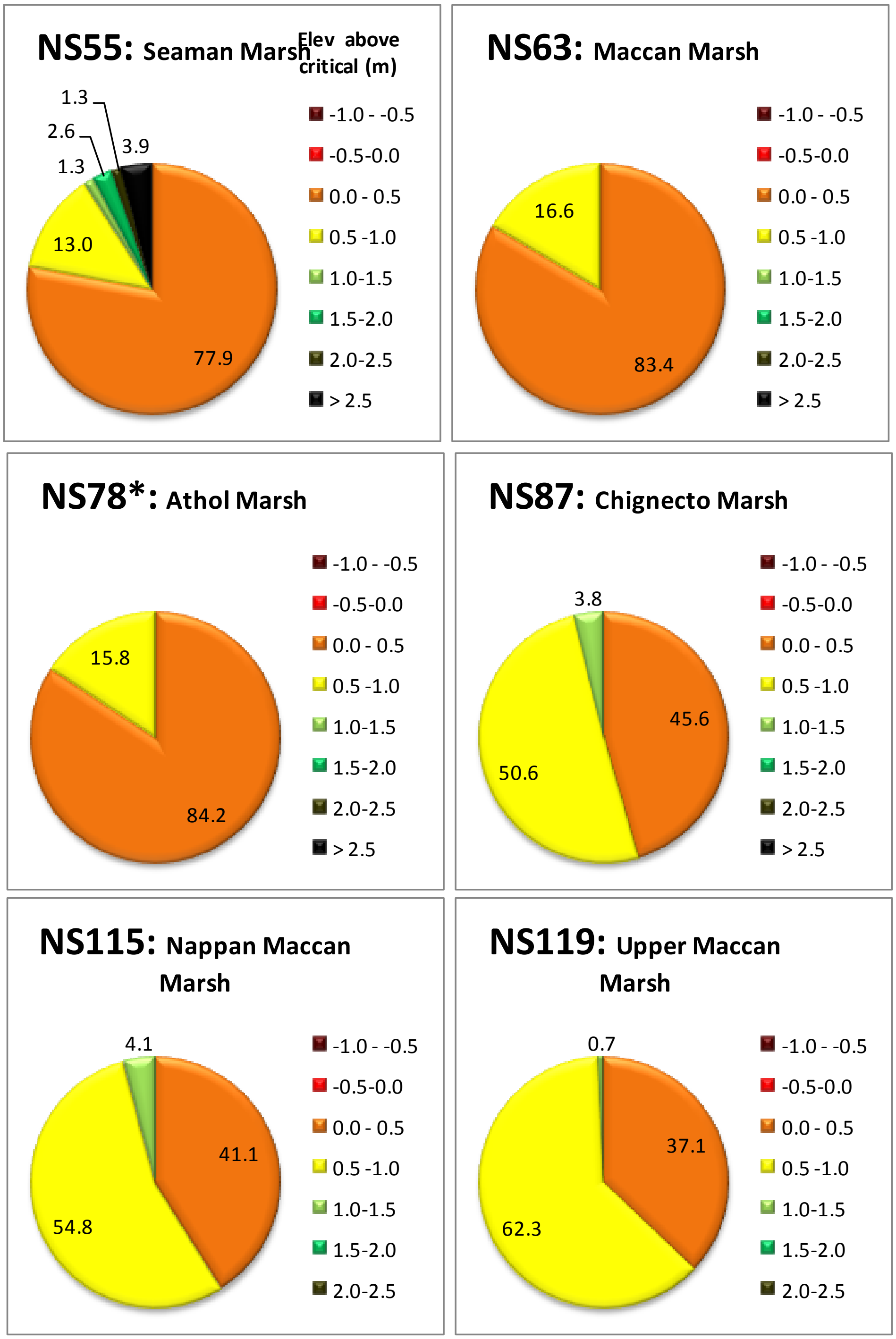


Figure 36: Proportion of dyke survey point elevations for marsh bodies (NS55, NS63,NS78*, NS87, NS115, NS119) within Cumberland County relative to critical elevation. Marsh bodies indicated with an asterix are not within the ACAS study area and will not be analyzed within this report.

3.2 Assessment of Dyke Profiles

MMRA annual reports from the late 1950s provided engineering recommendations for dyke construction. It was recommended that dykes should be constructed with slopes of 1:3 V:H on the sea side and 1:2 on the marsh side (Klassen, 2010). Over time however, continued topping with minimal adjustment of toe placement, has resulted in slope steepening in different areas of the Bay to reflect local conditions including availability of construction material, width of foreshore, and preservation of high quality agricultural land. Once the initial dyke design is established, it makes it hard for modifications to take place, particularly on the seaward edge. A preliminary assessment of a small selection of dyke profiles provided by the department of Agriculture shows that in practice, outside slopes (seaward) slopes are much steeper (1:1.5) than on dykes found elsewhere in the world (Figure 37) (pers communication D. Hingley, 2012). The inner slopes (landward) slopes are typically more on the order of 1:3 to 1:5 to allow for mowing. The general practice appears to be to shift the crest seaward (Figure 37) rather than lose agricultural land. The steep seaward slope will most certainly increase any wave loading against dykes that are exposed to long fetches. It will have less of an impact for those dykes that are found upriver or in the inner part of the estuaries. It is recommended that for dykes being considered for topping, that the cross sectional profile ratios are re-assessed for the given location to take into consideration hydrographic conditions and climate change (e.g. sea level rise and storm surge). It is recommended that the seaward slope of dykes exposed to dominant winds (e.g. Avonport NS92, Minudie NS54 or Converse NS44) be decreased where space is available although this could mean re-alignment of dykes in those areas.

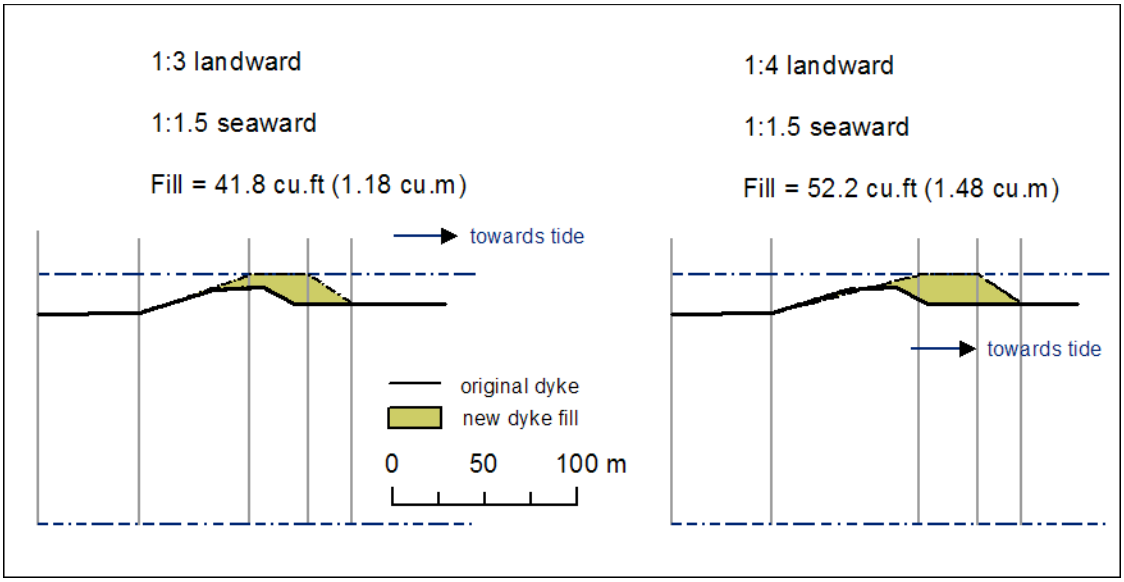


Figure 37: Example of an AutoCAD cross sectional profile for NS67 (not in ACAS area) provided by Darrel Hingley, NS Dept of Agriculture. The amount of fill required depending on the application of a 1:3 or 1:4 V:H slope is provided for dyke topping.

3.3 Assessment of Marsh Body Boundary

The marsh boundaries along the Bay of Fundy were created within the 1950 to 1970s (Butzer, 2002), through traditional field surveying and extending the marsh boundary to where the high water line elevation was located at that time. This high water line was calculated for each individual marsh body

(Table 8) and an associated dyke critical elevation was calculated to protect that area. This became the jurisdictional marsh body boundary and governs the types of activities that are permitted within it. Dykes were constructed to protect the agricultural land contained behind them although over time variances were granted to allow various forms of construction including sewage treatment, Ducks Unlimited impoundments, or other infrastructure (e.g. roads, industry) mostly in the Chignecto Isthmus, and towns of Wolfville, Windsor and Amherst. With the availability of LiDAR, these boundaries could be assessed as to their spatial accuracy (using the original HWL relative to CGVD28), and additional boundaries determined incorporating sea level rise. This analysis was performed as part of a 4th year applied geomatics course project for the Avon and Cornwallis River estuaries by Britanny MacIsaac.

In many areas there is good agreement with the original boundary delineated by the MMRA, particularly on viable agricultural land. In other areas, particularly those dominated by scrub, pre-existing buildings present or where new construction blocked tidal flow, the match is poor. For example, Figure 38 depicts the Elderkin marsh, north of the Town of Windsor. The construction of the 101 Hwy excluded tidal flow from the lower portion of the marsh body, resulting in a 25% decrease in area.

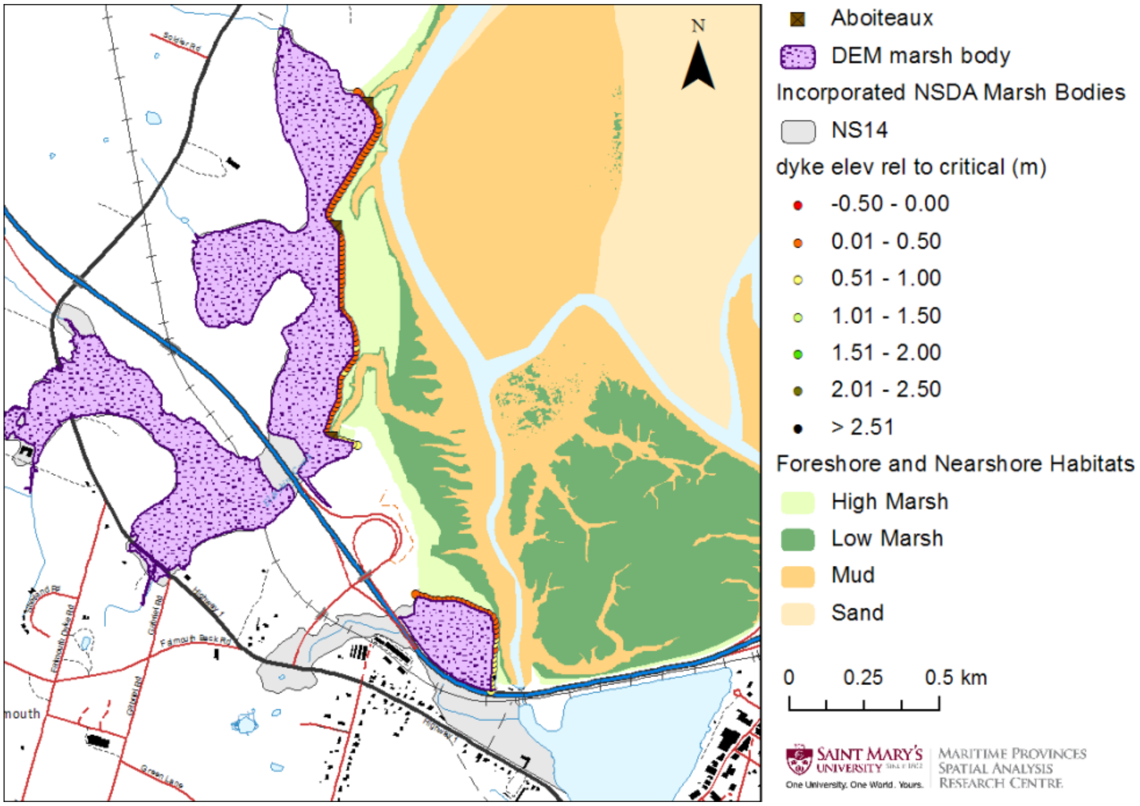


Figure 38: Comparison of NSDA jurisdictional marsh body and LiDAR derived boundaries for Elderkin Marsh (NS14).

In other areas there is a significant underestimation of the potential area flooded for the historical high water line. None is more apparent, nor has more consequences than the Tregothic marsh (NS68) in the town of Windsor (Figure 39). Although the difference in area is only 12%, the LiDAR HWL extent identifies a vulnerable flood zone within the Town that is not contained within an incorporated marsh body therefore is not subject to environmental constraints nor variance requirements within their planning by-laws (Town of Windsor, 2010).

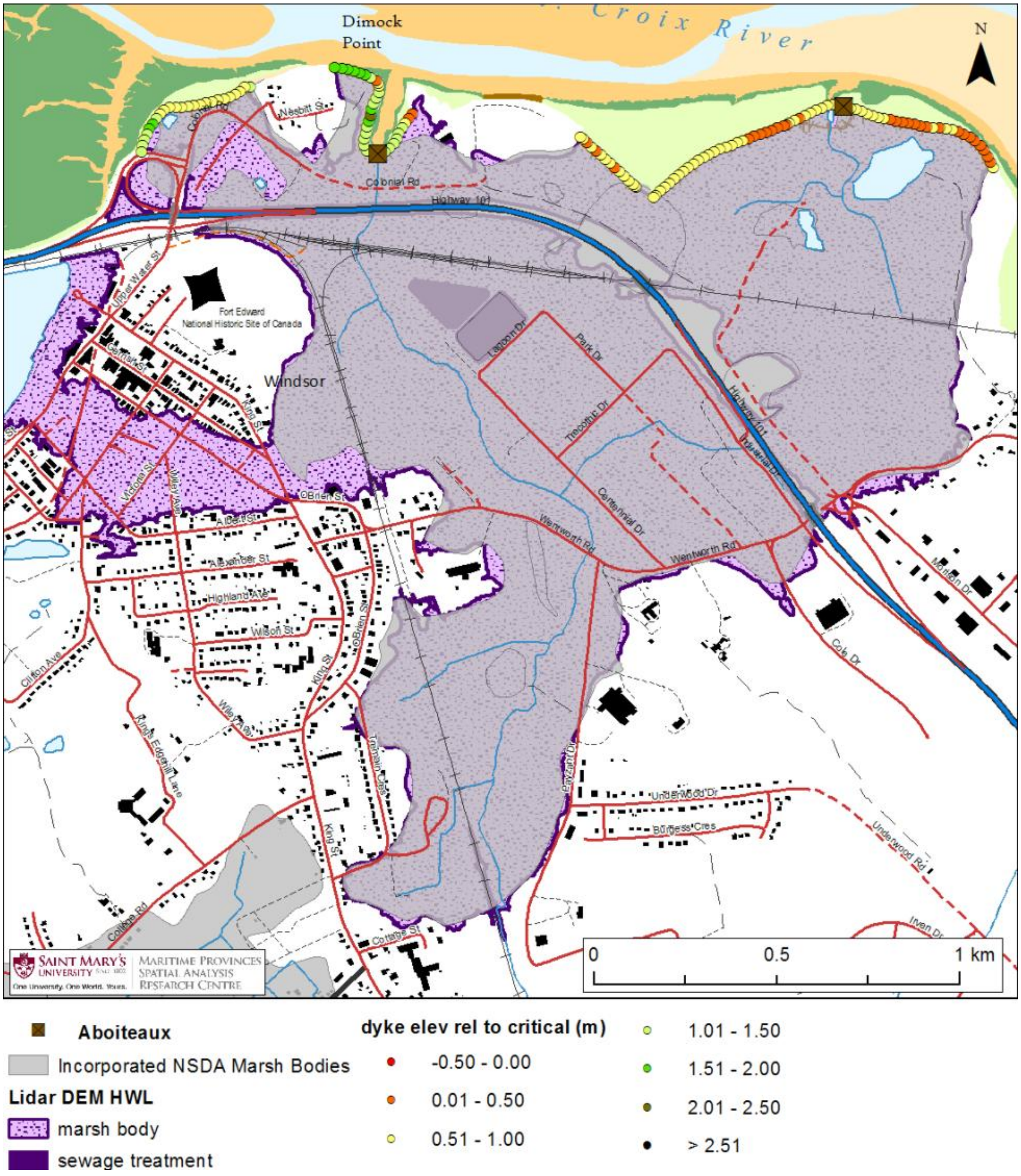


Figure 39: Comparison of NSDA jurisdictional marsh body and LiDAR derived boundary for Tregothic March (NS68).

The spatial extent of variances that occur within the Tregothic marsh are included in Figure 40 as are the dyke elevations relative to critical to illustrate the area's vulnerability.

Results of the project show that within thirty six marsh boundaries studied, there has been increase in area within thirty two of the marsh boundaries when comparing NSDA historic plans to newly created recommended boundaries that incorporate sea level rise. The increase ranges from 3% within NS75

(Armstrong Marsh) to a significant 63.7% within Upper Burlington Marsh (NS99) and 31.5% in NS93 (Greenhill Marsh) (MacIsaac, 2010).

Figure 41 provides an example of an area (Newport Town NS27) that was not initially incorporated due to the fact that the land was not cleared for agriculture at the time of the survey. Figure 42 illustrates the extent of variances that have been granted in the Town of Wolfville on NS65 Bishop Beckworth. It becomes a challenge to balance economic growth within a community and flood safety for a major storm event (e.g. Saxby Gale). It is particularly challenging when the probability of such a storm occurring is less than 3% and the perceived perception of safety behind existing dyke structures.

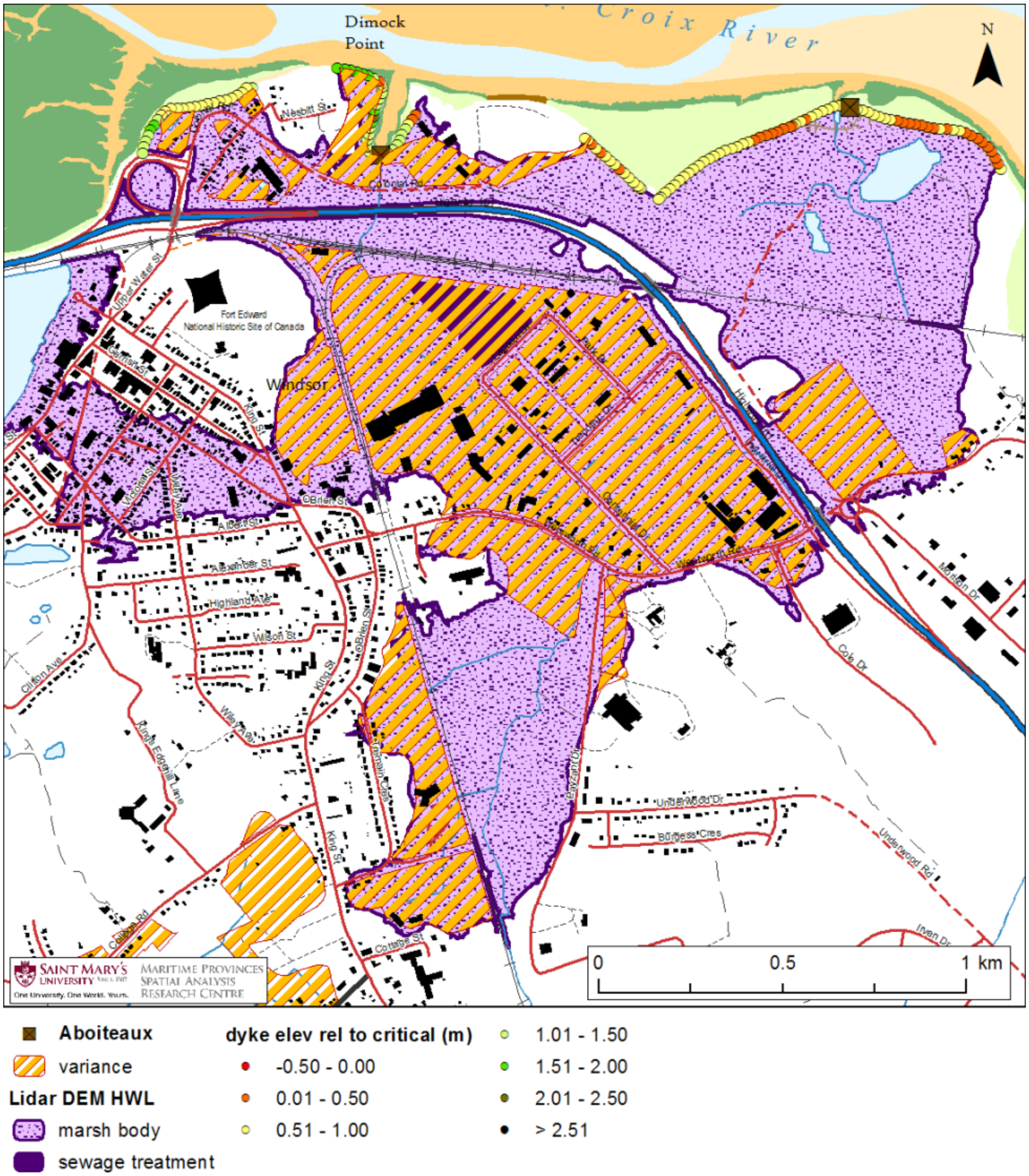


Figure 40: Comparison of LiDAR derived boundary for NS68 HWL and extent of variances.

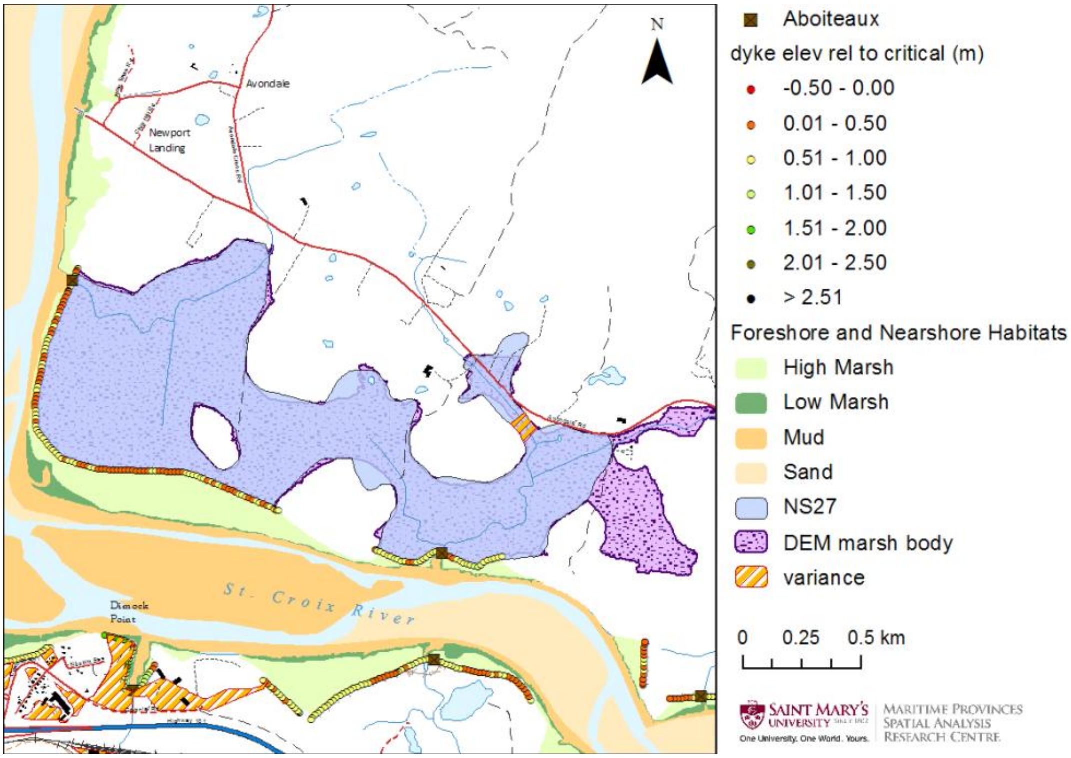


Figure 41: Comparison of NSDA jurisdictional marsh boundaries and LiDAR derived boundary for Newport Town marsh (NS27)

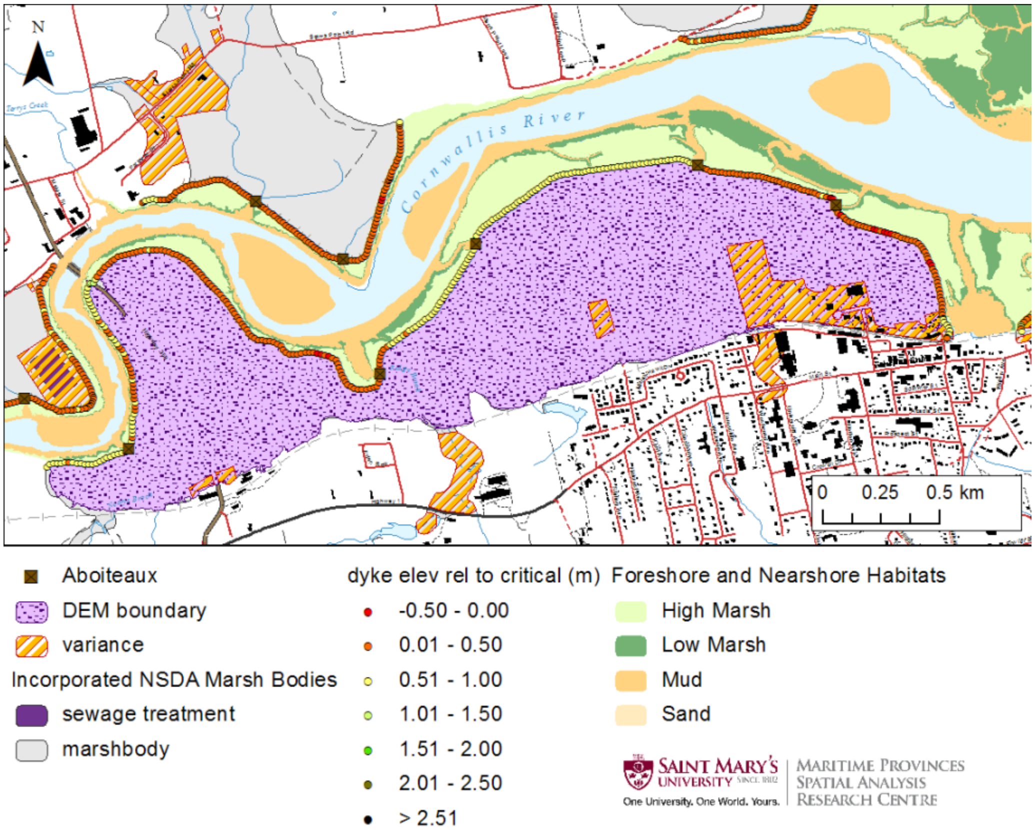


Figure 42: Comparison of NSDA marsh boundaries and LiDAR derived boundaries for Bishop Beckworth marsh (NS65) including variances near Wolfville, NS.

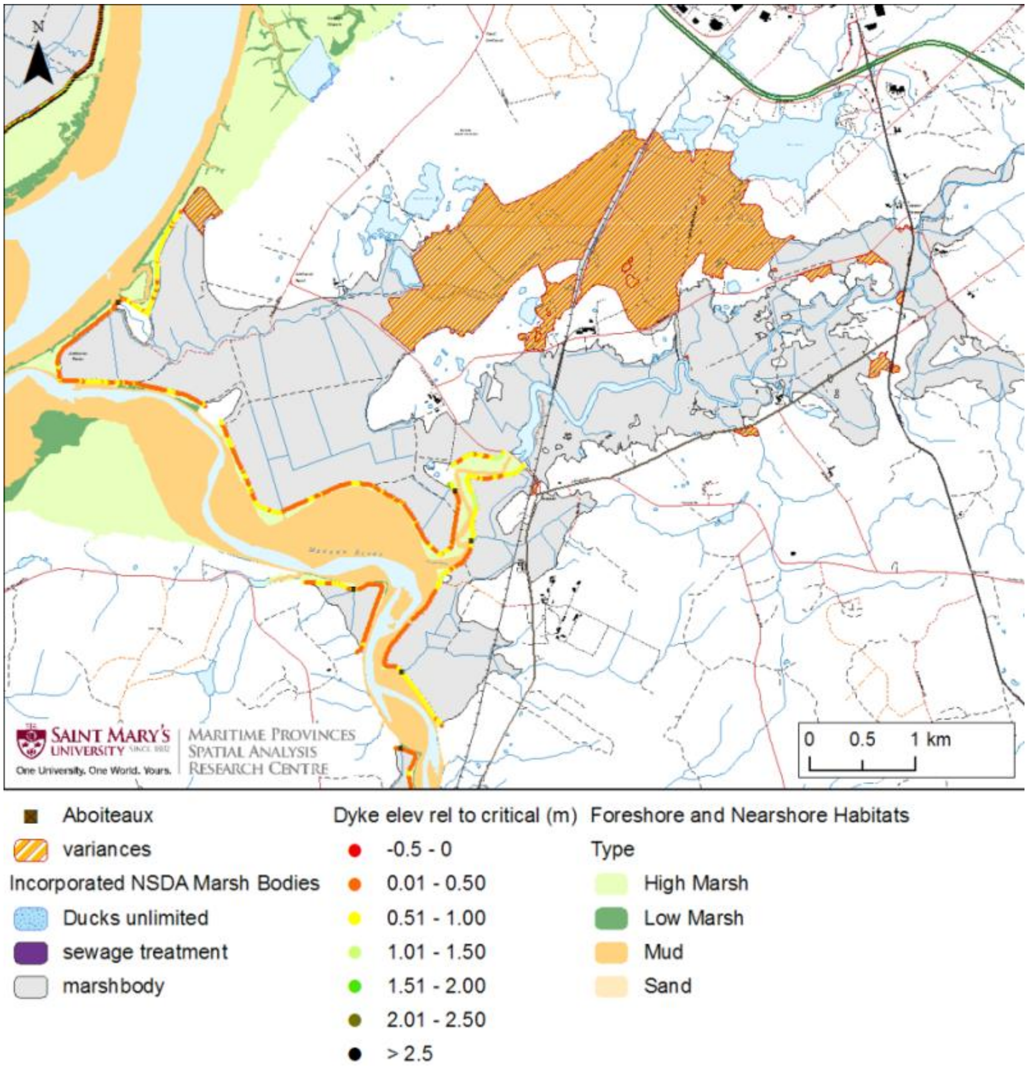


Figure 43: Extent of variances in NS42 Amherts Point , Cumberland County.

The Chignecto Isthmus is another area where a significant number of variances have been granted (Figure 43 and Figure 44) for Ducks Unlimited, sewage treatment, radio towers and most recently wind farms. In addition, both the TransCanada highway and CN Railway pass through those marsh bodies. A report by Browning, 2011 reveals that the value of land within the Amherst Area (NS44, NS53 and NS95) is worth approximately $4.9 M with only 17% of it associated with agriculture (Figure 46). This land is protected by approximately 15 km of dykes (Browning, 2011).

One final issue are dykes (or other protective structures) that are constructed and protect land under private or municipal ownership outside of a legislated marsbody boundary. This brings into question issues of maintenance and responsibility. Based on the Agriculture Marshlands Act, the Department of Agriculture is only responsible for dykes constructed to protect the legislated marshbody boundary. Figure 45 illustrates an area of land protected by dykes along the Kennetcook river that is under private ownership.

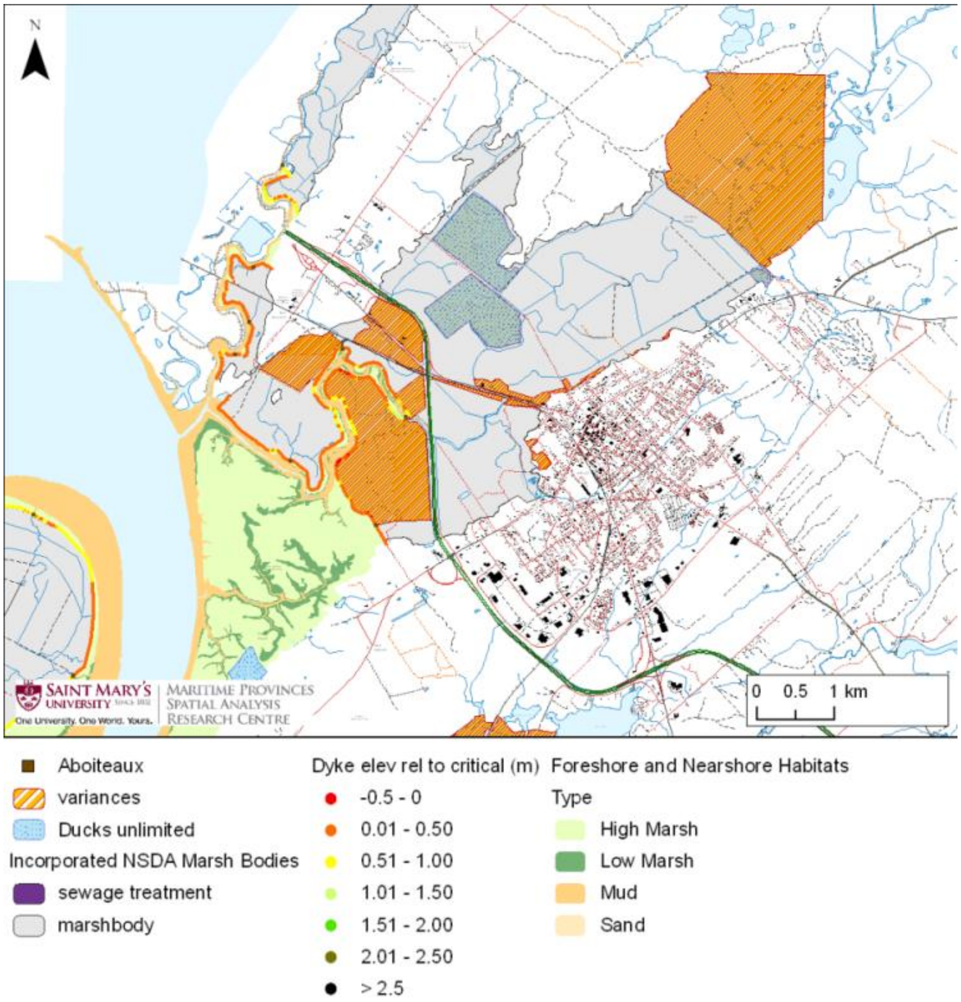


Figure 44: Incorporate marsh body at John Lusby including variances.

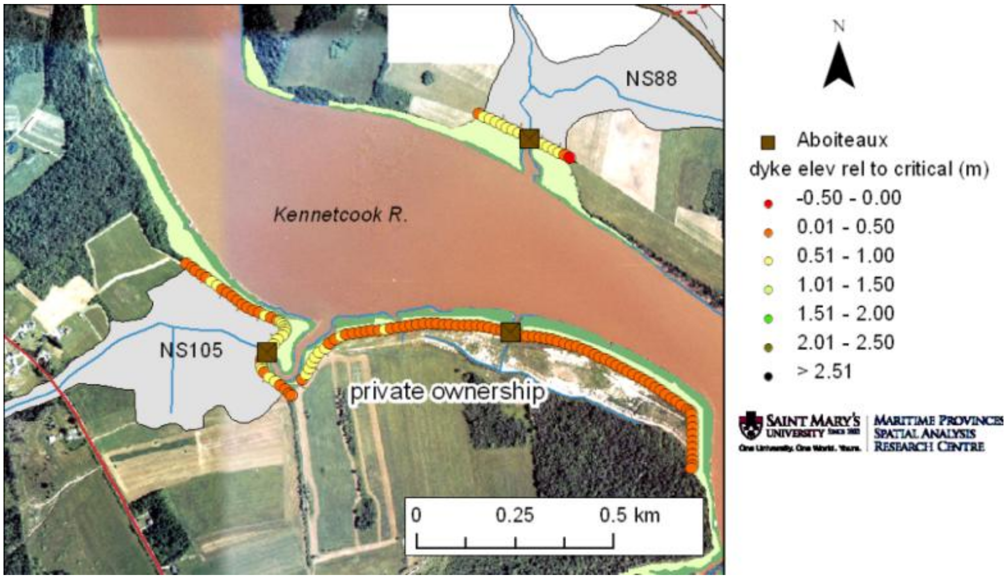


Figure 45: Example of dyked marsh under private ownership along the Kennetcook river.

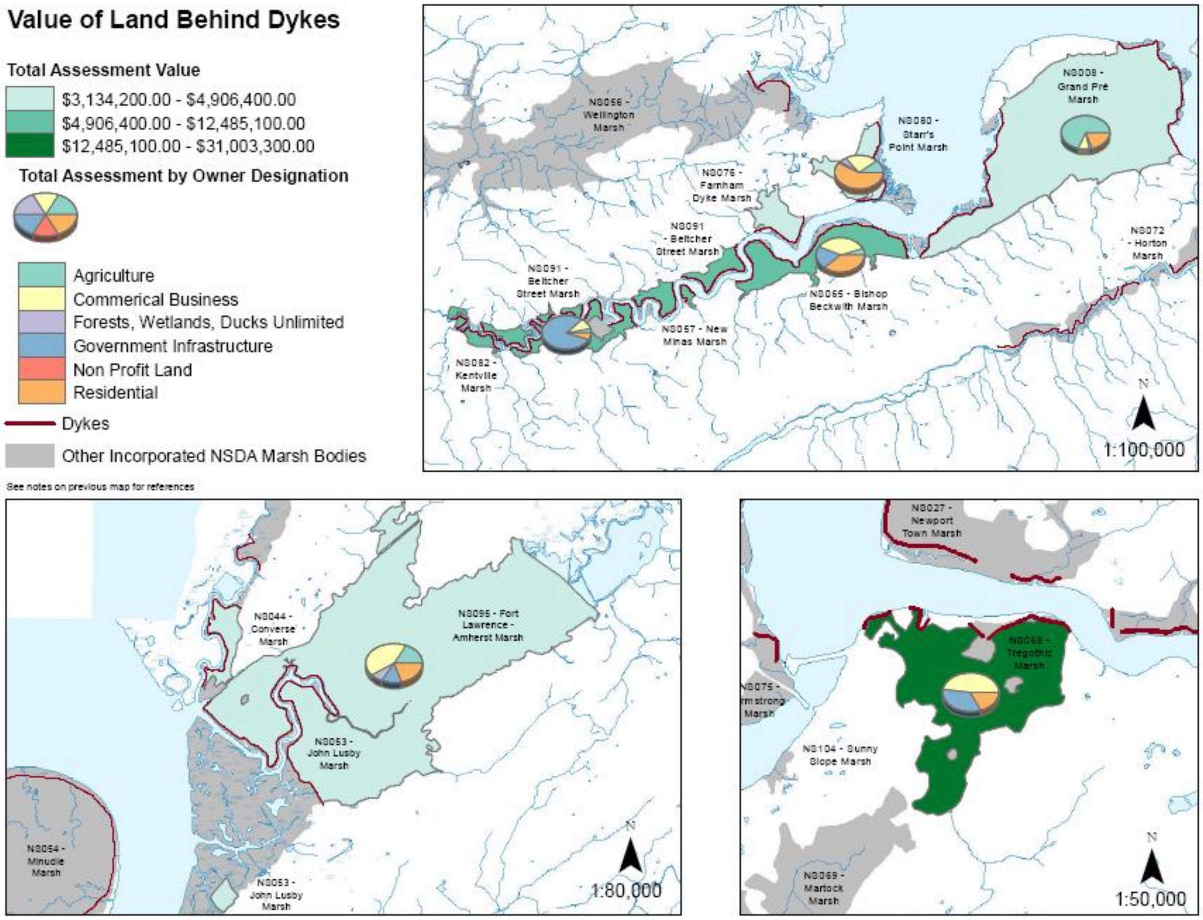


Figure 46: Distribution of assessed land value behind dykes based on Browning 2011.

3.4 Physical Assessment

Within the shorezone characterization project (Pietersma-Perrott and van Proosdij, 2012), shore zones within the ACAS study areas of the Cornwallis, Avon and Cumberland Estuaries were classified using satellite imagery, aerial photography and field observations. A total of 185 km were walked (representing approximately 40% of the coastline) and data were collected regarding the shoreline composition, type and material using shoreline photographs. They also documented evidence of erosion, sedimentation, storm damage and manmade shoreline protection. Detailed methods and data sources are provided in Pietersma-Perrott and van Proosdij (2012). Stability data are derived from direct field observation according to the following definitions (van Proosdij and Pietersma-Perrott, 2012):

Classification		Field Observation
Highly stabilized		No visible signs of erosion
Partially stabilized		Visible signs of erosion including cliffing, however little to no vegetation is slumping away from the coastline
Un-stabilized		Significant visible signs of erosion including cliffing, with vegetation slumping away from the coastline.

Table 9: Field shorezone classification scheme for stability assessment derived from Pietersma-Perrott and van Proosdij, 2012.

In addition, the aboiteaux superintendents and land protection surveyor were asked to spatially document areas of known concern using a large format map. These observations were mostly associated with areas of erosion where additional rock armouring would be required (Table 10). These observations were entered into the GIS and help to supplement our analyses.

Number on Maps	NSDA_no	Date	Name	Comment
0	NS092	13/03/2012	David Smith	Entire length(850ft) needs to be topped, has been overtopping in the past, #1 priority, dyke also needs additional rock. South end of dyke has major erosion, will soon go around dyke
1	NS092	13/03/2012	David Smith	Needs additional rock(large armour) place on 1000ft of dyke. North east storms hit area hard. Height of dyke okay.
2	NS008	13/03/2012	David Smith	Corner of east and north tract, critical area of north east storms. Rock work done in Feb 2011, but need more to help hold dyke.

3	NS008	13/03/2012	David Smith	South end of Tract #1 about 1200 - 1500ft of riverbank and foreshore need rock, height of dyke okay.
4	NS008	13/03/2012	David Smith	North section of East tract, about 2400ft needs additional rock.
5	NS008	13/03/2012	David Smith	Beyond dyke boundary to the west along shoreline needs rock work as eroding quickly. It is beyond NSDA boundary however it will someday go around end of dyke and flood the marsh on higher tides.
6	NS008	13/03/2012	David Smith	By sewer treatment plant on Tract # 2, about 1000 ft of foreshore is eroding and the riverbank is getting close to the old borrow pit
7	NS065	13/03/2012	David Smith	Rock protection work done Feb 2012, 3500 mt
8	NS065	13/03/2012	David Smith	Last 500 ft of dyke at the East end needs topping, no material to use at this site so will have to be trucked in
9	NS065	13/03/2012	David Smith	Section of dyke needs rock work, may need some minimal topping on this section also
10	NS076	13/03/2012	David Smith	Riverbank is eroding and getting close to dyke or borrow pit in places. Height of dyke is ok but will need to be made higher.
11	NS076	13/03/2012	David Smith	Rock work needs to be done on foreshore and riverbank. No observed overtopping but needs to be watched
12	NS111	09/03/2012	Craig Bauchman	This area is very stable with large tree established (over grown fence row).
13	NS045	01/03/2012	Gary Gilbert	Foreshore erosion
14	NS045	01/03/2012	Gary Gilbert	Dyke erosion
15	NS042	01/03/2012	Gary Gilbert	Foreshore erosion
16	NS093		Craig Bauchman	Needs rock
17	NS014		Craig Bauchman	Needs rock

Table 10: Summary of field observations by aboiteaux superintendants (March, 2012). Numbers on far left correspond to annotations on Figures in section 3.

3.4.1 *Kings County*

The northeastern sections of both Avonport Marsh (NS92) and Grand Pré (NS08) are exposed to strong waves from the northeast and long fetch over which the waves can be generated (Figure 23). As a result, the shoreline along these portions of the coast show strong evidence of erosion. This may be observed at the edge of NS92 ('0') where the entire length needs to be topped (Figure 47) and the aboiteau superintendent suggests that if erosion continues along the same train, it will undermine the dyke at the southern end (Table 10). At station '1' (Figure 48) new rock is required due to storm damage and it is estimated that large armour stones along a 300 m section. This section does not have any foreshore marsh and consists primarily of a sandy and eroding beach (Pietersma-Perrott and van Proosdij, 2012).

As mentioned previously, erosion can be generated by either wave activity or by tidal currents along the outer bank of a meander bend. This is the case observed at station '3' (Table 10) where the outer bend of the Gaspereau River is cutting into the bank, restricting foreshore development and eroding the backshore at high tide (Figure 48 and Figure 49).

The corner of the north and east dyke tract at Grand Pré is significantly impacted by northeastern storm events (Station '2' on Figure 48). Although the dyke was armoured in February 2011 additional material is required to hold the dyke as there is no foreshore marsh (Figure 48) at the tip. A shallow rock platform offers some protection to direct wave attack permitting the development of some foreshore marsh (Figure 49). The northern boundary of the eastern tract at Grand Pré is actively eroding (Figure 50) and will require additional rock armouring to be placed. In addition, it was recommended that this armouring be extended to the west beyond the boundary of the dyke to prevent erosion and flooding from the dyke edge (Figure 48 and Figure 51). Further to the west of this point, residents have armoured the shoreline to protect their homes and cottages (Figure 53).

Figure 47: Yuma geotagged photograph indicated on Figure 50 by 'C' at Avonport marsh NS92 showing low eroding dyke despite foreshore marsh. Photo taken on July 20, 2010 (Pietersma-Perrott and van Proosdij, 2012).

An additional area of concern for Grand Pré occurs along the western tract north (Tract #2) of the town of Wolfville at station '6' (Figure 54 and Figure 55). This section is located along the outer bank of the Cornwallis River and is also exposed to wave action from north waves at high tide. The eroding section is close to the sewage treatment plant and is eroding towards an old borrow pit (Table 10). This area will likely continue to erode due to the tidal current patterns in the area.

One of the most impacted areas is located along the eastern edge of Bishop Beckwith Marsh (NS65) just north of the Town of Wolfville (Figure 54). As mentioned previously, this area is heavily used by pedestrian and bicycle traffic and is adjacent to the Wolfville waterfront park or 'mud creek'. Additional rock was placed at station '7' on Figure 54 and is shown in Figure 56 ('F'). Photograph was taken from the landward edge of the marsh body.

Figure 59 was also taken along a similar section of dyke ('G') along NS65. Note the marked erosion of surficial grass cover due to heavy foot. This area appears to recently have been topped (note survey stakes). Erosion of this nature can place the dyke at significant risk of slope failure even if most of the wear appears to be on the landward edge. This is likely also contributing to the presence of dyke crest elevations less than critical reported earlier.

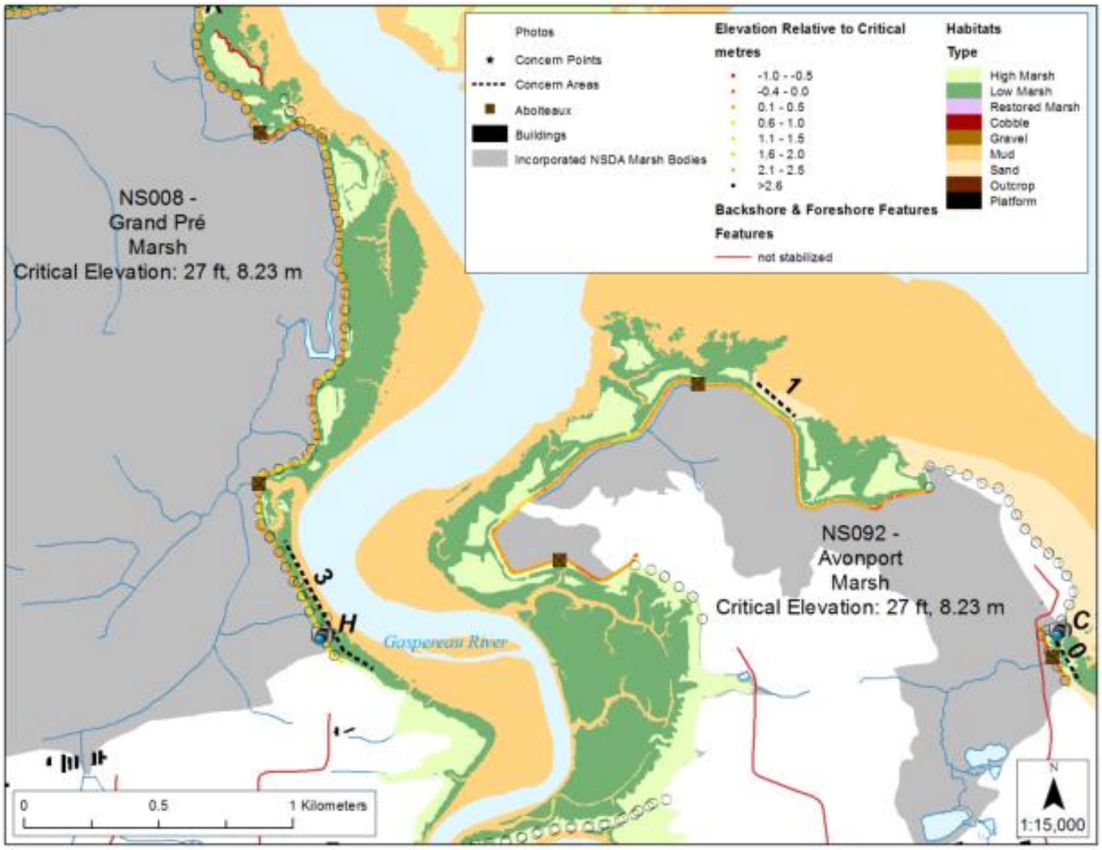


Figure 48: Shore protection, critical elevations and areas of concern as identified by aboiteaux supervisors along NS92 and NS08. Cartography produced by Barbara Pietersma-Perrott.

Figure 49: Eroding foreshore marsh and armouring along the backshore along the Gaspereau R. Indicated by 'H' on Figure 48 Photo taken July 23, 2010. (Pietersma-Perrott and van Proosdij, 2012).

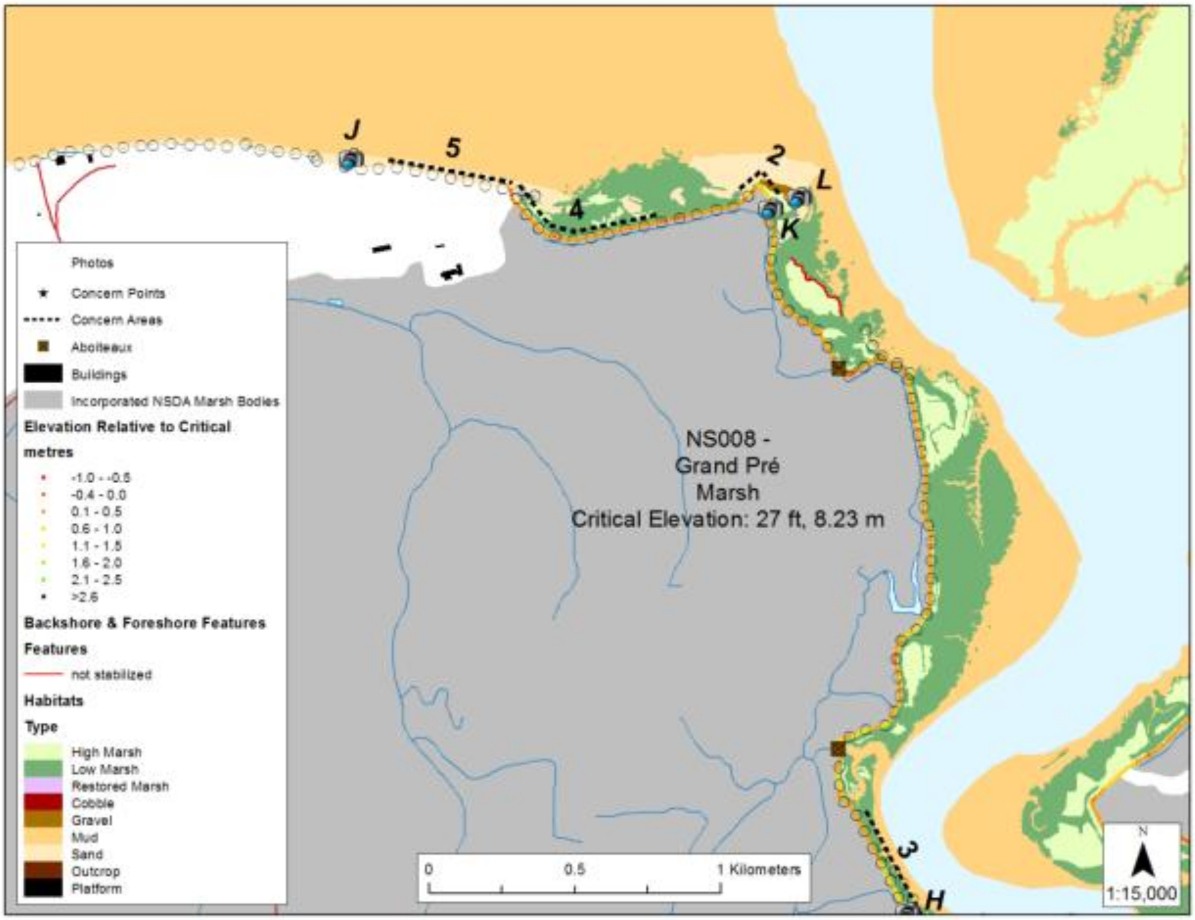


Figure 50: Areas of concern and shore protection at Grand Pre. Cartography produced by Barbara Pietersma-Perrott, 2012.

Figure 51: Eroding foreshore with remnant peat layer on northeast corner of Grand Pre indicated by 'L' on Figure 36. Photo taken July 21, 2010. (Pietersma-Perrott and van Proosdij, 2012).

Figure 52: Foreshore along northeast corner of NS08 protecting base of dyke indicated by 'K' on Figure 50. Photo taken July 21, 2010. (Pietersma-Perrott and van Proosdij, 2012).

Figure 53: Rock armouring along the backshore near Evangeline beach likely placed by property owners indicated by 'J' on Figure 50. Photo taken July 21, 2010 (Pietersma-Perrott and van Proosdij, 2012).

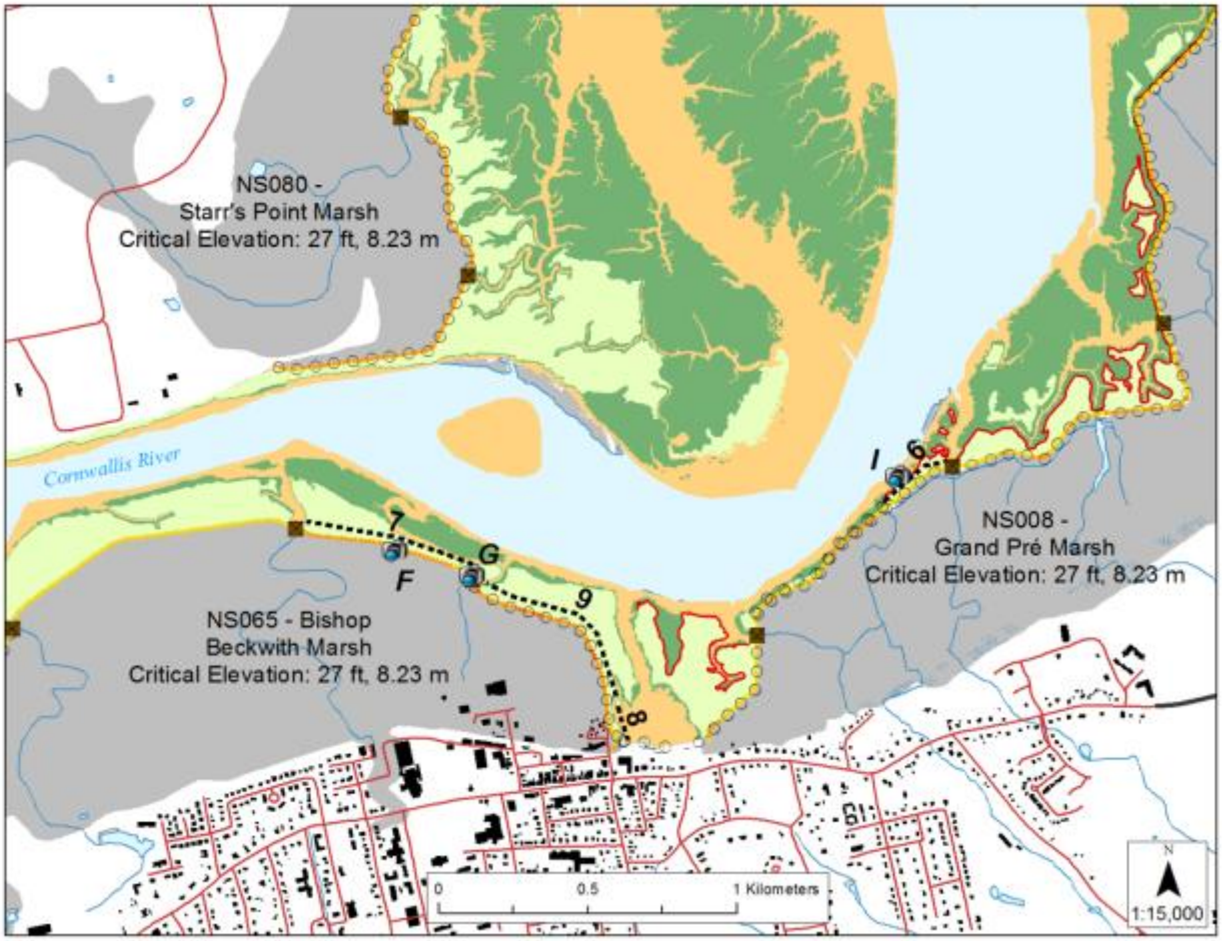


Figure 54: Areas of concern, shoreline armouring and critical elevations for Wolfville Area. Cartography produced by Barbara Pietersma- Perrott, 2012

Figure 55: Photo taken on July 21, 2010 along tract #2 NS08 showing eroding foreshore marsh (Pietersma-

Figure 56: Shore erosion along Wolfville harbour. Note development within floodplain area. Photo taken July 21, 2012.

Figure 57: Non-agricultural aboiteau in Wolfville draining into waterfront. Photo taken July 21, 2011.

The edge of the dyke at Bishop Beckwith near the Wolfville Waterfront park and Railtown developments will need to be topped (Figure 56) according to Land Protection personnel however there is no foreshore material (e.g borrow pit) that can be used therefore material will have to be trucked in, significantly increasing the cost. It is unlikely that marsh vegetation will establish in this area due to a large eddy that develops on the rising and falling tide, scouring the banks in addition to drainage from a non-agricultural culvert/aboiteau discharging in the vicinity (Figure 57). The aboiteau superintendent noted the need for additional rock and minimal topping however based on the recorded elevations below critical, and the infrastructure at risk, it is recommended that this section be raised.

Figure 58: Slumping marsh vegetation along north shore of Cornwallis River at NS76 identified at 'E' in Figure 60 Photo taken July 29, 2010 (Pietersma-Perrott and van Proosdij, 2012)

An additional section of dyke not identified in Table 10 is along the southern edge of Starr's Point Marsh (NS80) along the edge of the Cornwallis River. The bank has been eroding steadily over the last decade (note the old shoreline position in blue) and additional armouring will be needed or at least protection of the remaining foreshore marsh (Figure 54). Further up the Cornwallis River, the southern edge of Farnham Dyke marsh (NS76) exhibits steep, eroding marsh cliffs (Figure 58 and Figure 60). The section identified at station '10' is not currently armoured (Figure 60) however will likely need some form of protection in the near future. The banks are actively slumping in this region.

Figure 59: Surficial erosion of dyke surface at NS65 next to Wolfville Waterfront Park. Photo taken July 5, 2011.

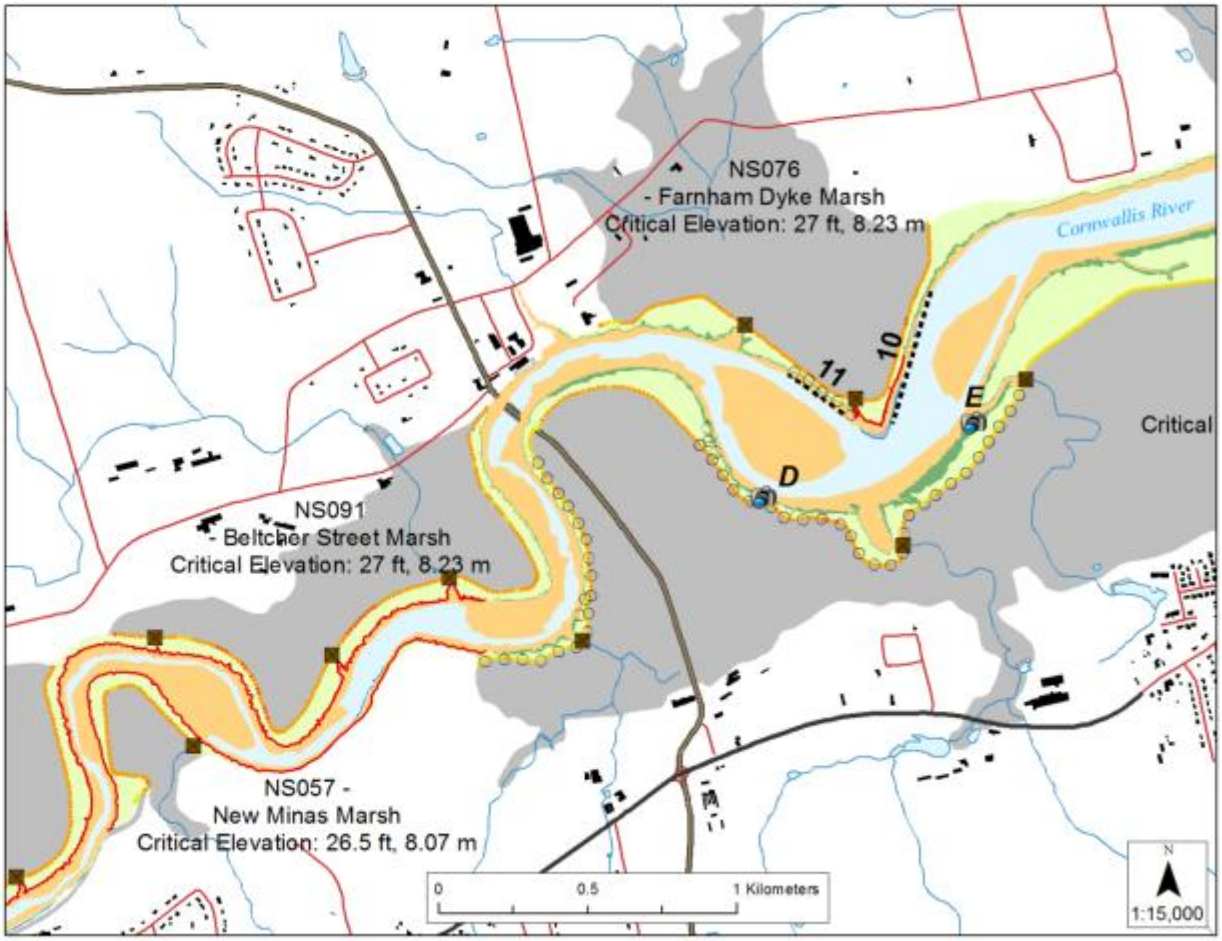


Figure 60: Areas of concern, shore protection and critical elevations along the Cornwallis River. Cartography produced by Barbara Pietersma, 2012.

3.4.2 *Hants County*

An area of on-going concern within the Avon River is along the shore of Elderkin Marsh just north of the Windsor Causeway (Figure 61). This area has progressively been armoured over time and is responding to the erosive force of the narrow tidal channel that contains most of the freshwater discharge from the tide gate. The development of the Newport bar has cause additional flow acceleration on the rising tide. Erosion will likely continue to accelerate as the bar continues to develop.

Figure 61: Photograph of eroding foreshore and slumping mud bank with shore protection along Elderkin marsh, Avon River and indicated by ' A' on Figure 62. Photo taken May 31, 2011.

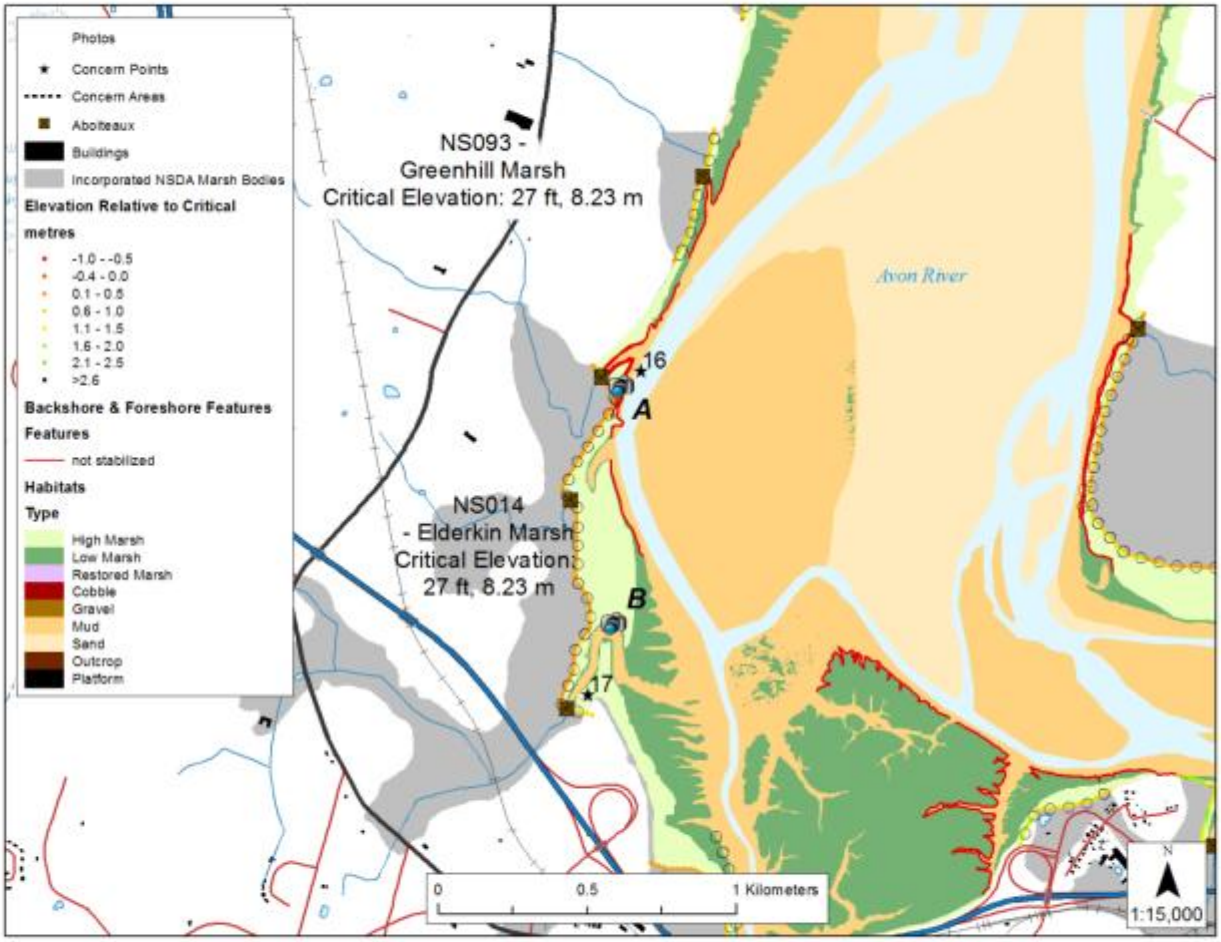


Figure 62: Shore zone characterization and areas of concern in the Avon River.

Figure 61 illustrates that bank failure can also occur due to slumping further compromising any armouring placed along that bank.

Interestingly, an area of concern in early 2000 has now developed new low marsh vegetation (Figure 63) which is protecting the dyke from additional erosion. The tide gate channel is gradually infilling on the western edge, facilitating the growth of *Spartina alterniflora.*

Figure 63: Extensive low marsh which developed seaward of former eroding high marsh cliff along Elderkin Marsh at location "B" on Figure 62. Photo taken May 25, 2011.

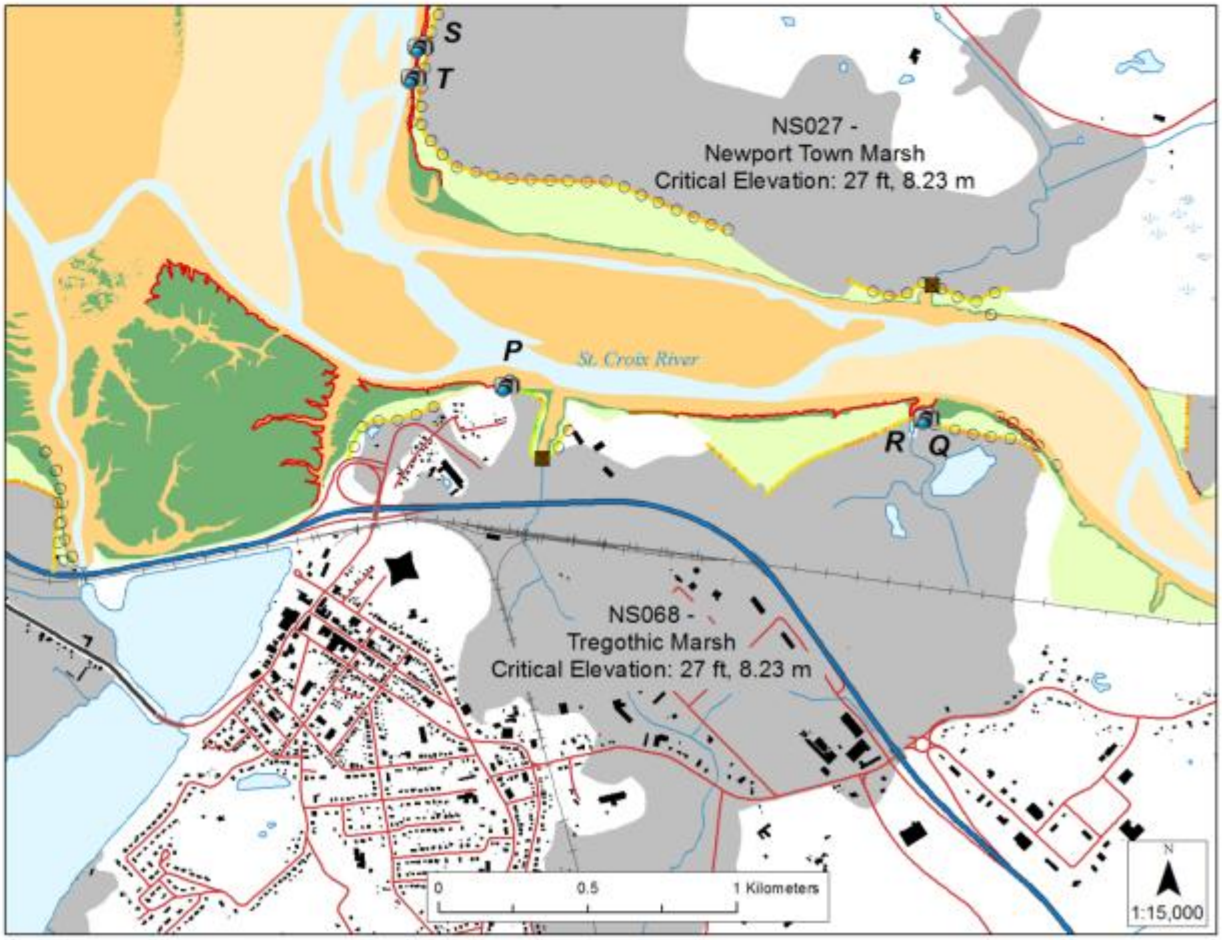


Figure 64: Areas of concern and critical elevations near Tregothic and Newport marsh bodies. Cartography produced by Barbara Pietersma, 2012.

Figure 65: Dyke toe erosion along Tregothic marsh at Station P on Figure 64. Photo taken on July 4, 2011.

Figure 66: erosion of shore armouring along Tregothic marsh at Station P on Figure 64. Photo taken on July 4, 2011

Figure 67: Dyke toe scour and erosion of armouring at Station 'Q' Figure 64 Photo taken July 4, 2011.

Figure 68: Eroding foreshore along Newport marsh, Avon river. Photo taken July 5, 2011.

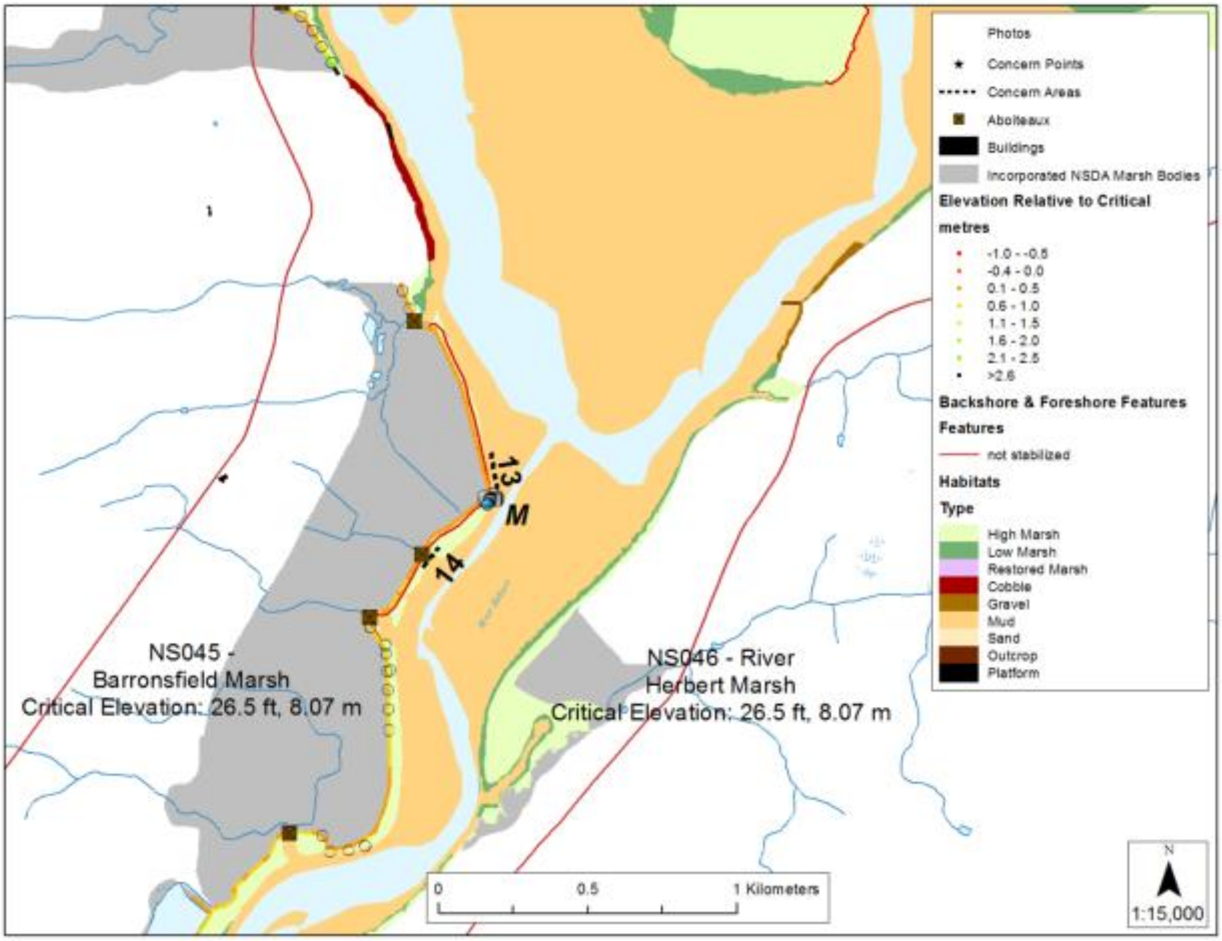


Figure 69: Areas of concern, foreshore marsh and critical elevations for marsh bodies along River Herbert. Cartography produced by Barbara Pietersma-Perrott, 2012.

The dyke protecting Tregothic marsh (NS8) and therefore a large portion of the town of Windsor displays visual evidence of extensive areas of erosion and loss of foreshore. Most of this is associated with the shift in the main thalweg to the south shore of the St. Croix River (Figure 64). This area is also of concern since it contains a number of significant aboiteaux and has a section of dyke below critical elevation.

Figure 70: Photograph along shore of NS45 taken on Aug 22, 2010

3.4.3 *Cumberland County*

In Cumberland County, there are a number of areas of concern identified by the aboiteau superintendents. Section 13 and 14 identified on Figure 69 are demonstrating both foreshore and dyke erosion along the eastern edge of Barronsfield Marsh (NS45) along the River Herbert (Aug 22, 2010). Currently these sections do not appear to be armoured and display evidence of slumping.

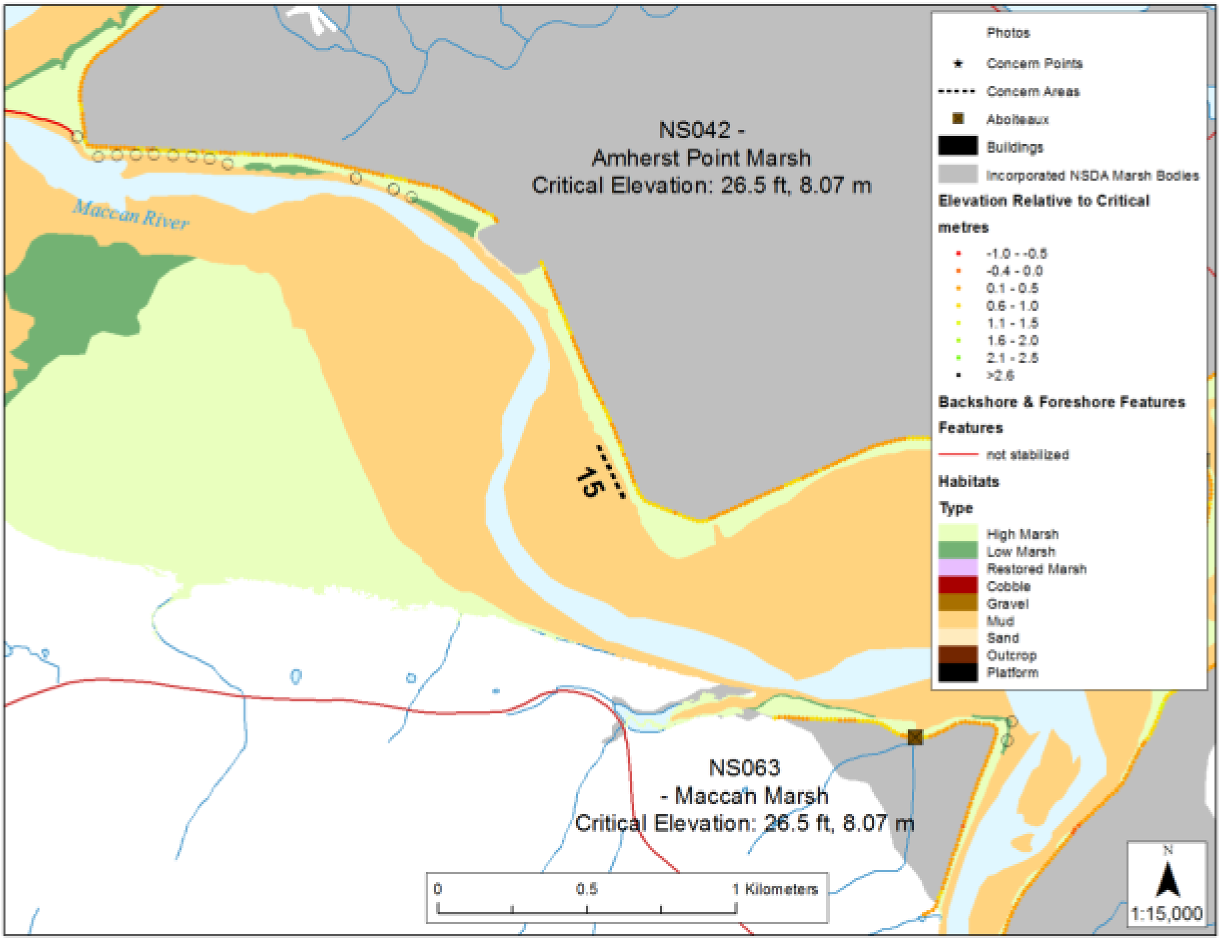


Figure 71: Areas of concern, shore zones and critical elevations for Amherst and Maccan marsh bodies. Cartography produced by Barbara Pietersma-Perrott, 2012.

Foreshore erosion was noted at Station 15 on the Amherst Point Marsh (NS42) (Figure 71 and Table 10) likely associated with large tidal flows coming up the Maccan River on the outer meander bend. Amherst point marsh itself (foreshore marsh extending in to the Maccan River) will likely be breached within the next year.

The western side of Minudie Marsh (NS54) shows evidence of erosion, cliffed foreshore and many areas along the dyke that are currently below critical elevation (Figure 72). At the present time, this area of underutilized for agriculture however it is one of the few large tracts of intact marshland that remains in the province and serious consideration needs to be made as to its fate. Artificial dyke breaching and managed realignment would open up significant salt marsh habitat and serve as a protective structure for dykes at the head of the Cumberland Basin along the Tantramaar marsh and the Maccan River. Alternatively it also could developed for sustainable agriculture activities such as organic beef grazing, etc.. A decision will need to be made within the next few years to prevent a natural breach from occurring which may threaten future agriculture activities. Although both NS53 (John Lusby) and NS44 (Converse Marsh) are protected by a large expanse of foreshore marsh (Figure 74), they are experiencing bank erosion due to flows of the La Planche River. This is also the site ('O' on Figure 74) of the complete failure of the 'new' 'Amherst' aboiteau (Figure 75) in Spring 2008. This aboiteau had been constructed from June to September 2006 and opened to tidal waters in March 2007. Settlement of the dyke and eventual dislodgement of the headwall and culvert occurred within a relatively short period of time (Figure 75). A number of engineering assessments were conducted and preliminary reasons for the aboiteau failure include soil conditions (clay close to the liquid limit and very soft), soil creep during construction, and vibration (Klasen, 2010).

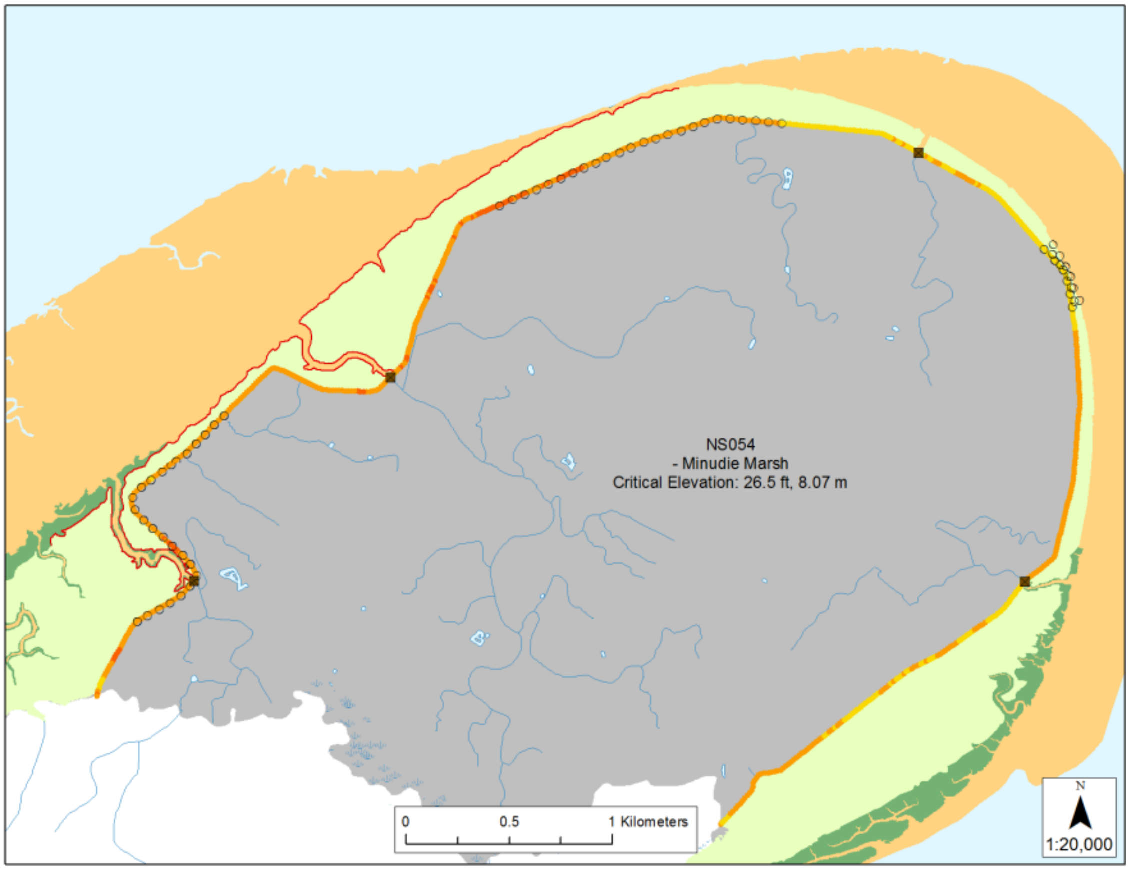


Figure 72: Critical elevations and shore zones for Minudie (NS54). Cartography produced by Barbara Pietersma-Perrott, 2012.

Figure 73: River bank erosion along La Planche River and NS44 Converse Marsh. Photo taken on Aug 20, 2010

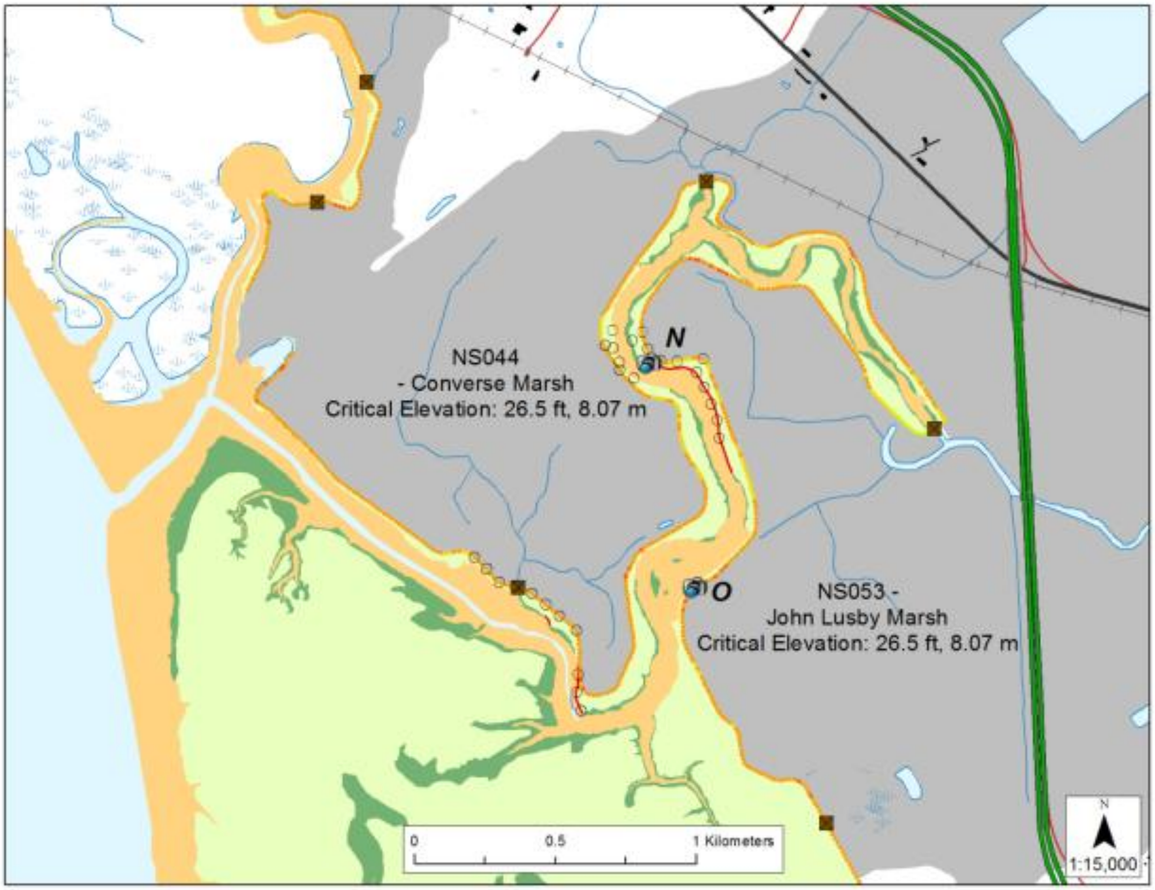


Figure 74: Areas of concern along the La Planche River, HS53 and NS44 marshes. Cartography by Barbara Pietersma-Perrott, 2012

Figure 75: Remnant aboiteau and pipe after failed aboiteau on the La Planche River (indicated by 'O' on Figure 74) along the John Lusby marsh. Photo taken Aug 20, 2010.

3.5 Drivers of Protection and Erosion

Dyke vulnerability is driven by a range of factors that are explored in more detail in Tibbetts and van Proosdij, 2012. The width of foreshore marsh, wave exposure, presence of intertidal bodies and tidal currents all influence the location and extent of erosion along a shoreline. In addition, management actions taken to protect dykes (e.g. armouring) or improve aboiteau drainage (e.g. channel re-alignment, abandonment) can and will influence natural morphodynamic processes (Robinson et al., 2004). This was examined for select portions of the Avon and Cornwallis River estuaries where historical imagery taken at low tide was consistent (Figure 76 to 81).

At the time of the MMRA in the 1940s and 1950s there was a trend towards land reclamation and dyke re-alignment (Figure 76) which had a significant consequence on the overall morphodynamics of the system (van Proosdij et al., 2009). Land claims can cause estuaries to switch to ebb-dominance, thus enhancing seaward sediment transport, erosion and increases in depth of the main channel (Friedrichs et al. 1992). By 1964, erosion had begun along the shore of NS27 Newport Town marsh and Figure 77 depicts the sequence of shore protection. Placement of rock can have the effect of increasing erosion at the edge of the protection zone, generating a feedback loop where the placement of more rock encourages more erosion. It should be noted that rock armouring at that time was placed along the dyke toe rather than foreshore marsh. The construction of the Windsor causeway in 1969 significantly altered the local hydrodynamics within the system (van Proosdij and Townsend, 2004). By 1973, a large mudflat had started to develop downstream of the new causeway structure (Figure 76), essentially sequestering sediment away from new foreshore development seaward of the existing dyke structures. New rock armouring was placed to protect the dyke toe from erosion. By 1992, new salt marsh vegetation (*Spartina alterniflora*) began to be established on the main mudflat immediately downstream of the causeway, likely colonized by rhizomes transported through ice rafting (van Proosdij and Townsend, 2004). This cause further sequestration of sediment and constrained the outlet of the Windsor tide gate channel, likely increasing velocities and eroding the toe of the dyke along the Elderkin Marsh (NS14) (Figure 77). By 2003, a fully developed low marsh community had developed downstream of the causeway, significantly reducing the tidal prism (van Proosdij et al., 2009) and increasing velocities within the now narrow channels. Since the marsh platform is higher in the tidal frame and rates of sediment deposition had decreased, more sediment was available to form new foreshore marsh on the southern shore of Tregothic marsh on the St. Croix river, across on Newport Town Marsh and southern end of Elderkin marsh near the tide gate (Figure 78). All of this new foreshore marsh meant that there was limited need for new rock armouring with the exception of the northern edge of Elderkin Marsh as the tidal channel migrated again, pushed downstream by the rapidly accreting Newport bar (van Proosdij et al., 2009) (Figure 78). By 2007, the main Avon channel had also shifted, requiring rock armouring along the western edge of Newport Town marsh and near aboiteaux structures along Elderkin marsh (Figure 78). In addition, NS Department of Agriculture began to change their approach to armouring by also armouring the edge of the foreshore (e.g. western bank of tide gate channel) to maintain as much foreshore as possible (Figure 78). Although a positive step, there are significant challenges due to accessibility, the unconsolidated nature of the marsh sediments and slope failure. It may be more effective to place rock along the foreshore in areas of high marsh which are more solid.

In the Cornwallis Estuary, significant realignment and reclamation of land was undertaken and new dykes constructed in the 1940s and early 50s (Figure 79). No shore armouring is present. Once again this had the effect of decreasing the intertidal area for sediment deposition and enhancing intertidal accretion. It could be argued however that limited foreshore was left seaward of the Grand Pre dyke.

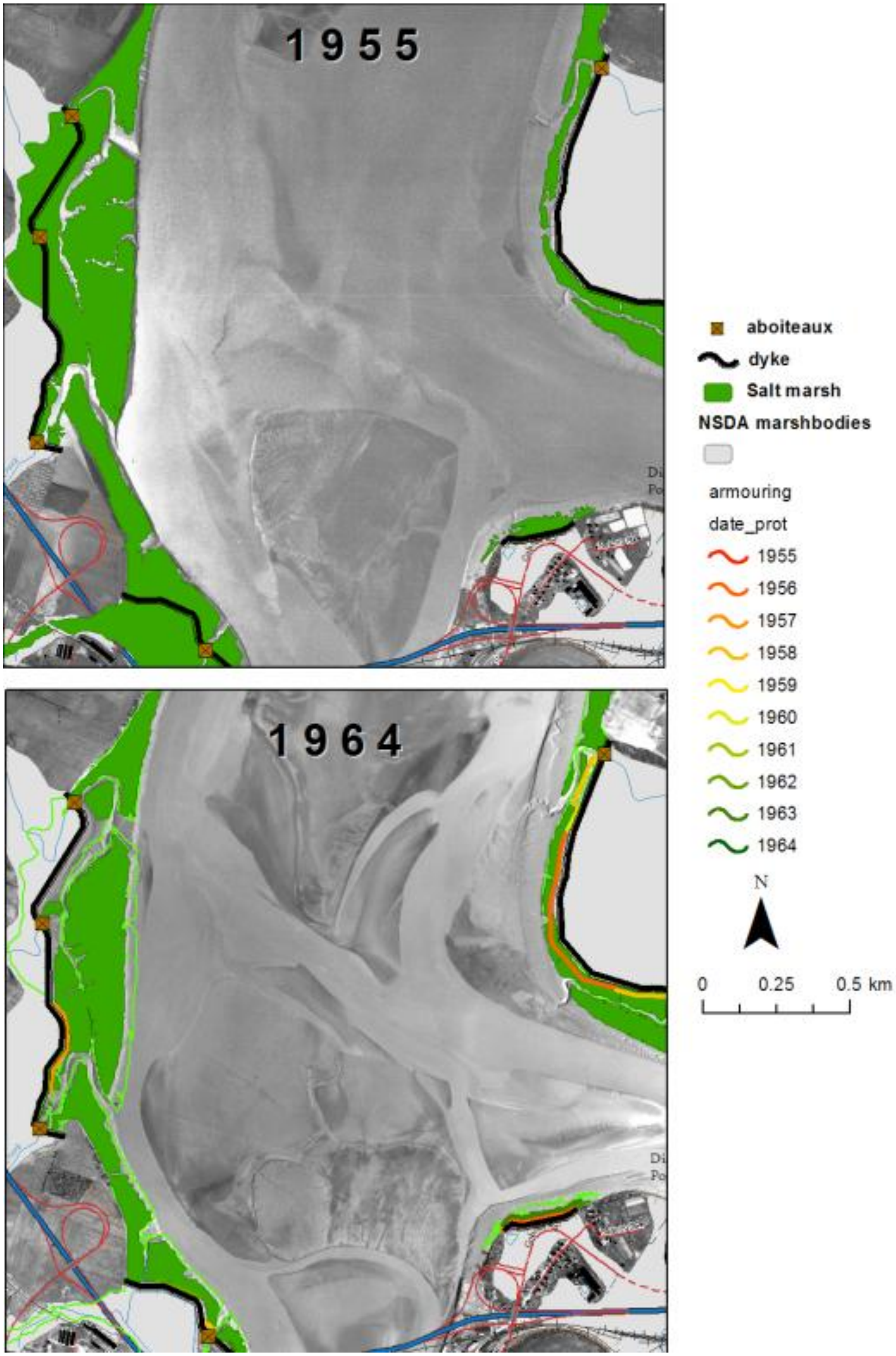


Figure 76: Extent of salt marsh habitat and placement of shore protection from 1955 to 1964 in the Avon River, North of the Town of Windsor

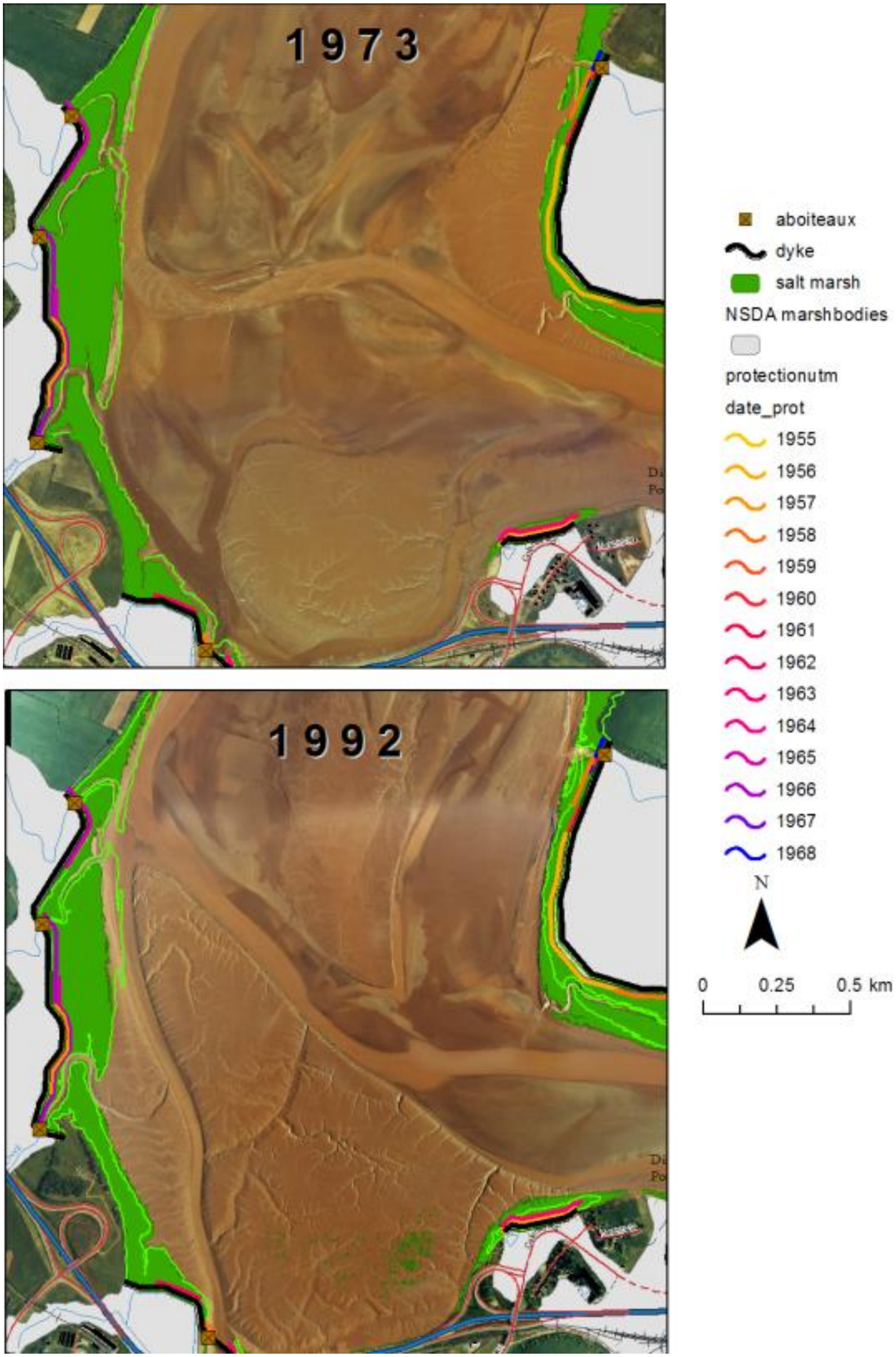


Figure 77: Extent of salt marsh habitat and placement of shore protection between 1973 and 1992 in the Avon River North of the Town of Windsor

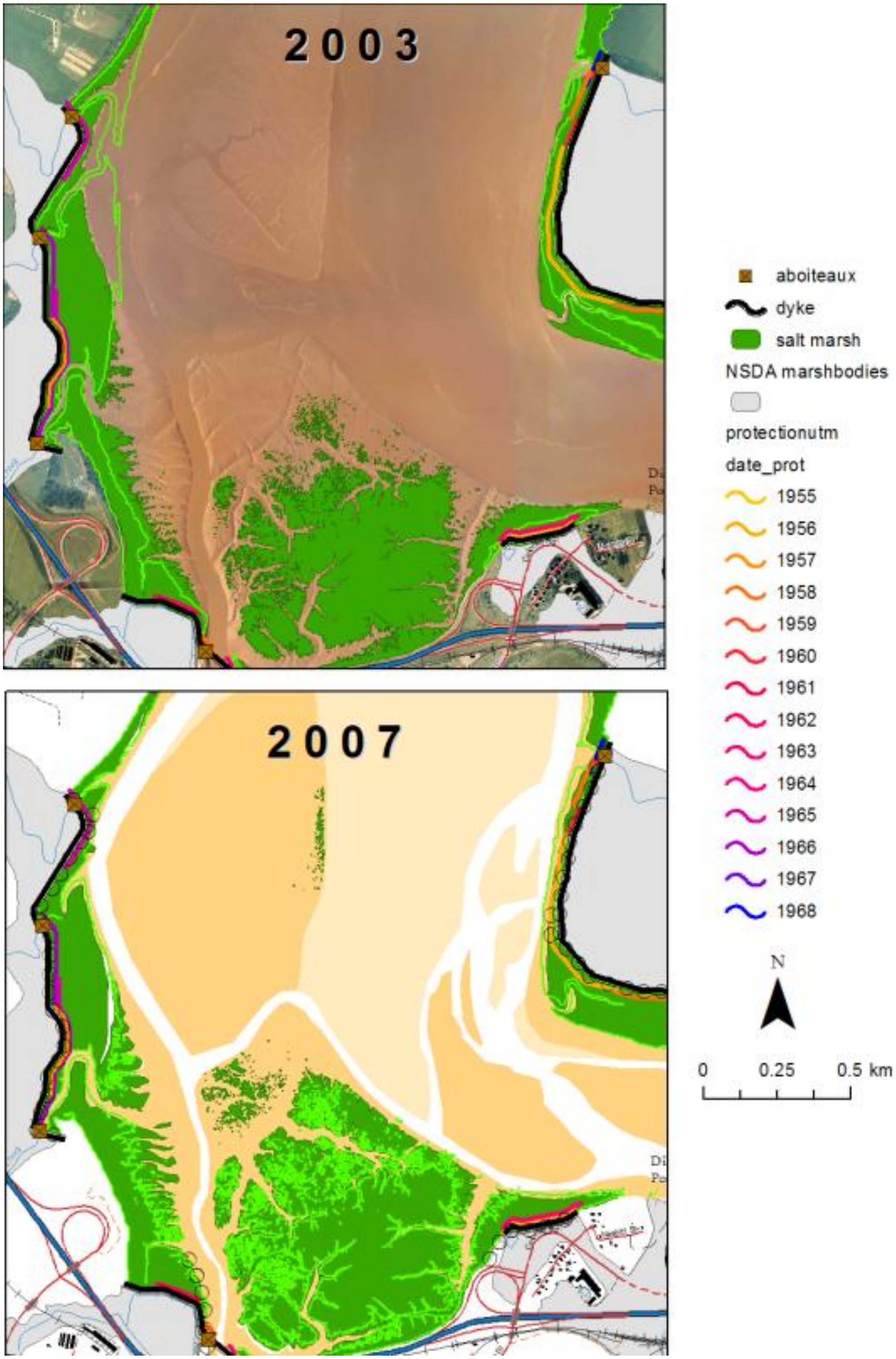


Figure 78: Extent of salt marsh habitat and associated shore protection between 2002 and 2007 for the Avon River, North of the Town of Windsor

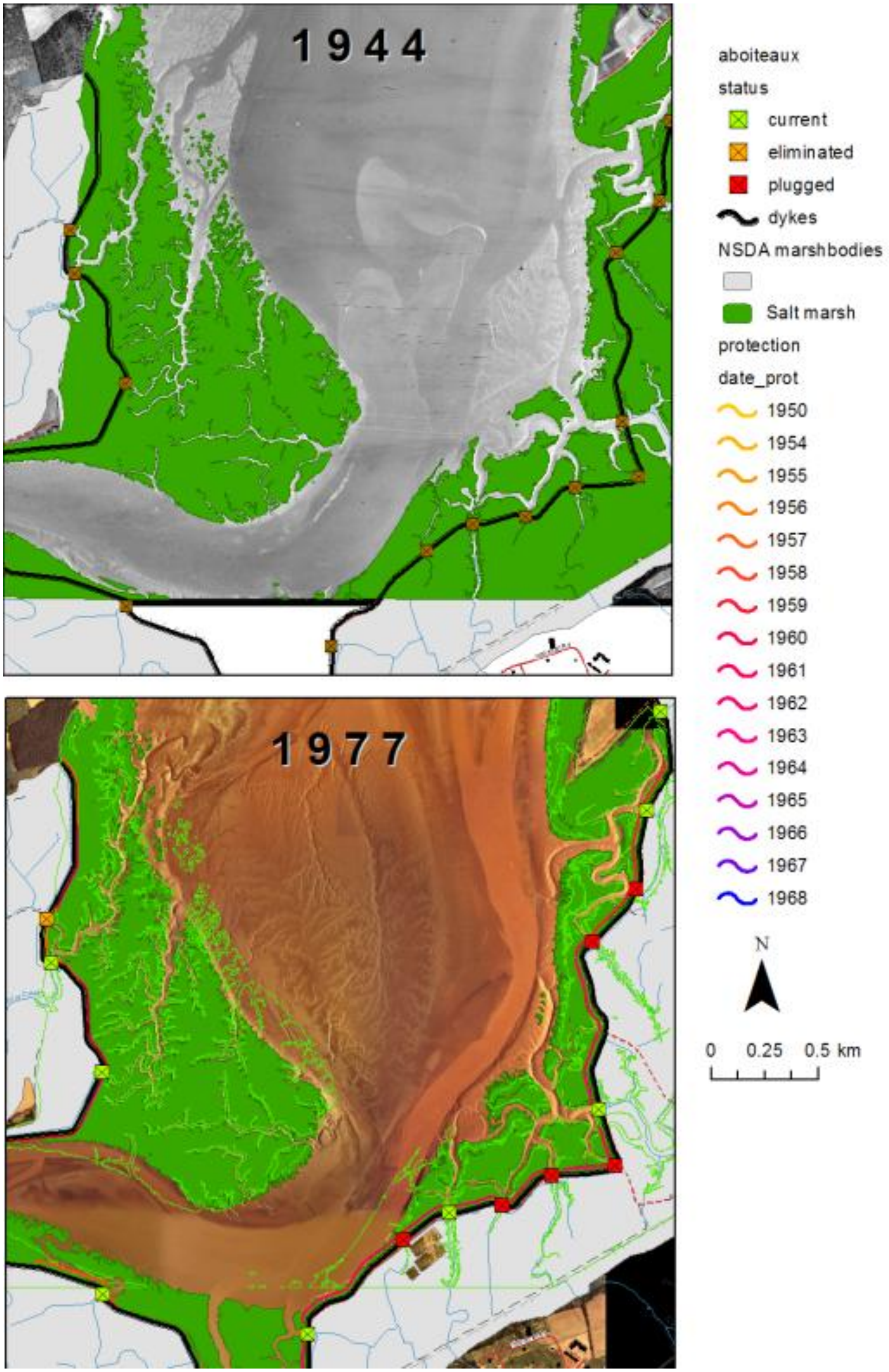


Figure 79: Extent of salt marsh habitat, associated shore protection and status of aboiteaux in the Cornwallis River, North of the Town of Wolfville. Note plugging and elimination of aboiteaux in 1960 and land reclamation in 1957.

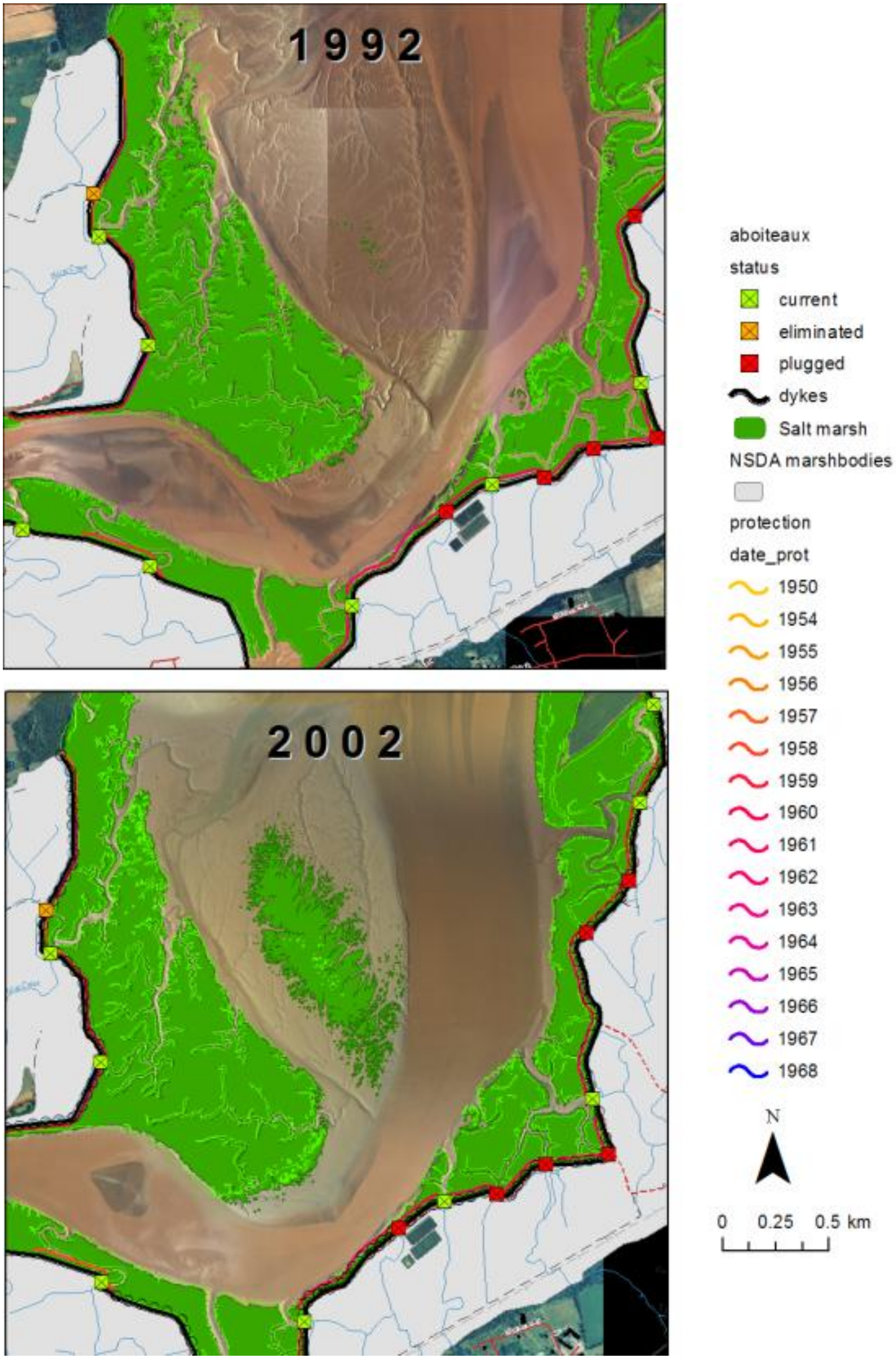


Figure 80: Extent of salt marsh habitat, shore protection and status of aboiteaux on the Cornwallis River, North of the Town of Wolfville in 1992 and 2002

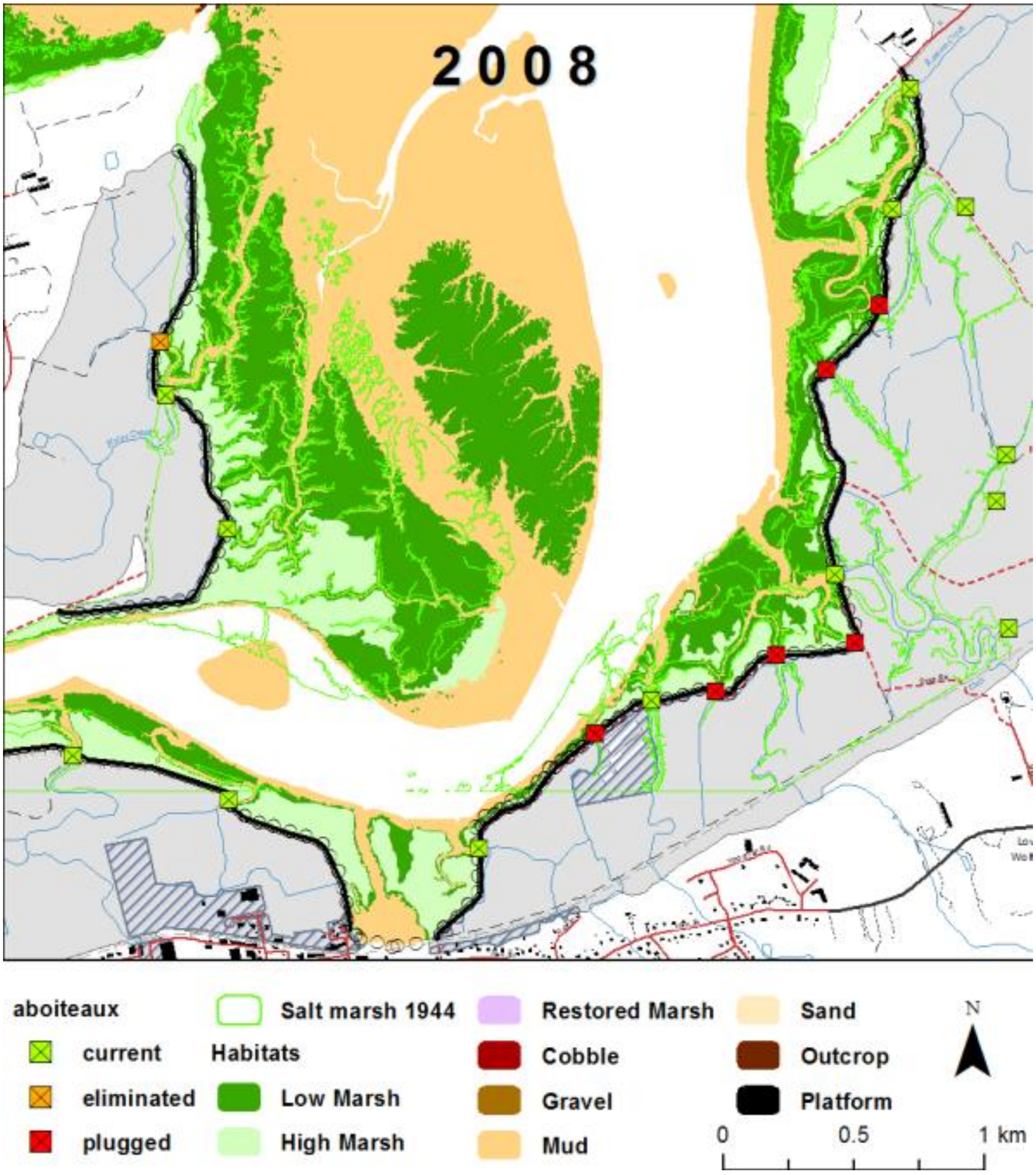


Figure 81: Comparison of salt marsh extent in 2008 with marsh present in 1944 in the Cornwallis Estuary, North of Wolfville. Note variances and placement of shore armouring

The growing intertidal sand flat caused flow acceleration along the margins, eroding marsh east of Starrs Point and the meander of the Cornwallis River eroded sections along Starrs Point and immediately east of Wolfville (Figure 79), requiring rock armour to be placed. The eroded material fed foreshore marsh development along Bishop Beckwich marsh near the Wolfville waterfront. By 1977, six out of the nine aboiteaux along the western shore of Grand Pre marsh were eliminated to reduce costs (Figure 79). This did not appear to have any immediate or long term effects with the exception of infilling smaller channels. By 1992, the increased freshwater flow velocities from one of the remaining aboiteau along the Grand Pre marsh may have contributed to the observed dissection of the foreshore marsh in that region (Figure 80). Rock armouring has been placed along the toe of the majority of dykes in the estuary and sediment continues to accumulate on the intertidal bar. Over the next 10 years, this bar became almost fully colonized by *Spartina alterniflora* and limited foreshore progradation was observed in adjacent marshes (Figure 80). Figure 81 illustrates the change in salt marsh between 1944 and 2008. Overall there has been a net gain of salt marsh in the estuary, with development of low marsh seaward of the remnant high marsh at the time of dyking. The shift in the natural channel of the Cornwallis River, accelerated erosion on the southern edge of Starrs Point and southwestern edge of Grand Pre near the town of Wolfville sewage treatment plant (Figure 81).

Figure 82: Shoreline exposure calculated using Wemo and presence of coastal features in the foreshore (Tibbetts and van Proosdij, 2012)

As mentioned previously, the presence and condition of foreshore marsh can offer significant erosion protection to the toe of the dyke (Doody, 2008; Leonard and Reed, 2002; Moeller and Spencer, 2002; Moeller, 2003; Moeller, 2006). Tibbetts and van Proosdij (2012) conducted a coastal vulnerability assessment for the Cornwallis estuary incorporating driving variables such as tide level and storm surge as well as biophysical variables (slope, foreshore width, vegetation, observed erodibility) and resilience. The coastline exposure values, as calculated using the Wave Exposure Model (WEMo) version 4.0, indicate the estimated level of wave energy for each 250 m segment of the coastline for a given tidal elevation. Figure 82 illustrates the distribution of exposure values for HHWLT and extent of foreshore marsh. It is evident that areas of minimal or no foreshore marsh and directly exposed to wave action will have a very high vulnerability to wave erosion. Conversely, areas that are exposed to a long fetch (e.g. Starrs Point) yet have significant foreshore marsh, have a very low vulnerability.

Exposure also relates directly to changes in the position of the coastline. The change in foreshore position was calculated using a software package called Analyzing Moving Boundaries Using R (AMBUR) developed by Jackson (2010). Throughout the Cornwallis estuary, the AMBUR analysis has shown that the average net change is -3m (± 5.8 m), between 1977 and 2008. Most of the estuary saw less than 40 m of erosion or no change during this time period with some areas seeing as much as 150 m in marsh progradation (Figure 83) (Tibbetts, 2012).

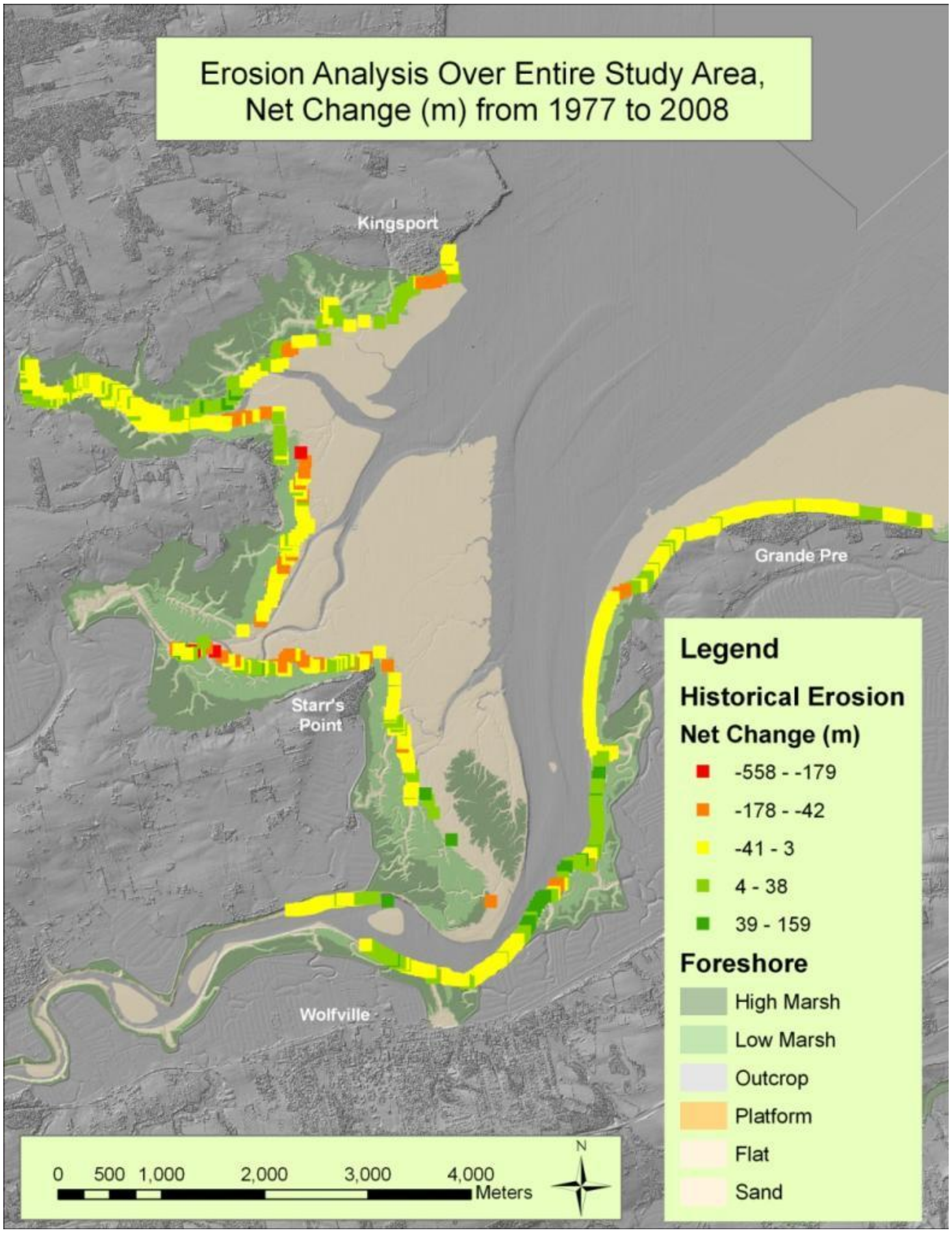


Figure 83: Historical change in lower foreshore from 1977 to 2008 (Tibett, 2012)

AMBUR was also used to calculate the width of foreshore every 250 m along the backshore for both the Cornwallis and Cumberland estuaries. This effectively provides a measure of the amount of protection that is currently being offered to individual dykes. This analysis was not performed for the Avon since most erosion in that area is associated with the migration of the Avon River channel rather than wave energy. 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 (Figure 22). 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.

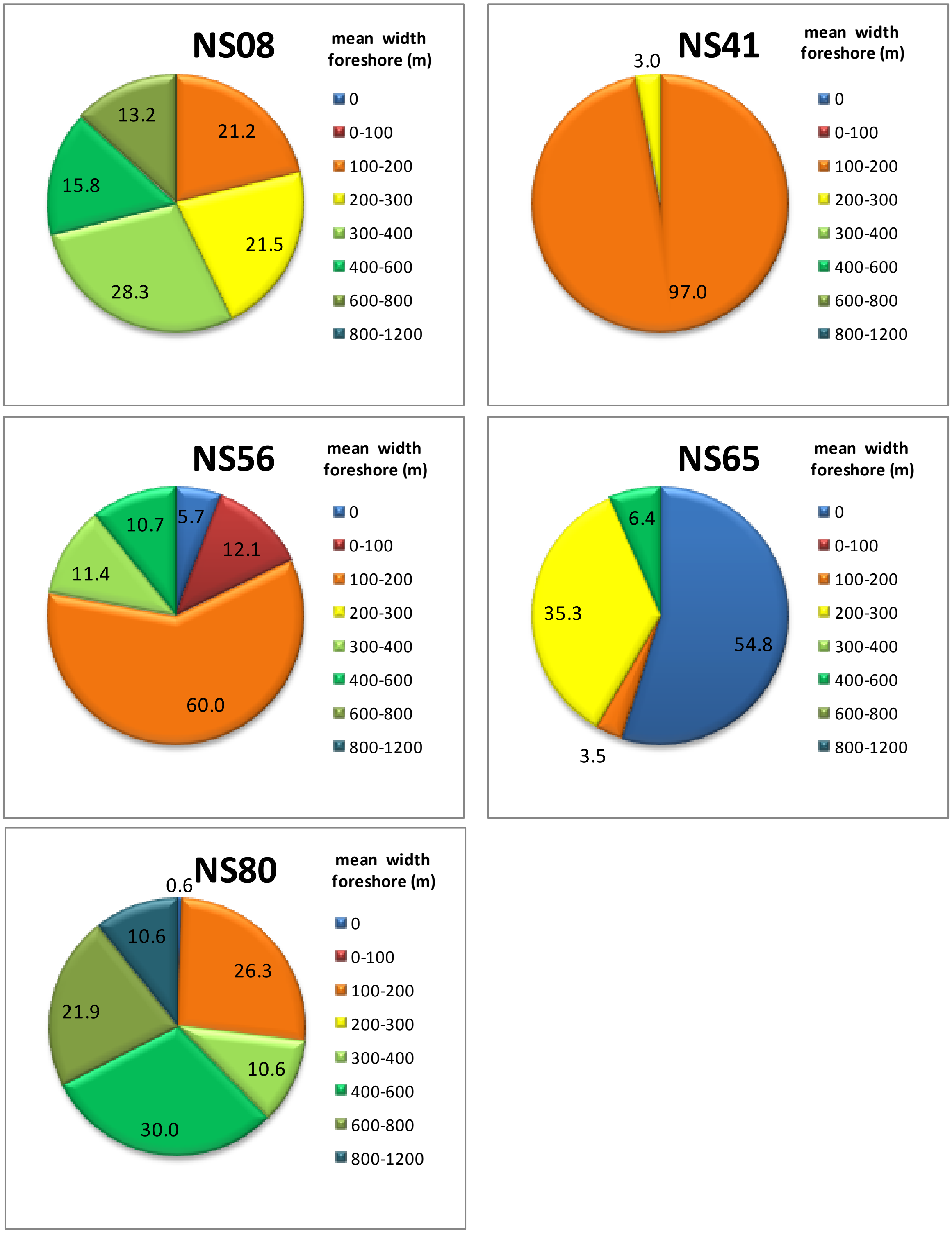


Figure 84: Mean width of foreshore in front of dykes in the Cornwallis Estuary for NS08 (Grand Pre), NS41 (Habitant), NS56 (Wellington), NS65 (Bishop Beckwith) and NS80 (Starrs Point).

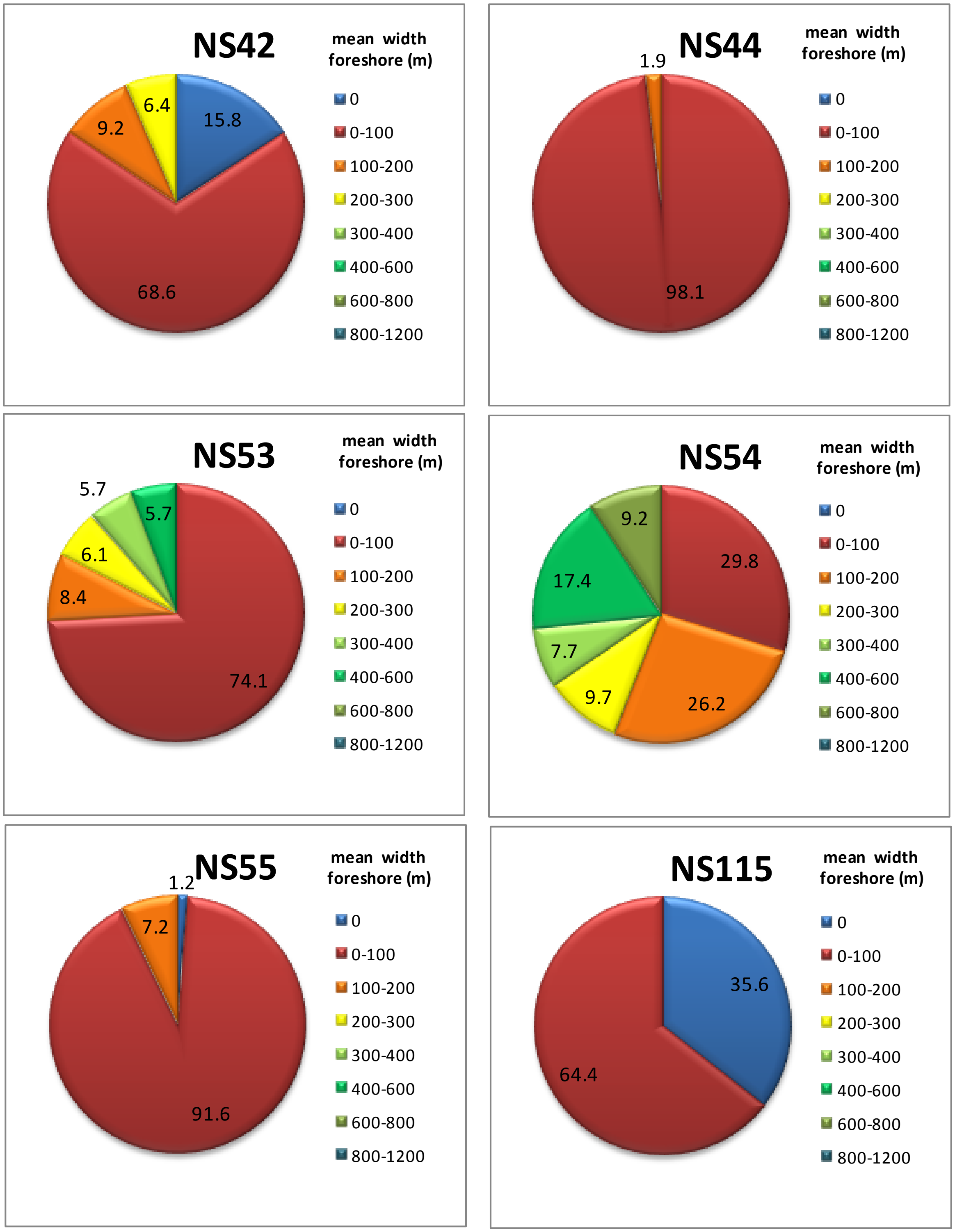


Figure 85: Mean width of foreshore in front of dykes for exposed marsh bodies in the Cumberland Basin for NS42 (Amherst Point); NS44 (Converse); NS53 (John Lusby); NS54 (Minudie); NS55 (Seaman) and NS115 (Nappan-Maccan).

Comparing Figure 84 and Figure 85, 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 (Figure 85, Table 8). 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.

In the Cornwallis estuary, the two main marsh bodies with the lowest amount of foreshore are NS56 (Wellington) and NS65 (Bishop Beckwith) (Figure 84). Both NS80 and NS41 are well protected. Grand Pre (NS8) have 21.2% of foreshore within the 100-200 m category and may be a good candidate for armour stone.

4 Dyke Adaption Options for Climate Change

Adaptation is defined by the IPCC as an *"adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities."* (IPCC, 2007a). This is not to be confused with mitigation, which is defined by the IPCC as "*technological change and substitution that reduce resource inputs and emissions per unit of output"* (IPCC, 2007b). In the context of Sea Level Rise (SLR), climate change and low-lying coastal areas, adaptation consists of techniques to minimize the effects of accelerated sea-level rise (ASLR) on coastal communities, whereas mitigation consists of reducing emissions to prevent ASLR from occurring in the first place.

Adaptation can be classified based on timing of implementation; anticipatory or reactive (Donald et al., 2008; Parks et al., 2007), the social scale of the adaptation; private or public (Parks et al., 2007; IPCC, 2007b) and the type of adaptation techniques used; management plans and policies or soft and hard engineering.

Anticipatory adaptation refers to actions that are taken and plans or policies that are put into place in anticipation of specific impacts of SLR. On the other hand, reactive adaptation occurs once the effects of SLR have become apparent (Donald et al., 2008) (Table 11). Anticipatory adaptation may occur by removing the risk by avoiding inappropriate development in vulnerable areas or reducing the likelihood of damage through environmental management (e.g. beaches, dunes, etc..). Reactive adaptation may reduce the potential impacts of risks by providing early-warning systems or by building appropriate flood and coastal defence infrastructure or altering buildings to withstand flooding (Table 11). Ultimately however, one can also accept the risk and not take any action (Donald et al., 2008).

	Anticipatory	**Reactive**
Private	Flood insurance Small-scale coastal defences Flood proofing	Sub-standard make shift coastal defences Evacuation
Public	Coastal setback Building codes Flood hazard mapping Large-scale coastal defences system Creation of natural systems	Flood warnings Compensation for mandatory relocation Sub-standard make shift coastal defences Evacuation (large-scale)

Table 11: Examples of types of adaptation measures in the context of SLR, climate change and low-lying coastal areas (Adapted from: Know Climate Change, 2012).

One could say that our current state of adaptation is both anticipatory and reactive as our realization of the need for planned (anticipatory) adaptation is a reaction to the effects of SLR that have thus so far occurred and have become apparent to us.

Adaptation techniques include management plans and policies and engineering techniques, which can be further broken down into soft and hard methods (Figure 86). Hard defences are solid constructed structures that prevent the interaction of land and sea and thus resist erosion and flooding (ie: breakwaters, revetments, sea walls) (French, 2001). Soft defences on the other hand, avoid the construction of solid structures and instead rely on the natural environment to reduce wave action. (ie: beach feeding, abandonment, managed realignment) (French, 2001). According to French (2001), sea walls are the most common type of coastal defence and range from earthen to concrete structures. Dykes are earthen embankments and are classified as a type of seawall (Figure 86).

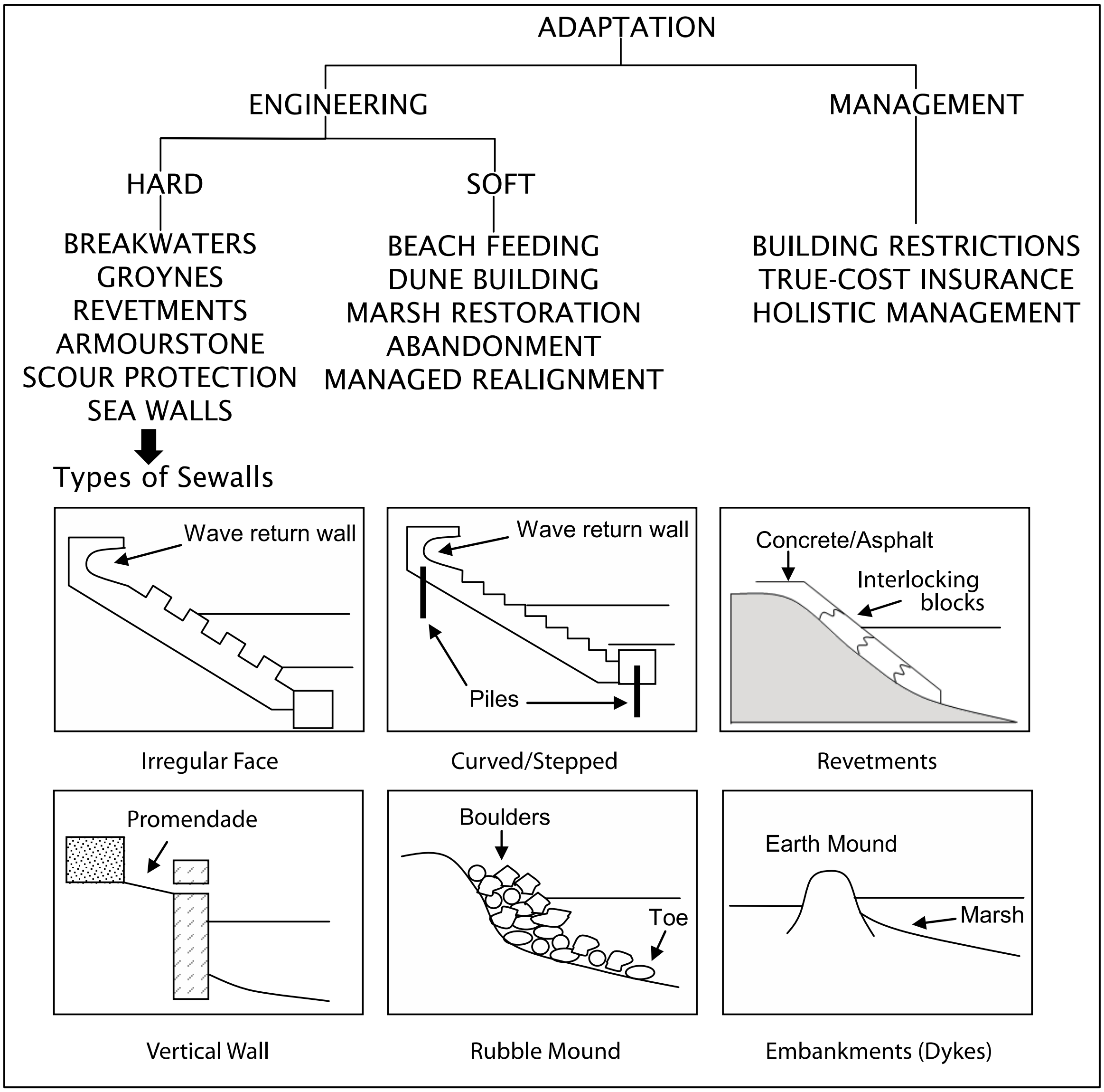


Figure 86: Adaptation techniques and types of seawalls (Adapted from: French, 2001).

Options for adaptation to the associated effects of SLR are called adaptation approaches and incorporate various adaptation techniques, social scales, and timing of implementation. Climate change literature refers to four main adaptation approaches (Lindham & Nicholls, 2010; French, 2001; Environment Agency, 2011a) three of which are possible in the Bay of Fundy:

- Hold the Line *(Protect)*
- Limited Intervention *(Accommodate)*
- Retreat the Line *(Retreat)*

The fourth approach, which is not applicable in this situation, is Advance the Line. It is important to note that the current dykelands in the Bay of Fundy were formed by advance the line techniques such as land claim, poldering and estuary closure (Nicholls et al., 2007). The following sections will provide a review of each of the adaptation approaches and present international examples of where these approaches are employed.

4.1 Hold the Line (PROTECT)

The Hold the Line approach consists of building or maintaining protective structures so that the position of the shoreline remains the same and private and public assets in the hinterland are protected (Environment Agency, 2011b; BC Ministry of Environment, 2011c). Holding the line generally involves the construction of hard defence structures, which fixes the coastline position and prevents the sea from interacting with the hinterland (French, 2001). Hard defences have two main functions: 1) to prevent coastal erosion and 2) to provide flood defence (United States Army Corps of Engineers, 2006; French, 2001). The most commonly used hard engineering techniques are seawalls, which include earthen embankments also known as dykes (French, 2001). Although dykes may help to prevent coastal erosion, it is important to understand that their sole purpose is to protect people, infrastructure and other important assets from flooding (BC Ministry of Environment, 2011a); or in the case of Fundy dykes, a primary mandate of protection of agricultural land.

In the case of SLR, dykes will be under more and more pressure to protect the hinterland from flooding. SLR will increase the depth of water at the dyke, produce higher waves, with more energy at the toe, deeper water offshore and enhance the erosion of the foreshore marsh. Overall, SLR will bring more energy closer to shore, accelerate erosion of dykes, increase dyke failure, cause toe vulnerability and contribute to higher wave run-up (Environment Canada, 2011; New Zealand Ministry for the Environment, 2004; United States Army Corps of Engineers, 2006).

Despite the challenges associate with dyke structures, they are the most commonly used structure to protect Canadian communities (Environment Canada, 2011). This is the case because of tradition, the perceived security from flooding that dykes provide, politics and a high value of hinterland, in which the benefits of using dykes far outweighs the cost of dyke construction and maintenance (French, 2001; Chang et al, 2001). A local example of this occurred in Annapolis Royal where the cost of constructing a dyke to protect against a 5.4 m flood was determined to be less than the potential cost of damages due to flooding (Parks et al., 2007).

4.1.1 *Disadvantages*

The main disadvantages associated with dykes as coastal defence structures are cost, coastal squeeze, and the land taken as a result of dyke heightening. Hard defence structures are not only expensive to build, but require large and continuous financial inputs for both armouring and maintenance. Although the cost of dykes varies with dimension, construction materials and location, their average costs can be estimated. In England and Wales the initial cost of earthen dykes cost approximately 970 000 (US$/km) and armoured dykes cost 4.7 million (US$/km). In the USA, the cost of dykes or levees ranges from 450 000 - 4.7 million (US$/km) and in New Zealand sea walls and revetments cost 900 000-1.3million (US$/km) (Nicholls et al., 2007, IPCC, 2007a).

Another major issue associated with dykes is the concept of coastal squeeze which occurs when there is no flexibility in the coastline (Figure 87) (French, 2001). It can be defined as the "*decline of intertidal habitat quantity or quality caused when these habitats become trapped between a fixed, landward boundary such as a sea wall and rising sea levels.*" (Lindham & Nicholls, 2010). As sea levels rise, the intertidal ecosystem attempts to migrate inland to keep pace with the rising sea levels, but the dykes present a barrier to inland migration and results in intertidal habitat loss and the increase in water depth at the dyke toe (French, 2001).

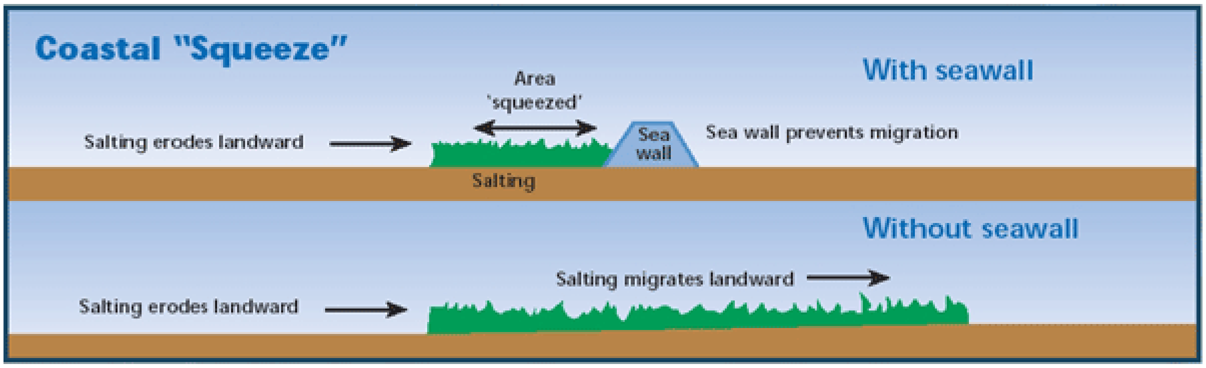


Figure 87: An example of coastal squeeze in the Severn Estuary (Adapted from: Severn Estuary Coastal Group, 2009).

Once dykes are put into place, it is extremely challenging to remove them without vast consequences (New Zealand Ministry for the Environment, 2008) and often, "hard defences can lead to coastal problems beyond those it was intended to solve." (French, 2001). In cases where dykes cannot be removed due to important infrastructure or high population density in the hinterland, the only choice for adaptation to SLR is to continue to strengthen the defence by increasing dyke crest elevation.

As is illustrated in Figure 878 raising dykes vertically to adapt to increases in sea level, also requires an increase in dyke width. Although in some cases strengthening of dykes does not interfere with hinterland infrastructure, in others the need for additional landtake interferes with the very structures that the dykes are meant to protect (Lindham & Nicholls, 2010). This is a very important concept to consider when dealing with ongoing ASLR and making decisions about appropriate adaptation approaches. Not only does dyke heightening cause potential future landtake issues, it is also costly. In New Orleans, dyke heightening costs on average 6.5-10.5 million US$/km (Hillen et al., 2010) and Lindham & Nicholls (2010), quote average worldwide dyke heightening costs at 0.9 – 29.2million per m rise in height.

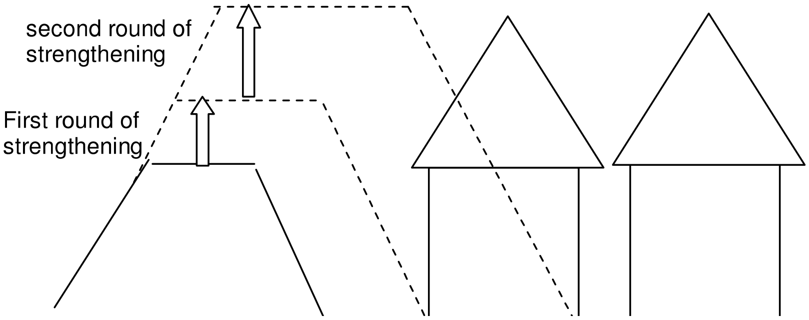


Figure 88: Example of strengthening a flood defence and possible conflicts with existing urban environment (Adapted from: Hillen et al., 2010).

Other disadvantages of dykes include but are not limited to, creating a false sense of security, which can increase development in hinterland, altering other coastal process and sediment budgets and scour of dyke toe (Lindham & Nicholls, 2010; French, 2001).

4.1.2 *Advantages*

Of all types of hard engineering structures for protection against floods, dykes are the most cost efficient choice (Lindham & Nicholls, 2010). However, the greatest advantage of dykes is their effectiveness in providing protection against flooding for areas with high population densities, essential services and important infrastructure. In these cases, dykes are by far the best solution, as any other choice of adaptation approach could prove to be more costly than dyke maintenance and strengthening. Other advantages include greater energy dissipation and reduced toe scour in comparison to seawalls and the ability to keep land that has already been claimed (French, 2001; Lindham & Nicholls, 2010; National Climate Commission, 2010).

4.1.3 *Recommended Usage*

Although dykes are the most commonly used structure to protect coastal Canadian communities, there are some scenarios in which dykes as a form of flood protection are considered the best adaptation approach. Some of these scenarios include:

- Highly developed urban areas (Ministry for the Environment, 2008).
- Areas with a long history of coastal protection (Ministry for the Environment, 2008).
- Areas with important dykeland agriculture, essential services, vulnerable historic building and important infrastructure (Parks et al., 2007).
- Areas that are unable to undergo a managed realignment scheme (Lindham & Nicholls, 2010).

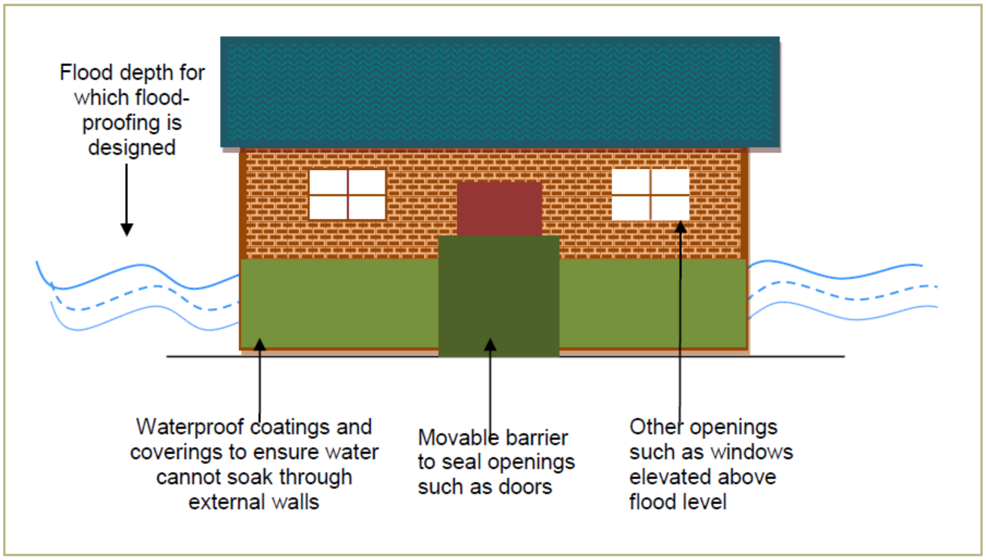
It is important to understand that the hold the line adaptation approach does not have to function on its own. Instead, most hold the line schemes would benefit from an approach that incorporated soft engineering techniques and management plans and policies as well such as coastal setbacks, beach nourishment and marsh foreshore creation to minimize erosion and scour.

4.2 Limited Intervention (ACCOMODATE)

The limited intervention approach is a decision to not invest in building flood defence structures, but instead the coast is managed to minimize potential human and infrastructure risk (Environment Agency, 2011b; Severn Estuary Coastal Group, 2010). This incorporates adapting land-based structures and activities to tolerate flooding and inundation, developing flood warning systems and coastal setback and creating flood hazard maps and building restrictions. Although there are many options for limited intervention approaches, the following options will be discussed in this section: Flood Proofing, Coastal Setback and Building Restrictions, Flood Warning and Flood Hazard Mapping (Lindham & Nicholls, 2010; Environment Canada, 2011).

4.2.1 *Flood proofing*

The main goal of flood proofing is to reduce or avoid impacts of coastal flooding upon structures (Lindham & Nicholls, 2010, Pilarczyk, 1998; BC Ministry of Environment, 2011c). Flood proofing can be divided into two types: wet flood proofing which allows waters to pass through or underneath existing structures and dry flood proofing which creates an impermeable barrier on structures up to the predicted height of flooding (Lindham & Nicholls, 2010). Figure 89 illustrates the characteristics associated with each type of flood proofing technique.



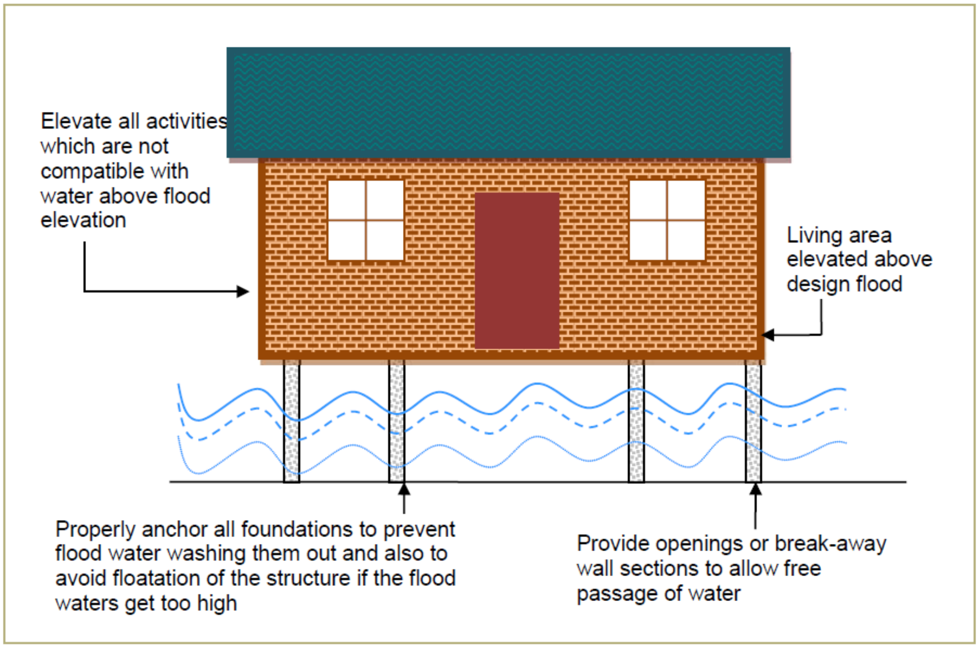


Figure 89: Examples of floodproofing (Adapted from: Linham & Nicholls, 2010).

Flood proofing can be achieved by a combination of the following options:

- Elevating strcutures above expected height of flood level (Green Shores, 2010).
- Elevating important utilities as opposed to the entire structure (BC Ministry of Environment, 2011c).
- Using water resistant materials (Pilarczyk, 1998).
- Creating watertight doors and windows (Pilarczyk, 1998).
- Building on fill to increase elevation of property (BC Ministry of Environment, 2011a).

- Creating floodwalls around ground level entrance ways (Pilarczyk, 1998).
- Providing structural reinforcement where necessary (Pilyarck, 1998).

Some advantages of flood proofing are that this approach does not require homeowners to relocate, it does not require additional land take, is relatively cheap in comparison to other defence measures and the flood proofing of a structure can be carried out by individuals. In the United States, flood proofing costs approximately 2.2 – 17 USD/ft^2 for flood damage resistant materials and approximately 29-96 USD/ft^2 to elevate structures (Lindham & Nicholls, 2010). On the other hand, this approach requires that the expected flood level be known so that homeowners know how high to flood proof their homes, it goes hand in hand with the creation of flood hazard maps to identify buildings at risk, which increases the overall cost and in most cases, residents still need to be evacuated (Lindham & Nicholls, 2011). It is recommended that this approach be adopted in areas where historic buildings and essential services are at risk to flooding, whether there are coastal defences present or not, and where flood risk levels are relatively low (Lindham & Nicholls, 2010; Pilarczyk, 1998).

CASE STUDY – BANGLADESH

As a result of the high cost of constructing and maintaining large dyke structures and the fact that employing a retreat approach is not an option in Bangladesh due to high coastal population densities and lack of free areas to relocate, flood proofing is a common adaptive approach. Common flood proofing techniques include building houses on walls of earth and constructing shelters on pillars. Illustrated in

Cyclone shelter and school house in Bangladesh (Pitchford, n.d.).

4.2.2 *Coastal Setback*

Coastal Setback is a set distance to a coastal feature within which all or certain types of development are prohibited or limited (Lindham & Nicholls, 2010; BC Ministry of Environment, 2011a). The setback distance is determined based on coastal topography, historic erosion rates and extreme water levels and provides a buffer between infrastructure and hazard (Lindham & Nicholls, 2010). According to Lindham & Nicholls (2010), two types of coastal setback exist: lateral setback which accommodates erosion and elevation setback which accommodates flooding. Since SLR produces both erosion and flooding, the actual setback distance is likely to be a combination of both. (See Figure 90)

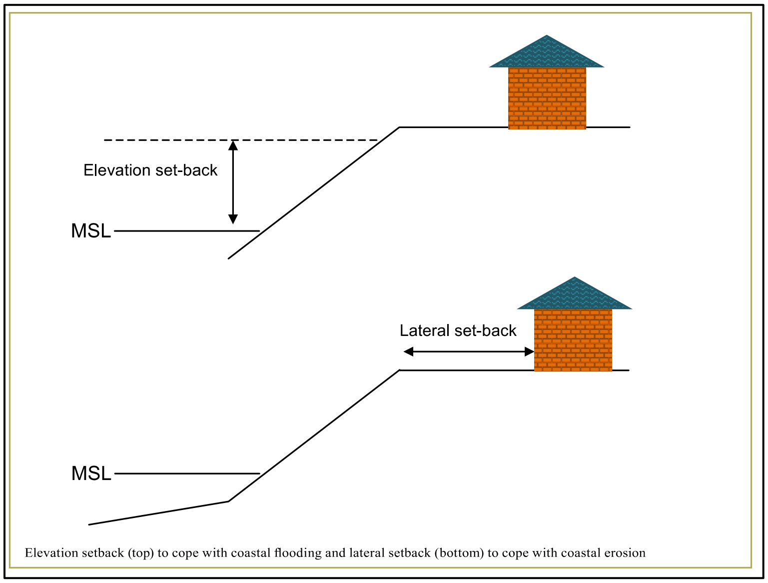


Figure 90: Elevation setback (top) to cope with coastal flooding and lateral setback (bottom) to cope with coastal exposure (Adapted from: Lindham & Nicholls, 2010).

In many cases coastal setback are advantageous because they are more cost effective than dykes, they allow the shoreline to be flexible, which allows it to respond to SLR, they help maintain the sediment budget, and they help to restore natural processes in the floodplain (BC Ministry of Environment, 2011a). On the other hand, SLR is likely to decrease the buffer between infrastructure and the hazard area and relocation may have to occur again. In the United States, the setback distance is reassessed every 10 years and adjustments to infrastructure are made accordingly (Lindham & Nicholls, 2010). Also, the process of land acquisition to create setback areas can become costly, especially if property has to be purchased from landowners. Coastal setbacks are very commonly used around the world and it is recommended that they be used in combination with other adaptation approaches such as salt marsh restoration or dyke construction. The two main coastal setback options are to have a restricted strip of land along the coast where no buildings are allowed, or various zones can be designated that allow certain infrastructure types in certain zones based on level of risk (Lindham & Nicholls, 2010). In the Netherlands the national government is responsible for a strip of public land along the coast (Richard et al., 2008). In Cape Town, South Africa a coastal act was passed in 2009 which aimed to create "coastal buffer zones" to limit inappropriate development in flood prone areas (Hillen et al., 2010).

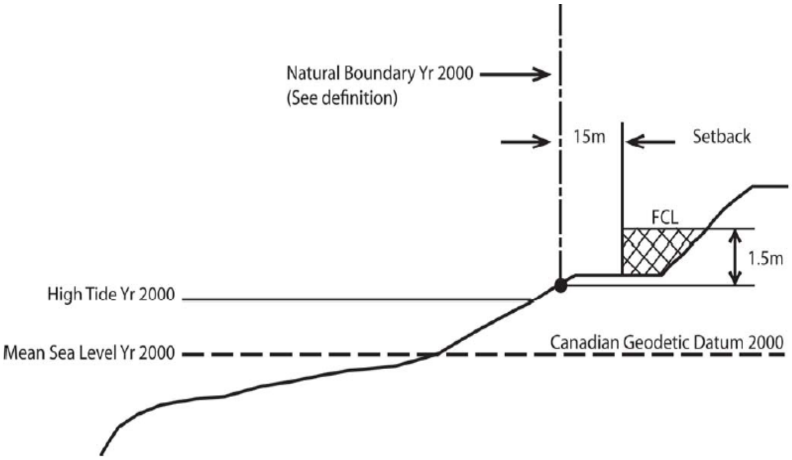


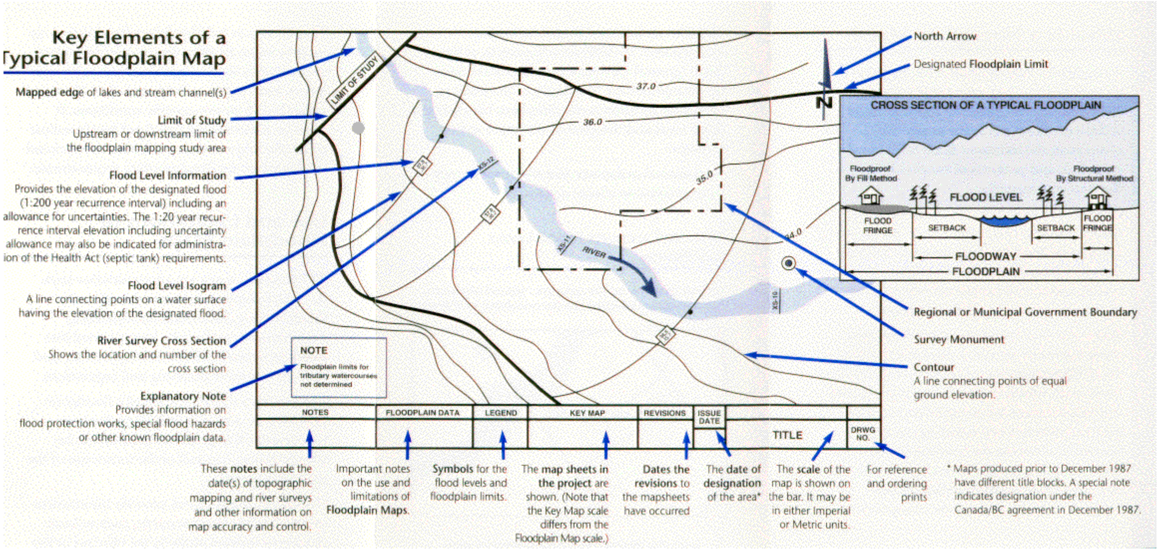
Figure 91: FCL and Setback (Adapted from: BC Ministry of Environment, 2011b).

Another example of coastal setback is illustrated for British Columbia in Figure 91 where the coastal setback for the year 2100 is designated as 15m from any flood protection structure (Reid, 2011).

4.2.3 *Flood Warnings*

Flood warnings are systems that detect and forecast threatening flood events so that the public can undertake necessary precautions in advance of a flood scenario (Lindham & Nicholls, 2010). Flood warnings have two complimentary stages: the initial warning and the consequent response to the warning. The initial warning is relatively useless if there are no plans in place to respond to various warning scenarios. As such, flood warnings go hand in hand with flood hazard mapping and evacuation planning (BC Ministry of Environment, 2011c). Some disadvantages associated with flood warnings are that the public's response to flood warnings is based on their knowledge and perception of flood risk and any inaccuracies in predicting these scenarios can lead to public complacency (Lindham & Nicholls, 2010). Also, accurate flood warnings require long-term data sets which may not exist in all areas (Pilarczyk, 1998). Flood warnings also have many advantages such as the large potential to reduce human harm in flooding scenarios, the notice to construct temporary flood defences where needed and the chance to evacuate vulnerable groups of the community (Pilarczyk, 1998; Lindham & Nicholls, 2010).

CASE STUDY – BRITISH COLUMBIA



Example of a Floodplain Map in British Columbia (Adapted from: BC Ministry of Environment, n.d.).

In British Columbia, a Flood Plain Mapping Program was developed in 1987 under the British Columbia Agreement Respecting Floodplain Mapping that restricted development in areas subject to flooding, discouraged financial assistance for development in flood prone areas, and required flood proofing measures in floodplain area (BC Ministry of Water, Land and Air Protection, 2004). The flood plain map delineates the expected area of flooding for a 200 year storm and depicts development, topography, flood levels and flood plain limits (for a 200 year storm) (BC Ministry of Water, Land and Air Protection, 2004).

4.2.4 *Flood Hazard Mappings*

Flood hazard mapping defines coastal areas that are at risk of flooding under extreme conditions and aims to increase public awareness of flood risk in a particular area (Lindham & Nicholls, 2010). This measure is generally used hand in hand with flood warnings, evacuation plans and coastal setback regulations. The main disadvantage of this approach is that in order to be effective it requires large, detailed mapping data and long-term extreme flooding event data, which can be very costly and time consuming. However, the advantages far outweigh the costs of flood hazard mapping as hazard maps are invaluable when it comes to managing flood risk. They are useful in emergency response, public awareness and perception, development, the insurance sector and for development of government policies and regulations. In the United States, flood hazard maps are created to determine flood insurance rates, flood boundaries, flood ways and where building codes are required based on location in flood prone areas (Pilarczyk, 1998). The United States Environmental Protection Agency has even developed SLR planning maps that indicate levels of shore protection for the entire Atlantic coast (Nicholls et al., 2007). Some examples of other areas that employ flood hazard mapping include Jamaica, United Kingdom, Netherlands and Australia (Lindham & Nicholls, 2010; BC Ministry of Water, Land and Air Protection, 2004; Hall et al., 2005; Ministry of Transport, Public Works and Water Management, 2011).

4.3 Retreat the Line (RETREAT)

The retreat the line approach consists of allowing the shoreline to move naturally, but strategically managing the process to direct it in certain areas. This type of approach is a planned withdrawal from the coast as opposed to an unplanned or forced retreat. The two techniques included in this approach are salt marsh restoration and managed realignment.

4.3.1 *Salt Marsh Restoration*

Salt marsh restoration is the rehabilitation of a previously existing salt marsh from one with impaired function to one that exhibits wetland functions. Salt marshes are the transitional areas in intertidal habitats between land and water and when restored are known to naturally reduce coastal flooding and erosion, provide environmental benefits and create new habitat (Robins et al., 2004). This type of approach is commonly used in conjunction with the managed realignment approach (Myatt et al., 2003; Lindham & Nicholls, 2010). In the face of climate change and SLR salt marshes are able to keep pace with rising sea levels by receiving enough sediment input to contribute to vertical growth therefore maintaining the seaward margin or by migrating the seaward margin inland to ensure the width of foreshore is adequate to reduce wave energy (Lindham & Nicholls, 2010; French, 2001).

4.3.1.1 Advantages

The greatest benefit associated with salt marsh restoration is their ability to attenuate wave energy and consequently minimize erosion and flooding (French, 2001; Lindham & Nicholls, 2010; Brooks et al., 2006). As waves pass over salt marshes, the increased bed roughness caused by salt marsh vegetation decreases the energy of the waves. Salt marshes are known to have the ability to attenuate up to 97% of incoming wave energy. This of course depends on the width of the foreshore, as a wider foreshore contains more vegetation, which provides greater resistance as the wave moves towards the shore (Lindham & Nicholls, 2010). Another advantage of salt marshes is their ability to naturally adapt to SLR. This characteristic alleviates the need to constantly adjust the height of hard structures, such as dykes, to accommodate increases in sea level and is extremely cost effective (Mallin et al., 2007). In fact the wave attenuation induced by salt marshes increases sediment deposition and vegetation helps to trap deposited sediment (Lindham & Nicholls, 2010). A study conducted by Mallin et al., (2007), demonstrates the ability of salt marshes to speed up or slow down accretion as sea level varies. Other salt marsh benefits include but are not limited to sediment trapping, providing habitats for fish birds and insects, increasing the “naturalness” of estuaries, increasing conservation potential, improving productivity of coastal waters providing recreational resources and ecosystem services such as water quality, climate regulation, accumulation sites for sediment, contaminants carbon and nutrients, breeding grounds for birds, fish, shellfish, and mammals (Lindham & Nicholls, 2010; French, 2001). Figure 92 illustrates examples of other ecosystem services provided by estuaries and saltmarshes.

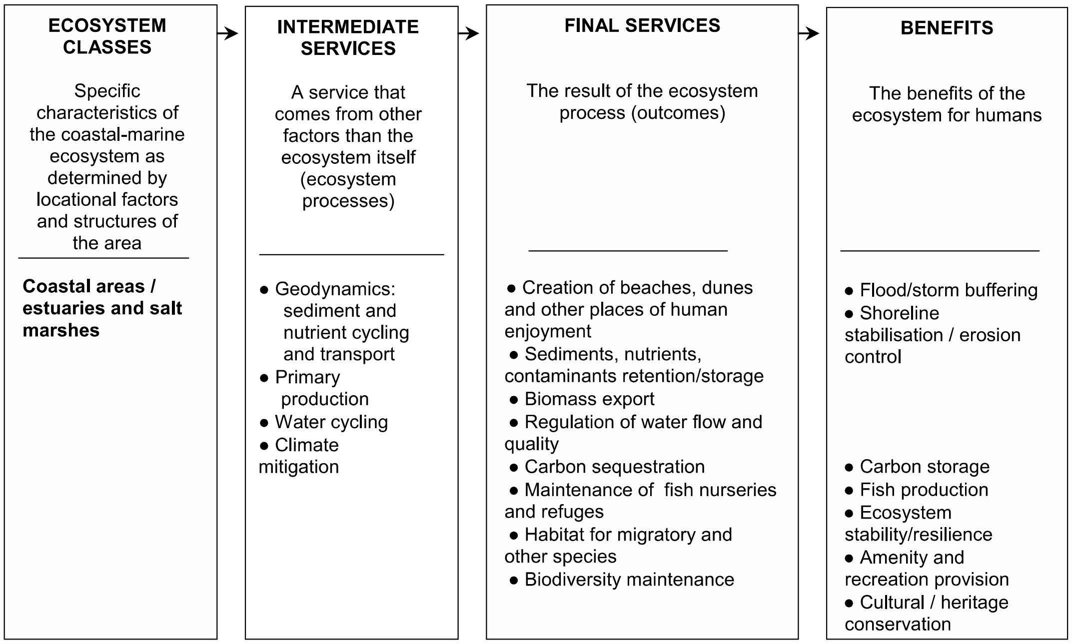


Figure 92: Ecosystem services provided by estuaries and saltmarshes (Adapted from: Luisetti et al., 2011).

4.3.1.2 Disadvantages

There are very few disadvantages associated with salt marsh restoration and it is clear from the previous section that the advantages far outweigh any potential disadvantages of this technique. The main disadvantage is the loss of land to the sea, which could potentially have high development or agricultural potential. Another possible issue could occur in the case that SLR outpaces the accumulation of sediment in which case the salt marsh could drown and all benefits associated with this approach could be lost (Linham & Nicholls, 2010).

4.3.1.3 Recommended Usage

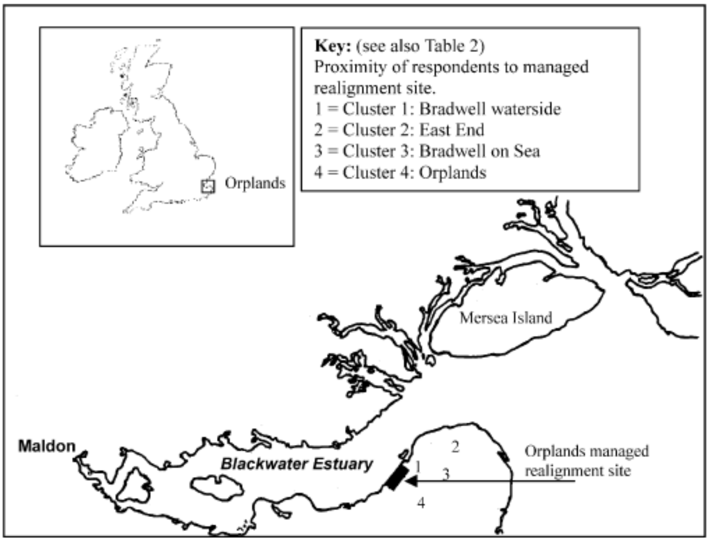
Salt marsh restoration is recommended for low-lying areas that are not highly developed or in areas where dykes are at the end of their construction life (BC Ministry of Environment, 2011c). It is important to note that salt marsh restoration can be used in conjunction with hard defences. In this case, the presence of salt marshes reduces dyke maintenance costs over time by reducing the amount of wave energy reaching the structure (Linham & Nicholls, 2010). In fact, observations made in the Pacific indicate that a forest of mangroves, which can be comparable to salt marshes in the case of wave attenuation, has the ability to reduce dyke maintenance costs by 25-30% (Linham & Nicholls, 2010).

4.3.2 *Managed Realignment*

Managed realignment consists of setting back the line of actively maintained defences to a new line inland of the original and promoting intertidal habitat between old and new dykes (Linham & Nicholls, 2010; French, 2001). In doing so private or public assets at risk may be relocated or abandoned (Ministry for the Environment, 2008). Managed realignment involves complete removal or a beach of the coastal defence, which allows the area behind the defence to flood (BC Ministry of Environment, 2011c). (Figure 68) Because this approach is managed or planned, it reduces the negative effects associated with abandoning flood defences (Linham & Nicholls, 2010). The main objectives of managed realignment are to create saltmarshes, which attenuate harmful wave energy and act as a flood defence and to establish integral intertidal habitat (BC Ministry of Environment, 2011c).

CASE STUDY – ORPLANDS, UNITED KINDOM

Orplands is located on the southern side of the Blackwater Estuary in Essex, United Kingdom and was the first full-scale managed realignment trial in the UK. It runs along 2 km of coast in the St. Lawrence Bay and the dykes that were once present protected 38 ha of land. In 1993 the dykes were deemed an inefficient coastal defence and the managed realignment scheme began in April of 1995. The scheme was carried out by breaching the earthen dyke in two places and creating a secondary line of defences landward of the old dyke. By choosing a managed realignment scheme over heightening and strengthening the existing dykes, the government saved over 797 845 USD. Today the majority of the Orplands site is vegetated as is deemed an effective coastal defence measure (Myatt et al., 2003).



Photograph (Grant, 2001). Orplands - Looking westwards along seawall from eastern end of site, showing badly eroding saltmarsh outside of the breached sea wall (to the right) and retreat site to the left of the picture. Figure (Adapted from: Myatt et al., 2003).

Managed realignment is an increasingly popular approach to coastal defence and can be combined with coastal setback, relocation, transfer of property rights, and salt marsh restoration measures (BC Ministry of Environment, 2011c; Sanò et al., 2011; Fish et al., 2008). According to the BC Ministry of Environment (2011c), it can be carried out on various scales, which require relocation within a property, relocation to another site, or large-scale relocation of settlements and infrastructure. Other names for the managed realignment approach are de-polderization, de-embankment, dyke re-opening, dyke realignment and managed retreat (Linham & Nicholls, 2010).

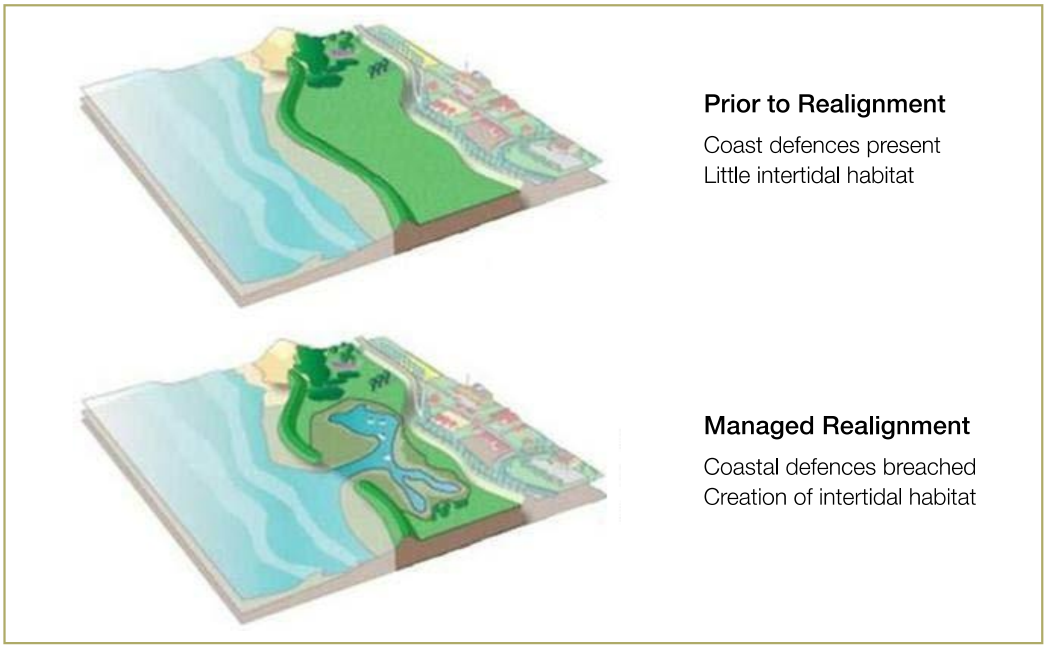


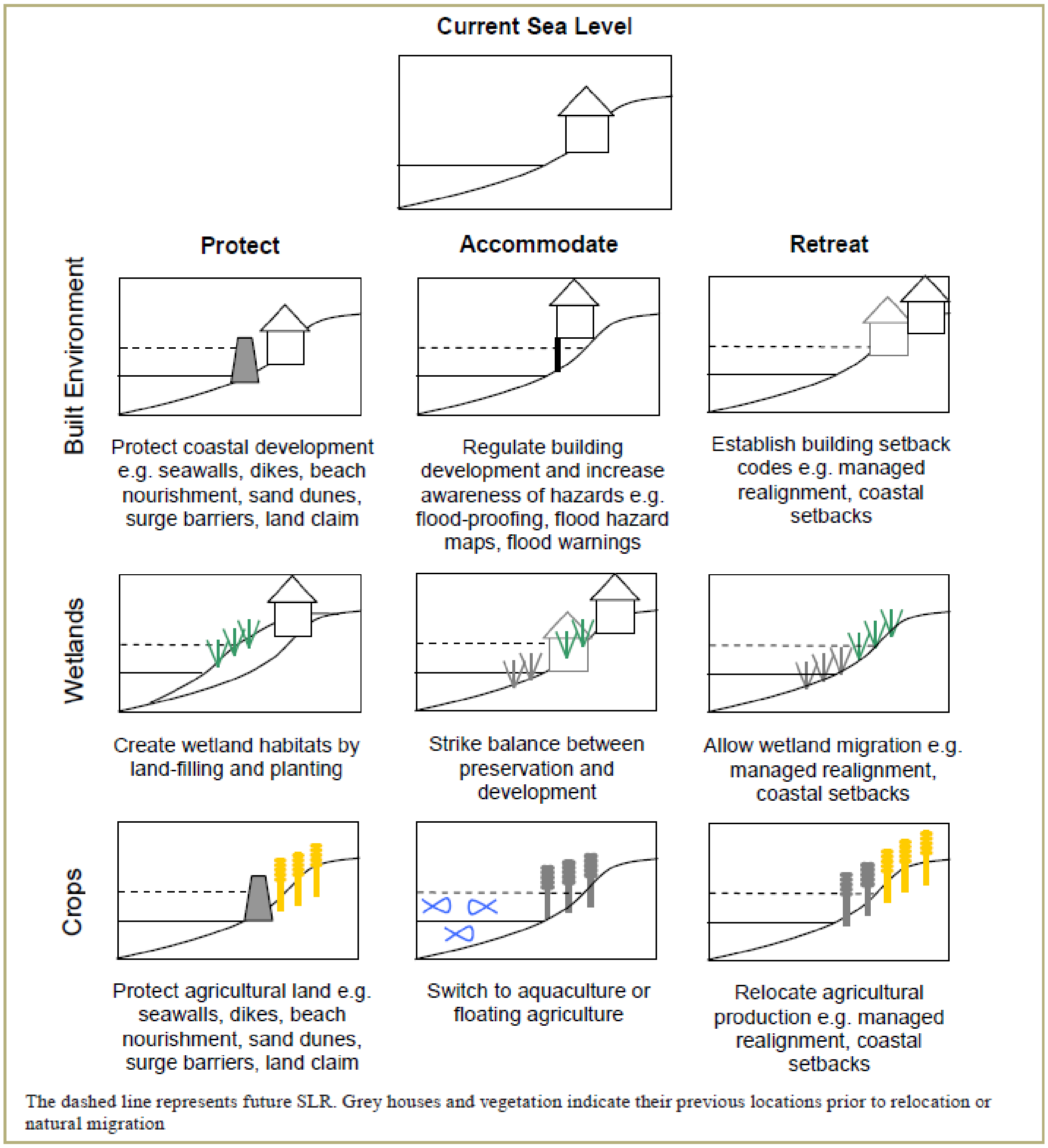
Figure 93: Mechanisms of managed realignment (Adapted from: Linham & Nicholls, 2010).

4.3.2.1 Advantages

Since salt marsh restoration is such an integral part of managed realignment, the benefits associated with salt marsh restoration (Section 4.3.2) apply to this approach as well. However, other advantages associated with this technique are its ability to make the coast less reliant on hard defences, its ability to adapt to unexpected climate change scenarios, its ability to reduce both coastal flooding and erosion and the reduction in coastal defence costs (Linham & Nicholls, 2010; French, 2001). In fact, a study carried out in the Humber Estuary comparing the costs associated with the use of managed realignment versus the use of hard coastal defences found that managed realignment schemes are more economically efficient over a sufficiently long time period (Turner et al., 2007).

4.3.2.2 Disadvantages

The greatest disadvantage of this approach has nothing to do with the technique itself, but with the public perception and acceptance of the use of this technique. Managed realignment generally requires a large portion of land to be yielded to the sea and in some cases large-scale relocation. Many people feel as though they are "giving into the demands of the rising sea" and have an issue with not defending their assets (French, 2001). However, it is commonly forgotten that the land originally belonged to the sea and the managed realignment scheme is restore a natural ecosystem and at the same time reducing the costs of coastal sea defence. In some cases relocation can be extremely expensive and according to a study carried out in the United Kingdom, the average cost of relocation is about 97 000USD per hectare (French, 2001). The potential need for relocation and the perception of giving into the demands of the sea can cause high political and social controversy and consequently managed realignment schemes suffer from lack of public acceptance (Linham & Nicholls, 2010). Currently, managed realignment schemes are very popular for use in agricultural land because they require little, if any relocation of infrastructure (French, 2001).



The dashed line represents future SLR. Grey houses and vegetation indicate their previous locations prior to relocation or natural migration

Figure 94: Three approaches to climate change adaptation (Adapted from: Linham & Nicholls, 2010).

Adaptation Approach	**Hold the Line**			**Limited Intervention**		**Retreat the Line**			
Definition[1]	Build or maintain artificial defences to that the position of the shoreline remains the same			No active intervention, but the coast is managed to minimize human and infrastructure harm		Allowing the shoreline to move naturally, but managing the process to direct it in certain areas			
Encompasses	**Dykes & Seawalls**			**Coastal setbacks, flood warnings, flood hazard mapping, flood proofing**		**Managed Re-alignment & salt marsh restoration**			
Outcomes[2]	Increased robustness			Increased Flexibility		Increased Adaptability			
Issues[1,2]	Potential impacts on fronting beaches •interruption of longshore sediment movement • increased erosion downdrift (terminal scour)• fixes coast and prevents its responses to SLR• stopping of some inputs to the sediment budget • coastal squeeze			Requires current risk of flooding to be known and communicated with the public • public perception may influence reaction to warnings • requires public education • size of coastal buffer zone will decrease over time • no guaranteed protection from severe storms & ASLR		Dangers of modification of tidal prism • uncertainties about hydrology & sediment movement • novelty of technique • complexity of potential compensation issue • issues of public perception			
Benefits[2,3]	Prevention of hinterland erosion • increased security for property from flooding • physical barrier between land and sea increases perceived safety of people • maintenance of hinterland value			Avoids need to relocate structures • more affordable, doesn't require land taken by building defences • assists in land use planning and development • provides greater flood risk awareness • facilitates evacuation if necessary • minimizes risk to life • preserves natural dynamics • helps maintain shoreline access		Increased wildlife potential for the estuary • increased intertidal width and wave attenuation capacity • increased conservation potential of habitats • improved protection against SLR • increased 'naturalness' of estuaries			
Essential Knowledge Requirements[2]	RSLR scenarios • extreme water levels • wave climate • local sediment budget • settlement			RSLR scenarios • extreme water levels • wave climate • bathymetry • coastal topography • level of shore protection •flood water velocity • land cover • effective warning threshold		Wave climate • tidal regime • coastal topography • sediment characteristics • vegetation • historic habitat distribution & cause of decline			
Secondary Knowledge Requirements[3]	Tidal regime • historic flood info • sediment characteristics • local sediment budget • settlement			Tidal regime • historic flood info • sediment characteristics • nearshore bathymetry •level of natural protection • historical erosion events		RSLR scenarios • nearshore bathymetry • historic flood info • land cover • availability of dredge sites • local sediment budget • historic habitat distribution & cause of decline			
Monitoring Requirements to Evaluation Option [3]	**Seawalls & Dykes:** topographic survey, bathymetric survey, shoreline position, structural integrity			**Coastal Setbacks**: shoreline position, flood events **Flood Hazard Mapping:** Flood events **Flood Proofing:** structural integrity, compliance with regulations, technology		**Managed Re-alignment:** ecological survey, scour & morphological change, intertidal accretion & erodibility **Salt Marsh Restoration:** shoreline position, ecological survey, intertidal accretion & erodibility			
Appropriate for[4]	**Existing Development**	**Infrastructure**	**Conservation Sites**	**Future planning allocation**	**Underdeveloped coast, or coast with obsolete development or infrastructure**	**Existing Development**	**Infrastructure**	**Conservation Sites**	**Future planning allocation**
Adopt Where	Important	Infrastructure	Protection of area is	Infrastructure or	Land use does not justify the	Protection of area	Shoreline is already	A feature moves	The retreat

	assets are present ie agricultural land, infrastructure, large populations	exists and cannot be moved ie. Essential services	critical to the conservation interest of the site ie. Archeological, cultural	development planned for the future which can justify the cost of prevention	cost of defence or defences are causing detrimental consequences elsewhere	is detrimental to conservation interests & has the potential to be improved with retreat schemes	retreating & the land use does not justify the cost of protection	with time, often in a cyclic manner	of defences has the potential to restore the natural function of the floodplain

Table 12: Adaptation Approaches Chart. Created from 1-(Environment Agency, 2011b), 2-(French, 2001), 3 –(Linham & Nicholls, 2010), 4-(Severn Estuary Coastal Group, 2009).

4.3.2.3 Recommended Usage

Along with all of the recommended uses for salt marshes, managed realignment schemes are also recommended to increase intertidal width in areas of marsh retreat, estuary functioning and habitat for flora and fauna (French, 2001). This approach is very commonly used in low-lying estuary environments and is also appropriate for conservation sites, retreating shoreline, and floodplains (Severn Estuary Coastal Group, 2009).

Adaptation Approach	Technique	Country Found in	Reference
Hold the Line	**Dyke/Seawall**	Bangladesh	Green Shores, 2010
		Belgium	National Climate Comission, 2010
		Bulgaria	French, 2001
		Germany	French, 2001
		Hawaii	French, 2001
		India	French, 2001
		New Zealand	IPCC, 2007a; Nicholls et al., 2007
		Portugal	French, 2001
		Singapore	Lee et al., 2009
		South Africa	Hillen et al., 2010
		Thailand	IPCC, 2007a
		United Kingdom	French, 2001
		USA	IPCC, 2007a

Table 13: Examples of countries using “Hold the Line” adaptation approach

Retreat the Line	**Managed Realignment**	Courtenay Region BC	Reid, 2011
		Germany	Rupp & Nicholls, 2007
		Hawaii	Abbot, 2008
		Netherlands	French, 2001
		New Zealand	BC Ministry of Environment, 2011c
		Puerto Rico	French, 2001
		Scotland	Midgley & McGlashan, 2004
		United Kingdom	Edwards & Winn, 2006
		USA	French, 2001
		Vietnam	Ving et al., 1996
	Salt Marsh Restoration	Brazil	French, 2001
		China	French, 2001
		New Brunswick	Mallin et al., 2007
		New Orleans	Hillen et al., 2010
		New Zealand	Ministry for the Enironment, 2004
		Nova Scotia	Mallin et al., 2007
		Phillipines	Green Shores, 2010
		United Kingdom	French, 2001
		USA	Seitz & Lawless, 2006

Table 14: Examples of countries using “Retreat the Line” adaptation approaches

Limited Intervention	**Coastal Setback**	Antigua	Linham & Nicholls, 2010
		Aruba	Linham & Nicholls, 2010
		Australia	Linham & Nicholls, 2010
		Barbados	Linham & Nicholls, 2010
		British Columbia	Reid, 2011
		Cayman Islands	Brooks et al., 2006
		Denmark	Linham & Nicholls, 2010
		Finland	Linham & Nicholls, 2010
		Germany	Linham & Nicholls, 2010
		Jamaica	Linham & Nicholls, 2010
		Nevis	Linham & Nicholls, 2010
		Norway	Linham & Nicholls, 2010
		Poland	Linham & Nicholls, 2010
		Spain	Linham & Nicholls, 2010
		Sri Lanka	Linham & Nicholls, 2010
		Sweden	Linham & Nicholls, 2010
		Turkey	Linham & Nicholls, 2010
		USA	Green Shores, 2010
	Flood Warning	Bangladesh	Linham & Nicholls, 2010
		Netherlands	Olsthoom & Tol, 2001
		USA	New York City Office of Emergency Management, 2012
	Flood Proofing	USA	Linham & Nicholls, 2010
		Vietnam	Linham & Nicholls, 2010
	Flood Hazard Mapping	Australia	Linham & Nicholls, 2010
		Bangladesh	Butzengeiger & Horstman, 2004
		British Columbia	BC Ministry of Environment, 2011b
		Jamaica	Linham & Nicholls, 2010
		Netherlands	Ministry of Transport, Public Works and Water Management, 2011
		Nova Scotia	Subramanian et al., 2006
		United Kingdom	Hall et al., 2005
		USA	FEMA, n.d.
	Building Restrictions	Cayman Islands	Brooks et al., 2006
		New Zealand	Ministry for the Environment, 2008
		Phillipines	Green Shores, 2010
		South Africa	Hillen et al., 2010
	Flood Insurance	USA	Pilarczyk, 1998
	Floating Agriculture System	Bangladesh	Linham & Nicholls, 2010

Table 15: Examples of countries using "Limited Intervention" adaptation approaches

5 Best Management Practices around the Globe

5.1 Netherlands

5.1.1 *Safety Standards*

In some cases there is no choice but to defend the coastline. This is the case in the Netherlands where 26% of the country is below mean sea level and 2/3rds of the country is prone to flooding (de Bake & Wolters, n.d.). The country's susceptibility to flooding was realized after the 1953 storm surge disaster, which resulted in over 1800 fatalities (DEFRA, 2006a). Immediately following the storm, the Government of the Netherlands founded the Delta Commission, which led to the development of the Deltaplan. The Deltaplan included closing estuaries, thus shortening the length of coastline needing protection creating safety standards for dyke rings and a national dyke improvement scheme (DEFRA, 2006a) (Figure 95).

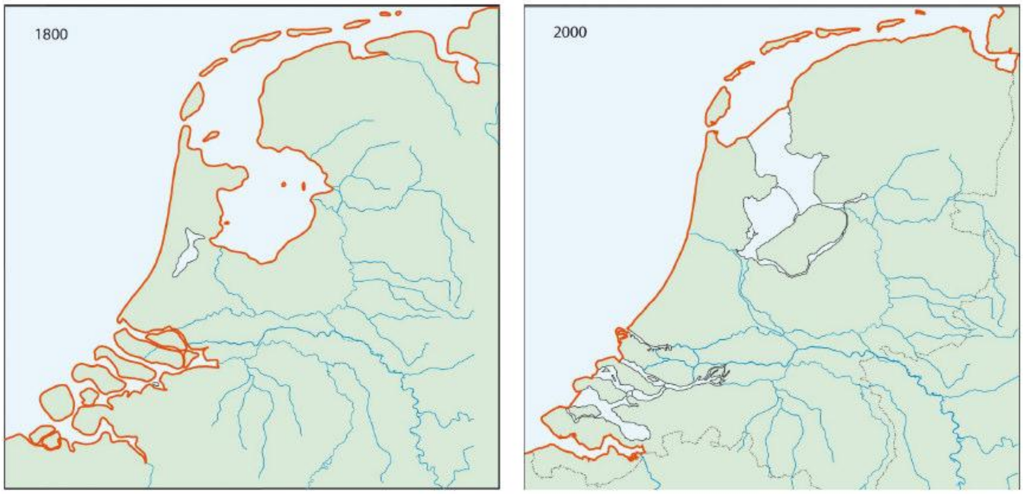


Figure 95: The Delta plan involved the construction of large tidal storm barrages to protect the coasts of the Netherlands (Adapted from Hillen et al., 2010).

In the Netherlands there are 53 dyke ring areas which can be defined as "areas vulnerable to floods that as a whole are protected by a single dyke" (Netherlands Environmental Assessment Agency and the National Institute for Public Health and the Environment, 2004). After the 1953 flood the Delta Commission proposed safety standards for the dyke rings along the Dutch coast, but eventually standards were also proposed for river dykes (Netherlands Environmental Assessment Agency and the National Institute for Public Health and the Environment, 2004). However, it was realized that not every dyke ring area required the same amount of protection and accordingly, proposed safety standards ranged from 1:1250 to 1:10 000 flood return periods (Pilarczyk, 1998). In 1996, the Flood Defence Act was created which incorporated the proposed safety standards into law (Jorritsma-Lebbink, 1996). The Act also dictates the responsibilities of the parties involved in flood management and requires a safety assessment of all primary flood defences to be carried out every 5 years.

The safety standards were determined by the Delta Commission who analyzed three key issues:

1. the most adverse water level that might have occurred in the 1953 disaster if all of the contributing factors were present at the same time at their maximum potential
2. flood frequency data

3. the cost of implementing measures to reduce flood risk compared with the cost of damage for Central Holland(Netherlands Environmental Assessment Agency and the National Institute for Public Health and the Environment, 2004).

The cost benefit analysis or economic optimization was performed for the area of Central Holland, which is highly developed, contains the large cities of Amsterdam, The Hague and Rotterdam and is extremely flood prone (van Alphen, 2012). This analysis compared the investments necessary to improve the level of protection and the avoided damage of flooding (van Alphen, 2012). (Figure 19) The costs associated with the avoided damage of flooding do not just include the cost of material damage, but also incorporate the loss of human life which has been estimated by the Netherlands to cost 2.2 million euros (ie: the Netherlands is prepared to invest 2.2 million euros to prevent one fatal traffic accident) (FEMA, n.d.).

The resulting cost-benefit-optimal protection level for the Central Holland area was 10^{-4} or 1:10 000. (Netherlands Environmental Agency and the National Institute for Public Health and Environment, 2004) However, it was decided that not all dyke ring areas required the same amount of protection and accordingly different standards were determined based on:

1. the difference in the value of the areas to be protected
2. the lower level of damage from freshwater floods as opposed to seawater floods
3. nature and historical interests in a particular area
4. river floods being much more predictable (Netherlands Environmental Agency and the National Institute for Public Health and Environment, 2004).

With this is mind the Delta Commission determined that less populated coastal areas should receive a protection level of 1:4000 per year. When safety standards were proposed for river dyke rings, a protection level of 1:1250 per year was deemed adequate for most areas and a protection level of 1:2000 per year was necessary in others (van Alphen, 2012). (Figure 96)

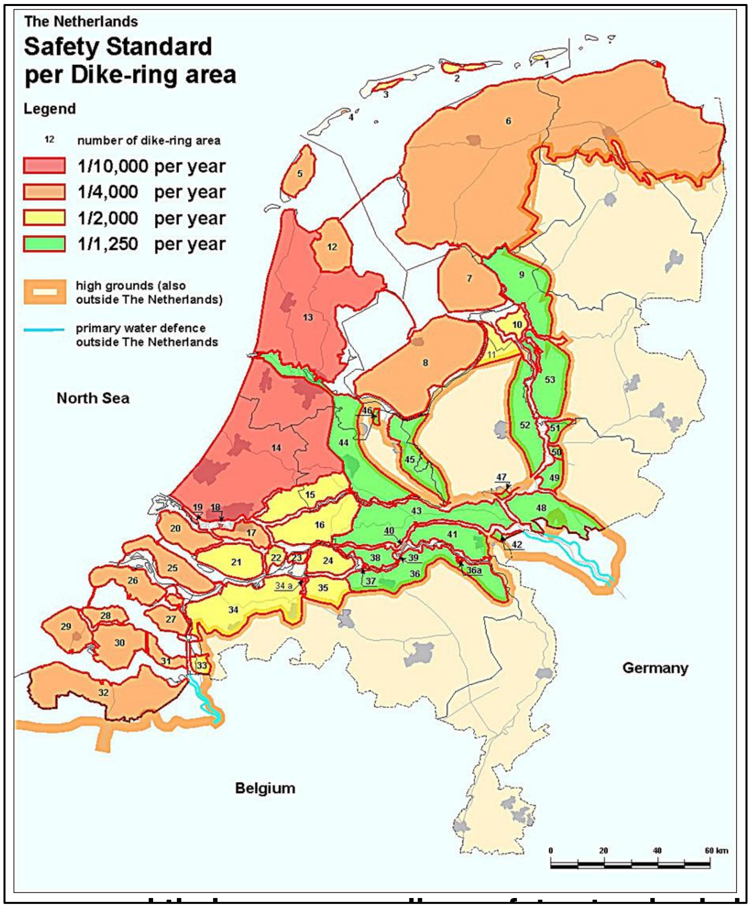


Figure 96: Dyke ring safety standards for the Netherlands (van Alphen, 2012).

Although the optimum protection levels determined by the Delta Commission cannot be directly transferred to other countries, Pilarczyk (2008) suggested very general flooding frequency allowances for various types of property (Table 4).

These general estimates may be useful as a first step in developing flood safety standards for marsh bodies in the Bay of Fundy.

5.2 England and Wales

5.2.1 *Shoreline Management Plans*

In the United Kingdom, coastal groups, with guidance from government officials, have developed Shoreline Management Plans (SMP's) for the entire coast of England and Wales covering almost 6000 km (Environment Agency, 2011a; Environment Agency, 2011b). These SMP's are non-statutory strategies that determine the best course of coastal management for a specific length of coast (Edwards & Winn, 2006). The recommendations use four potential management policies: no active intervention, hold the line, managed realignment and advance the line (Environment Agency, 2011b) and cover three time spans or epochs: short term (0-20 yrs), medium term (20-50 yrs), and long term (50-100 yrs) (Environment Agency, 2011b).

Hold the Line – keeping the line of the defence in its current location
No Active Intervention – no maintenance, repair or replacement of the existing defence structures takes place
Managed Realignment – the landward movement of defences, giving up some land to the sea to form a more sustainable defence in the long term
Advance the Line – reclaiming land from the sea by building new defences further seaward.
(Severn Estuary Coastal Group Associated Consultants, 2000)

The first set of SMP's were developed in 1990, but as new information about the coast became available it was necessary to complete a new set of SMP's (second generation SMP's) to include data such as ASLR, coastal defence lifespan, coastal habitat management plans (CHaMPs), and the importance of looking at flooding and erosion over large time scales etc. (Environment Agency, 2011a; DEFRA, 2006a). There are 22 second generation SMP's being prepared for 2011/2012 for the entire coast of Wales and England (Severn Estuary Coastal Group, 2010) and the following simplified steps can be adapted and used as an outline for developing SMP's for the coasts of the Bay of Fundy. A more in depth SMP "workflow plan" can be found in DEFRA (2006b), Figure 1.1 pg. 19.

Step 1: Determine SMP areas

The SMP areas are generally based on sediment cell boundaries where the "net along shore movement of sand and shingle changes direction." However in some areas, the policy units were modified to cover a length of coastline a particular coastal authority was responsible for (DEFRA, 2006). A *Sediment Cell* is a length of coastline and its associated near shore area within which the movement of coarse sediment is largely self-contained (Figure 97).

Figure 1: Boundaries of the first round of SMPs

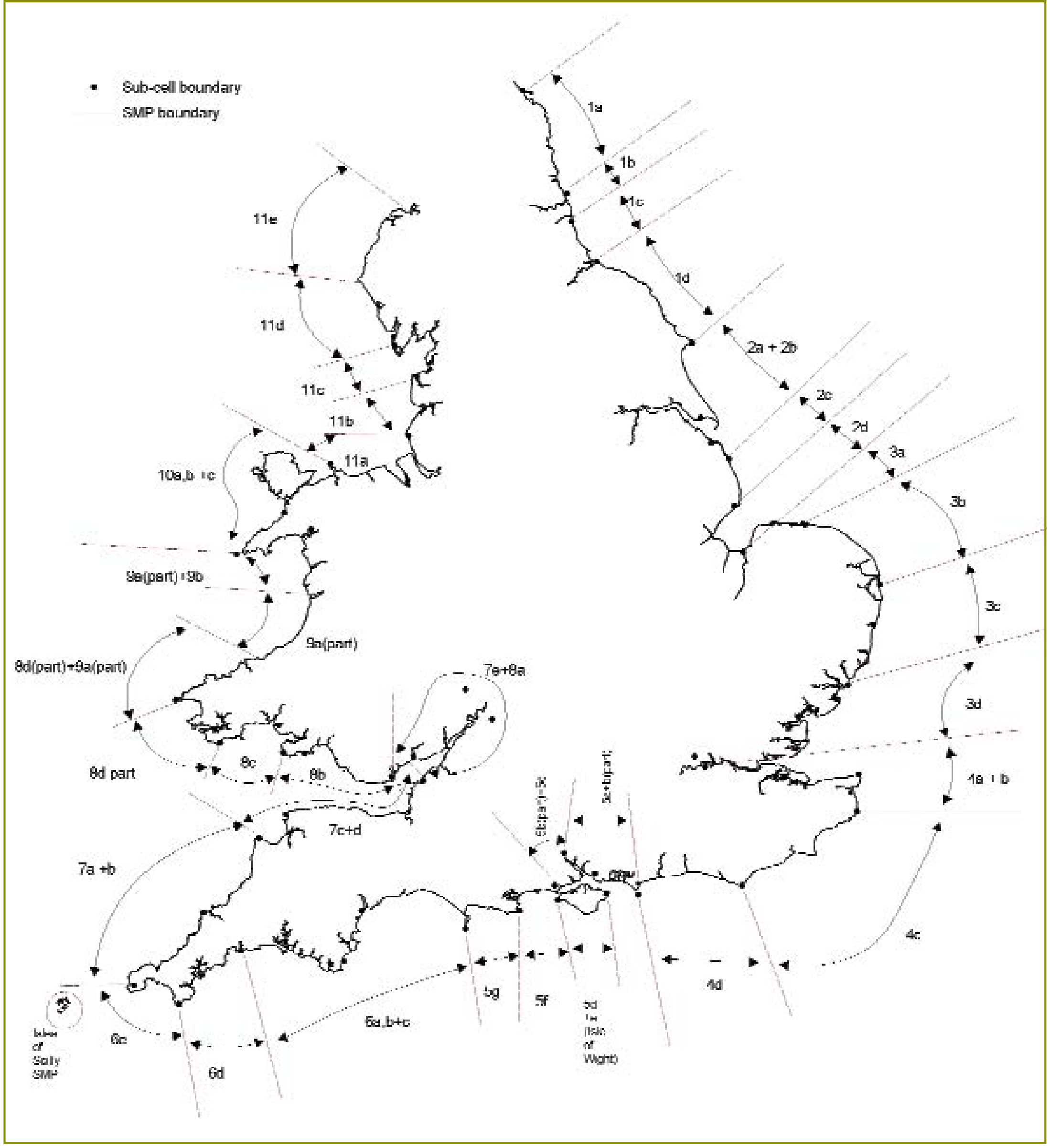


Figure 97: Illustration of the division of the England and Wales coastline into SMP areas based on sediment cell boundaries. (Adapted from: DEFRA, 2006).

Step 2: Name lead authority to develop SMP

Each SMP is developed by one local coastal group, which is deemed the lead authority. The lead authority also consists of at least one representative from all authorities with an operational responsibility in the plan area (ex: Environment Agency, internal drainage boards, local maritime authorities), a representative from local coastal planning authorities, and any other individuals from important coastal groups who have an interest in the shoreline (DEFRA, 2006).

Step 3: Determine Theme Areas

Once the SMP area is defined, it can be subdivided into theme areas based on regions, towns and cities (Figure 98).

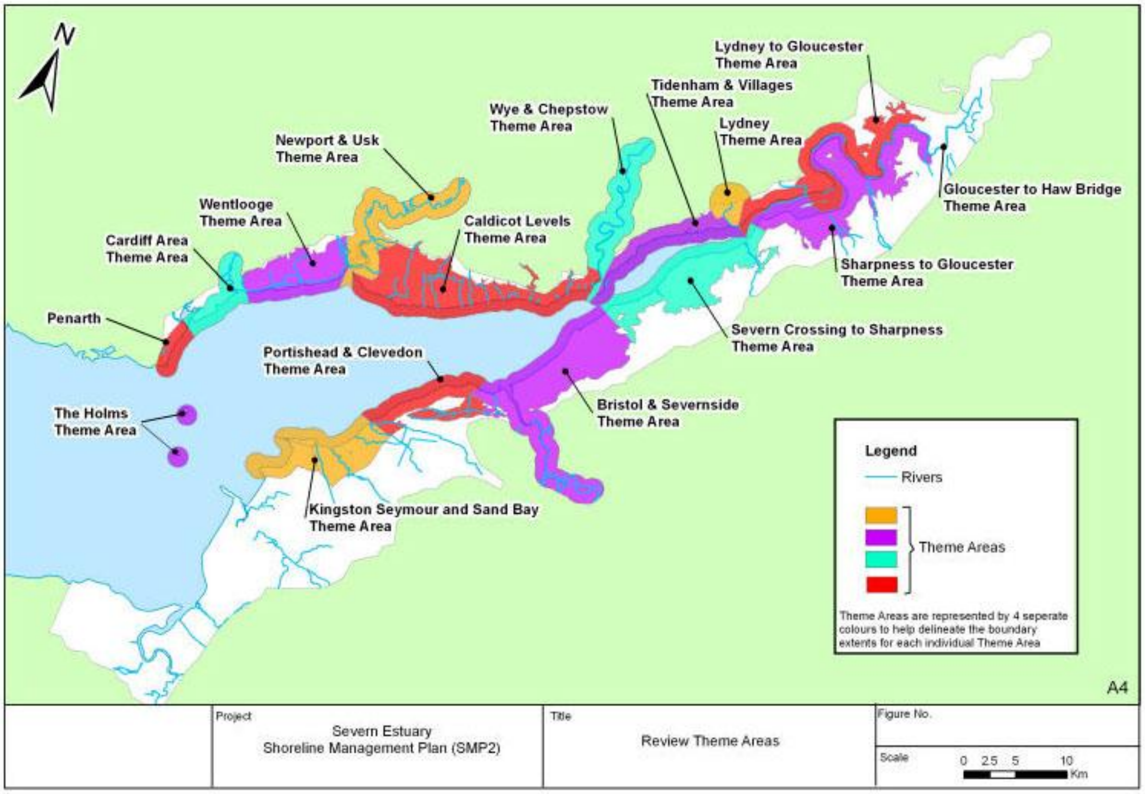


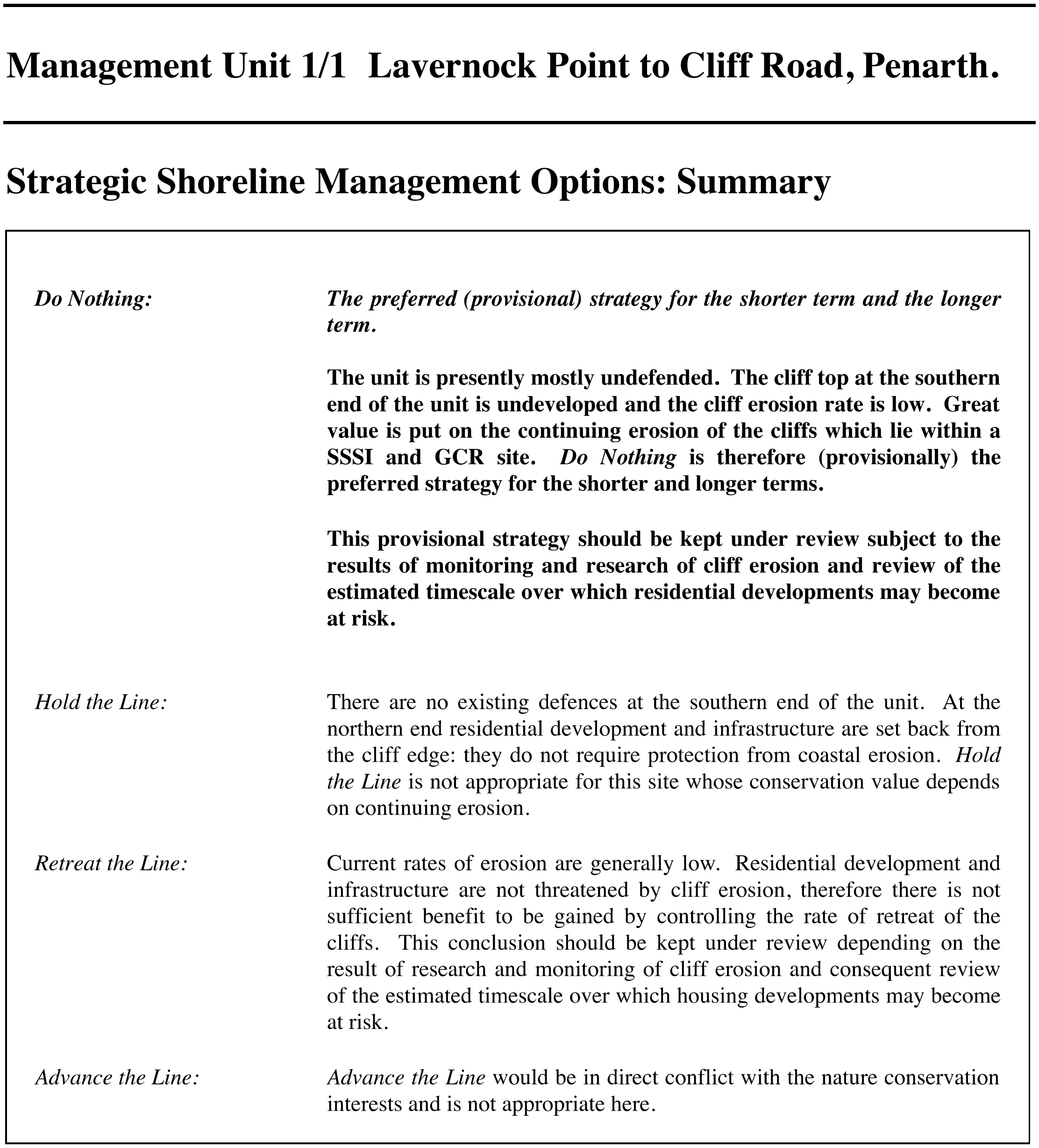
Figure 98: Theme subdivisions for coastal zone management plan delineation for the Severn Estuary including provisions for sea level rise (Adapted from: Severn Estuary Coastal Group, 2010).

Step 4: Determine Policy Units

Each Themed Area is further subdivided into policy units, for which a policy or a combination of policies is chosen to best manage that particular stretch of coast for three epochs (Severn Estuary Coastal Group, 2010). A *Policy Unit* is a length of shoreline with similar characteristics in terms of coastal processes and assets at risk that can be managed efficiently (DEFRA, 2006).

Step 5: Develop Strategic Shoreline Management Options

For each policy unit, a Strategic Shoreline Management Option is created which assesses the potential implementation of each of the four policy options for the specific length of coast for each of the three epochs and determines the preferred strategy.



Management Unit 1/1 Lavernock Point to Cliff Road, Penarth.

Strategic Shoreline Management Options: Summary

Do Nothing:	***The preferred (provisional) strategy for the shorter term and the longer term.*** **The unit is presently mostly undefended. The cliff top at the southern end of the unit is undeveloped and the cliff erosion rate is low. Great value is put on the continuing erosion of the cliffs which lie within a SSSI and GCR site. *Do Nothing* is therefore (provisionally) the preferred strategy for the shorter and longer terms.** **This provisional strategy should be kept under review subject to the results of monitoring and research of cliff erosion and review of the estimated timescale over which residential developments may become at risk.**
Hold the Line:	There are no existing defences at the southern end of the unit. At the northern end residential development and infrastructure are set back from the cliff edge: they do not require protection from coastal erosion. *Hold the Line* is not appropriate for this site whose conservation value depends on continuing erosion.
Retreat the Line:	Current rates of erosion are generally low. Residential development and infrastructure are not threatened by cliff erosion, therefore there is not sufficient benefit to be gained by controlling the rate of retreat of the cliffs. This conclusion should be kept under review depending on the result of research and monitoring of cliff erosion and consequent review of the estimated timescale over which housing developments may become at risk.
Advance the Line:	*Advance the Line* would be in direct conflict with the nature conservation interests and is not appropriate here.

Figure 99: An example of a Strategic Shoreline Management Options Summary for Management Unit 1/1: Lavernock Point to Cliff Road, Penarth. (Adapted from: Severn Estuary Coastal Group Associated Consultants, 2000)

Table 12 provides a summary of important characteristics, monitoring techniques, knowledge requirements and suggestions for adoption, for three adaptation approaches; Hold the Line, Limited Intervention and Retreat the Line, would be useful in determining a policy for each policy unit.

Step 6: Produce an interactive map where chosen policies for each policy unit are displayed (Figure 100).

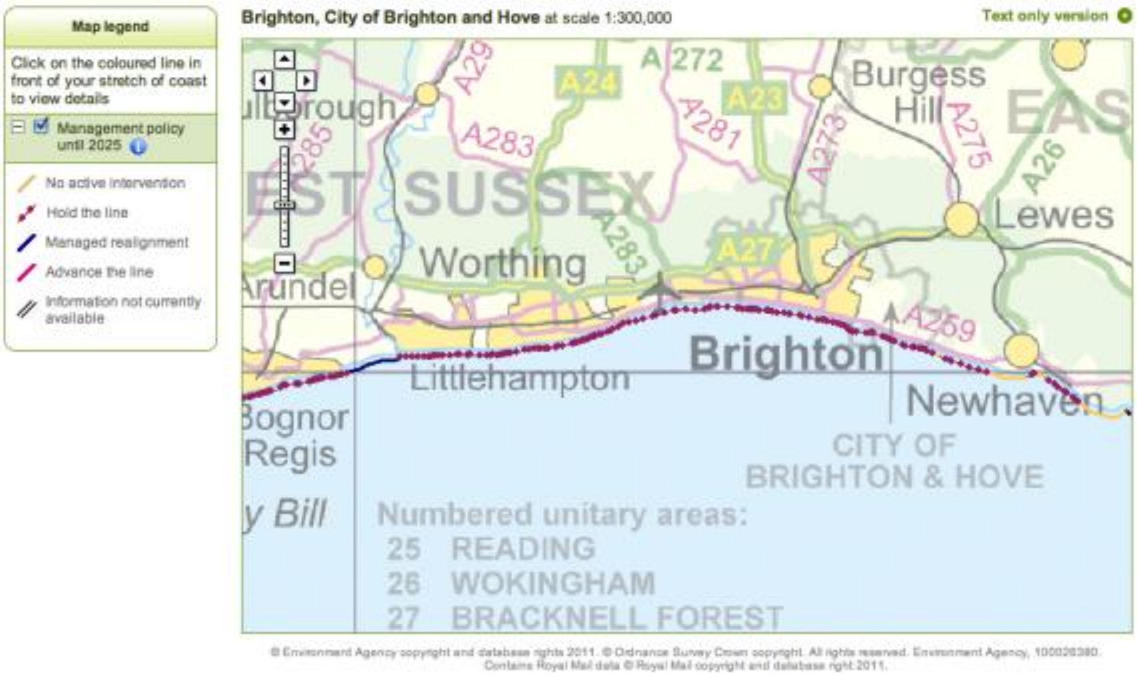


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Figure 100: Interactive map for Brighton, UK displaying management policies (Adapted from Environment Agency, 2011)

A useful example of a completed second generation SMP is the Severn Estuary Shoreline Management Plan Review (Severn Estuary Coastal Group Associated Consultants, 2000) as the Severn Estuary shows similarities to the Bay of Fundy; it has one of the highest tidal ranges in the world (~15 m), it forms a boundary between Wales and England, it has a rich archaeological history and the majority of surrounding land is agriculture.

6 Recommendations and Conclusions

The Nova Scotia Government cannot afford to protect all areas at risk of flooding. Efforts need to be targeted as to where it provides the best value to the taxpayer, however, this does not immediately preclude priority to protect fertile, productive agricultural land, even if this land is currently underutilized. It is recognized that Fundy dykelands no longer simply contain agricultural land and cooperation is required at federal, provincial and local levels to find funding for dyke heightening. A combination of both an engineering and management approach is recommended for the Fundy environment.

Based on an analysis of international best practices and existing conditions within the Fundy ACAS communities, the following recommendations are provided:

- Conduct a cost benefit analysis for marshbodies identified by Browning, 2011 as containing significant infrastructure using the methodology of van Alphen (2012) to balance the value of the land protected and cost of required infrastructure as well as degree of risk that the communities are willing to assume.

- Develop a differential determination of critical elevation incorporating sea level rise and storm surge for dykes protecting valuable infrastructure similar to Pilarcyk, 1998. For example, use a 1:100 year storm return period for high value areas (1.13 m) versus a 1:10 year storm (0.85 m) in primarily agricultural land. In these high value areas, a minimum of the predicted 2055 sea level rise estimate should be included.

- In areas where dykes are being topped, it is recommended that the proposed cross sectional profiles be carefully assessed and a decrease in slope (e.g. 1:2 or 1:3 ideally) be applied on the seaward side. Although this may come at the expense of some agricultural land as the dyke crest will need to shift landward, the trade off of a loss of 10 m of agricultural land versus the significant financial cost of dyke repair due to erosion is warranted.

- The allocation of variances should be significantly limited and flood proofing requirements should be mandatory. Applicants of proposed variances should be shown detailed maps of the extent (and depth) of potential inundation so that they are fully aware of the risk of building within this zone. Various products generated through ACAS are available to support these activities.

- Managed re-alignment should be considered in those areas that have less than 80 m of foreshore. In those cases, dykes should be re-aligned so as to provide a minimum of 100 m of foreshore and that foreshore be armoured. Efforts should be focused on proactive rather than reactive protection. However, not all foreshore should be armoured as sediments released through the erosion process will in turn nourish new marsh growth in other areas within the estuary.

- Small, underutilized tracts should be considered as candidates for salt marsh restoration if the cost of maintenance is significantly more than the value of the land that is being protected. However, large, intact tracts of agricultural land that are threatened yet underutilized should not necessarily be seen as immediate candidates for large scale restoration activities. Constrained managed realignment in areas of concern should be undertaken to prevent beaching and to protect fertile agricultural land for future generations.

- No additional salt marsh should be reclaimed even if there is significant growth of foreshore marsh seaward of an individual dyke structure. This foreshore marsh serves as a buffer for erosion and wave energy dissipation for future generations. Natural processes of erosion and progradation should be encouraged.

- In areas where communities benefit directly from the protection of dykes for their critical infrastructure, these communities should bear some of the costs of maintenance (e.g. ‘protection tax’ proportional to the amount of land at risk) in addition to the province and federal government. No one entity should bear the cost in its entirety.

Planning for flood risk requires collaboration and partnerships at all levels. This will include engaging provincial, municipal and community stakeholders in education and visioning activities to raise the understanding of current and future flood risks, use the products generated through ACAS to quantify this risk and decide as a community and a province, how best to address these risks. . It is important to note that while this report provides an evaluation of dyke vulnerability and adaptation options that can be applied to non-ACAS areas (e.g. Truro and Annapolis), it does not negate the need to conduct site specific vulnerability assessments for other areas of the Province. Fundy communities can successfully adapt to climate change providing there is sufficient political will, community acceptance and financial resources.

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8 Appendix A: Country Examples

CHINA

Coastal Geography

The coastline of China extends approximately 18 000 km along the Eastern side of the country (Chen & Chen, 2001; Cai et al., 2009). The elevation is generally higher in the west and lower in the east with the three largest rivers (Yangtze, Yellow and Pearl) flowing towards the eastern coast (Cheng, 2009; Lau, n.d.). These rivers form major river deltas that are fertile and popular for agriculture, industry and large cities (Cheng, 2009).

SLR in China

On average the rate of SLR affecting the coast of China is 1.4-2mm/a, but varies locally due to regional tectonic subsidence and subsidence due to groundwater withdrawal and sediment compaction (Chen & Chen, 2001). The impacts of SLR on coastal China include coastal erosion and retreat, coastal inundation, salt water intrusion into estuaries and aquifers, intensification of storm surge, coastal wetland loss, overtopping of dykes and loss of sea dyke efficacy (Chen & Chen, 2001; Cai et al., 2009; Han et al., 1995).

Coastal Protection

In China, dykes are the predominant coastal defence structure and have been the primary defence measure since AD600 when they were used along with sluices to enclose land for agriculture (Han et al., 1995; Lau, n.d.; Chen & Zong, 1999). After 1949 there was a large construction of flood systems in China and currently the estimates of the length of sea dykes along the coastline of China range from 9997km to 12 883km (Han et al., 1995; Chen & Chen, 2001). Although a large part of the Chinese coastline is protected by dykes not many can provide protection from a 1 in 100yr storm, let alone accelerated SLR (Cai et al. 2009).

Responsible Authority

At present, there are no authorities directly responsible for adaptation to SLR. However, the State Oceanic Administration under the Ministry of Land Resources is responsible for coastal zone management and the Ministry of Water Resources along with the local and national government are responsible for the planning of dyke building (Lau, n.d.).

Policy, Legislation and Strategies

In the 1990's a new strategy to manage coastal resources was implemented that focuses on "positive coastal protection" which attempts to dissipate wave and tidal energy in the foreshore (Cai et al., 2009). Since 1999, China has begun to look at soft defence structures such as beach nourishment and mangrove planting (Cai et al., 2009).

Summary of Practices

China has a large population along the coast and the coastal delta areas are economically important zones. If current dyke structures were not raised, then a 1m rise in sea level would result in a hazard area of 125 000km^2 home to 72 million people (Han et al., 1995). Since the upkeep and construction of dykes is economically very feasible for China, and the coastal zone has a high population density and is economically important, the best solution for China is to raise and strengthen pre-existing dykes and build additional dyke structures where needed (Lau, n.d.; Han et al., 1995).

Specific Areas or Regions Under Threat

Huanghe/Yellow River Delta – North China Coastal Plain

Tidal Range: Microtidal
SLR : SLR could cause extensive flooding and loss of coastal wetlands, erosion and saltwater intrusion. Area already has rapid subsidence and a 1m rise in sea level (combined with storm surge and tides) could result in flooding 60km inland (Han et al., 1995).
Dykes: Dykes provide protection to the majority of the coastal plain and have a crest elevation of +2 - +3 MSL (Han et al., 1995; Chen & Chen, 2001).
What Dykes Protect: City of Tianjin (pop. 8.3million), reservoirs, agriculture, highways, oil fields, and railways (Han et al., 1995).
Summary of Practices:
The dykes along the plain have a crest elevation of +2-+3MSL, but are not high enough to prevent flooding and storm surges. It is recommended that ~500km of dykes be built to prevent flooding from a 1m rise in sea level. This would cost about ~370million USD which is extremely affordable for the region (Han et al., 1995).

Zhujiang/ Pearl River Delta

Tidal Range: Microtidal (Huang et al., 2004)
SLR: Sea level is expected to rise ~30cm by 2030 (Huang et al., 2004). A 1m rise in sea level would result in a hazard zone of 7000km^2 for this area (Han et al., 1995).
Dykes: Dykes of ~2m in height provide protection for the entire plain and extend 3057.6km (Huang et al., 2004; Han et al., 1995).
What Dykes Protect: City of Guangzhou, entire coastal plain with a population of 12 million and a population density of 1230ppl/km^2, 368,500ha agricultural land, and industry (Huang et al., 2004; Han et al., 1995).
Summary of Practices:
Over the past 50 years reclaimed lands in the Pearl River Delta have been merged into ~100 Weis (The Chinese form of polders), which are protected by dykes (Huang et al., 2004). In the delta plain there are 3057.6km of dykes, but only 2608.6km of which are vulnerable to ASLR (Huang et al., 2004). As sea level continues to rise, the coastal plain will increasingly rely on dyke structures for protection and cost benefit analysis completed for the region indicates that the amount required to bring dykes up to standard for a 30cm rise in sea level would be ~ 262.9 million USD, but the potential economic loss from flooding is likely to be much greater. In 1994, a flood in the region resulted in economic loss of 350 million USD (Huang et al., 2004).

Canhgjiang/Yangtze Delta - East China Coastal Plain

Tidal Range: Microtidal (Han et al., 1995)
SLR: A 1 m rise in sea level in this area has the potential to flood 180 km inland and is likely to cause coastal erosion, raise groundwater table increase flood risk and prolong waterlogging resulting in reduced agricultural yields (Han et al., 1995; Chen & Zong, 1999).
Dykes: Existing coastal dykes protecting Shanghai are 464.6km in length, 8m high, 5-8m wide on top, have a 1:2 inner slope and a 1:3 outer slope. The total length of dykes in the Shanghai area is 720km and in general they have a crest elevation of +4-+6 MSSL (Han et al., 1995; Wang et al., 1995).
What Dykes Protect: City of Shanghai (population: 13 million, population density: 2104ppl/km^2), farmland, harbour facilities, and highly developed industrial and agricultural systems (Han et al., 1995;

Wang et al., 1995).

Summary of Practices:

In this area retreat and accommodate options are not feasible due to the presence of high population densities in Shanghai and the large investment in infrastructure behind the dykes. A two-levelled dyke is located along the bank of Huangpu River with a crest elevation of +5 m MSL (Han et al., 1995) and dykes around Shanghai are being strengthened to withstand a 1000 year return period flood (Wang et al., 1995). Dykes protecting agriculture are still few; however the city plans to adopt the following adaptation measures concerning agriculture: improving drainage quality, increasing and renewing pumping facilities and using crops that are more tolerant to waterlogged conditions (Wang et al., 1995).

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FRANCE

Coastal Geography

The entire French coastline is approximately 5500 km in length, which is divided into 3800 km on the Atlantic side and 1700 km on the Mediterannean side. Of the coastline, 10% are salt marshes, 1% are estuaries and 14% are artificial shores (Poumadère st al.,2008).

SLR in France

SLR in France is will lead to flooding, erosion, salt water intrusion and shoreline retreat (Paskoff, 2004; Deboudt, 2010). As of 2011, there is 27000 km^2 of flood prone areas in France and by 2100, the sea level is expected to rise 9-85 cm which would result in even greater inundation zones (Ministère de l'Écologie,2011; Deboudt, 2010). In France, the three most vulnerable areas are the Rhone River Delta, Languedoc Coast and Aquitaine Sandy Shoreline (Paskoff, 2004).

Coastal Protection

Of the 5550 km coastline, 550 km are protected by some coastal defence structure (Paskoff, 2004). Twenty percent (336 km) of the shoreline is protected by dykes and as of 2011, the country will be protected by 7600 km of dykes (Ministère de l'Écologie,2011).

Responsible Authority

In Germany, the responsible authorities include the Ministry for Ecology, Sustainable Development, Transport and Housing, the Directorate General for Risk Prevention and the Department for Natural and Water related Risks (Ministry for Ecology,2011).

Policy, Legislation and Strategies

In 1982, Germany created an insurance program called CatNat, which requires obligatory insurance for people living in harms way of natural disasters (Deboudt, 2010). Four years later, in 1986 the Loi Littoral (Coastal Zone Law) was developed which focused on management, development, protection and preservation of coastal areas (J. Dauvin et al., 2004; Paskoff, 2004). Examples from this law include restricting the construction of new roads along the shoreline outside of the urban area and restricting new building sites within 100 m from the coast (Paskoff, 2004). In 1995 the government adopted a new law for the prevention of natural hazards, and damage compensation called the Barrier Law in which landowners may be relocated and compensated when at risk (Pottier et al, 2005; Paskoff, 2004; Deboudt, 2010). This law included the establishment of PPRn's (Risk Prevention Plans), which control development through land use and construction regulations (Deboudt, 2011).

Summary of Practices

The summary of practices for France is largely outline in its policy, legislation and strategies. The most recent strategy is the development of the PPRn's in 1995. By 2007, 30% of coastal communities had approved PPRn's and by 2011, 8450 PPRn's have been approved (Deboudt, 2010; Ministère de l'Écologie,2011). Traditionally, France, like many other European countries, relied haveily on hard coastal defence structures (Paskoff, 2004). Today, France is still reliant on hard defence structures to prevent flooding along low lying, vulnerable sections of the coast, even though the costs of building a sea wall range from 1400-2000 CDN/m (Paskoff, 2004).

Specific Areas or Regions Under Threat

Rhone River Delta/ Carmargue

Tidal Range: Microtidal
SLR: In this area SLR is approximately 2.1mm/a. It has natural subsidence which could be compensated for by input of sediment from the Rhone River save for the large upstream dams which prevent this. Another major issue in this area is salt water intrusion from SLR (Paskoff, 2004).
Dykes: The Rhone River Delta Plain has approximately 100 km of river and sea dykes, seawalls and groynes (Poumadère st al.,2008; Paskoff, 2004). However, many of the dykes are susceptible to overtopping (Paskoff, 2004).
What Dykes Protect: Dykes in this area are responsible for protecting housing, human activity, agriculture, a population of 60 000, privately owned salt pans, and a nature reserve of 85 000ha, which is a pink flamingo resting area (Paskoff, 2004;Poumadère st al.,2008).
Summary of Practices:
In 2008, a group of stakeholders came together for a workshop on potential solutions for future ASLR in which a mock 5-6 m SLR scenario was assessed. Stakeholders suggestions included conducting a cost benefit analysis and possibly retreating the defences to restore the natural functioning of the Rhone River Delta (Poumadère st al.,2008). In areas such as Faraman, coastal defences would need to be raised and strengthened to protect the coast from SLR, however retreat could be used in less populated areas, and realignment of the salt pans is also recommended in contrast to investing more money in deteriorating hard defences (Paskoff, 2004).

Languedoc

SLR: Languedoc is well known for its vineyards and SLR could cause serious damage to these crops through salt water intrusion (Paskoff, 2004).
Dykes: The area is also well known for its beaches, but the presence of hard defence structures to protected beaches are causing major scour and threatening these ecosystems (Paskoff, 2004).
What Dykes Protect: In this area, dykes protect resorts, beaches, buildings and tourism facilities (Paskoff, 2004).
Summary of Practices:
Due to the high value of the tourism and wine industry in this area, the only option it to continue using hard defences to protect the coast and to invest in artificial beach nourishment to restore the beaches (Paskoff, 2004).

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GERMANY

Coastal Geography

Germany's coast is approximately 3700 km long with 1600km along the North Sea and 2100 km along the Baltic Sea (Sterr, 2008). As is the case with many countries, the coastal region of Germany is heavily used and densely populated (Tol et al, 2008). Overall, the coast is low-lying and consists primarily of marshes, dunes and beaches (Sterr, 2008).

SLR in Germany

In Germany SLR, along with a subsidence of approximately 5cm/100yrs, is likely to cause rising water tables, coastal erosion, sediment deficits and saltwater intrusion (Sterr, 2008). With just a 1 m rise in sea level, approximately 15 000 km^2 is in danger of flooding and over 300 000 people are considered to be at risk (Sterr, 2008; Tol et al, 2008).

Coastal Protection

Along the Baltic coast, the densely populated areas are protected by 560 km of dykes and along the North Coast, which is more exposed to the open sea, dykes protect 1340 km (85%) of coastline (Sterr, 2008). The dyke heights along both coasts are determined according to the "Coastal Protection Master Plans" (Sterr, 2008).

Responsible Authority

In Germany, each of the state governments are responsible for their individual section of coast and any adaptive approaches (Sterr, 2008; Tol et al, 2008). Accordingly, each coastal state has its own coastal policy and varying levels of protection (Tol et al, 2008; Rupp et al, 2002). Each state government is also responsible for building and maintaining coastal protection and flood defences, but receives 70% of its funding from the federal government (Rupp et al, 2002).

Policy, Legislation and Strategies

Since coastal adaptation measures are determined for each individual state, there are no uniform policies, legislation or strategies for the country (Tol et al, 2008). However, state adaptation strategies can be found in their Coastal Protection Master Plans (Tol et al, 2008).

Summary of Practices

Historically, Germany is known for its use of hard defences, such as dykes and embankments, to protect the coast and its extensive practice of land claim. However in the past 20 years, efforts have been made to increase the use of softer coastal defences (Rupp et al, 2002). Even though the benefits of using soft defences is well understood, due to the large economic risk associated with coastal flooding and the realized need to develop an extensive flood defence system to combat SLR, Germany still uses the long-term strategy of dyke building in most areas (Tol et al, 2008). In other areas, such as those with low population densities, partial dyke set back has been used (Tol et al, 2008). However, the ultimate decision on whether or not dykes are built in Germany is based on a cost-efficiency analysis as opposed to the commonly used cost benefit analysis (Rupp et al, 2007).

Specific Areas or Regions Under Threat

North Sea

Tidal Range: Mesotidal

SLR: At this location, a rise in sea level would result in the requirement of intense pumping to avoid salt water intrusion (Tol et al, 2008)

Dykes: The coastline along the North Sea is heavily dyked, as the entire low-lying shoreline has dyke protection (Rupp et al, 2002). In this area, dyke heights range from 7.5 – 8.8 m and are overall in excellent condition (Lau, n.d).

Summary of Practices:

The exposure of the German coastline to the North Sea results in the need for 85% of the 1155 km coastline to be protected by hard defences (Lau, n.d). In 2001, additional dykes were constructed along this coast, but due to the shallow intertidal profile, salt marshes were created in front of the dykes to provide a wave buffer (Lau, n.d). Although salt marshes were used as an advance the line technique, the use of a managed retreat scheme along the North Sea coast is highly unlikely due to the large presence of hard structures (Rupp et al, 2002).

Baltic Sea

Tidal Range: Microtidal

Dykes: Of the 2100 km coastline along the Baltic Sea, only 27% of it is protected by hard defences such as dykes and revetments (Tol et al, 2008; Rupp et al, 2007). However along this coast, many of the dykes do not meet the requirements for SLR.

Summary of Practices:

Currently the average annual cost of protecting this shoreline is 133-200 million CAD. However, dykes in this area are nearing the end of their design life and require a significant input of money (Tol et al, 2008). Accordingly, managed realignment is being used more frequently, as it is a cheaper and more environmentally sustainable defence option (Rupp et al, 2002).

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NEW BRUNSWICK

Coastal Geography:

The coast of New Brunswick extends for approximately 5500 km along the Gulf of St. Lawrence and the Bay of Fundy and makes up 87% of the provincial boundary. The coast along the Bay of Fundy is predominated by rocky cliffs and salt marshes (Environment and Local Government, n.d).

SLR in New Brunswick

The sea level in New Brunswick is rising at a rate of 0.3-0.4 cm/a and the rate of SLR is likely to double by the end of the century (Marlin et al, 2007; Ollerhead, 2011).

Coastal Protection

The dyke system in New Brunswick consists of 80 km of dykes, 76 water control structures, 3 tidal dams and 112 km of marsh roads and bridges and protects over 37000 acres of marshland (Marlin et al, 2007).

Responsible Authority

The Department of Agriculture, Aquaculture and Fisheries, whose mandate is to protect agricultural land from flooding, owns the majority of dykes in the province and is responsible for maintaining infrastructure of coastal defences (Marlin et al, 2007; van Proosdij, 2011; Robichaud, n.d). The remainder of dykes are owned by private landowners and the CNR (Canadian National Railway) (Marlin et al, 2007).

Policy, Legislation and Strategies

Some current, relevant legislation for New Brunswick includes the New Brunswick Wetlands Conservation Policy, New Brunswick Coastal Areas Protection Policy, Municipalities Act, Clean Environment Act, Watercourse and Wetland Alteration Regulation, Environmental Impact Assessment Regulations and the Marshland Reclamation Act (Marlin et al, 2007). The most important of these policies is the Marshland Reclamation Act created in 1982, with a mandate to protect agricultural land and create marsh bodies. However, this act has not been updated since its creation (Robinson et al, 2004).

Summary of Practices

The majority of salt marshes in New Brunswick have been dyked and turned into agricultural fields or other developments with the majority of the infrastructure having been constructed in the early 1950's (Robichaud, n.d; Marlin et al, 2007). According to (Singh et al, 2007), converted salt marshes are some of the regions most fertile land but 41% of the land isn't being used. Although traditionally, New Brunswick has been reliant on hard defences there is increasing interest in using soft measures, primarily salt marsh restoration. More recently, partial dyke abandonment is being practiced in areas such as Musquash where the costs of protection exceed the value of the land (van Proosdij, 2011). According to (Ollerhead, 2011), "we are ready to use salt marsh restoration as an adaptation and it is proven that areas in New Brunswick can keep pace with RSLR, however socially and economically we are not ready".

Specific Areas or Regions Under Threat

Aulac Dyke

Tidal Range: Macrotidal

What Dykes Protect: In this areas the Aulac dyke is responsible for protection of freshwater impoundments, agriculture, communication and transportation infrastructure and an historical site (Marlin et al, 2007).

Summary of Practices:

The 1500 m Aulac dyke was originally built tens of metres back from the marsh edge, but overtime, due to the process of coastal squeeze the dyke marsh edge retreated that the dyke became exposed to direct erosion (Singh et al, 2007, Marlin et al, 2007). The New Brunswick Department of Agriculture, Aquaculture and Fisheries invested 50000-60000 CAN annually for 6 years in armourstone and dyke maintenance. Eventually it was realized that it was more economically feasibly to realign the dyke 130 m back from its original position and in the process raise the dyke by 4 feet (Singh et al, 2007). In 2010, this process began and the once dyked land was returned back to a functioning salt marsh (Ollerhead, 2011)

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ENGLAND AND WALES

Coastal Geography

England and Wales have a coastline of approximately 6000 km which contains numerous estuaries such as the Blackwater, Humber and Severn and high-grade agricultural land and major cities are predominately found in floodplains (Environment Agency, 2011; Mai et al, 2008). A prominent feature along this coast is saltmarshes of which 80% are legally protected as SSSI's (Site of Special Scientific Interest) and NNR's (National Nature Reserves) (Edwards et al, 2006). The majority of the lowest lying land exists in the Severn Estuary located on the western coast (Rupp et al, 2007).

SLR in England and Wales

England and Wales naturally suffers from subsidence and with ASLR, there are 5.2 million properties at risk of flooding (Department for Environment, Food and Rural Affairs, 2011; Rupp et al, 2002) Currently 5% of the population of the United Kingdom live in the 12200 km^2 that is flood prone and the areas with highest economic risk due to flooding are London and Hull (Mai et al, 2008).

Responsible Authority

In England and Wales, DEFRA (Department for Environment, Food and Rural Affairs) is responsible for creating national policy for flood and coastal erosion risk management, but does not build or manage flood defences (Department for Environment, Food and Rural Affairs, 2011). The EA (Environment Agency) on the other hand is responsible for managing flood risk from main rivers, the sea and reservoirs and building flood defence structures (Hall et al, 2005; Rupp et al, 2002). Lastly, LLFA's (Lead Local Flood Authorities) are responsible for local flood risk from sources such as groundwater and surface runoff, but also assist the EA in the management of flood defences (Rupp et al, 2002; Hall et al, 2005).

Policy, Legislation and Strategies

Along with the SMP (Shoreline Management Plan) strategy already explained in the body of this report, England and Wales have many policies, legislations and strategies for managing flood risk. In 2001, DEFRA developed the "Making Space for Water" strategy, which focuses on promoting the use of resistant and resilient building techniques and managed realignment schemes (Lonsdale et al, 2008). Along with this program, DEFRA, through the Environmental Stewardship Scheme, offers financial compensation to land owners who undertake habitat creation through managed realignment (Parrott et al, 2008). The most prominent strategy in England and Wales is the newly developed Flood and Water Management Act 2010, which promotes more comprehensive management of flood risk for people, homes and businesses (Hall et al, 2005). In December 2011, the next stage of the Flood and Water Management Act came into play (Department for Environment, Food and Rural Affairs, 2011).

Summary of Practices

Traditionally, England and Wales extensively practiced land claim and dyking. But over the past 20 years, there have been great efforts to increase the use of soft defences for flood protection (Rupp et al, 2002). The process of managed realignment is becoming more and more prominent in the United Kingdom and is promoted for both flood defence and habitat creation (Edwards et al, 2006). The majority of these managed realignment sites are located on the eastern coast of England and Wales (Rupp et al, 2007). Due to future ASLR and the knowledge of the immense benefits of salt marshes in combating SLR and erosion, England had made a target for the creation of 140 ha/yr of salt marshes

(Rupp et al, 2002). In 2002, the Environment Agency created the National Food Defence Database (NFCDD), which offers an inventory of flood defences and their structural condition (Shepherd et al, 2008).

Specific Areas or Regions Under Threat

Thames Estuary

Tidal Range: Macrotidal

Dykes: The Thames Barrier was built in 1981 and along with other flood defences it provides the city of London with protection from a potential 1 in 1000yr storm. However, on the southern, dykes protecting agricultural land are only build to provide protection from a 1 in 200yr storm (Lonsdale et al, 2008).

What Dykes Protect: The Thames Estuary experiences the highest risk of flood damage due to the concentration of high value assets located in this area including farmland, people, property and infrastructure (Lonsdale et al, 2008).

Summary of Practices:

In the face of SLR, the three options discussed in a locally held workshop to combat this issue were to protect London with an outer barrage, relocate enterprises, infrastructure and people, and reshape London with some areas being inundated and some areas being protected. Along the river banks, there was also discussion of the heightening of embankments, but was deemed an unviable option for SLR beyond 2 m (Lonsdale et al, 2008).

Humber Estuary

Tidal Range: Macrotidal

Dykes: A coastline survey conducted in 1990, determined that the majority of the dykes along the coast of the Humber Estuary were in good condition, with only some in poor condition or unable to meet flood protection standards (Edwards et al, 2006).

What Dykes Protect: The Humber Estuary is home to the United Kingdom's largest complex of ports, chemical and oil refining industries and electricity generating stations. It also contains ecologically important intertidal habitats, a high density of people and high grade agricultural land (Edwards et al, 2006).

Summary of Practices:

Since the early 17th century, this area has undertaken large scale land claim schemes and the current strategy mostly consists of holding the line of defence by raising dykes, but also completing manage realignment schemes in some areas (Edwards et al, 2006).

Blackwater Estuary

Tidal Range: Macrotidal

Dykes: Overall, the coastal defences used in this area are earth embankments, concrete embankments and seawalls. Specifically, the area of Essex in the Blackwater Estuary has 443 km of seawalls of which 23% have been improved in the past 20 years (Parrott et al, 2008).

What Dykes Protect: Dykes in this area protect large areas of low-lying, moderate-poor agricultural land (Parrott et al, 2008).

Summary of Practices:

The agricultural land located in the Blackwater Estuary is land that once belonged to the sea and thus is reclaimed land. In most areas, the cost of defending this low-moderate grade agricultural land is not economically efficient and accordingly many areas in this region are prime candidates for managed realignment schemes (Parrott et al, 2008). In fact, the Essex estuaries located in the Blackwater Estuary contain some of the first examples of managed realignment schemes such as Orplands, Tollesbury and Abbotts Hall (Parrott et al, 2008).

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