DAVID SUZUKI FOUNDATION
One nature.

Managing Natural Assets to Increase Coastal Resilience

Guidance Document for Municipalities

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Making Nature Count

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Glossary

Accretion	The buildup of sediments to form land or shoaling in coastal waters or waterways. Natural accretion is the buildup of land on the beach, dunes or in the water by natural processes, such as waves, current and wind. Artificial accretion is a similar buildup of land resulting from built structures such as groins or breakwaters, or activities such as filling and beach nourishment, or also aggradation (NSW-OEH 2018).
Asset management	An integrated process, bringing together skills, expertise and activities of people with information about a community's physical assets and finances so that informed decisions can be made, supporting sustainable service delivery (AMBC, 2019).
Avoided costs	An estimate of the monetary value of a non-market good or service, like that provided by natural assets, based on calculating costs that would be avoided if it were maintained in a current or improved state, or added (e.g., by comparing costs that would occur with and without the natural asset option).
Backshore	The zone of the shore or beach lying between the foreshore and the coastline comprising the berm or berms and acted upon by waves only during severe storms, especially when combined with exceptionally high water (NSW-OEH 2018).
Bathtub model	An inundation model that assumes an area with an elevation less than a projected flood level will be flooded like a “bathtub.” Flooding areas are determined through a simple calculation procedure in a GIS environment where the elevation in each cell of a DEM is compared against a predicted sea level and all cells with values lower than the predicted sea level are considered flooded (Yunus et al. 2016).
Bathymetry	Measurements of the shape of the bed or the depth of a body of water (NSW-OEH 2018). Water-based equivalent to a topographic digital elevation model.
Beach	An area that is generally composed of sand or pebbles or similar sediment that extends landward from the lowest astronomical tide to the line of vegetation or bedrock or structure (NSW-OEH 2018).
Beach erosion or Erosion	Landward movement of the shoreline and/or a reduction in beach volume, usually associated with storm events or a series of events, which occurs within the beach fluctuation zone. Beach erosion occurs due to one or more process drivers: wind, waves, tides, currents, ocean water level and downslope movement of material due to gravity (NSW-OEH 2018).
Beach nourishment	Beach restoration or augmentation using clean dredged or fill sand. Dredged sand is usually hydraulically pumped and placed directly onto an eroded beach or placed in the littoral transport system. When the sand is dredged in combination with constructing, improving or maintaining a navigation project, beach nourishment is a form of beneficial use of dredged material (NSW-OEH 2018).
Beach profile or Profile	A cross-section taken perpendicular to a given beach contour; the profile may include the face of a dune or seawall, extend over the backshore, across the foreshore and seaward underwater into the nearshore zone (NSW-OEH 2018).
Berm	A nearly horizontal ridge on a beach at or above the high-water mark but before the dune or embankment formed by the deposition of beach material by wave action or using mechanical means as part of a beach renourishment scheme. Some beaches have no berm; others have several (NSW-OEH 2018).

Chart datum	A chart datum is the water level that depths displayed on a nautical chart are measured from. On most modern charts in Canada the value of 0 metres elevation represents the mean lower low water (low tide).
Co-benefits	Additional ecosystem services provided by natural assets beyond the targeted focal services (e.g., flood management is the focal service, co-benefits might include habitat provision, recreation opportunities and more).
Design storm	A hypothetical extreme storm with waves that coastal protection structures will often be designed to withstand. The severity of the storm (i.e., return period) is chosen in view of the acceptable level of risk of damage or failure. A design storm consists of a design wave condition, a design water level and a duration (NSW-OEH 2018).
Discount rate	In the context of the underlying models in the CT, the discount rate is applied annually in the calculation of expected present value over a given time horizon. Expected present value reflects the value of the stream of avoided storm damages over time due to a change in habitat and discounts the value of those avoided damages in distant periods when the discount rate is greater than zero.
Dune (coastal)	Vegetated and unvegetated sand ridges built up at the back of a beach. They comprise dry beach sand that has been blown landward and trapped by plants or other obstructions. Stable sand dunes act as a buffer against wave damage during storms, protecting the land behind from saltwater intrusion, sea spray and strong winds. Coastal dunes also act as a reservoir of sand to replenish and maintain the beach at times of erosion (NSW-OEH 2018).
Ecosystem services	The benefits people derive from ecosystems (Millennium Ecosystem Assessment 2005)
Fetch	The length of open water over which wind blows without obstruction to generate storm waves.
Foreshore	The beach area including the intertidal zone and backshore; or the part of the shore lying between the crest of the seaward berm (or upper limit of wave wash at high tide) and the ordinary low-water mark, that is ordinarily traversed by the uprush and backrush of the waves as the tides rise and fall; or the beach face, the portion of the shore extending from the low-water line up to the limit of wave uprush at high tide (NSW-OEH 2018).
Grey infrastructure (also "hard infrastructure")	Engineered assets that provide one or multiple services required by society, such as transportation or wastewater treatment (IISD: https://iisd.org/savi/faq/what-is-grey-infrastructure/) and that are built using human-made materials.
Groin (also Groyne)	A shore-protection structure built (usually perpendicular to the shoreline) to trap littoral drift or retard erosion of the shore; or a narrow, roughly shore-normal structure built to reduce longshore currents and/or to trap and retain littoral material. Most groins are of timber or rock and extend from a seawall, or the backshore, well onto the foreshore and rarely even further offshore (NSW-OEH 2018).
Longshore	Parallel to and near the shoreline (NSW-OEH 2018).
Managed retreat (also Managed realignment)	Relocation landward, out of a coastal risk area, of homes and infrastructure under threat from coastal erosion, recession or inundation. It may also involve the deliberate setting back (moving landward) of the existing line of sea defence to obtain engineering or environmental advantages. During a managed retreat process, a new foreshore area or new intertidal habitat may be created (NSW-OEH 2018).
Mean Higher High Water (MHHW)	The average height of the highest of the high tides over a time period (usually 19 years, also known as a Tide Datum Epoch).

Mean Lower Low Water (MLLW)	The average height of the lowest of the low tides over a time period (usually 19 years, also known as a Tide Datum Epoch).
Municipal natural assets	Municipal natural assets are the stock of natural resources or ecosystems that are relied upon, managed or could be managed by a municipality, regional district or other form of local government for the sustainable provision of one or more municipal services (MNAI, 2017).
Nature-based solutions	Solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions (EU 2021).
Nearshore	A section of water near the coastline where waves steepen and break.
Static water level	The local water surface elevation as a result of the combined storm surge, tides and sea-level rise, but excluding wave runup and wave height.
Storm surge	The increase in coastal water level caused by the effects of storms. Storm surge consists of two components: the increase in water level caused by the reduction in barometric pressure and the increase in water level caused by the action of wind blowing over the sea surface (wind setup) (NSW-OEH 2018).
Submerged structure	An offshore benthic object (natural or anthropogenic) that it is below water surface but is still able to attenuate waves such as a rock, shipwreck or coral /oyster reef.
Wave propagation	Progression and transformation of wave characteristics (wave height, period) in time and space (e.g., from offshore to nearshore), specifically due to processes such as refraction, diffraction and dissipation by bottom friction (including from vegetation) and wave breaking.
Wave attenuation	Reduction of wave energy (and therefore wave height) due to bottom friction, specifically related to increase in bottom friction with the presence of offshore natural or human-made assets.
Wave setup	The wave-induced increase is local water level at the shoreline.
Wave runup	Maximum vertical reach of the wave swash on a beach or structure above the still-water level. It generally represents the maximum landward incursion of a wave.

Abbreviations

CHS	Canadian Hydrographic Service
CT	Coastal Toolbox
DEM	Digital Elevation Model
EWLAT	Canadian Extreme Water Level Adaptation Tool
GIS	Geographic Information System
InVEST	Integrated Valuation of Ecosystem Services and Trade-offs
MNAI	Municipal Natural Assets Initiative
MHHW	Mean Higher High Water (see Glossary)
MLLW	Mean Lower Low Water (see Glossary)
RCP	Representative Concentration Pathway (emissions)
SLR	Sea-level rise
UTM	Universal Transverse Mercator

1. About this Guidance Document

1.1. What is the Municipal Natural Assets Initiative?

The Municipal Natural Asset Initiative (MNAI) is a not-for-profit organization whose mission is to make natural asset management a mainstream practice across Canada. MNAI has worked with local governments throughout Canada to support communities seeking to identify, understand, measure and manage natural assets.

MNAI has a methodology, which is rooted in ISO-based asset management principles and a growing suite of tools and case experience to support local governments in developing natural asset inventories, and natural asset management more broadly. The suite of tools is constantly being updated and improved as experience in the nascent field of natural asset management grows.

The methodology and tools are delivered through ongoing support from the MNAI technical team over the course of municipal initiatives for which the goal is to begin adoption of natural asset management. The levels and details of this support are described in a Memorandum of Understanding that MNAI signs with local government partners.

The methodology generally follows the assess, plan and implement steps depicted below.

Figure 1-1. The natural asset management methodology applied by the Municipal Natural Assets Initiative.

1.2. Why Natural Assets?

As local governments in Canada recover from two decades of declining public infrastructure investments, they remain painfully aware of the ever-increasing costs of delaying repairs, rehabilitation and replacements. This is exacerbated by an increase in extreme weather events that demands adaptable and resilient solutions to deliver services while containing costs. Many municipalities are developing an asset management strategy to better manage their infrastructure. A logical extension of the asset management approach is the inclusion of "natural capital," which complements the forward-thinking solutions of asset management plans. Natural capital refers to any physical asset (i.e., a natural asset) within the natural environment that provides societal value by contributing to any natural process that benefits humanity (Voora and Venena, 2008).

Natural assets such as wetlands, forests, creeks and coastal dunes/beaches provide many critical services to communities and are important assets in the sustainable provision of core municipal services. A coastal dune, for example, can provide flood and erosion mitigation services that would have to be replaced by a hard/grey engineered alternative if it were lost.

However, while natural assets are key to sustainable service delivery, they are generally not accounted for and/or are undervalued in asset management practices. If natural assets are not managed responsibly, their value will depreciate and their ability to provide services from which humans benefit will diminish. Indeed, like any asset, natural assets need to be carefully managed to ensure a sustainable supply of services.

Until recently, most local governments lacked policies and tools to quantify the benefits supplied by natural infrastructure assets and to incorporate these benefits into their asset management and financial frameworks. Recognizing this, MNAI began articulating the relationship between humans and nature by developing tools and approaches for municipalities to use in measuring and managing the contribution natural systems make to communities.

A growing number of Canadian local governments are now recognizing that it is as important to understand, measure, manage and account for natural assets as it is for hard/grey ones. Doing so allows them to manage risk by better understanding what services from natural assets have not been accounted for, and how those services may be affected under conditions of climate change. In looking at the value that is or can be provided by natural assets, many are also finding that the quality of the services can meet, and in some cases exceed, those from traditional assets like pipes, culverts, groundwater wells or seawalls — but at a much lower cost and with many other benefits such as cooler cities, recreation opportunities and habitat.

1.3. The Coastal Resilience Project

As more research is directed toward the concept of natural infrastructure, it is becoming clear that coastal ecosystems can provide substantial protection from flooding and erosion, often at less cost and with greater long-term resilience compared to traditional grey infrastructure (Arkema et al. 2017). These ecosystems also provide a number of other services or "co-benefits" such as carbon storage, water quality regulation, nutrient cycling, unique recreation opportunities and habitat. Many of these benefits can complement hard/grey infrastructure investments like seawalls or breakwaters by supplementing the focal services they provide, protecting them from damage or replacing them entirely. Failing to include the value provided by coastal natural assets in policy and management decisions has contributed to a global disappearance of these ecosystems and an associated loss of ecosystem services (Barbier 2007). If the economic benefits of these assets were better understood, it would facilitate their inclusion in municipal asset management and, by recognizing their true worth to society, contribute to protection of coastal ecosystems. Rising sea levels threaten coastal zones through a range of coastal hazards, including (i) the permanent submergence of land by higher mean sea levels or mean high tides; (ii) more frequent or intense coastal flooding; (iii) enhanced coastal erosion; (iv) loss and change of coastal ecosystems; (v) salinization of soils, ground and surface water; and (vi) impeded drainage. Over the next century, without adaptation, the vast majority of low-lying coasts and communities face substantial risk from these coastal hazards (Oppenheimer *et al* 2019).

The objective of the MNAI *Managing Natural Assets to Increase Coastal Resilience Project* (Coastal Resilience Project) is to help participating local governments identify, prioritize, value and manage key coastal natural assets as part of core local government asset management systems. To do this, MNAI created a simulation model called the Coastal Toolbox (CT) that, used within the MNAI natural asset management methodology (Figure 1-1), can help municipalities identify their relevant natural assets, understand the value of those natural assets and use that information in municipal planning and management decisions.

The CT was pilot-tested with two coastal communities possessing very different coastlines: the Town of Gibsons on British Columbia's rugged west coast, and the community of Pointe-du-Chêne in New Brunswick, which is partly protected by the finely sanded Parlee Beach and coastal dunes that slope gently into the Northumberland Strait. The pilot application of the toolbox considered variables such as the effects of climate change on sea-level rise, different storm sizes and frequencies and multiple asset management alternatives relevant to each community, such as beach nourishment, dune enhancement, shoreline planting and eelgrass planting. These two pilot studies supplied a "proof-of-concept" of the CT and provided Gibsons and Pointe-du-Chêne with new information that will inform natural asset management decisions. The studies also helped develop a friendly user interface in ArcGIS Pro so that the CT can be easily used by municipal staff. In addition to providing general guidance about coastal natural asset management, this document serves as the User Guide for the CT.

1.4. Purpose and Structure of this Guidance Document

The purpose of this Guidance Document is to provide coastal communities with guidance about how to inventory their coastal natural assets, develop asset management options and evaluate alternatives using the Coastal Toolbox within the broader MNAI natural asset methodology (Table 1-1). Following some discussion about Canadian jurisdictional considerations for coastal asset management, an overview of the CT is provided, followed by a step-by-step procedural guide for effective utilization of the toolbox, and supplemented by several appendices that offer additional detail about CT steps, coastal ecosystems and the services they provide, common strategies for storm-surge protection (green, grey and hybrid), and a list of relevant legislation and policy.

If you wish to use this guide solely to operate the CT, we recommend reviewing Chapters 4 and 5, then starting with the installation instructions in Appendix E.

2. The Coastal Toolbox

2.1. Overview

The Coastal Toolbox is a GIS-based simulation and analytical tool designed to help local governments identify, prioritize, and manage key coastal natural assets as part of their day-to-day asset management practices. To build the toolbox, the "Wave Attenuation & Erosion Reduction: Coastal Protection" component of the InVEST Natural Capital Project (Release 3.1.1 – no longer available online) was adapted. It was originally built to investigate flood vulnerability and cumulative structural damage across a given shoreline of interest. In the spirit of that earlier model, and most InVEST tools, the goal is to provide an end-to-end evaluation that traces the impacts of biophysical processes on ecosystem components through to cost or benefit estimates associated with focal ecosystem services that are affected. The toolbox is intended for preliminary evaluations of coastal storms, beach erosion, offshore wave propagation, flooding and structural damage with a special emphasis on Canadian shorelines (Figure 2-1). The intent of the modified toolbox is for it to serve as both an exploratory learning tool for Canadian municipalities and as a "first pass" evaluation of flood and erosion mitigation benefits provided by coastal natural assets. Assessments from the CT will help communities decide whether more detailed studies are warranted, aid in community outreach and education and inform the design, development and proposal of asset management policies that consider coastal natural assets.

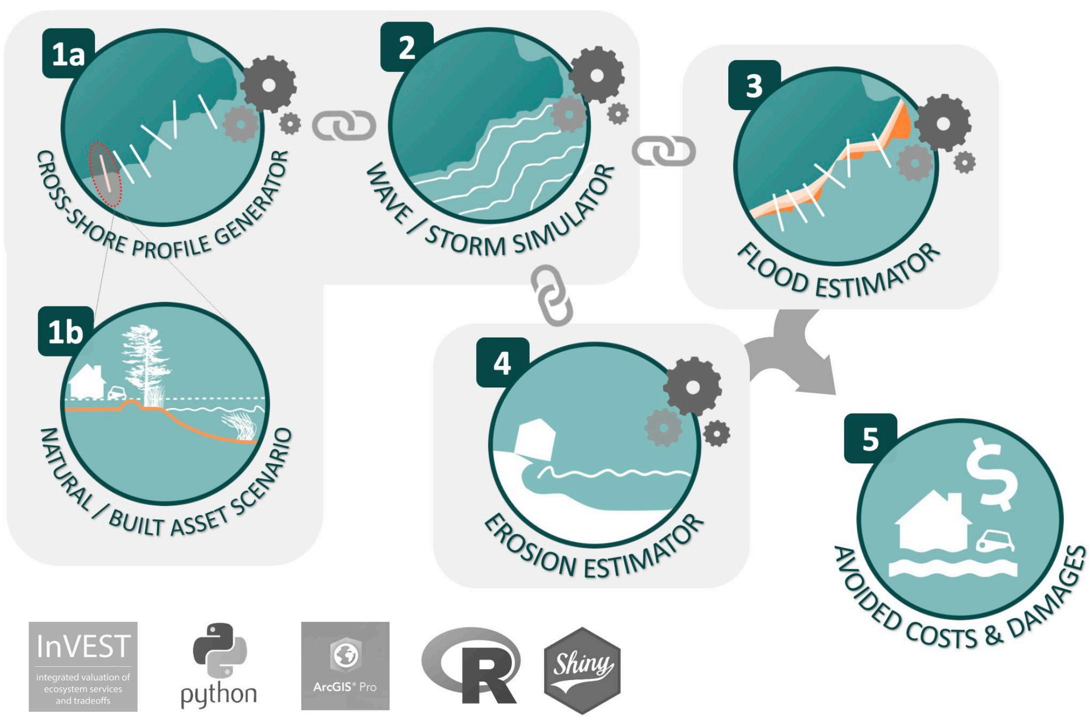


Figure 2-1. Conceptual diagram of the Coastal Toolbox.

Figure 2-1 provides a simplified conceptual diagram of the CT's main components and its general workflow. Users provide the necessary input spatial datasets, then one-dimensional cross-shore profiles are generated along the shoreline (1a) and for each profile a natural (or built) asset scenario is constructed by the user (1b). Based on the wave and storm size settings provided, which are defined by the user based on the storm recurrence period, or representing a specific known extreme event, the model then simulates a storm along each profile (2), estimates the resulting flood damages to structures by interpolating flood extent between profiles (3) and estimates erosion damages (4) before providing outputs in total damage costs from long-term floods and erosion. These outputs are then compared across with/without scenarios to determine avoided costs, if any, from implementing the natural asset scenario (5). The CT is capable of simulating either the addition/enhancement or loss of coastal natural assets depending on how the user constructs the scenarios. Figure 2-2 illustrates the full process from assembling data to utilizing the CT in ArcGIS Pro, then acquiring, viewing and interpreting outputs. In addition to some additional steps required before getting started, these steps are the focus of the next three chapters in this guide, which Table 2-1 outlines in more detail.

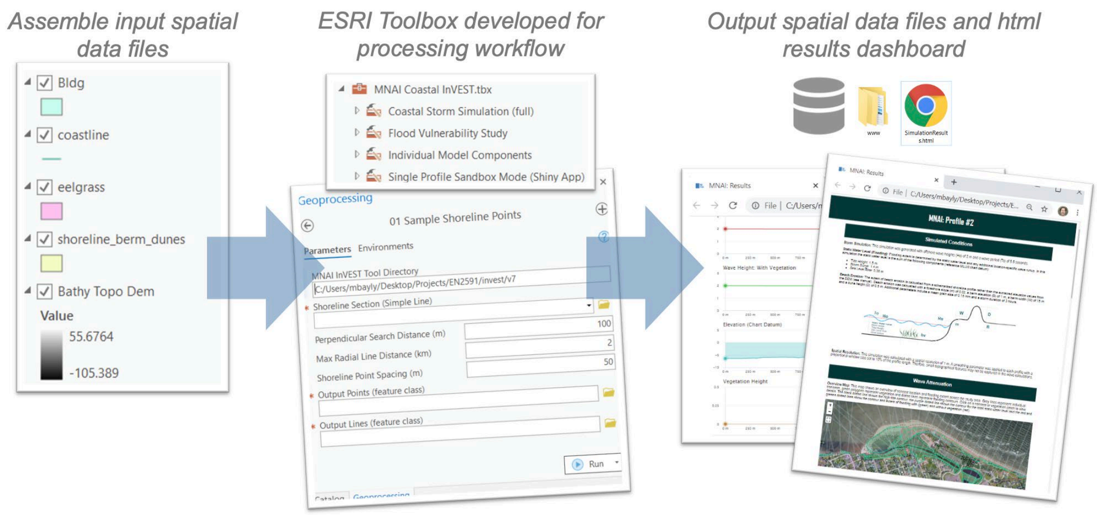


Figure 2-2. The Coastal Toolbox user-workflow from data inputs to model processing to data outputs.

Table 2-1. The core elements of applying the Coastal Toolbox from getting started to running the model and interpreting results.

Getting Started (Ch. 3)	Running the Model (Ch. 4)	Interpreting Results (Ch. 5)
Coastal Jurisdiction & Management Context *What jurisdictional regulations and policies should we consider?*	**Cross-shore Profile Generator** *What coastal segments (beaches) are we most interested in?*	**Cross-sectional Profile Characteristics & Sandbox Mode** *What are the characteristics of each cross-sectional profile? What happens to profile results if parameter settings are altered?*
Convening a Team *What expertise is required to perform this assessment?*	**Baseline & Natural Asset Scenario Setup** *What will we compare our natural asset alternatives to? What ones will we model?*	**Wave Attenuation** *What impact did the natural asset alternative have on wave size?*
Compiling a Natural Asset Inventory *What coastal natural assets does our community already possess?*	**Coastal Storm Simulator** *What storm intensity, frequency, duration do we want to evaluate?*	**Wave Runup** *What impact did the natural asset alternative have on landward incursion of waves?*
Characterizing Baseline Conditions *What are the characteristics of the coastline and the current condition of its natural assets? Any risks?*	**Flood Estimator** *What is the extent of flooding based on interpolation across cross-sectional profiles and cumulative water levels?*	**Flood Damages** *What is the number of inundated structures and total structural damage based on depth-damage curves?*
Identifying & Selecting Natural Asset Alternatives *What natural asset alternatives might mitigate flood and erosion damages?*	**Erosion Estimator** *How much beach is lost?*	**Erosion Damages** *How much did the beach retreat (distance and volume)?*
Acquiring & Processing Data *What data do we need and how do we prepare it?*	**Cost Estimator** *What is the total value of damages?*	**Avoided Cost Estimates** *How much damage will be avoided in dollars ($) from implementing the natural asset alternative?*

2.2. Strengths and Limitations

Prior to describing the Coastal Toolbox and applying this user guide, it is important for users understand its strengths and limitations to determine if the CT is a good fit for the desired use case and, if so, to aid in interpreting results. As shown in Table 2-1, the CT comprises multiple sub-modules, each of which makes simplifying assumptions to facilitate model implementation and ease of use for a broader audience. These assumptions limit the representation of various complex coastal processes, which makes the toolbox more suited for relatively coarse preliminary evaluations than detailed engineering studies. These "first pass" estimates can be useful for any community and will be particularly helpful for smaller or more remote communities that do not have immediate access to the resources needed to conduct more detailed studies. The following key strengths and limitations should be kept in mind when considering whether the model will be able to answer the questions users are interested in, and during the analysis and interpretation of CT results.

Key strengths:

1. The wave propagation model in the wave/storm simulator (Figure 2-1) allows users to **simulate offshore storms and evaluate wave transformation along profiles**. Users can compare profiles in different locations to evaluate how wave propagation is affected by offshore bathymetry. Submerged vegetation patches such as kelp, eelgrass or marsh areas can be added along the profile with specific blade width, density and height characteristics to evaluate wave propagation with and without vegetation. The wave model can be useful for visualizing the maximum wave height and energy offshore from the beach. The ability to add and remove vegetation patches can also be useful to evaluate natural asset management

options like eelgrass restoration/enhancement.

2. For a given design storm, the coastal erosion model allows users to **estimate the beach retreat distance at each cross-shore profile using offshore wave characteristics, bathymetry and foreshore characteristics** such as the beach grain size, foreshore slope, berm width and height and dune characteristics. Users can therefore compare changes in erosion across alternative management actions (or inactions) such as “beach nourishment” from modifying the foreshore slope or grain size, dune improvement or by adjusting berm characteristics.

3. After the initial setup, alternative scenarios can be implemented and computed very easily (in a matter of minutes), making it possible to ask questions, evaluate results and refine questions quickly in a live workshop-like environment. This general workflow has been useful in discovery sessions during team meetings and larger planning sessions with other stakeholders.

4. The coastal flooding model used by the flood estimator (Figure 2-1) **interpolates values between shoreline profiles to generate a 2D rasterized floodwater surface elevation**. This is then integrated with building footprints, building values and structural depth-damage curves to estimate the total structural damage costs for each storm simulation. These values can be used to assess the vulnerability of communities to flooding and sea-level rise. The toolbox also offers a “flood vulnerability” function to evaluate cumulative damages with incremental increases in the total water level.

5. All erosion and flood damage cost estimates can be summarized over any given time horizon (e.g., 100 years) and/or for different statistical storm return periods (e.g., 1-yr, 10-yr, 100-yr, etc.).

Key limitations:

1. Despite having an easy-to-use interface, it is highly recommended to have a qualified professional (skilled in a relevant field of expertise) operating the CT, such that a proper understanding and interpretation of the inputs and outputs of the different tools can be made. On its own, the tool has the potential to oversimplify complex coastal processes and could lead to incorrect assumptions. Without expert knowledge of coastal processes, the results can be difficult to interpret and could lead to incorrect assumptions

2. Wave propagation and morphological evolution are modelled along individual **one-dimensional (1D) cross-shore profiles**, therefore processes such as wave-current interaction, multi-directional wave conditions, wave diffraction, longshore drift and lateral sediment transport are not accounted for in the outputs. Each cross-shore profile assumes target beaches to be “longshore-uniform,” meaning that interactions with complex features on either side of the profile such as narrow inlets, estuaries, channels and points cannot be adequately captured. Modelled storm simulations should be customized for a specific area of interest to represent the dominant exposure aspect to the beach (e.g., a south-facing beach should be modelled with waves coming from southern directions).

3. The CT model is not suitable for wave agitation inside harbours as the one-dimensional approach cannot include 2D processes (wave diffraction, reflection, transmission) that greatly influence the wave penetration patterns in complex geometries like harbours.

4. After storms, beaches may also regenerate and may show additional accretion from longshore drift and onshore sediment transport that is driven by smaller waves and tidal currents. For each beach profile, the CT provides a simplified estimate of horizontal beach loss (retreat) after a storm, but it **does not estimate subsequent sediment accretion, seasonal changes to a beach or any other type of cut/fill transport**. Therefore, the overall long-term net effect of erosion from a given storm is not fully captured in the model.

5. The erosion estimates derived with the CT are based on simple theoretical profile stability equations. The topographic and bathymetric data sets could vary significantly based on the year in which they were completed for each respective area. Actual sedimentation and erosion conditions may vary, in some cases significantly, depending on several additional physical processes that are not included in the CT. The CT morphological component is recommended only for *relative* comparison between the proposed scenarios.

6. The model is designed to estimate shoreline retreat distances (erosion) along sandy shores. Although the model can still be run for mud, gravel and cobble beaches to estimate wave propagation and flooding, quantitative **erosion estimates are only valid for sandy beaches**.

7. The flood model operates as a "bathtub" type flood inundation model (see Glossary), which assumes very little spatial variation in water levels and does not consider overland flow dynamics. This means the water level is simply raised globally to a fixed "still-water level" based on user-defined inputs of tide, storm surge and sea-level rise. The model then estimates the height of wave runup at each profile and adds these values to the total flood level. The final output is a raster dataset of the water surface elevation over an elevation surface (i.e., DEM). Therefore, **the model cannot simulate the effects of dikes or retaining walls as it does not simulate overland flow or hydrodynamic processes**. Onshore depressions that may otherwise be protected from flooding are inundated in a bathtub flood model. Inundation maps resulting from bathtub-type models tend to overestimate the inundated area.

8. Flood maps generated with the CT do not necessarily identify all areas subject to flooding, particularly in localized settings of small size with possible flooding sources other than coastal (including but not limited to stormwater or sewer overflow). For this reason, the flood maps and flood data products are not prepared for, or suitable for, legal and surveying purposes.

9. The model uses *avoided costs* as the main value comparison between natural asset and baseline alternatives and only estimates the value of focal ecosystem services (not co-benefits). Unlike other economic valuation methods, **cost-based approaches cannot evaluate the *net* welfare benefits to society from a natural asset alternative (i.e., benefits minus costs, considering both consumer and producer surplus)**. However, other economic valuation methods can be costly to deploy, with many requiring primary data collection. For focal ecosystem services like erosion and flood mitigation, MNAI has also found that replacement costs and avoided costs are the most readily accepted by municipal asset accountants. To obtain net benefits and to estimate the economic value of co-benefits, we recommend alternative approaches (e.g., contingent valuation, choice experiments, travel costs, hedonic pricing, production functions, benefit transfer).

2.3. Disclaimer and Copyright

The CT is released as free software and can be redistributed or modified under the terms of the GNU Lesser General Public License as published by the Free Software Foundation, either Version 3 of the License, or any later version (see http://www.gnu.org/licenses/). The CT is distributed in the hope that it will be useful, but without any warranty, without even the implied warranty of merchantability or applicability for a particular purpose. See the GNU General Public License for more details. The CT is developed as part of a cooperation between the David Suzuki Foundation, the Municipal Natural Assets Initiative, ESSA Technologies Ltd. and CBCL. Although the easy-to-use interface suggests the opposite, it is highly recommended to have a qualified professional (skilled in a relevant field of expertise) operating the CT, such that a proper understanding and interpretation of the inputs and outputs of the different tools can be made. None of the results should be relied upon alone by either principals or third parties. All results should be interpreted with a considerable range, and sensitivities should be assessed.

3. Getting Started

3.1. Objective Setting and Jurisdictional Considerations

Because the Coastal Toolbox can inform coastal planning and management activities in multiple ways that are unique to each local context, it is important to start a CT modelling exercise by setting project objectives and identifying unique jurisdictional considerations.

In standard policy and project cycles, objective setting typically starts with problem definition; that is, eliciting multiple perspectives from affected parties about the causes of the problem, favoured solutions and supporting evidence, then combining these perspectives into a single, representative articulation of the problem. This step is often performed by planners via community outreach and may already be complete by the time a community is ready to use the CT, or it may be built in to a broader coastal natural asset program that utilizes the CT.

The process of problem definition uncovers key uncertainties that need to be addressed to solve the problem (e.g., where coastal natural assets are likely to have the most benefit). Helping to answer these "big questions" is often one of the key objectives of modelling, but for action to occur, model results must then be operationalized to support community initiatives. Understanding in advance what those potential initiatives are helps structure the modelling exercise and ensures outputs will be useful rather than simply existing in a "black box" that is difficult to interpret for practical purposes. Using an example from the pilot study in Gibsons, B.C., the inset box lists some types of community initiatives the CT can inform.

In identifying similar lists, it is helpful for practitioners to ask questions like: **Where** is shoreline flooding and erosion a problem? **Why** is it a problem? **What** management levers are available to address the problem? **How** could those management levers be applied? **What** jurisdictional overlaps are relevant?

Problem definition is also typically where jurisdictional overlaps are revealed, which helps to identify affected interest groups that may need to be included in the process (see Section 3.2 – Convening a Team).

Uses for the CT in Gibsons, B.C.

In the early stages of piloting the CT with the Town of Gibsons, B.C., discussions were held to understand the ways in which CT outputs might be useful to the community. Participants highlighted the following:

- Informing municipal land-use plans and zoning
- Refining development permits
- Providing additional rationale to support funding applications
- Informing council about costs and risks associated with different coastal protection decisions
- Supporting conversations with provincial and federal governments
- Communicating with private landowners
- Supporting general community outreach and education

Canadian coastal jurisdiction is complicated because, depending on the nature of the problem, it may overlap with coastal areas and processes that are under the purview of federal, provincial, municipal and/or Indigenous governments. To identify jurisdictional overlaps, practitioners will need to consider whether an infrastructure asset *and the mechanisms that influence the asset* are on land, in the intertidal zone or subtidal zone. Importantly, answers may differ for how natural versus hard/grey infrastructure assets and management mechanisms available in one jurisdiction may influence natural assets in another. For example, septic systems that exist along coastlines may cause microbial or nutrient pollution in nearshore areas, which may subsequently affect nearshore seagrass beds. While subtidal seagrass beds may not fall within municipal jurisdiction, bylaws related to coastal septic systems can influence the condition of seagrasses.

Broadly, local governments have jurisdiction over *land use* in coastal areas, with authority beginning at the high-water mark. Land management mechanisms that are relevant to coastal protection include zoning bylaws, development permitting and other policies laid out in official community plans. Whether land ownership is public or private can influence the extent to which it is possible to develop coastal natural assets, so collaboration with private landowners is another less-formal mechanism that may be important to pursue.

Table 3-1 provides a general overview of the levels of government that may be relevant for different types of nature-based coastal protection. Determining which management mechanisms under which jurisdictional purview are relevant requires understanding how specific ecosystems function to deliver the services these natural assets offer. To aid in this understanding, Appendix A describes key coastal ecosystem types and illustrates the pathways linking biophysical processes that supply flood and erosion protection. Alongside hard/grey alternatives, Appendix B describes the natural asset solutions shown in Table 3-1, Appendix C discusses coastal jurisdiction issues more comprehensively and Appendix D provides a general overview of relevant legislation, policy, and market instruments.

Table 3-1. Levels of government that are broadly applicable for different flood- and erosion-protection approaches. Jurisdictional purview may differ on a case-by-case basis.

Nature-based approach to flood and erosion protection	Municipal governments	Provincial governments	Federal government	Indigenous governments
Beaches & dunes	x			x
Coastal wetlands	x			x
Salt marshes		x		x
Seagrasses		x	x	x
Reefs		x	x	x
Barrier islands	x	x	x	x

3.2. Convening a Team

Natural asset management strategies require a multidisciplinary, team-based approach. The MNAI process therefore involves convening a team of community representatives from across a range of disciplines. Team composition may vary depending on local capacity, jurisdictional overlap (see Section 3.1) and technical needs. This step is important because while we have attempted to make the CT as user-friendly as possible, and while many outputs are intuitive to interpret, the multiple sub-modules that make up the toolbox (Figure 2-1) represent complex coastal dynamics that are commonly outside the expertise of local governments operating alone. A coastal natural asset team should include representatives from all levels of government that have jurisdictional overlap with any proposed asset management activities. Including technical experts on the team such as local planners, coastal engineers, ecologists and GIS specialists will help to ensure the right information and coastal system dynamics are being incorporated into the model and will aid in interpretation of results. Including local planners, stakeholders and Indigenous representatives will ensure the team has access to the local knowledge and expertise necessary to inventory coastal natural assets, characterize baseline conditions and identify candidate natural asset alternatives that are relevant for the community.

3.3. Compiling a Natural Asset Inventory

MNAI's natural asset methodology (Figure 1-1) includes the development of an inventory of focal ecosystem services important to the community and the natural assets that support them. Development of this inventory is a critical first step in strengthening a community's natural infrastructure portfolio. It permits a general assessment of the condition of these assets as well as any risks they might be facing and supports the evaluation of co-benefits that may not be possible to integrate into models like the CT within time and budget constraints. Some of these additional ecosystem services may be of interest for future modelling exercises, and it is useful to keep them in mind prior to commencing modelling because unexpected opportunities for model integration may arise.

Once a team is convened (see Section 3.2), developing a coastal natural asset inventory starts with asking some key questions to help identify the ecosystem components that are providing (or could provide) ecosystem services through ecological processes. Some questions the team may wish to consider include the following:

- Where are the areas of concern for flooding or erosion? Where are the areas with no concerns?
- In the areas with no concerns, are there **ecological components or processes** reducing flooding and erosion? For example, are existing vegetation (e.g., eelgrass beds) attenuating waves or topographic features (e.g., dunes) mitigating inundation from high-water events? If so, these components and processes can be added to the inventory of natural assets and earmarked for protection.
- In the areas of concern, are there **ecological components or processes** reducing the risk of flooding and erosion but not enough to alleviate concern? If so, these can be added to the inventory of natural assets and earmarked for protection alongside restoration or enhancement efforts.
- Additionally, for the areas of concern, are there ecosystem components that do not currently exist (but may have in the past) that could reduce the flooding and erosion? If so, these can be considered for restoration or enhancement efforts.

To aid in responding to these questions, Appendix A lists ecological components existing within different ecosystem types that commonly provide ecosystem services associated with flooding and erosion. The Appendix also discusses the pathways (i.e., ecological processes) by which the ecosystem components provide those services. Identifying key ecological components can be informed by local and/or Indigenous knowledge as well as existing datasets. Because the process includes data gathering, it is helpful to identify a data custodian at the start. As data are being compiled, it can be helpful to present the information in an easily digestible way for the team, while at the same time creating a robust approach for managing the natural asset data. One approach to natural asset inventory management that MNAI has successfully applied is the development of a web-based interactive dashboard (see Figure 3-1). The interactive nature of such a tool supports community learning and project communication needs by permitting users to drill down into the data to explore geographic differences across jurisdictional boundaries, and to examine the condition of, and any risks associated with, each natural asset.

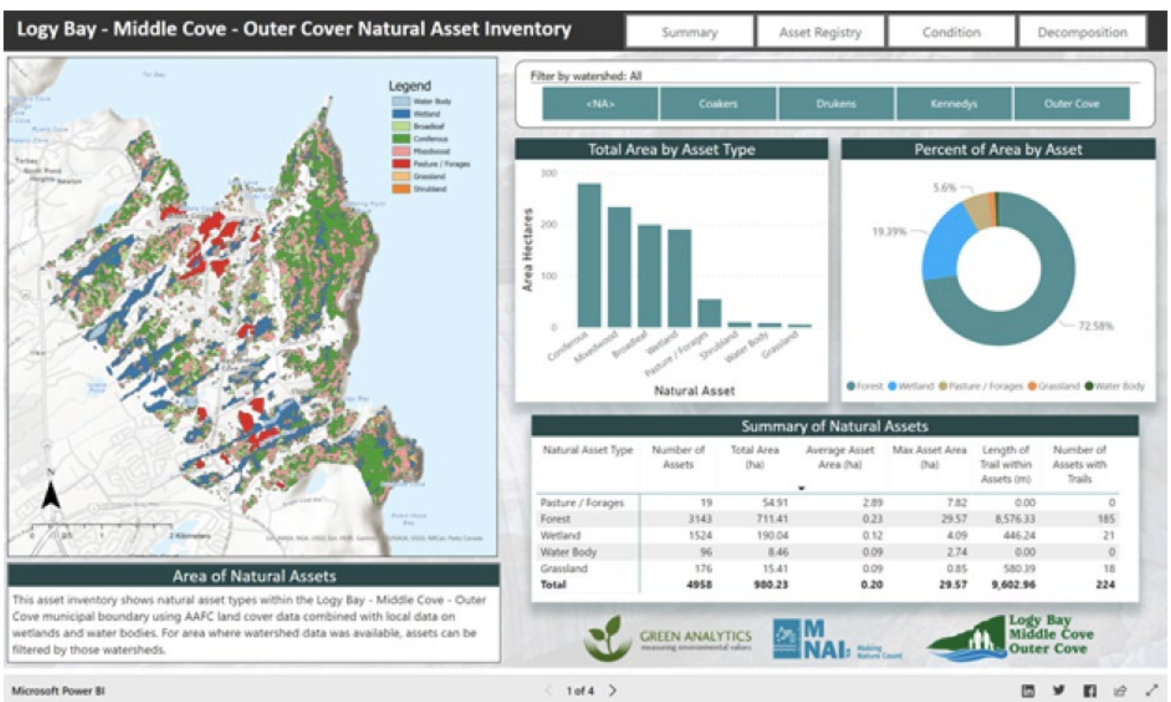


Figure 3-1. Example of MNAI Natural Asset Inventory.

3.4. Characterizing Baseline Conditions and Identifying Natural Asset Management Alternatives

Once a natural asset inventory is complete, it is possible to begin characterizing baseline conditions and developing natural asset alternatives. For modelling purposes, a baseline is a representation of the study area for the characteristics of interest and can represent current, historical or future conditions. The main purpose of a baseline is to provide a point of comparison with alternative coastal protection options that use natural assets and/or grey/hard infrastructure alternatives. Most communities will want to conduct studies with the CT using current conditions as their point of comparison. To support developing a baseline and natural asset management alternatives, Figure 3-2 provides a schematic of a coastal profile from offshore to backshore with natural asset options that might be considered at different points along the profile. Model parameters that are "tunable" in the CT to represent these different alternatives are also shown.

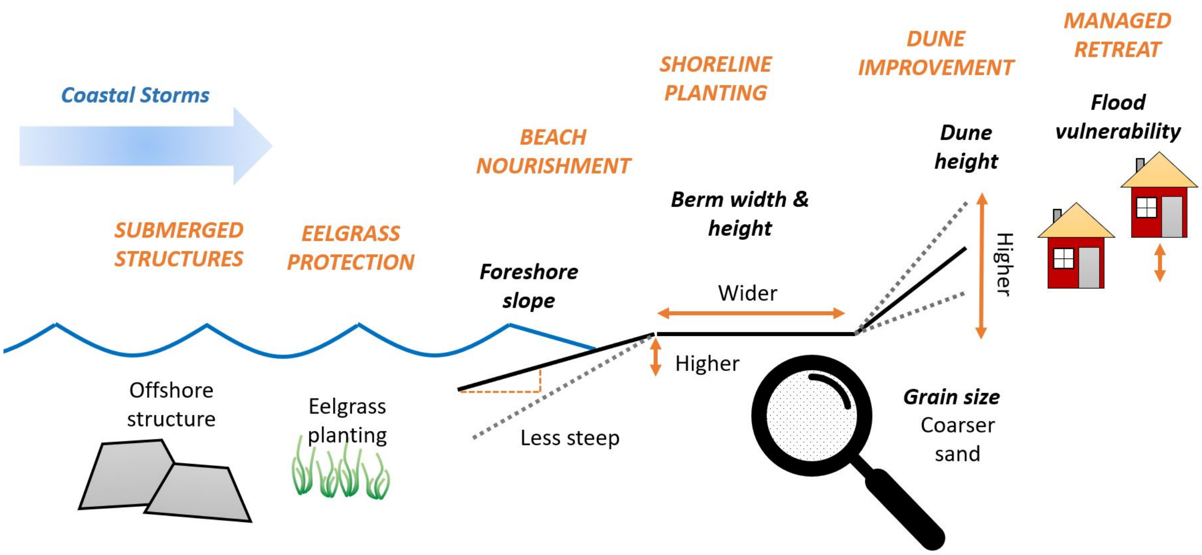


Figure 3-2. Tunable model parameters and example applications of the MNAI Coastal InVEST toolbox.

Table 3-2 lists example model parameter settings for baseline and three natural asset management alternatives. Communities will need to apply these settings based on local conditions, which can be obtained using field measurements, LiDAR and/or satellite data and existing land and building values. Note that each of the three natural asset alternatives shown in Table 3-2 represents only one of potentially several options that can be explored under the same category. For example, Beach Nourishment #2 might envision a larger dune of five metres, with all other parameter values held constant.

Table 3-2. Example parameter settings for baseline and natural asset management alternatives at a single beach segment

CT Parameters	Baseline	Beach nourishment #1	Eelgrass planting #1	Submerged structure #1
Foreshore slope	3%	9%	3%	3%
Berm height	0.5m	1.5m	0.5m	0.5m
Berm width	10m	20m	10m	10m

Dune height	1m	3m	1m	1m
Grain size	200 µm	350 µm	200 µm	200 µm
Eelgrass patch width	NA	NA	200m	NA
Structure distance offshore	NA	NA	NA	300m
Structure depth	NA	NA	NA	3m Chart Datum
Structure height	NA	NA	NA	1.5m
Structure width	NA	NA	NA	10m
Land value (erosion)	$50/m²	$50/m²	$50/m²	$50/m²
Structure value (flood)	Total assessed value of each structure input to CT with building footprint shapefile			
Depth-damage estimates	Assigned to each structure in building footprint shapefile (e.g., using U.S. HAZUS depth-damage curves, or locally derived depth-damage curves)			
Discount rate	3%			

Figure 3-3 shows how baseline and natural asset alternatives can be compared to estimate the value of any benefits in terms of avoided costs.

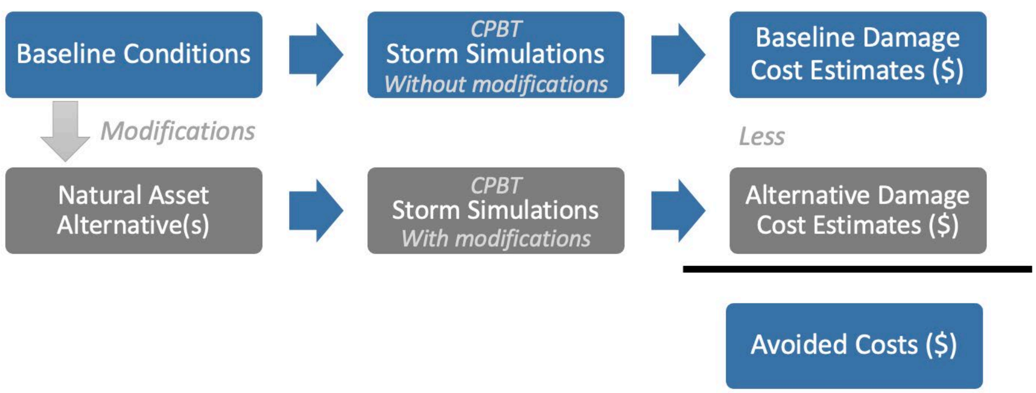


Figure 3-3. Comparing baseline conditions with natural asset alternatives to provide avoided cost estimates.

For erosion costs, the CT calculates damages based on the value of a section of beach ($/m²), which is derived externally by the user and input into the toolbox as part of the beach attribute input data or defined globally for the entire coastline. For example, an average of the most recent assessed values for selected lands near the coast could be used (e.g., see Pointe-du-Chêne pilot study — $150/m²). It is important to remember that over the long term, beaches may regenerate with summer accretion and winter retreat during storms. We expect that the beach value should range from $50/m² to $500/m² in the model. However, it should be understood that assigning a fixed dollar value to a section of beach is a hypothetical exercise and may be difficult (or impossible) to rationalize in some locations. Users should rely on relative differences between scenarios.

For flooding costs, the CT assesses total damages across all structures in the study area based on percentage damage estimates per structure that are derived from depth-damage curves (see Appendix E). It should be noted that most depth-damages curves only represent structural damage. In reality, damage costs are likely to be higher if structure contents, vehicles and other assets are included in the calculation. Per cent-damage estimates are then multiplied by structure values (e.g., from building footprint attribute data). Similar to the erosion estimate, these values can be derived from the most recent assessed values. If direct structure values are not available, they may be derived by subtracting total property value from land value. A given property can have more than one structure on the lot. When this is true, structure values should be assigned by distributing the total structure value proportionally across all buildings on the lot based on footprint area (e.g., if the total structure value is $100k and the property has one 10m² structure and one 15m² structure, the value of these structures can be approximated as $100k*(10/25m²)=$40k, and $100k*(15/25)=$60k). If neither land value or property values are available, then users could potentially assume a fixed building cost (e.g., $100 to $300 per square foot) and then calculate an approximate structure value based on the building footprint polygon area of each structure (be mindful of unit conversions)[1].

Approaches to evaluating natural asset options for a given study area will vary depending on the type of natural asset a community wishes to explore. Some options can be assessed easily using the CT by simply varying the standard parameter settings (e.g., dune height, beach width). Other options may require the use of proxies like increasing the grain size parameter to represent added stability from shoreline planting, while still other options may not be feasible to assess using the toolbox. For a series of candidate natural asset alternatives, Table 3-3 provides guidance about what the CT can and cannot do, and which parameters can be adjusted to represent the different options ("Model Mechanism" column). For erosion and flooding, we provide low, medium and high model feasibility ratings based on underlying model limitations. Options with low modelling feasibility in the CT may still be valuable to a community and can be explored separately.

[1] For further information, see NRCANs flood damage estimate guide: https://geoscan.nrcan.gc.ca/starweb/geoscan/servlet.starweb?path=geoscan/fulle.web&search1=R=327001

Table 3-3. Example applications of the MNAI Coastal Toolbox.

Natural asset option	Asset management action	Modelling feasibility	Model mechanism	Modelling feasibility rating	
				Erosion	Flooding
Dune/bank restoration	Establishing, preserving or enhancing beach dunes and backshores	Dune height is a direct input to the erosion estimator for sandy beaches (Kriebel and Dean 1993). Backshore bank elevations can be substituted for dune height, but users should keep these values under 5m. The model cannot simulate the effects of steep vertical backshores or retaining walls. *Warning: In the CT, dunes can only influence flooding through wave runup and cannot block water (see "Bathtub Model" in Glossary).*	Adjustment of the dune height parameter. Increasing the dune height will decrease erosion and wave runup estimates.	**High**	**Medium/Low**
Shoreline planting and revegetation	Planting and revegetating beach backshores and upslope areas	There are no direct mechanisms available in the model to investigate flood and erosion reduction benefits offered by shoreline planting. However, substituting coarser grain size values can be used as a proxy for shoreline planting. We took this approach in two pilot studies but have not validated with field data.	Modification of the beach substrate grain size as a proxy representation of added beach stability provided by shoreline planting. Increasing this parameter will reduce wave runup estimates.	**Medium**	**Medium**
Beach nourishment	Modifying the foreshore slope, altering the grain size (coarser/finer material), adjusting the storm berm height and width	Berm dimensions, foreshore slope and sediment grain size are direct inputs to the erosion estimator for sandy beaches (Kriebel and Dean 1993). Model predictions are limited to sandy shores. Erosion predictions for gravel/pebble beaches are not feasible.	Adjustment of foreshore slope, grain size, berm width and berm height. Shallow slopes will be more resilient to erosion, while steep slopes will be more susceptible to scouring. Wider and taller berms are less vulnerable to erosion. Altering these parameters will modify wave runup estimates.	**High** (for sandy shores)	**High** (for sandy shores)

Natural asset option	Asset management action	Modelling feasibility	Model mechanism	Modelling feasibility rating	
				Erosion	Flooding
Intertidal and subtidal planting	Restoring, preserving, and/or planting eelgrass meadows, kelp beds or intertidal salt marshes	The original InVEST tool's ability to predict wave propagation along a profile with or without vegetation was retained, which is a useful output. However, long-term reductions in bottom velocity from subtidal vegetation leading to erosion reduction are not reliably captured by the model. The impact of the vegetation on flood extents are also not reliably captured.	As additional input data to the CT, include intertidal or subtidal vegetation polygon(s) with blade width, density and height attributes. Adding these inputs will result in wave attenuation, but the model cannot reliably evaluate resulting changes in beach loss or flood extent.	Low (beach loss) High (wave attenuation)	Low (flood extent) High (wave attenuation)
Submerged structures	Establishing submerged structures offshore to reduce storm damage (e.g., artificial reefs)	A dedicated function is available to determine the % wave height reduction possible from submerged structures based on their height/width and depth. The CT does not estimate erosion and flooding from submerged structures.	As additional input data to the CT, include submerged structure polygons with height and width attributes. Adding these inputs will result in wave attenuation, but the model cannot reliably evaluate resulting changes in beach loss or flood extent.	Low (beach loss) High (wave attenuation)	Low (flood extent) High (wave attenuation)
Managed retreat	Explore managed retreat alternatives, either moving buildings or elevating their footprint	Flood damage is calculated from the building footprint layer, the simulated flood water elevation and the DEM. Modifying the building footprint layer or the DEM in a way that represents managed retreat will modify flood damage estimates. The model can only represent structural damage through flooding (not erosion or weathering).	Substitute alternative building footprint layers that represent milestones in a phased retreat action plan, and/or modify the DEM as a proxy for structural improvements (e.g., increase DEM elevation around a structure to represent building improvements).	N/A	High
Estuaries, tidal ponds, lagoons, spits and tombolos	Explore the protective benefits of coastal features along the shoreline	It is not possible to accurately estimate changes to erosion or wave propagation in wetted areas in the vicinity of complex coastal feature. The bathtub-type flood model will not capture drainage or flow around these features (see "Bathtub Model" in Glossary).	N/A	Not feasible	Not feasible
Log placement and anchored driftwood	Evaluate placement options for large, anchored logs and driftwood	The CT cannot estimate erosion in the vicinity of fixed foreshore structures such as anchored driftwood or rock walls. These features will also not be captured in the flood model.	N/A	Not feasible	Not feasible

Natural asset option	Asset management action	Modelling feasibility	Model mechanism	Modelling feasibility rating	
				Erosion	Flooding
Improved drainage	Evaluate potential reductions to erosion and flood water levels from improved drainage	The CT cannot estimate potential benefits from improved drainage for erosion or flooding since it does not include any onshore hydrodynamic processes.	N/A	Not feasible	Not feasible
Breakwater modifications	Assess vulnerability of infrastructure behind breakwaters	The CT can only estimate runup for sandy shores with a single water-land interface along a profile. The model cannot simulate wave evolution behind a large protruding structure. The model can, however, model submerged structures. If users wish to model wave evolution behind a breakwater, they should shorten their profile to start behind the breakwater and then end at the shore.	N/A	Not feasible	Not feasible

Identifying natural asset alternatives should occur with the convened team. Usually, a long list of options is generated, and a set of selection criteria are then used to isolate a short list of options that are feasible to model (Table 3-4). Selection criteria should consider the potential for each option to provide focal services (i.e., flood and erosion protection), and other co-benefits, as well as its overall implementation and modelling feasibility. In evaluating the options based on these criteria it is important to consider whether reliable precedents exist; whether specific co-benefits of interest would be supplied by the option, such as aesthetic appeal, habitat provision, runoff management or water quality regulation; whether significant engineering or design limitations exist; and whether the CT is capable of simulating the option. Note that some options that do not make the short list may simply be inherently difficult to model. This does not mean they are not feasible to implement and should therefore not be discarded as candidate management alternatives. While every place is unique, it is helpful to understand which types of approaches are generally viewed as best suited for a particular situation. Each coastal protection situation can be characterized by (1) the coastal hazards that are being faced, (2) the focal services that are important to protect or enhance and (3) what co-benefits would be provided by natural asset alternatives (see Appendix B for a more detailed description).

Table 3-4. An example criteria-based selection matrix for identifying a short list of natural asset options from a longer list of candidate options (from the MNAI Point-du-Chêne pilot study). Rows with an 'x' indicate selected options.

		Other Benefits		Feasibility			Modelling	
Option Name	**Flood & Erosion Protection**	Co-Benefits	Climate Change Adaptability	Community Implementability	Asset Policy & Planning Relevance	Achievable Cost	Modelling Feasibility	
Current and Future-Climate Baselines								
1. Parlee Beach								
2. Point near wharf								
Adapting Parlee Beach for Coastal Protection under Current Conditions and Projected Climate Change								
Pb1. Dune improvement	H	M		H			H	x
Pb1a. Beach nourishment	M	L		H			H	x
Pb2. Shoreline planting A	M	M		H			H	x
Pb3. Shoreline planting B	M	H		M			H	x
Pb4. Eelgrass planting	L	M		M			H	x
Pb5. Tidal pond restoration	M	H		M			L	
Pb6. Submerged structure	H	H		L			H	x
Pb7. Managed retreat	H	H		L			L	
Enhancing the Point for Coastal Protection under Current Conditions and Projected Climate Change								
P1. Shoreline armouring	M	L		M			M	
Development Pressures that Reduce Coastal Protection under Current Conditions and Projected Climate Change								
D1. Marsh loss	M	L		M			L	

3.5. Acquiring and Processing Input Data

Assembling the input datasets for a novel shoreline of interest is required to use the CT. For each key input dataset, this section provides a series of "data profiles" that describe the dataset and offer some guidance for acquisition and formatting. While necessary for the CT, going through the process of acquiring and preparing these data is also a valuable exercise for communities wishing to evaluate coastal natural assets and green-shore initiatives more broadly. These input datasets are widely applicable to other coastal assessment, monitoring and modelling exercises and will therefore aid in building a core data foundation that can readily transfer to future studies.

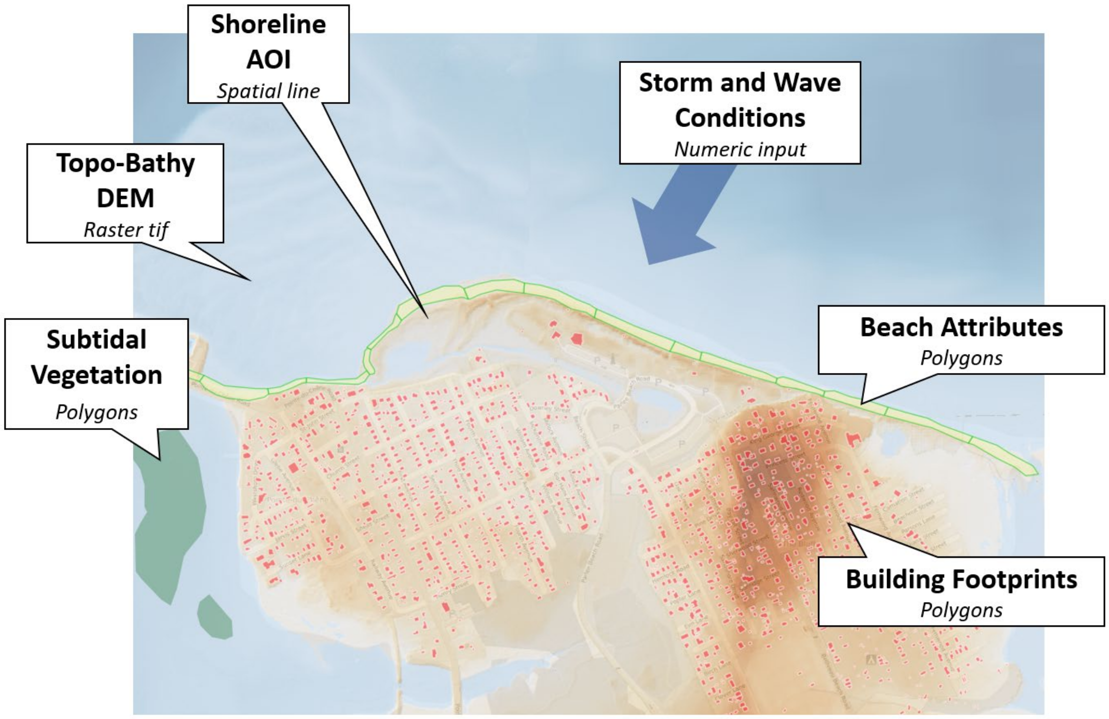


Figure 3-1. Overview of key input parameters for the Coastal Toolbox.

#1 Shoreline Area of Interest (AOI)

Description	Spatial polyline
A shoreline area of interest (AOI) is used to define the target shoreline region for modelling. All predictions and exports are generated for the area of interest. The shoreline AOI is manually created in a GIS program. Users will need to digitize the approximate position of either the low- or high-tide line.	

Format: Spatial polylines

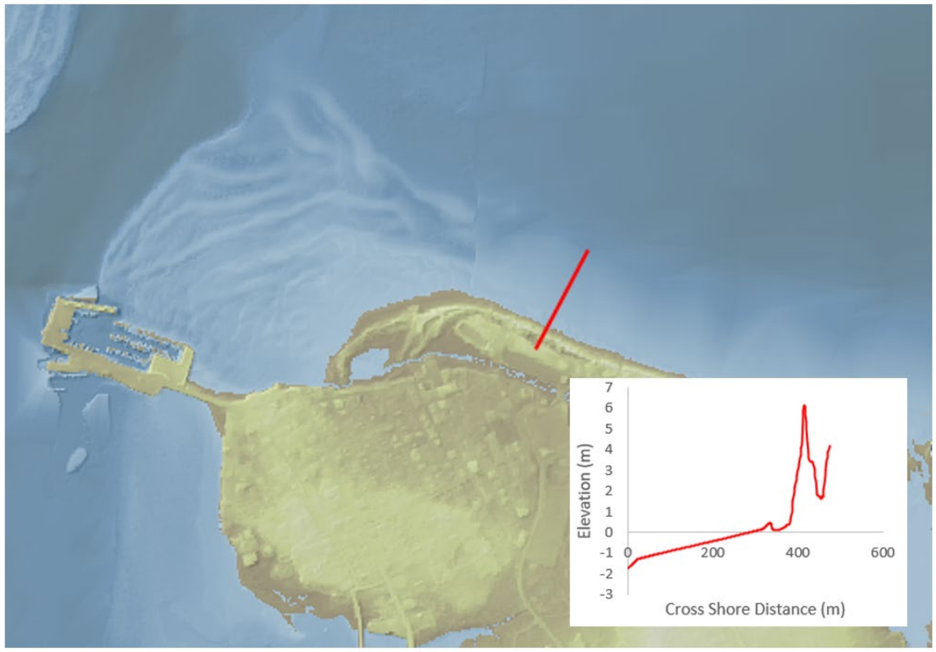
Optimal source: Users should digitize (trace) the shoreline along their area of interest in a GIS program. The shoreline should be simplified to avoid sharp corners. We suggest manually tracing the shoreline using basemap satellite imagery. The shoreline polyline is used to generate perpendicular cross shore profile and therefore it should not contain too much detail.

#2 Seamless Topographic-Bathymetric Digital Elevation Model (DEM)

Description

A seamless topographic-bathymetric digital elevation model (DEM) is used to populate elevation data for each of the cross-shore profiles. This information is then used to evaluate wave propagation, coastal erosion and flooding.

Elevation raster with 0 set to MLLW (Chart Datum)



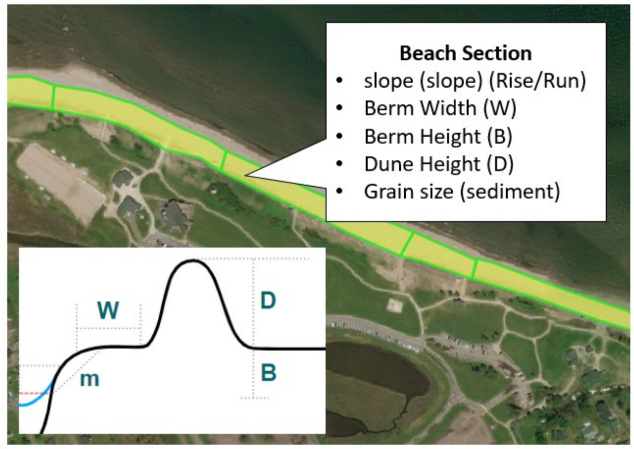
Format: A raster elevation dataset that extends on land and into the water to represent a water-free surface. It is important that the dataset is vertically referenced to the chart datum such that 0 m represents the low tidal water level. This dataset should also be in units of metres for the x, y and z dimension. This may require projecting the raster dataset to a local UTM zone.

Size: Processing time will increase exponentially with raster resolution and extent. Aggregating high-resolution raster elevation surfaces to a resolution of no more than five metres per pixel is recommended. The final topo-bathymetric dataset should be no more than 200 MB in size in an uncompressed TIF format. If your coastline is large and you wish to process at a high resolution, breaking your area into subsections is recommended.

Optimal source: Ideally, this dataset can be produced by merging municipal LiDAR data with raw offshore bathymetric data from the Canadian Hydrographic Services. However, in many cases these data may be missing for either topography, bathymetry or both. If so, there are several alternative methods for generating this data from freely available online sources (see below). Topographic data are used for flood extent estimates and therefore should be as precise as possible.

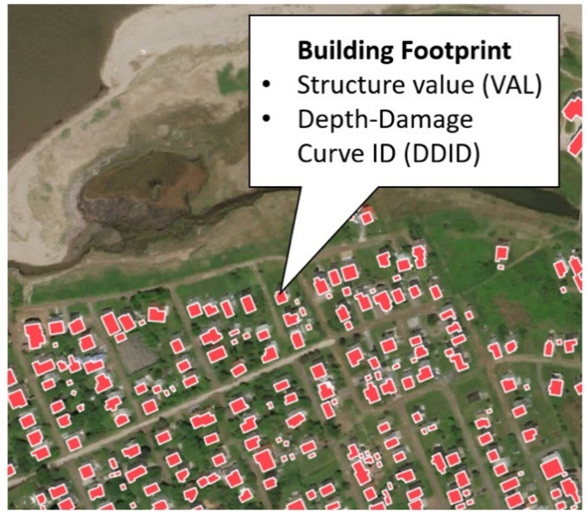
Alternative source: Data from the Canadian DEM can be merged with the CHS 100m Non-Navigational DEM (https://open.canada.ca/data/en/dataset/d3881c4c-650d-4070-bf9b-1e00aabf0a1d), offshore depths can be even estimated with nautical charts, or simply enter a fixed depth for each profile using the model's parameter settings. Taking into account the local vertical datums of each dataset is key to generating a seamless topo-bathymetric surface.

#3 Beach Attribute Polygons

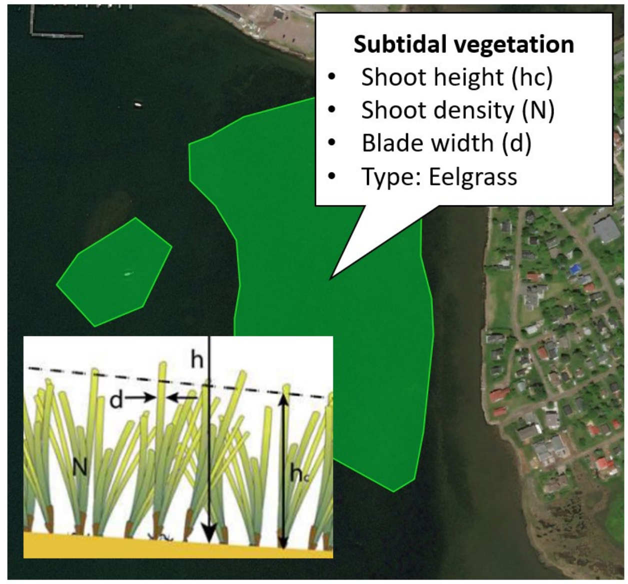
Description	Polygons with foreshore attributes
Beach attribute data for slope (slope), grain size (sediment), berm height (B), width (W) and dune height (D) and beach value (V) must be provided for each shoreline section of interest. These attributes are used by the erosion model to estimate beach retreat for a given storm. Spatial polygons can be provided for each geomorphically unique beach section. If beach attributes along the coastline are relatively homogeneous then a single polygon can be used to characterize the entire beach. Users of the tool will need to decide what constitutes a unique beach section. Subdividing beaches based on major changes to topography, aspect or perhaps a local reference breakpoint (e.g., North of Pier, South of Pier) is recommended.	

Format: Spatial polygons for each beach section. Polygon attribute data must include the following variables with exact, case-sensitive field names and data formats:
[slope] Numeric, foreshore slope as rise over run.
[W] Numeric, the berm width in metres.
[B] Numeric, the berm height in metres.
[D] Numeric, the dune height in metres.
[sediment] Numeric, the sediment grain size in millimetres.
[V] Numeric, the beach value per metre squared in dollars.
Source: Information of the beach characteristics will ideally be derived from field surveys, previous studies or extracted from high-resolution LiDAR datasets. Satellite imagery can also be used to help identify unique beach sections. A simple sieving sediment analysis would be beneficial and provide a better understanding for the representative sediment size and properties to be used as input in the CT.

#4 Building Footprints

Description	Polygons with structure attributes
To estimate the number of flooded structures and total flood damage costs. These data must be prepared as spatial polygons with attributes for structure type, area, value and depth damage curve ID. Each structure must have a field named VAL (for the structure value in Canadian dollars) and a DDID field of a numeric code for the HAZUS depth-damage reference curve ID. Ensure that there are no overlapping or duplicated polygons.	

Format: Spatial polygons of building footprints. Polygon attribute data must include the following variables with exact, case-sensitive field names and data formats:
[DDID] Character, depth-damage curve ID.
[VAL] Numeric. Structure replacement value.
Optimal source: Ideally, these data are supplied directly by the local government authority (e.g., municipality, regional district). Assessed building values are generally not available to the public, but this information may be available on request.
Alternative source: If building and structure footprint/value data are unavailable, buildings can simply be manually digitized with attributes added in by hand. If the study area is too large for digitization, using a provincial parcel dataset (such as the BC Parcel fabric) and taking an inner buffer of the parcels based on a lot-size-to-building-size ratio for the AOI (e.g., 5:1, 20%) is recommended. Structure values can then be assigned to these hypothetical buildings based on a regionally relevant building cost value (e.g., $150/ft²) and multiplied by the polygon area.

#5 Subtidal Vegetation (Optional)	
Description	**Polygons with subtidal vegetation attributes**
If included, subtidal vegetation patches can be used to model wave attenuation from eelgrass, kelp or marsh patches offshore or in the intertidal environment. These data must be prepared as spatial polygons with blade width (in metres), density (blades per m^2) and blade height (in metres) attributes for a given vegetation type. Polygon attributes must be labeled as "d" for blade width, "N" for shoot density and "hc" for blade height. These attributes will be unique to each community and can be approximated in GIS or generated from field survey data.	

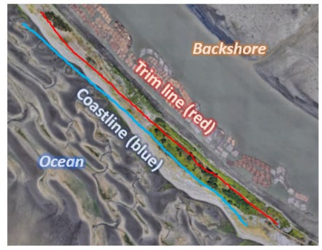
Format: Spatial polygons of the vegetation patches. Polygon attribute data must include the following variables with exact, case-sensitive field names and data formats:
[hc] Numeric. Blade height in metres.
[N] Numeric. Shoot density as number of shoots per metre squared.
[d] Numeric. Blade width in metres.
[Type] Character. Either "Eelgrass," "Kelp" or "Marsh."
[Cd] Drag coefficient as per Guannel et al 2015. If local data are not available, we recommend using 0.1 as the drag coefficient for eelgrass.
Source: These polygons are generally created outside of the CT and should be developed from field survey or design options from restoration planting projects.

#6 Backshore Trimline (Optional)

Description

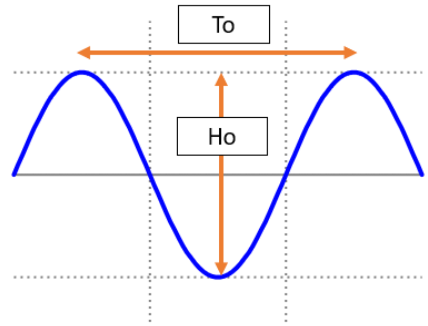
In some (rare) instances when users are trying to run the model along a narrow coastline with a large body of water in the backshore behind the beach and dune (such as a peninsula, or a beach along a river/estuary, lagoon, etc.), the model can get confused because it is unable to determine in which direction is the ocean and in which is the backshore (land). An optional backshore ***trimline*** can be included to help inform the model where the target area ends and ensure proper cross-shore profile orientation.

Backshore trimline (red) running parallel with coastline



Format: Spatial line object drawn by hand and set back about 50 metres from the coastline. The line should roughly trace the coastline but be set back on land. Including a backshore trimline can help to ensure proper cross-shore profile orientation and prevent processing errors, but its inclusion is optional.

Source: Hand-drawn set back on land from coastline.

#6 Storm Parameters	
Description	**Numeric inputs**
Numeric parameters are provided to the model to simulate a coastal storm. The storm parameters include Significant Wave Height (Ho, metres), Peak Wave Period (To, seconds), the storm surge elevation (in metres), selected sea-level rise projection estimates for the simulation period and the tidal elevation at the time of the storm.	

Format: Numeric inputs supplied by the CT user.
Sources: Significant wave height and peak wave period parameters can be estimated from historic regional studies, calculated via an extreme value analysis of wave data from neighbouring offshore buoys, long-term wave hindcast data or estimated using a helper function within the CT that estimates the wave height and period from wind speed and fetch.[2] Sea-level rise (SLR) and tidal elevation estimates can be obtained using the Canadian Extreme Water Level Adaptation Tool (EWLAT) and corroborated with Fisheries and Oceans Canada's Tide Tables. For SLR, at the EWLAT website[3], navigate to a community of interest, then switch to the Sea-Level Rise tab to find a good reference value. We expect SLR to range from -0.5 to 1.2 metres (in the next 80 to 100 years). Storm-surge elevation data are typically gathered from regional reference studies or analysis of historical tide gauge data (usually available at harbours in Canada). Storm-surge values can be expected to range between 0.1 and 1.5 metres, depending on the community. Larger storm surges are possible, especially when considering more extreme events; e.g., >100-year return period. Storm surge will vary significantly depending on the local coastal geometry, pressure fields and wind conditions.

3.6. Packaging Input Data for Use in the CT

When the requirements for the above datasets have been satisfied, assemble all spatial layers into a new ArcGIS Pro project for your area of interest. The key files in the layer menu should include the Coastline (spatial line), Beach Attributes (spatial polygons), Buildings (spatial polygons), submerged vegetation (spatial polygons), a TopoBathy DEM (raster) and a trimline (optional — spatial line). Remember to convert all datasets to a local UTM zone projection so that x and y lengths are in units of metres. The Topo-Bathy DEM should also be adjusted such that the vertical datum (0 meters) is set to the local chart datum. It is also strongly recommended to run a check geometry tool on vector layers to ensure there are no topology errors.

[2] The wave condition estimates based on the wind and fetch would still require long-term wind data from a meteorological station and are only applicable for environments where swell waves are not the main source of wave energy; for example, enclosed bays.
[3] https://www.bio.gc.ca/science/data-donnees/can-ewlat/index3-en.php

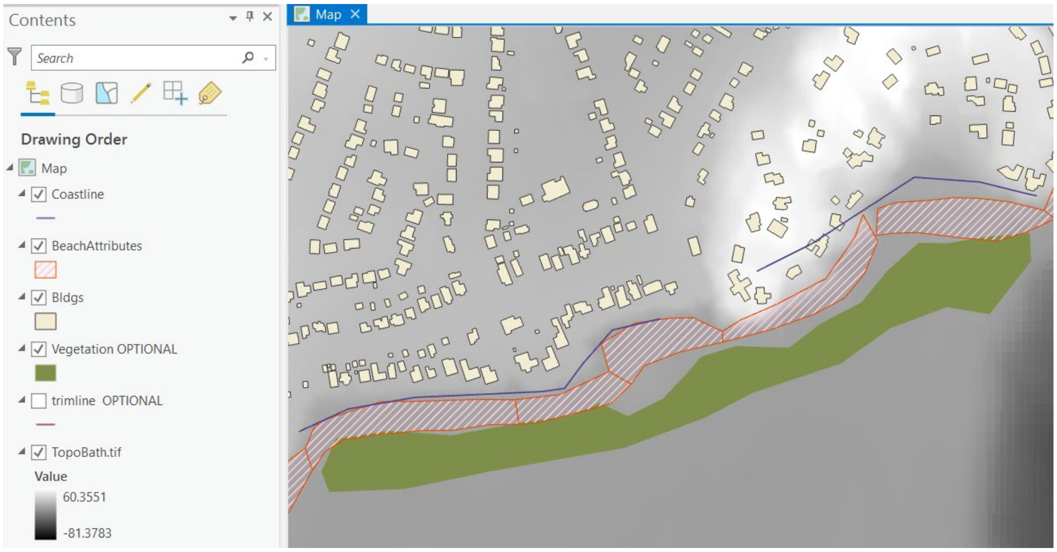


Figure 3-2. Spatial input datasets for running the CT model.

3.7. Installing the CT and Loading Input Data

Refer to Appendix E for detailed installation instructions of the CT software. You must have ArcGIS Pro installed on your machine to use this toolbox (download ArcGIS pro: https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview). The toolbox is designed to work under the most basic licensing options, so there is no need to enable Spatial Analyst or any other extensions. Note that the package will not work on ArcMap or older ESRI software products.

4. Running the Model

This section provides an overview of the Coastal Toolbox workflow. For installation instructions and function details, see Appendix E.

4.1. Step 1: Test Run Using Default Parameter Settings

With the CT installed and running (see Appendix E) and after all input datasets are prepared in the appropriate formats (see Section 3.5) and linked to the CT, it is good practice to first run the model using its default parameter settings. Defaults are supplied as starting point and are useful to ensure all input data are properly formatted, that the model is functioning as expected and for the user to gain familiarity with the general workflow. Outputs from this exercise will not be a good representation of the study area. If there are errors, it signals a need to re-check input data and input parameter settings. Each time the full CT is run, a summary output folder is created in the working directory and results are summarized in a single-page HTML file. This HTML file packages the outputs into a simplified report format with supporting text, figures and summary tables.

To test run the model, follow these steps (Figure 4-1):

1. *In ArcGIS Pro, open the Catalog pane and navigate to the MNAI_CPBT.tbx (you may need to add it as a new folder connection).*
2. *Expand the "Coastal Storm Simulation (full)" tool and open the "Coastal Storm Simulation" function. Fill in all mandatory fields, including the simulation name, working folder and spatial data inputs (see Appendix E for details).*
3. *Click "Run" and allow several minutes for the model to produce an output file folder dataset. This will be saved in the user-specified output directory.*
4. *Navigate to the output directory and open the HTML file to view the summary report in a web browser (use Google Chrome or another modern web browser to view summarized results from their storm simulation). Spatial data outputs are saved in the corresponding output www/data sub-folder for additional post processing if needed.*

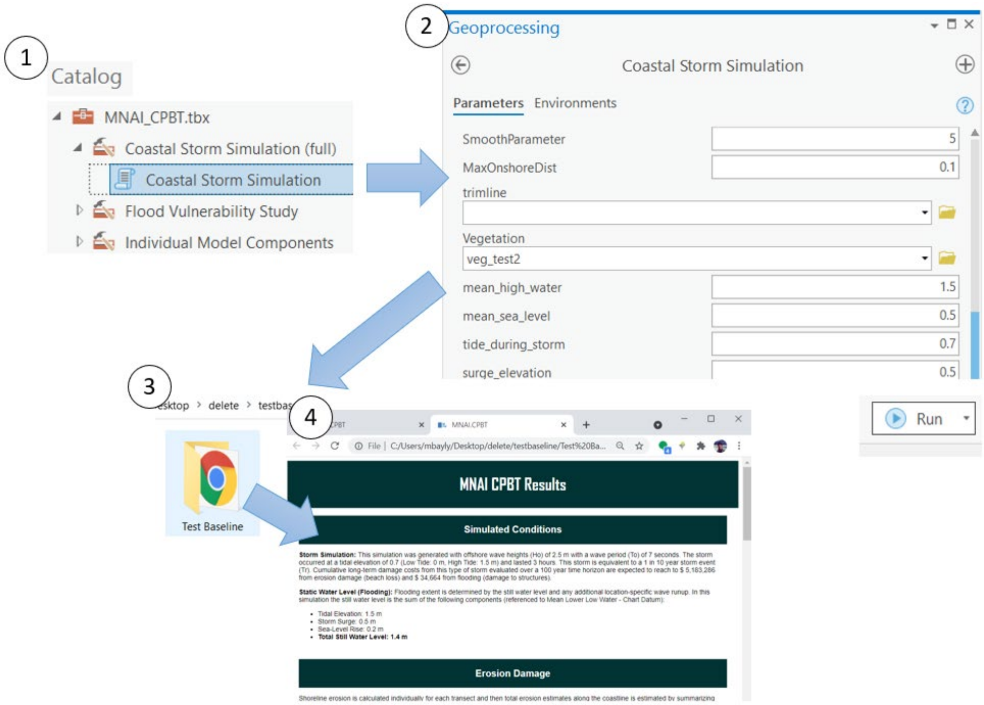


Figure 4-1. Model-testing workflow.

4.2. Step 2: Exploring Baseline Conditions

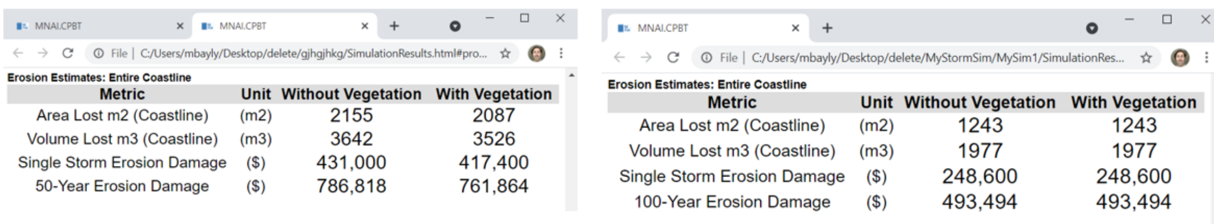
As described in Section 3.4, communities will need to define their own baseline parameter values and adjust them in the CT. The baseline is one of many "scenarios," or combinations of parameter settings, that can be tested, and the model is run for each individual parameter set. The other scenarios represent natural asset management alternatives like those listed in Table 3-3 that can be compared with the baseline to determine if those alternatives provide any flood- or erosion-mitigation benefits. To adjust the parameter settings and run a baseline scenario, follow the same steps described above for the default parameter settings, but substitute in baseline conditions for your area of interest. Ideally all data inputs and fields should be customized for your area of interest, but pay special attention to:

1. *Spatial inputs (coastline, beach attributes, buildings, etc.)*
2. *Tidal elevations*
3. *Storm simulation parameters (storm-surge elevation, wave height (Ho), wave period (To) and return period (Tr). Users should choose and design a hypothetical storm scenario for their area of interest when modelling baseline conditions and natural asset alternatives. The CT does not design a storm for an area of interest; however, the wind-wave model (Appendix E) can be used to estimate wave height and wave period. See section 3.5 for support on designing storm parameters.*
4. *Property values (for shoreline erosion). A default global value of $200/m² is provided, but users should change this value to reflect current conditions for their area.*
5. *disc (annual discount rate) and the time horizon. Users should consider if the default values are relevant for their project objectives.*

The full model should take anywhere from two to 10 minutes to run depending on the size and resolution of the input TopoBathy raster and profile density. If the model is taking longer to complete, you can try decreasing the resolution of the raster, decreasing the project extent, adjusting any of the other parameters to generate coarser analyses, or splitting your coastline into subsections and running simulations on each. If the model fails to complete, the problem is most likely an issue with the input spatial datasets (i.e., check data formats). After the model run is complete, the output folder will be populated with results and data. For detailed instruction and function arguments please refer to the User Guide (Appendix E). If results from a baseline run of the model are drastically misaligned with expectations, it signals a need to recheck input data and input parameter settings. See Section 5 for guidance on how to interpret results.

4.3. Step 3: Run Simulations for Natural Asset Design Alternatives

After users are satisfied with the baseline conditions, they can begin to model natural asset scenarios and compare them to the baseline model run for a given storm. Any number of parameters can be changed between baseline conditions and alternative conditions to represent different natural asset scenarios, but tidal elevations and storm parameters should be kept constant across all scenarios to facilitate comparison. Users can also implement combinations of alternatives to evaluate the cumulative effects of combined actions. To evaluate natural asset design alternatives, users re-run the model but save outputs to a different output folder and then compare results in the HTML output file to those from the baseline. To aid in finding output data folders, it is helpful to choose meaningful names for each simulation (e.g., *baseline, foreshore_treatment1, foreshore_treatment1_with_setback* etc.). Printing or reviewing the summary HTML files on multiple monitors can help when attempting to cross-evaluate differences (Figure 4-2).



Metric	Unit	Without Vegetation	With Vegetation
Area Lost m2 (Coastline)	(m2)	2155	2087
Volume Lost m3 (Coastline)	(m3)	3642	3526
Single Storm Erosion Damage	($)	431,000	417,400
50-Year Erosion Damage	($)	786,818	761,864

Metric	Unit	Without Vegetation	With Vegetation
Area Lost m2 (Coastline)	(m2)	1243	1243
Volume Lost m3 (Coastline)	(m3)	1977	1977
Single Storm Erosion Damage	($)	248,600	248,600
100-Year Erosion Damage	($)	493,494	493,494

Figure 4-2. Cross-evaluating differences in model summaries.

Note that in addition to altering parameter values in the ArcGIS Pro input data form, another way to test different natural asset design alternatives is to modify the baseline input datasets. When this approach is taken, be sure to make copies of each altered input dataset with informative labels and then substitute them into the CT functions for each natural asset design alternative. For example, if a project aimed to improve eelgrass distribution through restoration or enhancement work, users could have two copies of the submerged vegetation input feature class: a) a baseline condition copy showing the current distributions of eelgrass, and b) a modified copy showing the distribution after planting and enhancement work. Similarly, to represent a managed retreat scenario, users could duplicate the building layer and move or modify buildings near the waters' edge, adjust their depth damage curve or even change the structure value to 0 to represent fortifying improvements that would prevent flood damage. Figure 4-3 below shows alternate shapefile copies in the ArcGIS Pro layer menu.

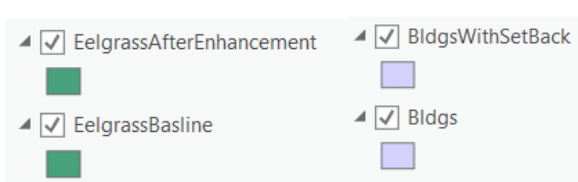


Figure 4-3. Alternate shapefiles in the ArcGIS Pro layer menu.

Similarly, to simulate beach and foreshore modifications, we suggest making multiple copies of the beach attributes polygon layer, for example, with one layer representing baseline conditions and a second layer representing a natural asset alternative. Users can then edit attribute values in each alternative layer to represent different natural asset alternatives (e.g., edit foreshore slope and berm height attributes to simulate actions such as beach nourishment). Figure 4-4 shows a beach polygon layer with attributes that can be edited in ArcGIS Pro.

Figure 4-4. Beach polygon layer with attributes that can be edited in ArcGIS Pro.

The model can then be run multiple times for each natural asset design alternative and outputs can be prepared between scenarios. The screen shot below (Figure 4-5) shows an example project output directory for four user-defined scenarios from four separate model runs. In each scenario, the user substitutes different parameter settings or input data to simulate a possible management action (or inaction). Scenarios should always be compared to baseline conditions for a given storm.

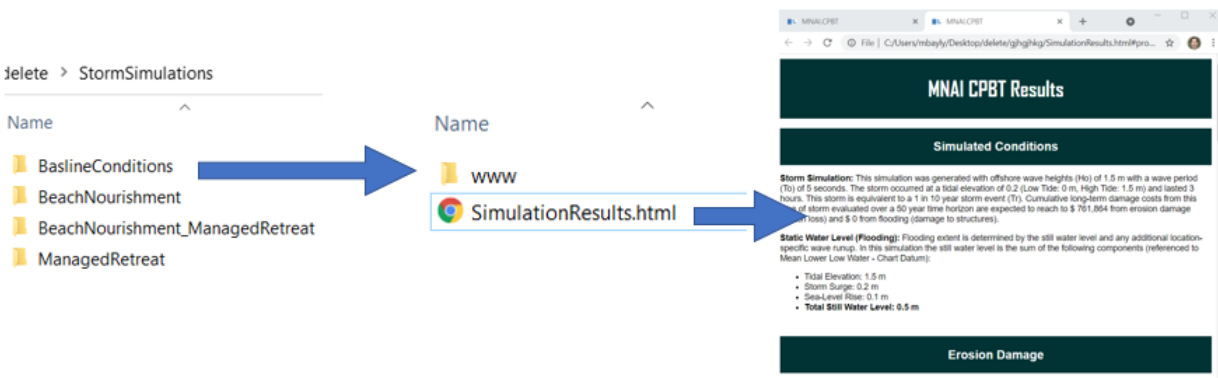


Figure 4-5. Example project output directory for four user-defined scenarios from four separate model runs.

4.4. Step 4: Avoided Costs Calculation

Calculating avoided cost is one approach to estimating of the monetary value of a good or service provided by a natural asset. This approach uses the difference between costs that are projected to occur from a hazard, like floods or erosion, with and without the asset. For each natural asset scenario, the CT can calculate avoided costs from floods and erosion relative to the baseline scenario over a user-specified time horizon (e.g., 100 years). Cost outputs are provided in “present value,” which means they are discounted annually at some rate, then summed to get a cumulative, discounted amount over the full time horizon. This discounting is standard practice by economists to capture the fact that people value $1 today more than they value $1 in the future. The CT uses a default discount rate of three per cent.

4.5. Optional: Run the Full CT or Sub-models

Users have the option to run the full CT or partial sub-models of the CT individually (Figure 4-6). As described in the preceding steps, to run the full model, users expand the “Coastal Storm Simulation (full)” tool and run the “Coastal Storm Simulation” function. To run partial sub-models individually, users instead expand the “Individual Model Components” tool and run each of the numbered sub-model functions in order. The full model runs all of these sub-models behind the scenes from start to finish to generate the storm simulation report. Running the full CT is advantageous if users want to quickly generate an automated report from a full storm simulation to aid in comparing overall results for baseline conditions and built or natural asset alternatives. The sub-models are helpful for special-use cases and for users who are interested in a specific aspect of the tool, such as outputs from the wave model, but have limited use for other components. Operating the sub-models permits users to walk through all steps, checking outputs as they go. This can help in identifying the right parameter settings and promotes learning about the model and its functions to get the user more familiar with the underlying processing workflow. Note that the sub-models rely on outputs of the other sub-models so they must be run in the numbered sequence (e.g., profiles must be generated [01 Sample Shoreline Points] before users can run the elevation extraction function [02 Extract Profile Elevation]).

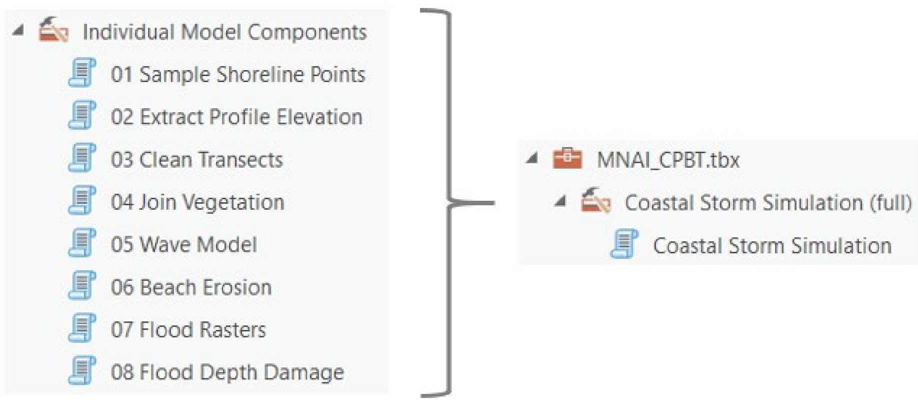


Figure 4-6. Running the full model or partial sub-models.

4.6. Other Components

There are several other components of the CT that may be useful for evaluations but are outside of the standard CT workflow. These components include a submerged structures calculator, a flood vulnerability tool and a single-profile sandbox tool. Detailed use of these features is documented in Appendix E.

The Submerged Structures calculator

The submerged structure calculator (Figure 4-7) is not part of the standard CT workflow but is instead provided as a stand-alone tool to calculate potential wave height reductions from the presence of a submerged structure with specific dimensions. The CT does not incorporate submerged structures into the full analysis but provides a simple calculator to look at proportional wave height reductions for structures of various sizes. The intent of this tool is to allow users to conduct a quick feasibility test of submerged structures for their area of interest. This calculator is not location-specific. Users simply provide a desired water depth that, for example, might represent the depth at a spot location in their area of interest, structure dimensions and approximate wave parameters. In many cases even large structures may have limited wave attenuation potential. The outputs of this calculator can be used as a coarse first-pass to determine if it is worth exploring engineering options for submerged structures in greater detail outside of the CT. This supplementary tool does not perform any cost analysis or cost-benefit estimates. Argument details for this function are provided in Appendix E.

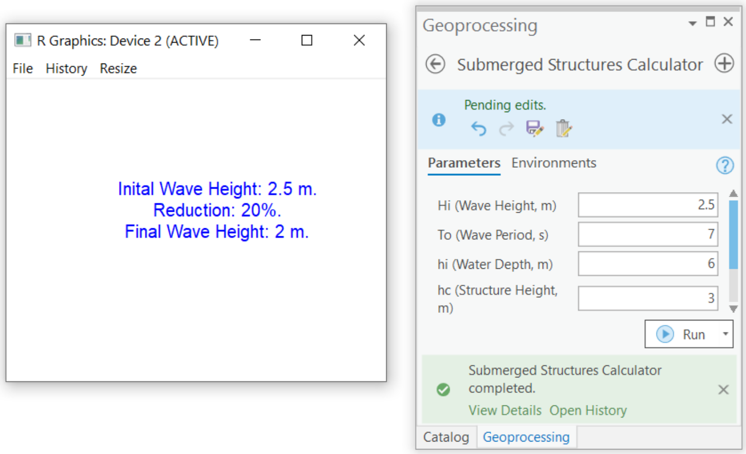


Figure 4-7. Submerged structures calculator.

The Flood Vulnerability tool

The flood vulnerability assessment function calculates the total structural damage cost from flooding at different water levels (Figure 4-8). It can be used to assess the vulnerability of a single community or compare sub-sections along a coastline. This tool allows users to determine the floodwater-level elevation that may result in significant flood damages to their community. For example, if one community does not experience any damage until floodwater levels reach 15 metres above the chart datum, then we can conclude that it is more resilient to coastal flooding than a community that is expected to experience millions of dollars in flood damage if the water level reaches two metres above the chart datum. The function can also be used to identify tipping points in floodwater elevations that result in significant increases in flood damage. These can then be referenced to local sea-level rise projections as part of a risk analysis. The input arguments and outputs for the flood vulnerability assessment function are explained in Appendix E.

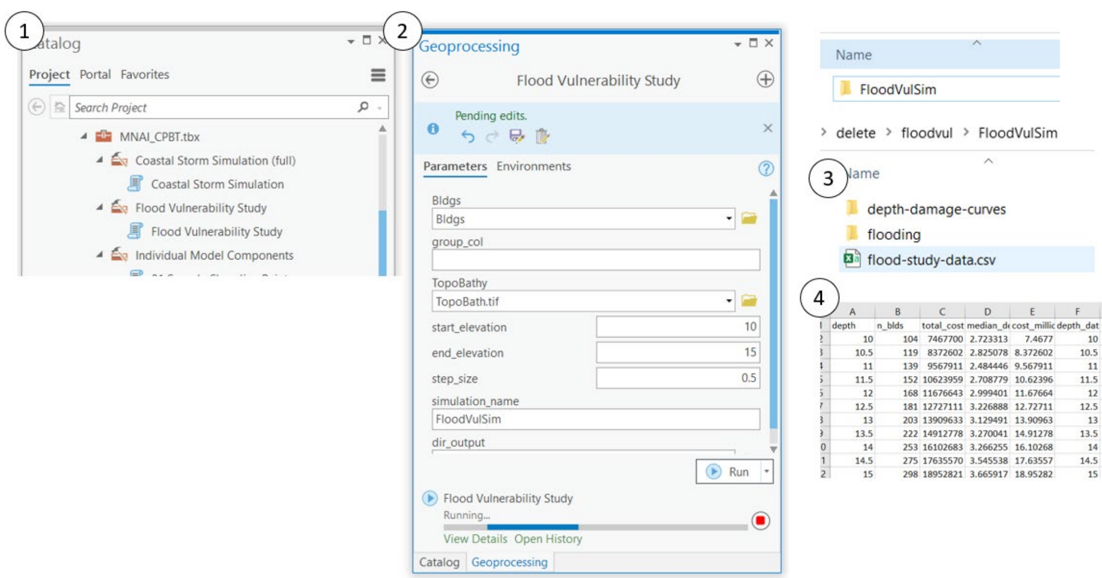


Figure 4-8. Flood vulnerability study tool.

The Single Profile Sandbox Explorer

To facilitate rapid assessments of features and design alternatives along a single cross-shore profile without running the full tool, the CT is accompanied by a web-based R-Shiny application that permits users to explore single elevation profiles along a shoreline in "sandbox mode" (Figure 4-9). This extension can be useful for designing various natural asset alternatives without having to run the full CT mode to answer questions like: How steep should my beach be to minimize erosion? Where should eelgrass meadows be located to attenuate waves? What storm severities will result in significant erosion at my site? To use this tool extension, users upload a csv of an individual cross-shore profile from the main model's output data and then interactively change foreshore parameters, offshore vegetation and storm conditions directly in a web browser without the need for ArcGIS Pro or any local software (See Appendix E for instructions).

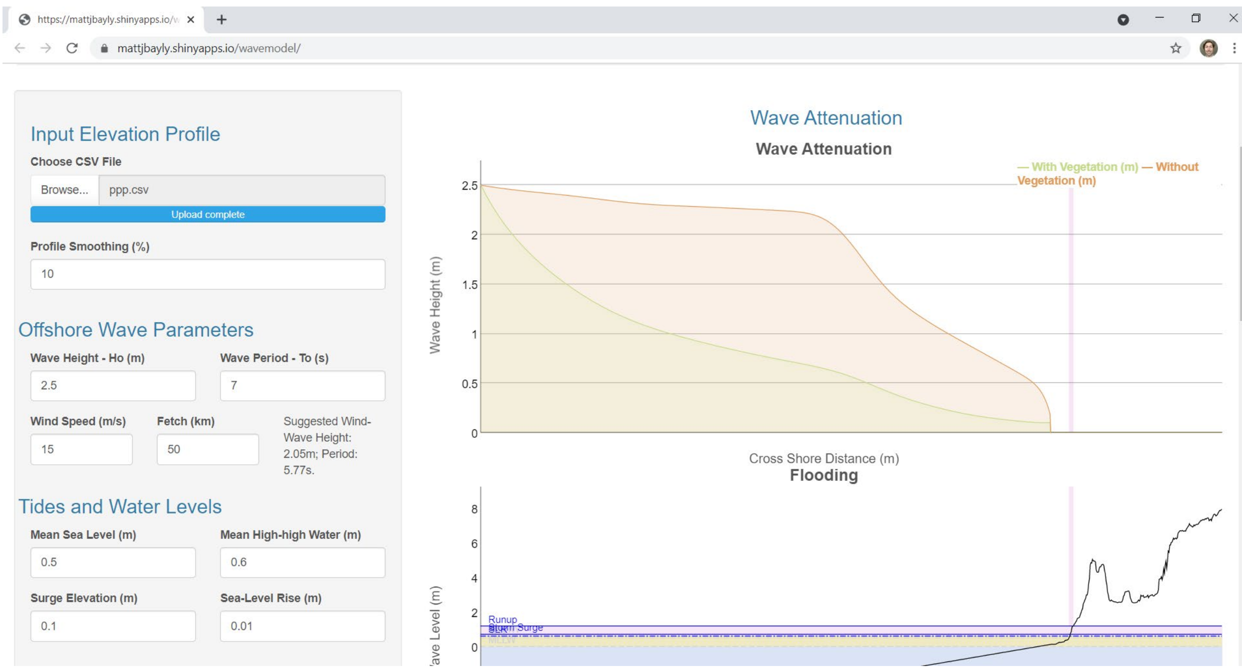


Figure 4-9. R-Shiny Extension: Individual profile sandbox mode (web-based tool).

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5. Interpreting Results

As described in Section 4, each time the full CT is run a summary output folder is created and results are summarized into a single-page HTML file. This file packages the toolbox's outputs into a simplified report with text, figures and summary tables. Here, we provide guidance for interpreting the report.

5.1. Overview

The HTML report is accessed by navigating to the output directory (created from CT in ArcGIS) and then opening the SimulationResults.html file (Figure 5-1). We suggest viewing this file in Chrome, Edge, Firefox or Safari — some features may not appear correctly if viewed from older web browsers such as Internet Explorer.

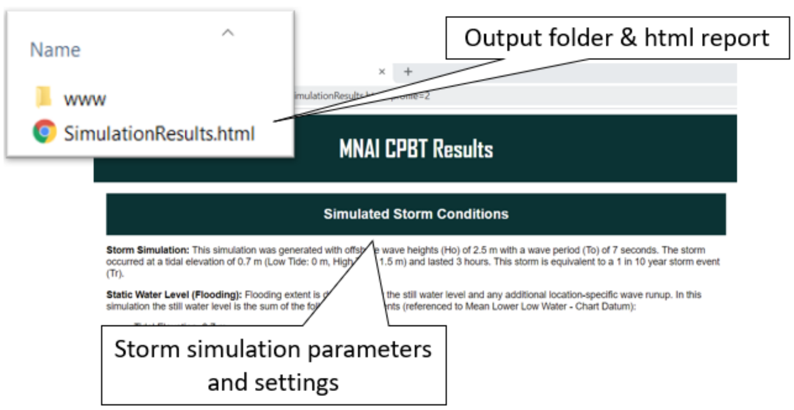

Figure 5-1. *Opening the HTML report from the file explorer.*

The report is organized into six main sections: Simulated Storm Conditions, Management Scenarios, Erosion Damage, Flooding and Structural Damage, an Overview Map, and Wave Attenuation. Note that some sections in the HTML report include results for the entire coastline and/or for the currently selected profile in the report's Overview Map. For example, the Erosion Damage section contains both types of result, while the Flooding and Structural Damage section only reports results for the entire coastline and the Wave Attenuation section only reports results for the profile that is currently selected in the Overview Map. To view detailed results for a different profile, click on another profile in the Overview Map, and the page will be reloaded with results for that profile.

The Simulated Storm Conditions section summarizes the storm, surge and tidal parameters that were used to generate the simulation. The Management Scenarios section provides an overview of the scenario represented in the HTML report. The Erosion Damage section summarizes the foreshore condition along the entire coastline and at the currently selected profile. The Flooding and Structural Damage section summarizes the flood damage and number of structures affected by the storm. The Overview Map displays the location of all cross-shore profiles evaluated, the flood contours and any other offshore vegetation patches added to the simulation. The Wave Attenuation section provides plots of wave height attenuation along the cross-shore profile. Note that the wave attenuation plots show differences between cross-shore profiles with and without submerged vegetation, but these are only relevant if the simulation is run with submerged vegetation (i.e., the user selected a vegetation polygon in the ArcGIS Pro user interface when setting up and running the model).

5.2. Simulated Storm Conditions

For reference purposes, the simulated conditions section provides a brief summary of the unique storm parameters used to generate the simulation (Figure 5-2).

Simulated Storm Conditions

Storm Simulation: This simulation was generated using storm characteristics set by you in Coastal Protection Benifit Toolbox. The settings you applied include: an offshore wave height (Ho) of 2.5 meters with a wave period (To) of 7 seconds; a tidal elevation of 0.7 m (Low Tide: 0 m, High Tide: 1.5 m); a storm duration of 3 hours; and a storm return period (Tr) of 1 in 10 years. You also supplied a Sea-level Rise estimate of 0.2 m, and a Storm Surge elevation of 0.5 m. The total still-water level was 1.4 m before accounting for local wave runup.

Figure 5-2. Simulated Storm Conditions section of the HTML report output.

5.3. Management Scenarios

The management scenarios section provides a description of the scenario, which was previously entered by the user in ArcGIS Pro, and displays foreshore parameter settings for the currently selected cross-shore profile (Figure 5-3). Note that these foreshore parameter settings are listed here because one or more may be altered to represent the scenario described in the Scenario Description.

Management Scenario

Scenario Description: Scenario Description

The management scenario you designed is based on both the input data you provided and the parameter settings you applied in ArcGIS Pro. The Scenario Description above was supplied by you in ArcGIS Pro and should articulate in plain language the management scenario your input data and parameter settings are meant to represent. For convenience, in the table below, you will find the foreshore characteristics for the profile that is currently selected in the Overview Map (see map below). These characteristics are based on both parameter settings and input data supplied by you and will therefore differ at each profile location. To switch to a different cross-shore profile, click on an alternate profile in the Overview Map (profiles are the lines perpendicular to the coastline). The foreshore parameter data in this table will update if there are differences.

Foreshore Parameters: Current Profile

Slope	Berm Height	Berm Width	Dune Height	Sed. Size	Land Value
0.06 (rise/run)	1 m	9 m	1.1 m	0.15 mm	200 $/m2

Figure 5-3. Management Scenario section of the HTML report output.

5.4. Erosion Damage

The erosion damage section provides a summary of erosion results across the entire coastline and at the current profile. The erosion summary results for individual profiles will change based on the selected cross-shore profile, but the erosion summary results across the entire coastline will remain consistent regardless of the active profile. To switch to a different profile, click on the blue lines on the overview map (Figure 5-4).

Figure 5-4. Switch between profiles by clicking one of the other blue lines perpendicular to the beach on the map.

Main Erosion Results for the Entire Coastline

The first table in the Erosion Damage section (see Table 5-1) extrapolates from all 1D cross-shore profiles to obtain rough 2D estimates across the entire coastline for the following metrics.

10. Area Lost m2 (Coastline): Area lost is summarized as the total beach area (m^2) eroded from the storm as a cumulative product of the retreat distance and the length of coastline between each cross-shore profile.
11. Volume Lost m3 (Coastline): Volume lost is summarized as the total beach volume of sand (in m^3) eroded from the storm as a cumulative product of the retreat distance, the length of coastline between each cross-shore profile and the berm height (as depth). Volume is approximated by using berm height as a depth measurement, but this is a crude estimate and values may off by several orders of magnitude. Erosion volumes should only be used for relative comparisons between options or locations.
12. Single Storm Erosion Damage: Damage from the simulated storm is reported in dollars. Note that this first value is the instantaneous damage from the storm and does not consider a time horizon, discount rate or storm return period. The erosion damage from a single storm is simply a product of the area lost at each cross-shore profile multiplied by the beach value (land value) and distance between profiles (See Section 3.5).
13. ###-Year Erosion Damage: This metric reports the present value of erosion damages caused over the user-defined time horizon, or the cumulative discounted damages. This value is calculated based on the erosion damage from the simulated storm, the storm return period, the time horizon and the annual discount rate (disc). For example, if a simulated storm had a 10-year return period and caused $5,000 in damages each time it occurred, the 100-year erosion damage value would be $50,000 if the annual discount rate were set to 0%. Time horizon assessments are useful to compare damages from coastal storms. In many instances, high-frequency but low-intensity storms may ultimately be more damaging than some rare but high-intensity storms.

Supplementary Erosion Results for Specific Cross-shore Profile

The second table in the Erosion Damage section provides a detailed estimate of erosion at the cross-shore profile that is currently selected in the Overview Map (Table 5-1). The following output metrics are provided for each profile:

14. Vertical Wave Runup: Vertical wave runup, or simply “wave runup,” is the maximum vertical extent of wave uprush on a beach or structure above the still-water level. Wave runup is an important process in causing and/or promoting bluff erosion, and it contributes to local flooding as water is pushed up onto the foreshore. In the CT, wave runup is governed largely by offshore wave attributes and foreshore parameters of a given beach segment in the beach attribute spatial polygon layer.

15. Beach Retreat Distance: These values represent the lateral retreat distance in metres (i.e., how far is the beach shifted shoreward) following a large storm. The lateral beach retreat distance is used to calculate the final area and volume loss estimates and is useful conceptually as a single one-dimensional parameter to understand erosion impacts.

16. Beach Retreat Percentage: These values represent beach retreat as a proportion of berm width, which is a useful metric because it permits users to compare results across different beaches and projects. Beach retreat percentage is calculated by dividing the retreat distance by the berm width and converting it to a percentage. As values approach 100 per cent, the storm could be characterized as *totally eroding the beach*; however, users are reminded to review and understand the limitations of the toolbox (Section 2.2).

17. Beach Retreat Index: The beach retreat index scales the retreat percentage from one to five based on the beach retreat percentage (0: 0%, 1: 1 – 25%, 2: 25 – 50%, 3: 50 – 75%, 4: 75 – 100% and 5: >100%). This scaling helps to avoid false precision with high underlying uncertainty in various sub-models. We suggest using these index values rather than focusing too heavily on exact retreat distances.

Table 5-1. Erosion Damages section of the HTML report output.

Erosion Damage

Overview: Shoreline erosion is calculated individually for each profile and then a total erosion estimate along the full coastline is interpolated by summarizing values across all cross-shore profiles. Local erosion at each profile may vary due to beach and foreshore parameters and offshore wave attenuation. In the tables below, erosion is reported first for the entire coastline and then, in the second table, for the currently selected profile. Click on another cross-shore profile in the Overview Map below to view results for a different individual profile. Full coastline results are derived by interpolating and summarizing values across all cross-shore profiles along your coastline section.

Details: For each profile, wave runup and lateral beach retreat distances are calculated using the supplied foreshore parameters at the profile location and offshore wave conditions. Using these outputs, the area (m2) of beach lost is calculated by multiplying the lateral beach retreat distance by the longshore (see Glossary in User Guide) extent between profiles. The volume (m3) of beach lost is calculated by multiplying the berm height by the retreat distance and longshore exent. Erosion damage estimates ($) are calculated by multiplying the area of beach lost by the beach property value ($/m2). These estimates are coarse but provide some indication of potential beach retreat following a storm that is useful for relative comparisons with other scenarios.

Main erosion result for the entire coastline

Metric	Unit	Value
Area Lost m2 (Coastline)	(m2)	12672
Volume Lost m3 (Coastline)	(m3)	21416
Single Storm Erosion Damage	($)	2,534,400
100-Year Erosion Damage	($)	8,008,448

Supplementary erosion results for the currently selected profile (change via Overview Map)

Metric	Unit	Value
Vertical Wave Run Up (Transect)	(m)	0.785
Beach Retreat Distance (Transect)	(m)	8.57
Beach Retreat Percentage (Transect)	(%)	95
Beach Retreat Index (Transect)	(1-5)	4

5.5. Flood Damages

Unlike the erosion damage summaries, the flood damage summary is not associated with individual profiles so only a single summary table is provided that represents results across the entire coastline (Table 5-2). However, users can reference the wave runup elevations in the erosion damages results to understand how the model is interpreting local differences in water-surface elevation. The following output metrics are provided:

18. Flooded Structures: Flooded structures are the number of individual structures that are predicted to be wetted from the floodwaters. Even if a structure is flooded by a very shallow water depth it is still added to this total. Note that individual properties may hold more than one structure.
19. Median Flood Depth: The median flood depth is the median depth of all flooded structures. Note that all non-flooded structures are excluded before calculating the median.
20. **Max Flood Depth**: The max flood depth is the maximum flood depth across flooded structures with flooding being the sum of static water levels and wave runup.
21. Flood Damage (Single Storm): The flood damage cost is first reported for the current storm based on the structure flood depths, the structure values and their associated depth damage curves. This value represents the total structural damage cost following the simulated storm. It does not consider a time horizon or storm return period.
22. Flood Damage (###-Year Summary): The final value reports the present value of long-term flood damage cost projected over the user-defined time horizon. This value is calculated from the damage cost of the current simulated storm, the storm return frequency, the long-term time horizon and the annual discount rate (disc).

Table 5-2. Flood and Structural Damages section of the HTML report output.

Flooding and Structural Damage

Overview: The MNAI CPBT estimates flooding from the sum of still-water level and local wave runup. The still-water level is the sum of the tidal water level during the storm (0.7 m), the storm-surge elevation (0.5 m) and any sea-level rise (0.2 m). Under the simulated conditions the total still-water level of this storm reached 1.4 m. In some areas the flood water level is may be further increased by local wave runup – the vertical extent of wave onto a beach or structure above the still water level. Local wave runup will vary for each profile since it is a product of the beach and foreshore parameters.

Damages to buildings, or structural damages, are calculated using depth-damage estimates to make a proportional adjustment to the building values. Building values were originally assigned by you as part of the building footprint input data (see User Guide). The flood water depth at each building is first calculated, then the value of the building is multiplied by the corresponding depth-damage proportion (%) using, for example, depth damage curves from the documentation for USACE HAZUS model. For each building, the proportionally adjusted value represents the replacement cost of flood damages, which are then added up across all affected structures in the study area. Based on the storm return period of 10 years (Tr), which you specified, the present value of damage costs is calculated over 100-years at an annual discount rate of 0.03.

Metric	Unit	Value
Flooded Structures	(#)	110
Median Flood Depth	(m)	0.2
Max Flood Depth	(m)	3.8
Flood Damage (Single Storm)	($)	3,542,048
Flood Damage (100-Year Summary)	($)	11,192,483

5.6. Overview Map

An overview map is provided for the storm simulation (Figure 5-5). Clicking on the profiles will navigate the user to different profiles and update any profile-specific information throughout the HTML report. The dashed lines represent flood contours. The black dotted line shows the high-tide contour, the purple dotted line shows the contour for the total static (still) water level and the red and green dotted lines show the contour and extent of flooding with (green) and without vegetation (red).

Figure 5-5. Overview Map portion of the Wave Attenuation and Overview Map section of the html report output.

5.7. Wave Attenuation

For the currently selected cross-shore profile only, the final section shows wave attenuation results along the profile *if* an intertidal/subtidal planting scenario is being explored. If no such scenario is applied, this section of results will show no wave attenuation. Navigating to a different profile using the overview map will update these data to show results for the newly selected profile (Figure 5-6). The first two plots show wave attenuation without (red) and with (green) vegetation. The third panel shows a depth profile with zero set to the chart datum (MLLW). The fourth panel shows the position and height of any vegetation patches along the transect (if there is no vegetation this will appear as a flat line).

Users can evaluate the wave attenuation properties of submerged vegetation by comparing the wave heights with and without vegetation. If submerged vegetation is present along the profile but the wave heights are constant between the two plots, that indicates the vegetation is either too deep or its properties are insufficient for the wave to "feel" the vegetation and be affected. The CT does not account for all the different mechanisms by which vegetation may reduce coastal erosion and wave energy, but this tool provides a simplified feasibility check on the potential direct wave attenuation properties of submerged vegetation.

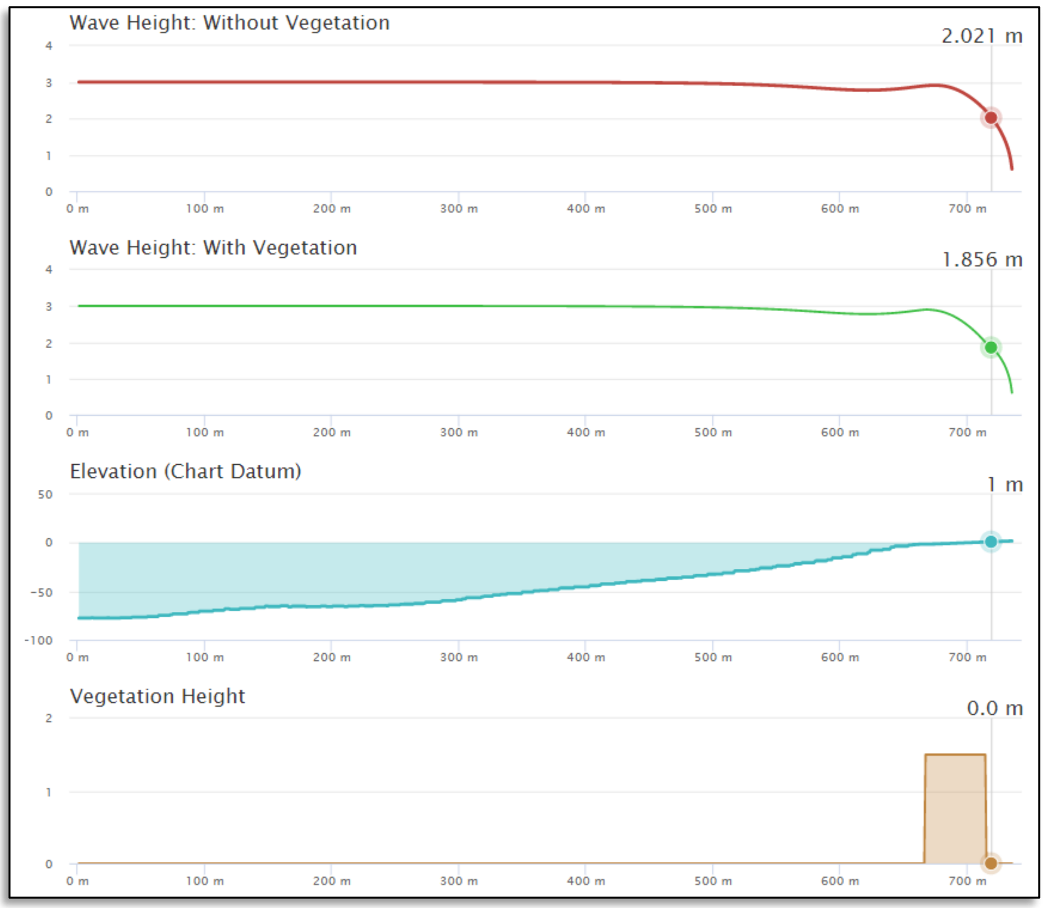

Figure 5-6. Wave Attenuation portion of the Wave Attenuation and Overview Map section of the HTML report output.

6. What's Next?

6.1. Planning Based on Model Results

The natural coastal asset inventory and valuation provides a basis for taking concrete, evidence-based actions to protect and manage the assets that support flood mitigation and erosion control. Results may also provide an initial, coarse understanding of the implications of climate change on target services.

A key next step is to translate project results of into core management and financial processes. This often starts with the development of a natural asset policy.

A natural asset management policy formalizes commitments to integrate nature into asset management at the strategic level in local governments. An asset management policy sets out what the local government will do in terms of asset management and is generally council-endorsed. It describes principles that the local government will follow when implementing asset management practices to meet its strategic objectives; who will be responsible for ensuring the policy will be implemented; and the scope of assets and services covered by the policy.

An example of principles included in a good practice asset management policy from the Federation of Canadian Municipalities Leadership in Asset Management Program include:

1. Service delivery to customers, which centres decision-making on delivering defined levels of service that reflect customer expectations while balancing risk and affordability.
2. Long-term sustainability and resilience, which requires that services and infrastructure assets be socio-culturally, environmentally and economically sustainable over the long-term. This involves long-term planning that manages risks, incorporates triple bottom line (socio-cultural, environmental, economic) considerations, climate change awareness and resilience.
3. Holistic and integrated approach, where decisions are made collaboratively across departments and disciplines.
4. Fiscal responsibility, which requires robust asset management decision-making processes to make the best use of available funds to deliver services to communities.
5. Innovation and continual improvement, which recognizes that asset management is an ongoing process and that a culture of continual improvement will enable the local government to deliver services to the community and stakeholders more effectively and efficiently.

Natural assets can be included in the scope of an asset management policy. Consideration of natural asset ownership is critical at this stage. In some cases, management and monitoring of the assets is possible without ownership (such as the management of Gibsons' aquifer). In other cases, negotiation with senior government is required to identify roles and responsibilities (such as with watershed management). In situations where regulations are required to protect an asset, the presence of conflicting needs may make management for local services difficult or impossible (for example in the case of a provincial forest that provides local stormwater conveyance but also has an active harvesting licence). In these latter cases, local governments may wish to build a business case for further discussions with senior government officials.

A good practice asset management policy usually starts with the policy's intent, describes how the policy will support the achievement of the local government's strategic objectives, and lists the strategic documents that it is aligned with, like an official community plan or a municipal strategic plan. Strategic documents related to conservation, protection or management of natural assets such as climate adaptation strategies, urban forest management plans and/or source-water protection plans can be included.

The setting of performance levels is important for community buy-in by clearly articulating what to expect and what it will cost. This process should be a key tool in managing public expectations in terms of service and budget limitations. Internally, within a local government, this process sets the stage for identifying efficiencies as gaps can be more easily identified and corrected; for setting priorities; and for weighing the consequences of risks.

Levels of service for infrastructure refers to the quality, function and capacity of the service being provided (e.g., what transportation services does the community expect and what assets are needed to provide them?) The basic question to be addressed is: How long do we expect the asset of interest to function under the current operations and maintenance? Some service-level definitions will be basic, such as complying with applicable laws. Others will be quantitative, such as the ability of an asset to handle storm events of a given size; or qualitative such as citizen satisfaction with a trail system.

Identifying service levels, today and into the future, involves:

- Council: determine the desired level of service
- Staff: determine asset risks
- Council and staff: negotiate costs for varying levels of service. This involves balancing the full life-cycle costs of assets needed to provide the desired levels of service given a budget envelope.

The process is similar for conventional and natural infrastructure, with a notable exception: natural assets generally provide multiple services, and prioritizing one group of services can involve trade-offs with other groups of services (e.g., prioritizing water storage for flood attenuation in a coastal wetland may restrict recreational benefits). Modelling programs, such as Artificial Intelligence for Ecosystem Services or ARIES (http://aries.integratedmodelling.org), are in development to understand ecosystem service synergies and trade-offs.

6.2. Implementation

The implementation stage of asset management involves acting on asset management plans, policies and strategies to meet performance-level targets and minimize risks in a cost-effective manner. The setting of performance levels is important for community buy-in by clearly articulating what to expect and what it will cost. This process should be a key tool in managing public expectations in terms of service and budget limitations. Internally, within a local government, this process sets the stage for identifying efficiencies as gaps can be more easily identified and corrected; for setting priorities; and for weighing the consequences of risks.

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6.3. Monitoring

Asset management is iterative, with each cycle aiming to deepen knowledge to realize efficiencies, meet service levels and minimize risk within a budget. To determine if progress is being made, progress indicators should be identified. They should be specific, measurable, attainable, relevant and time-bound (SMART).

Measurement and reporting can be particularly relevant during periods of change, whether financial (e.g., refining the value of natural asset services), environmental (e.g., changing impacts due to climate change) or social (e.g., changing service-level demands). Updates may be related to:

- New assets
- Retired assets
- Refurbished or replaced assets
- Replacement cost changes
- Updates to operating, maintenance and monitoring costs
- Asset condition information
- Service levels — actual and demanded

Each local government may develop its own set of indicators and frequency of reporting. They may also wish to focus reporting on one set of assets to begin and incorporate additional asset classes over time as a standardized process is developed.

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Appendix A – Coastal Ecosystems and Ecosystem Services

Coastal Ecosystem Types

Marine coastlines support a wide variety of ecosystems. Table A-1 provides details about the major coastal ecosystem types that exist in Canada. Note that the types presented below are not mutually exclusive. For example, seaweeds such as kelp often grow in rocky shoreline areas and mudflats may exist within an estuarine area.

Table A-1. Major coastal ecosystem types in Canada.

Ecosystem type	Description
Seagrasses and seaweeds	Seagrasses and seaweeds are found in and adjacent to estuaries and other coastal wetland ecosystems. Seagrasses help to stabilize sediments and provide critical habitat and food for juvenile fish species, acting as nurseries that provide protection from predators (Barbier 2007; PON Secretariat 2009). Seaweeds are found in a variety of marine environments and play a similar role to seagrasses, providing habitat and encouraging biodiversity. Recently, there has been increased research interest in the potential for coastal vegetation (such as seagrasses and seaweeds) to reduce the impact of storms and act as a buffer for inland communities. Other ecosystem services provided by seagrasses and seaweeds include water purification, maintenance of fisheries, carbon sequestration, tourism and recreation (Barbier 2007).
Rocky shores	Rocky shores are highly productive ecosystems because the rocks provide essential habitat for both flora and fauna. Vegetation such as kelp and rockweed grow in abundance. Snails, mussels and other invertebrates attract marine birds and other predators that feed in this intertidal and nearshore subtidal zone. In addition to the critical habitat they provide, rocky shores act as a barrier between the ocean and inland ecosystems, protecting communities from storms. They also provide erosion control. Their beauty attracts tourists, which can sometimes lead to damage from human disturbance (PON Secretariat 2009).
Intertidal mud flats	Intertidal mud flats often occur within estuaries and form from the mud and sand that is deposited from both the river and the sea. They are highly productive ecosystems because they receive a continuous supply of nutrients that are mixed by the tide. When they are exposed at low tide, the deposited nutrients and sediments provide food and habitat for a multitude of species of flora and fauna (PON Secretariat 2009).
Estuaries	Estuaries occur at the mouth of a river where it drains into the ocean, forming an important transition zone between the river environment and the marine environment. Coastal wetland ecosystems (e.g., tidal salt marshes and coastal saline ponds) that are connected to these estuaries are highly productive ecosystems due to the steady influx of nutrients from the rivers that flow into them. These ecosystems benefit surrounding communities by protecting them from flooding and storms. They are extremely biodiverse and improve water quality, acting as a filter for inland water flowing to the ocean (PON Secretariat 2009).
Salt marshes and brackish wetlands	Salt marshes and brackish wetlands are vegetated wetlands in the intertidal zone along saline water bodies (Barbier 2007; King and Lester 1995). While salt marshes are generally located in the intertidal zone and are characterized by being influenced by salt water, brackish wetlands often exist close to the mouths of rivers in estuarine environments and receive both freshwater and saltwater input. Both of these ecosystems provide a number of services, including food provision, wave attenuation, erosion control, water purification, fisheries habitat, carbon sequestration and recreation (Arkema et al. 2017; Barbier 2007; NTSC 2015). Unfortunately, around 50 per cent of salt marshes have been destroyed or degraded globally (including more than 67 per cent on Canada's Atlantic coast (Austen and Hanson 2007) and more than 90 per cent on the U.S. west coast), resulting from a mix of invasive species, eutrophication, climate change, sea-level rise, global warming, increased CO2 concentrations, hydrologic changes, development, disturbance and pollution (Barbier 2007). Grey infrastructure such as bulkheads and rip-rap revetments also pose a threat to coastal marshes as they prevent the marsh's tendency to migrate upslope to keep up with sea-level rise (Gittman et al. 2014).

Ecosystem type	Description
Beaches	Beach ecosystems occur where waves deposit sand. Different types of sand are deposited depending on the local geology and ecology, with sand being a result of both the weathering of rocks and the breakdown of shells and coral. Beaches provide a variety of ecosystem services, including critical habitat for flora and fauna, coastal protection from extreme weather events, erosion control and carbon sequestration (Barbier 2007; PON Secretariat 2009). Beaches are also popular recreational areas and attract high numbers of tourists, which can positively impact coastal economies but also leaves these ecosystems vulnerable to human disturbance (PON Secretariat 2009).
Dunes	Sand dune ecosystems form in exposed coastal areas by wind and waves depositing sand onto the beach. Vegetation helps to stabilize the dunes, which in turn leads to more sand accumulating. Dunes provide critical habitat for both flora and fauna, although the species that live there must be able to tolerate the harsh exposure inherent to these ecosystems. Dunes also act as barriers that protect inland ecosystems and communities from storms. Due to their popularity as recreation areas, sand dune ecosystems are vulnerable to human disturbance. Trampling of vegetation can lead to destabilization of the dunes, which leads to negative impacts on the other species that live there (Barbier 2007; PON Secretariat 2009).
Coastal shrubs and bushes	Coastal ecosystems abound with a variety of coastal shrubs and bushes. This vegetation provides food and critical habitat for many species of fauna. The stems and roots of coastal shrubs and bushes stabilize sand dunes and sediment, preventing erosion and keeping those ecosystems intact. Coastal shrubs and bushes also provide wave attenuation, potentially reducing damage to coastal communities during storm events (PON Secretariat 2009).
Coastal forests	Coastal forest ecosystems occur within two kilometres of the coast and can be made up of either deciduous or coniferous tree species, or a mixture of both. Forests abutting the coastline are susceptible to harsh winds and exposure, resulting in stunted trees. These ecosystems provide important habitat for wildlife, food for people, erosion control, water-quality protection, nutrient cycling and carbon sequestration. They also provide wave attenuation, shielding inland communities from the harsh conditions associated with large storm events. Development of these coastal forests threatens these ecosystems and can increase erosion and lead to habitat fragmentation (PON Secretariat 2009).

Coastal Ecosystem Services

Because ecosystem processes do not occur in isolation, services provided by coastal ecosystems are highly interdependent. For example, degradation of the erosion-control benefits provided by a salt marsh can impact its water-purification functions, which can in turn impact habitat quality, leading to a decrease in recreation and tourism opportunities. Table A- 2 provides a summary of the types of ecosystem services provided by shoreline and nearshore vegetation (Barbier 2011). Coastal protection and erosion control are in boldface because this project is focused on those services. Further information about how different ecosystem types provide ecosystem services is detailed in the Natural and Hybrid Infrastructure Approaches section in Appendix B.

Table A- 2. Summary of ecosystem services provided by seagrass and salt marsh ecosystems (Barbier 2011).

Ecosystem service	Ecosystem processes and functions	Controlling factors in seagrass beds	Controlling factors in salt marshes
Raw materials and food	Generates biological productivity and diversity	Vegetation type and density, habitat quality	Vegetation type and density, habitat quality, inundation depth, healthy predator populations
Coastal protection	**Attenuates and/or dissipates waves**	**Wave height and length, water depth above canopy, bed size and distance from shore, wind climate, beach slope, species diversity and density, reproductive stage**	**Tidal height, wave height and length, water depth above canopy, marsh area and width, wind climate, marsh species and density, local geomorphology**
Erosion control	**Provides sediment stabilization and soil retention in vegetation and root structure**	**Sea-level rise, subsidence, tidal stage, wave climate, coastal geomorphology, species diversity and density**	**Sea-level rise, tidal stage, coastal geomorphology, subsidence, fluvial sediment deposition and load, marsh grass species and density, distance from sea edge**

Water purification	Provides nutrient and pollution uptake, as well as retention	Species diversity and density, nutrient load, water residence time, hydrodynamic conditions, light availability	Marsh grass species and density, marsh quality and area, nutrient and sediment load, water supply and quality, healthy predator populations
Maintenance of fisheries	Provides suitable reproductive habitat and nursery grounds, sheltered living space	Species diversity and density, habitat quality, food sources, hydrodynamic conditions	Marsh grass species and density, marsh quality and area, primary productivity, healthy predator populations
Carbon sequestration	Generates biogeochemical activity, sedimentation, biological productivity	Species diversity and density, water depth, light availability, burial rates, biomass export	Marsh grass species and density, sediment type, primary productivity, healthy predator populations
Tourism, recreation, education	Provides unique and aesthetic landscape, suitable habitat for diverse flora and fauna	Biological productivity, storm events, habitat quality, species diversity and density	Marsh grass species and density, habitat quality and area, prey species availability, healthy predator populations

Pathways of Effects

To understand how coastal ecosystems can deliver ecosystem services it is necessary to understand the ecological processes that connect the ecosystem components to the desired services (Arkema et al. 2017). The desired services that are the focus of this project are flood and erosion protection derived from wave attenuation by shoreline and nearshore ecosystem components. Relevant ecosystem components can be physical (e.g., topography/bathymetry) and biological (e.g., plant density). Connecting these ecosystem components and processes to ecosystem services can be made explicit using a pathways of effects conceptual model. Figure A-1 displays a conceptual model that identifies the pathways by which components of the ecosystem (and built coastal protection assets) are linked to biophysical processes that can provide flood and erosion protection. Acknowledging how climate change is fundamentally transforming the system, Figure A-2 displays another conceptual model with a focus on how climate change–related drivers interact with coastal protection assets to affect flood and erosion. Both conceptual models highlight how management actions or human actions influence coastal protection assets through policies and practices that protect and restore natural assets or create and maintain built assets. It is these actions that provide levers for municipalities (and others) to interact with the system in a way that promotes desired outcomes.

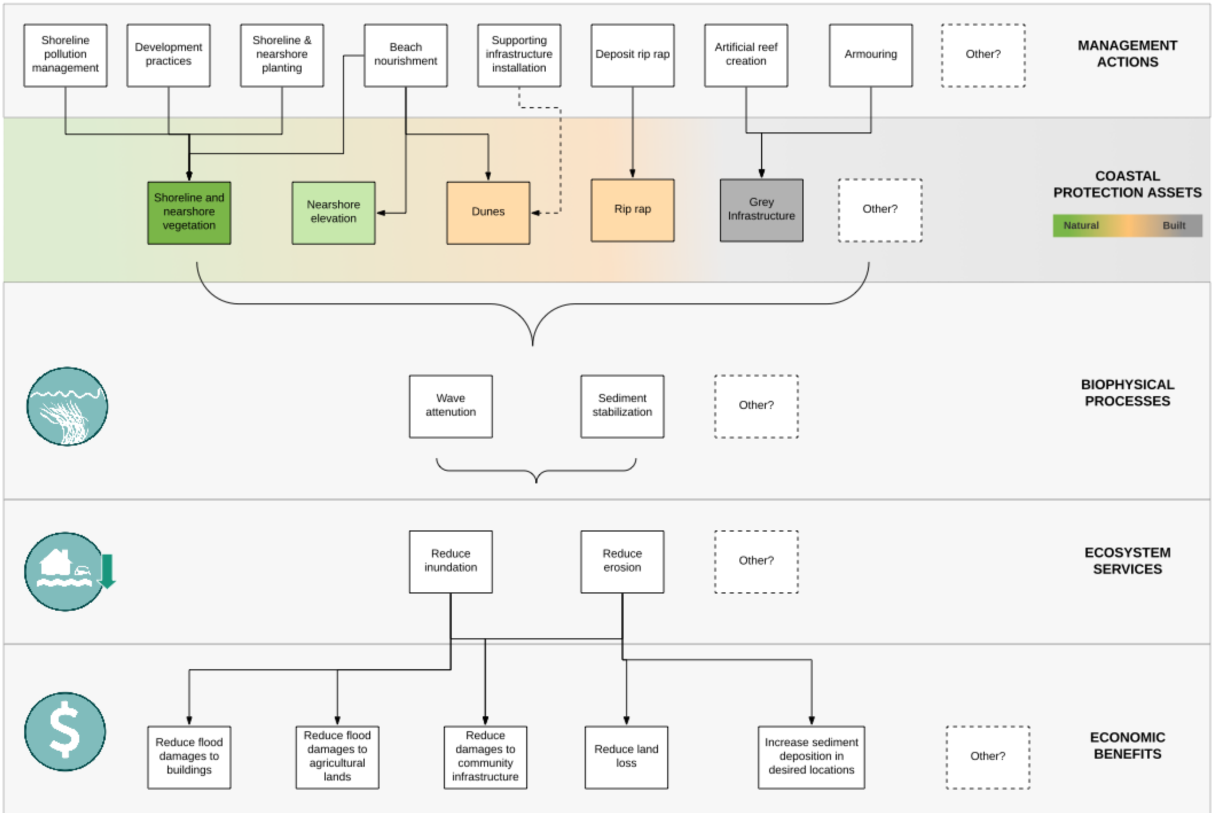


Figure A-1. Conceptual model displaying pathways of effects from coastal protection assets to flood and erosion protection benefits.

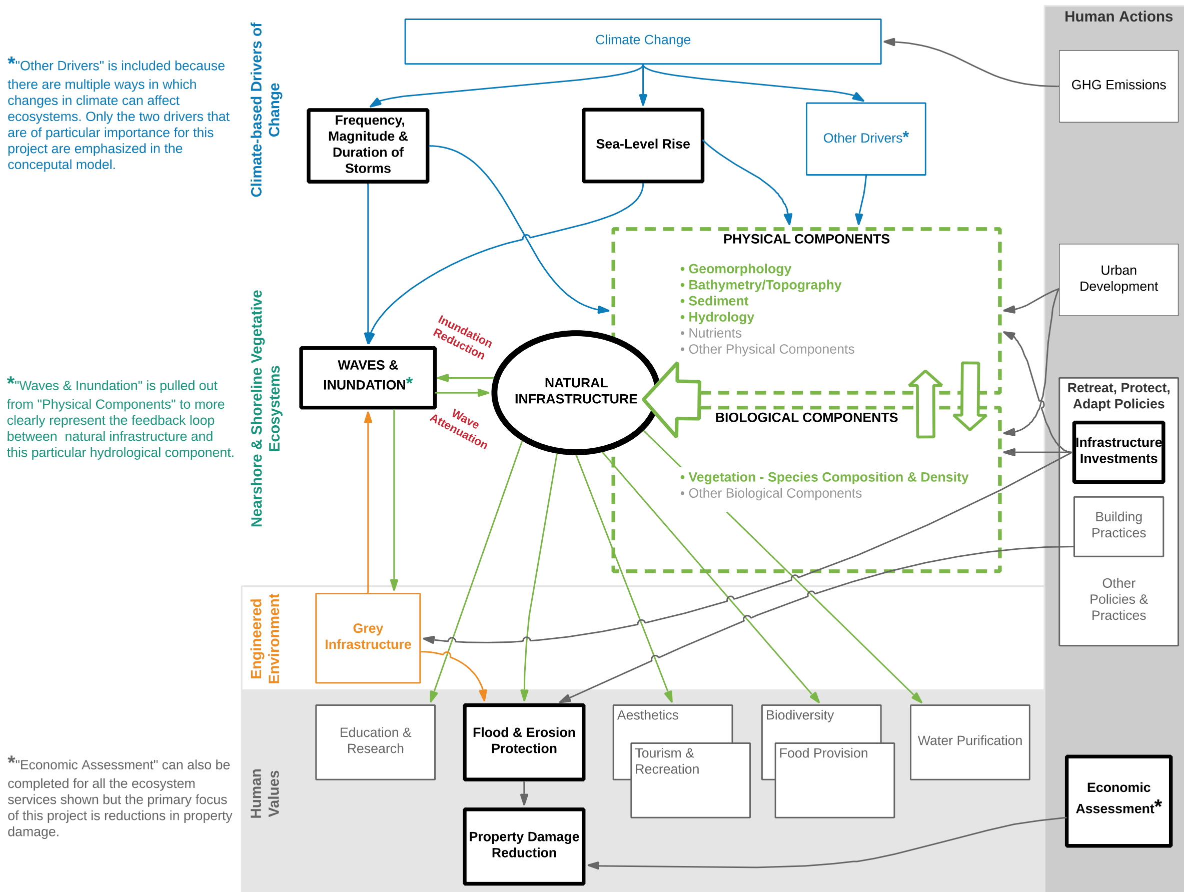


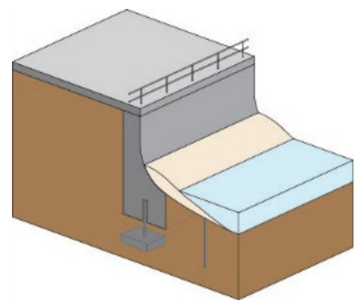
Figure A-2. Conceptual diagram displaying how climate change–related drivers interact with natural and grey infrastructure to influence flood and erosion protection. The diagram also displays how human actions can affect different processes.

Appendix B - Strategies for Flood and Erosion Protection

Hard/Grey Infrastructure Approaches

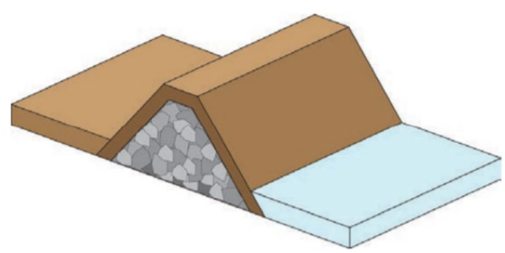
Historically, the preferred response to flooding and erosion has been to "harden" a shoreline using bulkheads, revetments and similar engineered structures that typically form a fixed delineation or barrier in the water/land continuum that would otherwise be the natural, shifting shoreline (Restore America's Estuaries 2015). Hard structural measures to address coastal storm hazards are typically static, engineered features designed to reduce wave damage and flooding, and may also decrease shoreline erosion. Sometimes termed "grey infrastructure" or "hard engineering," these structures include (National Research Council 2014):

Seawalls: Seawalls are constructed parallel to the shoreline to reduce impacts from storm surge and waves to developed lands behind the seawall. Seawalls may be vertical or curved, or designed as a mound built from rock or concrete blocks. The seawall reflects wave energy back to the sea, and therefore can increase erosion on the coastal side of the wall. Depending on lateral currents, seawalls may also cause increased erosion of adjacent, unprotected coastal areas (National Research Council 2014).



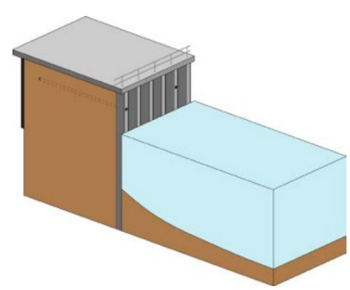
Source: NYC Department of City Planning (2013)

Levees and floodwalls: Levees and floodwalls are onshore engineered structures most commonly constructed along riverine floodplains. They are designed "to contain, control, or divert the flow of water so as to provide protection from temporary flooding." Levees (i.e., dikes) are typically wide earthen embankments that are designed to control flooding over a large area up to a specific water level (National Research Council 2014; NYC Department of City Planning 2013). However, levees can also be used in coastal settings, where they may be paired with other mitigation features, such as revetments or coastal wetlands that buffer the levee against erosive wave forces. Floodwalls are typically vertical concrete walls, and usually constructed in areas where there is insufficient space for the wide footprint of an earthen levee. Floodwalls can also be constructed on top of a levee when space limits any further expansion of the levee footprint (National Research Council 2014).



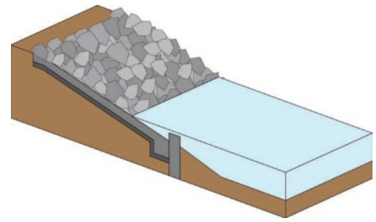
Source: NYC Department of City Planning (2013)

Bulkheads: Similar to seawalls, bulkheads are built parallel to the shoreline, and are generally constructed with stone, rock, or concrete. Rather than preventing coastal flooding, their primary function is usually to stabilize shorelines and prevent erosion (NYC Department of City Planning 2013).



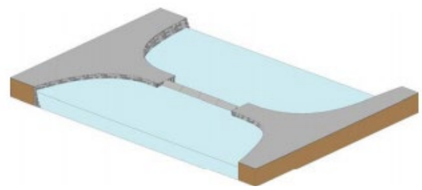
Source: NYC Department of City Planning (2013)

Revetments: Often used as alternatives to bulkheads, revetments are essentially piles of stone or rubble designed to prevent erosion and reduce impact force from wave action.



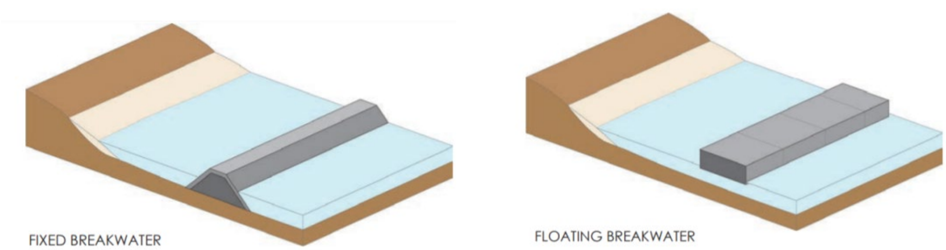
Source: NYC Department of City Planning (2013)

Storm-surge barriers: Storm-surge barriers are designed to block storm surges from propagating inland via rivers or other waterways. Gates in the barriers are left open to allow water to flow through under normal conditions but can be closed when storm surges are expected (National Research Council 2014).



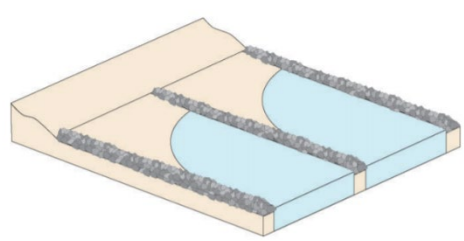
Source: NYC Department of City Planning (2013)

Breakwaters: Breakwaters are offshore structures typically made of rock or stone intended to break waves, reducing the force of wave action. By breaking down large waves, breakwaters allow sediments and materials carried by water to accumulate at the shore, extending the beach, nourishing a wetland or protecting shoreline structures. By reducing the force of waves, they also protect shorelines from erosion and may contribute to some reduction in total flood levels for surge events (NYC Department of City Planning 2013). Breakwaters may be either fixed or floating, depending on the water depth and the tidal range. Fixed breakwaters may be either submerged (or “low-crested”) or above water (“emerged”). Floating breakwaters can tolerate higher water levels than fixed breakwaters, but only waves shorter in length, and are commonly used to protect boats and marinas from waves and wakes. Fixed breakwaters are typically better suited to address significant wave forces found along the oceanfront. Breakwaters must be anchored to the sea bottom, with piles being the most reliable and long-lasting type of anchor (NYC Department of City Planning 2013).



Source: NYC Department of City Planning (2013)

Groins: Groins are structures that extend perpendicularly outward from the shore, and are typically constructed out of concrete or stone rubble, timber or metal sheet piles. They are constructed to trap sand, prevent beach erosion and break waves. Ideally, they maintain a beach wide enough to protect from storms through controlling the amount of sand moving alongshore. They are often used in conjunction with beach nourishment, as they can extend the lifespan of beach nourishment projects. On their own, groins lead to increased erosion on adjacent beaches. They are usually constructed in a series down a beach, called a groin field (NYC Department of City Planning 2013).



Source: NYC Department of City Planning (2013)

Natural and Hybrid Infrastructure Approaches

Natural or "soft" systems, sometimes in combination with human engineered elements, are designed to protect or reintroduce natural systems that will provide land-protection functions and reduce adverse impacts to terrestrial and aquatic ecosystems (National Research Council 2014). A living shoreline is "Any shoreline management system that is designed to protect or restore natural shoreline ecosystems through the use of natural elements and, if appropriate, manmade elements. Any elements used must not interrupt the natural water/land continuum to the detriment of natural shoreline ecosystems" (Restore America's Estuaries 2015). Natural and hybrid approaches can include protecting, restoring or creating natural shoreline ecosystems that provide ecosystem services. Figure B-1 displays an example shoreline with natural asset approaches employed. The following paragraphs provide details about relevant ecosystems[4].

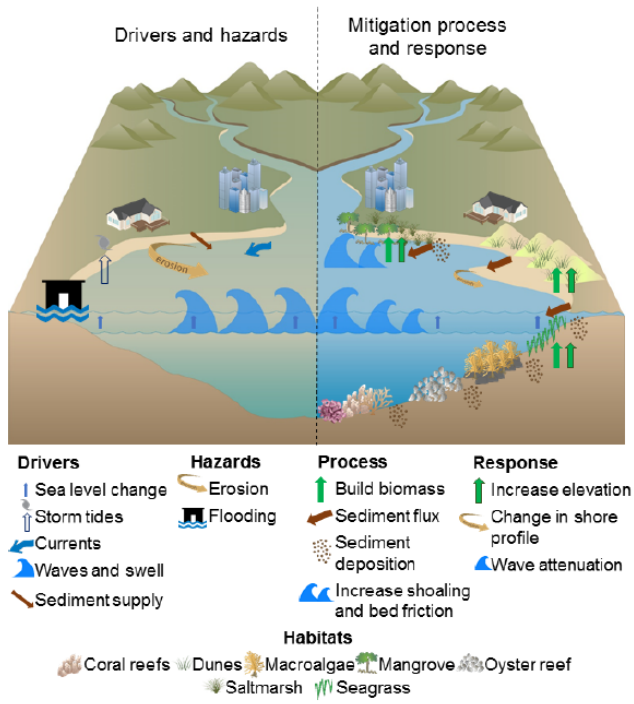
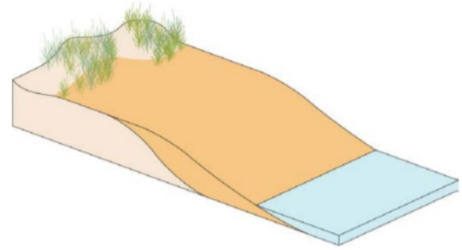


Figure B-1. Example shoreline displaying relevant drivers and hazards (including erosion and flooding) and approaches to respond that include accounting for natural assets. Source: Morris et al. (2017).

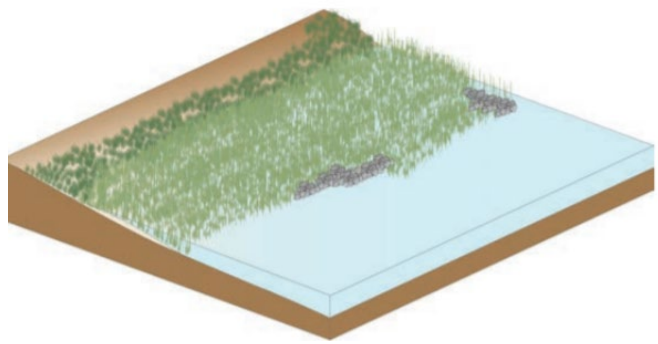
[4] Note: These paragraphs contain some information about ecosystem types, which is also Appendix A. Appendix A is focused on detailing the characteristics of the habitats whereas this section is designed to provide more detailed information related to flood and erosion protection.

Beaches and dunes: Beaches and dunes are natural protective features that provide a sandy buffer to protect from waves and flooding, and are sometimes reinforced with vegetation, geotextile tubes or a rocky core. Beaches act as a buffer between breaking waves and upland structures, reducing the force of waves and reducing amount of damage from a storm. Dunes offer additional protection by strengthening the ability to dissipate waves and can offer additional height to protect from surge. Reinforced or "armoured" dunes act as sand-covered seawalls to protect from surge events and can withstand heavy wave action (NYC Department of City Planning 2013).



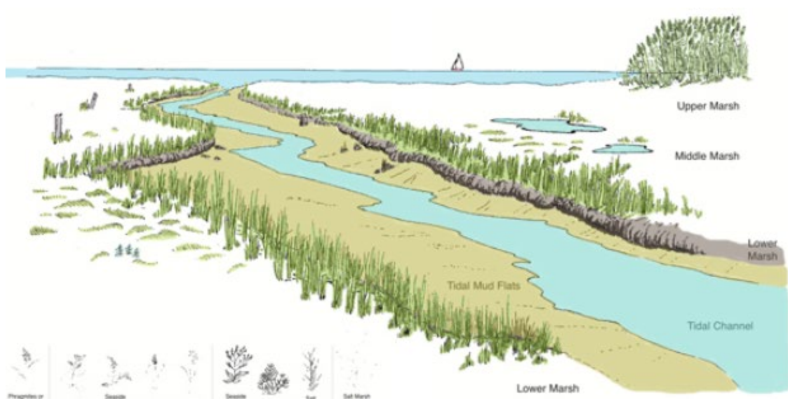
Source: NYC Department of City Planning (2013)

Coastal wetlands: Tidal wetlands can help reduce risks from coastal hazards. Smaller wetlands areas can protect from wave forces and provide moderate protection from shoreline erosion. Large wetland areas can slow down the rate of surge through friction, and if large enough, may provide some reduction in flood heights depending on the speed and intensity of the storm. Wetlands also have some ability to reduce risk from frequent inundation and periodic low-surge flooding (NYC Department of City Planning 2013). Fringe wetlands — smaller-size wetlands along the coast — can dissipate wave energy and provide erosion control to stabilize shorelines, though they are unlikely to reduce the height or extent of coastal flooding (NYC Department of City Planning 2013; Morgan et al. 2009). In addition, tidal wetlands provide many ecological functions, using plants and soils to retain and filter water while creating wildlife habitat. Wetlands may be constructed or restored to foster these benefits, and existing ones can be protected to ensure existing benefits are not lost.



Source: NYC Department of City Planning (2013)

Salt marshes: Salt marshes are coastal wetlands that are flooded and drained by salt water brought in by the tides. They are marshy because the soil may be composed of deep mud and peat (NOAA 2021b). Salt marshes provide some level of floodwater attenuation by absorbing water and moving water in a sheet flow toward the coast (Batker et al. 2010). In addition to mitigating high-frequency, low-magnitude coastal hazard events, marsh processes such as wave attenuation, sediment deposition and elevation building also contribute to long-term maintenance of the coastline. This is especially relevant for areas with significant projected increases in sea level (Shepard et al. 2011).

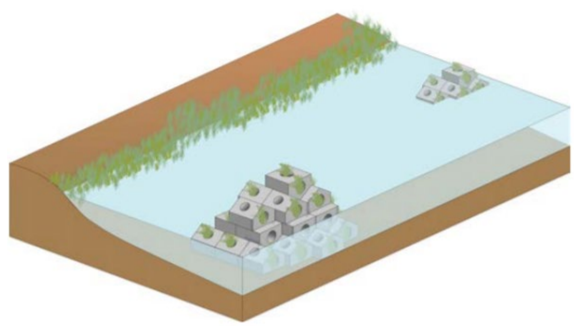


Source: Outer Island (n.a.)

Seagrasses: Seagrasses are the largest submerged aquatic vegetation ecosystem (Ondiviela et al. 2014). Eelgrass (*Zostera marina*) is a common seagrass species that plays an important role in coastal ecosystems, especially estuaries. Eelgrass beds provide a variety of ecosystem services, including reducing the force of waves, stabilizing sediments and providing habitat for various types of animals, including fish and invertebrates. They also form a substrate for other plants, are food for various marine organisms and are an efficient carbon sink (Environment and Climate Change Canada 2010).

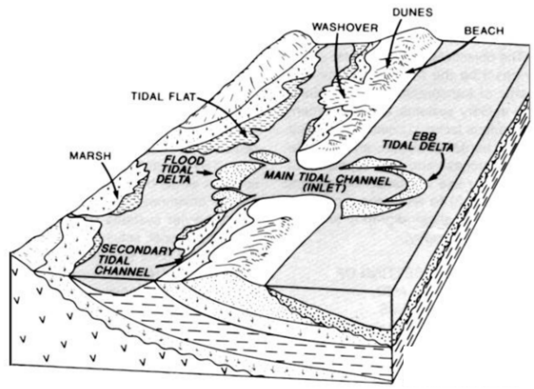
Source: portvancouver.com

Reefs: Reefs occur both naturally (e.g., coral) and artificially, and they provide a complex, three-dimensional biogenic structure that can attenuate erosive wave energy, stabilize sediments and reduce marsh retreat (NYC Department of City Planning 2013; Scyphers et al. 2011). Coral reefs constitute a first line of defence from erosion and flooding through wave attenuation and sand production and retention (Elliff and Silva 2017; Ferrario et al. 2014; Pascal et al. 2016; Reguero et al. 2018). Fringing natural reef crests function much like low-crested breakwaters (Beck et al. 2016), dissipating wave energy and protecting the shoreline (Gallop et al. 2014; Sheppard et al. 2005). Coral reefs also generate fine coral sand, supplying shores with sand generated by physical forces as well as the biota (Bellwood 1995). Live coral provides the reef with shallower geometrical complexity and more surface roughness that dissipate wave energy through friction and wave-breaking (Quataert et al. 2015). Correspondingly, coral mortality increases the wave energy reaching shores as the reef presents less friction to waves and removal of the coral skeletons increases the depth of water over the reef flat (Reguero et al. 2018; Sheppard et al. 2005). Artificial reefs are submerged, or partially submerged, structures made of rock, concrete or other materials that are designed to provide marine habitat for plants, invertebrates, fish and birds, while also attenuating waves. Similar to breakwaters, artificial reefs dissipate wave energy, protect shorelines from erosion and minimize sediment movement. They can also contribute to reduction in overall flood levels for surge events. In beach locations, offshore reefs can minimize the frequency that beach nourishment needs to occur (NYC Department of City Planning 2013).



Source: NYC Department of City Planning (2013)

Barrier Islands: A barrier island is a constantly changing deposit of sand that forms parallel to the coast. As wind and waves shift according to weather patterns and local geographic features, these islands constantly move, erode and grow, or can disappear entirely. They are generally separated from the mainland by tidal creeks, bays and lagoons. Beaches and sand dune systems form on the side of the island facing the ocean. The side facing the shore often contains marshes, tidal flats, and maritime forests. These areas are important habitat for seabirds, fish, shellfish and nesting sea turtles. These islands are critical to protecting coastal communities and ecosystems from extreme weather. Beach dunes and grasses on barrier islands absorb wave energy before the wave hits the mainland, resulting in smaller storm surges and less flooding on the mainland shoreline (NOAA 2021c).



Source: University of Miami (n.d.)

Choosing a Strategy

While every place is unique, it is helpful to understand which types of approaches are generally viewed as best suited for a particular situation. Each coastal protection situation can be characterized by (1) the coastal hazards that are being faced, (2) the focal services that are important to protect or enhance and (3) what co-benefits would be provided by natural asset alternatives. The following tables (Tables, B-1, B-2, and B-3) provide insight into these three characteristics as a guideline for communities, and can be further refined.

Table B-1. Ability of various approaches to address coastal hazards. Contents based on NYC Department of City Planning (2013).

Approach	Ability to address hazards					
	Event-based				Gradual	
	Storm surge (high)	Storm surge (low)	Wave action	Sudden erosion	Frequent flooding (from sea-level rise)	Gradual erosion
Beaches & dunes	H	H	H	M	H	M
Coastal wetlands	L	M	M	M	L	H
Salt marshes	L	M	M	M	L	H
Seagrasses	L	M	M	M	L	H
Reefs	L	L	H	H	L	H
Barrier islands	H	H	H	H	L	H
Seawalls	H	H	H	H	H	H
Levees & floodwalls	H	H	M	M	H	M
Bulkheads	L	M	M	M	H	H
Revetments	L	M	H	H	H	H
Storm-surge barriers	H	H	H	H	L	L
Breakwaters	L	M	M	M	L	H
Groins	L	L	M	M	L	H

Table B-2. Ability of various approaches to provide focal ecosystem services. Contents based on U.S. Army Engineer Research and Development Center (ERDC, 2015).

Approach	Ability to provide focal services				
	Reduce storm surge and related flooding	Reduce flood height, lengthen time to peak	Reduce wave attack	Property value protection	Erosion protection and control
Beaches & dunes	x	x	x	x	x
Coastal wetlands	x	x		x	x
Salt marshes	x	x	x	x	x
Seagrasses	x		x	x	x
Reefs	x		x	x	x
Barrier islands	x		x	x	x
Seawalls	x	x	x	x	x
Levees & floodwalls	x	x	x	x	x
Bulkheads	x		x	x	x
Revetments	x		x	x	x
Storm surge barriers	x		x	x	x
Breakwaters	x		x	x	x
Groins				x	x

Table B-3. Ability of various approaches to provide co-benefits. Contents based on Morris et al. (2017).

Approach	Ability to provide co-benefits					
	Maintenance of wildlife	Raw materials and food	Fisheries provision	Nutrient cycling, water purification	Carbon sequestration	Tourism, recreation, education, research
Beaches & dunes	x	x		x	x	x
Coastal wetlands	x	x	x	x	x	x
Salt marshes	x	x	x	x	x	x
Seagrasses	x	x	x	x	x	x
Reefs	x	x	x	x		x
Barrier islands	?					x
Seawalls						x
Levees & floodwalls						x
Bulkheads						x
Revetments						x
Storm surge barriers						x
Breakwaters						x
Groins						x

Appendix C – Coastal Jurisdiction

Coastal natural asset management is complicated by the fact that jurisdiction over coastal areas is relevant to federal, provincial, municipal and Indigenous governments. Before evaluating natural asset alternatives, it is important to understand these jurisdictional considerations. Doing so can aid in identifying the questions to explore with the model (i.e., what to consider using the model for given the jurisdictional situation), identifying key project participants, understanding project feasibility and costs, and identifying data custodians.

At the federal and provincial levels, the *Constitution Act* (1867) provides a framework for the division of jurisdictional authority (Stewardship Centre for British Columbia 2014), and the *Oceans Act* divides coastal areas into zones (Figure C-1). The federal government has jurisdiction over coastal waters and submerged lands from the low watermark (i.e., low tide) to the outer edge of the Exclusive Economic Zone (EEZ) shown in Figure C-1. Relevant federal departments for coastal management include Fisheries and Oceans Canada, Environment and Climate Change Canada, Transport Canada and Parks Canada. For federal waters and submerged lands, activities that fall under federal jurisdiction include management of mineral and hydrocarbon resources, protected areas, environmental assessments and marine pollution. In addition, the federal government has jurisdiction over navigation and shipping in all navigable waters, including inland waters, as well as fishing in all tidal waters (West Coast Environmental Law 2019).

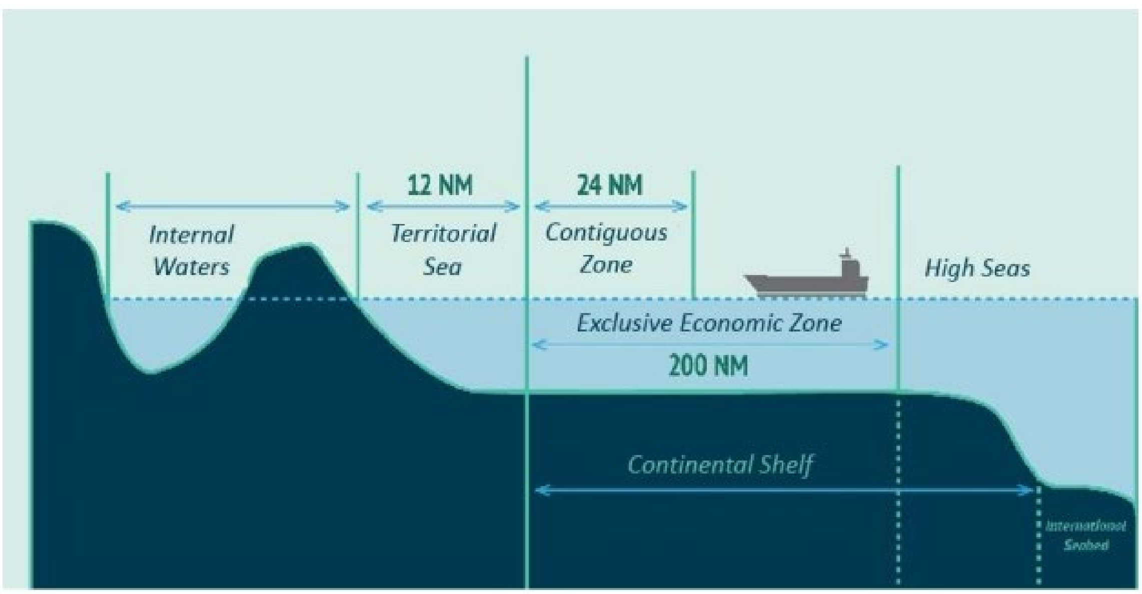


Figure C-1. Canadian coastal jurisdictional areas (West Coast Environmental Law 2019).

Provincial governments have jurisdiction over intertidal areas from low tide to the natural boundary shown in Figure C-2, as well as inland waters and submerged lands, which can include areas between islands and mainlands, such as the waters between Vancouver Island and mainland British Columbia (West Coast Environmental Law 2019). Many marine activities require joint federal-provincial authorization (e.g., marinas, renewable energy projects) because jurisdiction for these activities is shared between provincial and federal governments (West Coast Environmental Law 2019). Provincial and federal governments may also jointly establish marine protected areas and regulations to protect coasts from marine pollution (East Coast Environmental Law 2018)[5].

[5]See The Role of Provincial and Territorial Governments in the Oceans Sector (DFO): https://www.dfo-mpo.gc.ca/oceans/publications/pg-gp/page02-eng.html

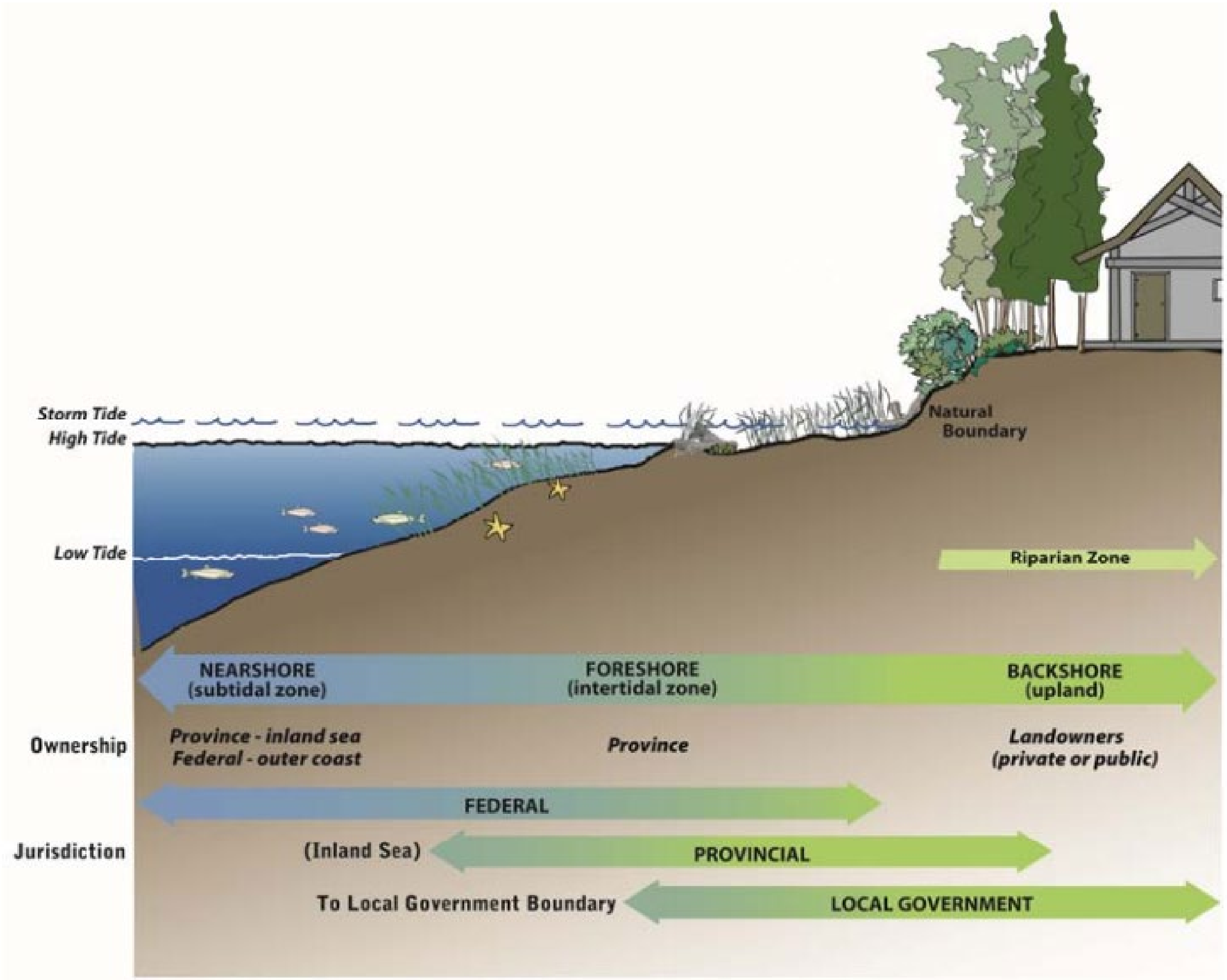


Figure C-2. Provincial coastal jurisdictional areas — British Columbia example (Stewardship Centre for British Columbia 2014).

Unlike federal and provincial jurisdiction, which is defined in the Canadian Constitution, municipal jurisdiction is granted by provincial statute (East Coast Environmental Law 2018). Municipal entities generally have jurisdiction over land use in coastal areas, so their authority begins at the high-water mark. This multilevel jurisdictional context means that for any given municipal shoreline, multiple levels of government may be relevant. For example, federal jurisdiction is applicable if a proposed development or management activity would impact the marine environment or provide services like wharves for fishing or recreational vessels; provincial jurisdiction is applicable if tenured activities would be affected; and municipal jurisdiction is applicable if the activity involves land use along the shore that is relevant to local zoning bylaws.

Indigenous communities have unique rights and title relevant to coastal resources and lands. Section 35 of the *Constitution Act* (1982) affirms Indigenous and treaty rights. Any Crown activities or development that may adversely affect these rights requires consultation with the Indigenous Peoples who may be affected (East Coast Environmental Law 2018).

Table C-1 displays a British Columbia example of the jurisdictional activities pursued by different levels of government at different locations along a shoreline.

Table C-1. Jurisdictional activities conducted by multiple levels of government at different locations along a shoreline – British Columbia example (see for location of backshore, foreshore and nearshore). (Stewardship Centre for British Columbia 2014).

	Local Government (LG) municipal, regional	Provincial Government	Federal Government	First Nations
Backshore	Plan and regulate land use through Official Community Plans (OCPs), zoning, development permits, etc.	Issue tenures (permit, licence of occupation, lease or grant) and sale of provincial Crown lands	Protection of commercial aboriginal and recreational fisheries, including shoreline (riparian) vegetation and timing windows	Planning and regulation on Reserve lands; may have claims to Aboriginal Title and Rights in other areas
Foreshore	Land use planning & regulation extends into the surface of the water that lies within Local Government (LG) boundary	Issue tenures over foreshore	Fish and fish habitat protection Protect public navigation in listed waters	Same as above
Nearshore	Land use planning and regulation extends into nearshore areas that lie within LG boundary	Issue tenures over nearshore areas in inland seas	Same as above	Same as above

Appendix D – Relevant Legislation, Policy and Market Instruments

This Appendix provides an overview of the types of federal and provincial legislation and regulations, municipal management levers and market-based instruments relevant to managing coastal natural assets in Canada.

D1. Relevant Federal Legislation and Regulations

- *Fisheries Act* – requires projects to avoid causing serious harm to fish unless authorized by DFO, enables closures of fish stocks from harvest (e.g., Rockfish Conservation Areas) and creation of ecologically significant areas that require enhanced protection. Fisheries Act (justice.gc.ca)
- *Migratory Birds Convention Act* – protects most species of migratory birds, and their nests and eggs, and applies to all land regardless of ownership. Migratory Birds Convention Act, 1994 (justice.gc.ca)
- *Canada Wildlife Act* – allows for the creation of wildlife areas for research or conservation purposes. Canada Wildlife Act (justice.gc.ca)
- *Canadian Navigable Waters Act* – requires projects to avoid substantially interfering with navigation in a scheduled navigable water. Canadian Navigable Waters Act (justice.gc.ca)
- *Canadian Environmental Assessment Act* – focuses on major projects and their potential environmental effects that are within federal jurisdiction. Canadian Environmental Assessment Act: An Overview - Canada.ca
- *Canadian Environmental Protection Act* – regulates emissions and scheduled substances. Canadian Environmental Protection Act, 1999 (justice.gc.ca)
- *Species at Risk Act* – prohibits killing, harming, harassing, capturing, taking, collecting and/or possessing any endangered, threatened or extirpated species, as well as destruction of identified critical habitat. Species at Risk Act: description - Canada.ca
- *Oceans Act* – allows for designation of marine protected areas to protect marine species and their habitats or unique habitats and areas of high biodiversity or biological productivity. Oceans Act (justice.gc.ca)
- *Canada National Marine Conservation Areas Act* – enables the establishment of national marine conservation areas. Canada National Marine Conservation Areas Act (justice.gc.ca)
- *Canada Shipping Act* – allows for the regulation of marine shipping activity to protect environmentally sensitive areas and species. Canada Shipping Act, 2001 (justice.gc.ca)
- *Canada National Parks Act* – allows for the designation of national parks/park reserves that may include a marine component (e.g., Pacific Rim National Park Reserve). Canada National Parks Act (justice.gc.ca)
- *Oil Tanker Moratorium Act* – prohibits vessels carrying more than 12,500 tonnes of crude or persistent oil from mooring, loading or unloading at any port on the B.C. north coast. Oil Tanker Moratorium Act (justice.gc.ca)
- *Fishery (General) Regulations* – allow for the creation of marine refuges under Variation Orders as well as imposition of conditions on fishing licence for conservation and protection of fish. Fishery (General) Regulations (justice.gc.ca)

D2. Relevant Provincial Legislation and Regulations for the Provinces of the Two Pilot Communities Evaluated During Development of the Coastal Toolbox

British Columbia

- *Fish Protection Act* – the Riparian Area Regulation (RAR) protects freshwater riparian area vegetation during land development. Although provincial, RAR is administered by local governments. FISH PROTECTION ACT (gov.bc.ca)
- *Wildlife Act* – includes conservation and management of wildlife populations and habitat, including for fishing, hunting and trapping. Wildlife Management Areas and restriction of activities within them are also designed under this act. Wildlife Act (gov.bc.ca)
- *Land Act* – allows for the granting of land, and the issuance of Crown land tenure in the forms of leases, licences, permits and rights-of-way. Land Act (gov.bc.ca)
- *Local Government Act* – may require a development permit or building permit if specified in the official community plan (OCP), and a flood plain bylaw may restrict uses, require construction requirements or require minimum setbacks in certain areas. Local Government Act
- *Ecological Reserves Act* – provides for the establishment and administration of ecological reserves, including for the protection of at-risk species and their habitat as well as for scientific research and education. Ecological Reserve Act (gov.bc.ca)
- *Environmental and Land Use Act – allows cabinet to designate areas by order in council and make regulations. This act is highly flexible, allowing cabinet to tailor protection and allow certain types of development only, or regulate how the land is used.* Environment and Land Use Act (gov.bc.ca)
- *Heritage Conservation Act* – enables the protection of sites containing physical evidence of human habitation or use prior to 1846 from damage or alteration; applies to public and private lands. Heritage Conservation Act (gov.bc.ca)
- *Park Act* – allows for establishment of parks, recreation areas and conservancies, as well as "designated wildland areas" where no development may occur (e.g., Broughton Archipelago Park). Park Act (gov.bc.ca)
- *Forest and Range Practices Act* – enables the designation of Wildlife Habitat Areas, which are meant to protect small areas of land for specific species of animals and plants as part of B.C.'s Identified Wildlife Management Strategy (e.g., Marbled Murrelet Wildlife Habitat Areas). Forest and Range Practices Act (gov.bc.ca)

New Brunswick

- *Coastal Areas Protection Policy* – implemented through the Watercourse and Wetland Alteration Regulation, regulates activities in coastal areas in the interest of maintaining ecological integrity, as well as the buffering capacity of coastal areas. Coastal-CB (gnb.ca)
- *Clean Environment Act* – regulates pesticide use, contaminants, restoration of land, wetland designation, coastal designation and electricity generation. Clean Environment Act (New Brunswick) (ecelaw.ca)
- *Species at Risk Act* – prevents species listed as extirpated, endangered or threatened from being killed, harmed, harassed or taken, and protects identified recovery habitat. Bill 28 - Species at Risk Act (gnb.ca)
- *Parks Act* – protects natural areas cabinet has designated as provincial parks from development, harvest and destruction. NEW BRUNSWICK - Parks Act (isthatlegal.ca)
- *Fish and Wildlife Act* – enables the creation of wildlife refuges and wildlife management areas, regulates

hunting, fishing, possession and sale of wildlife in the province. SNB 1980, c F-14.1 | Fish and Wildlife Act | CanLII

- *Protected Natural Areas Act* – allows for the creation of areas protected from all forms of development, as well as restricted areas deemed to be very sensitive and requiring provincial permits to access. Protected Natural Areas Act (gnb.ca)

D3. Municipal Planning and Management Levers

At the municipal level, communities can employ a variety of tools and strategies to shape land use and resource management activities to protect coastal natural assets. Municipal jurisdiction in coastal areas begins at the high-water mark, placing communities in a position to regulate shoreline land use critical to the function of coastal natural assets. Local government planning, such as regional growth strategies or official community plans, can establish land-use patterns that last for centuries. Local governments implement these plans using a variety of legislative powers, often granted under municipal government acts at the provincial level. Some of these legislative powers are:

- Zoning bylaws – can put official plans into effect through legally enforceable controls on how land is used and what can be built. By implementing zoning bylaws:
    - Communities can control the distribution of natural and grey infrastructure on the shore near coastal assets, influencing runoff, nutrient flows and erosion.
    - Municipalities can implement coastal or shoreline buffer zones that regulate human activities adjacent to coastal natural assets.
- Other bylaws – municipalities have the legislative authority to regulate activities such as landscaping, water use, tree removal and fertilizer and pesticide use. They can also regulate septic systems adjacent to coastal areas and other activities that influence coastal ecosystems.
- Development permitting and provisions – municipalities can regulate and restrict local development such that there are minimal disruptions to the natural functioning of adjacent shoreline ecosystems.
    - This can include restricting development in proximity to coastlines and watercourses to limit the impacts of new construction on sensitive shorelines and wetlands.
    - This can also include special requirements for development in natural areas. The District of North Vancouver, for example, has implemented Natural Environment Development Permit Areas, requiring landowners wishing to develop in those areas to follow guidelines to safeguard the environment, provide compensation for affected natural areas, commission environmental impact assessments or even provide a security in the form of a cash deposit. (natural-environment-development-permit-area-brochure.pdf [dnv.org]).

D4. Market Instruments

Taxes

- Governments at multiple levels can incentivize long-term private stewardship of important natural areas via property tax exemptions (e.g., the government of Ontario's Conservation Land Tax Incentive Program | Ontario.ca and the Island Trust Conservancy Ways to Protect your Land: Register a NAPTEP Covenant (islandstrustconservancy.ca).
- Similar tax exemptions and reductions can be used to incentivize private property designation under management plans, ensuring the ecological integrity of these areas (Managed Forest Tax Incentive Program | Ontario.ca).
- Governments can also move away from direct and indirect tax policies that incentivize the degradation and

overexploitation of natural areas.

Insurance

- Insurance shifts the financial consequences of risks (such as storms and floods) from a household or community to an insurer that receives a premium in exchange for having to reimburse clients after a disaster occurs.
- At the municipal level, insurers can incentivize natural asset enhancement by reducing insurance premiums for public infrastructure when adjacent natural assets are restored or enhanced, which decreases the risk and severity of a potential disaster.
- Premium reductions can be front-end loaded and combined with government contributions to facilitate restoration.

Subsidies and grants

- Government funding that incentivizes natural asset enhancement and management at municipal and regional scales.

Payments for ecosystem services

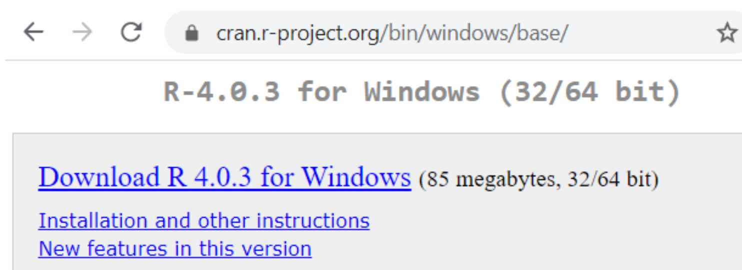
- Payments for ecosystem services (PES) are voluntary transactions wherein a "user" provides financial compensation to a service provider for a well-defined environmental service (Engel et al. 2008).
- In the case of municipal natural asset management, compensation would come from "downstream" beneficiaries (e.g., other municipalities) for enhancement or maintenance of upstream natural assets such as beaches/dunes, submerged structures, eelgrass and kelp, and riparian vegetation that provide coastal protection benefits "downstream."
- Services provided upstream may include improved land-use practices, improved water-quality regulation and other activities that can improve the condition of coastal natural assets and provision of ecosystem services downstream.
- In government-financed PES systems, the buyer is a third party acting on behalf of the service users. Under this structure, the Government of Canada could compensate municipalities for adopting land-use practices and maintaining upstream natural assets that support coastal natural assets.

Appendix E – Installation and Model Components of the Coastal Toolbox

Initial installation:

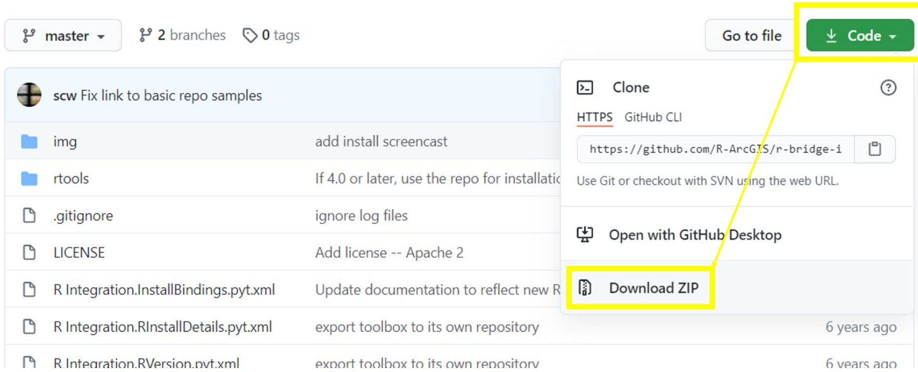
Follow the steps below to install the toolbox on your local machine. Note that you only need to do this once. After the toolbox is installed, you should be able to use it at any time without repeating these steps. You must have ArcGIS Pro installed on your machine to use this toolbox (download ArcGIS pro: https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview). The toolbox is designed to work under the most basic licensing options so there is no need to enable Spatial Analyst or any other extensions. Note that the package will not work on ArcMap or older ESRI software products. It is assumed that users have basic familiarity with ESRI software, spatial data formats and fundamental concepts of GIS. Toolbox installation involves three steps: installing R, installing the R-ArcGIS Bridge and installing the CPBT.ArcGIS.Tbx toolbox. Some warning messages are okay, but if you see a red error message, look into the details to see why a step may have failed.

- **Download and install R for windows**
    - Visit the R Project download page https://cran.r-project.org/bin/windows/base/
    - Click download R #.#.# for Windows note that the version may be different that the version listed at the time of writing, but make sure you have installed R version 4.0.5 (or later)

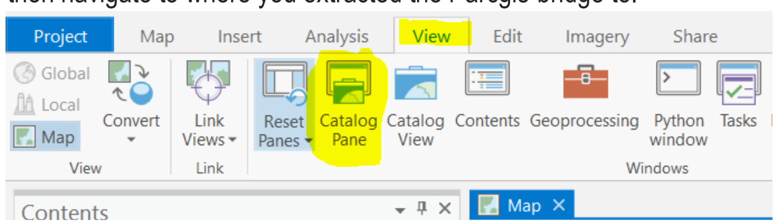


    - Unzip the folder and follow the installation instructions. Be sure to install the 32-bit file and the 64-bit files (default option).

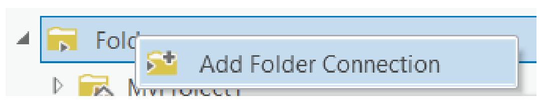
- **Download and install the R-ArcGIS Bridge for ArcMap**
    - Navigate in your web browser to https://github.com/R-ArcGIS/r-bridge-install
    - Follow the instructions below and review the instructions on the link above if you get lost.
    - Download the repository as a zip folder and extract the files.



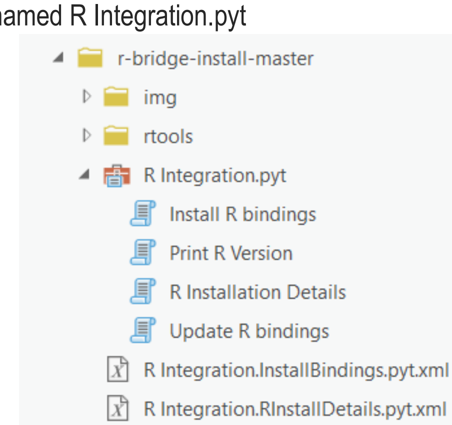
- Unzip the folder to a local directory that ArcGIS Pro can access
  - r-bridge-install-master.zip
- Start a new (blank) empty project in ArcGIS
- While in ArcGIS > open the Catalog pane > then open folder Connections > click Connect to a New Folder and then navigate to where you extracted the r-arcgis-bridge to.



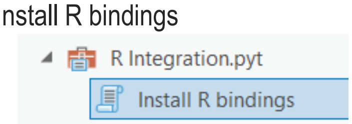
- Add the folder 'r-bridge-install-master' as a new folder connection.



- Expand the red toolbox named R Integration.pyt

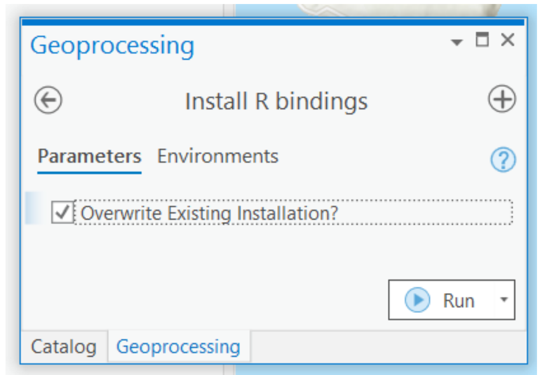


- The click the blue script titled Install R bindings

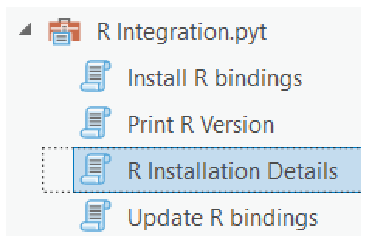


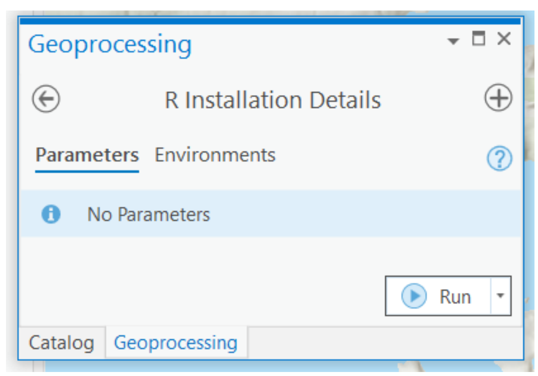
- Checkbox for Overwrite existing installation (recommended)

- Then Click the “run” button. *Some warning messages are okay ☺.*

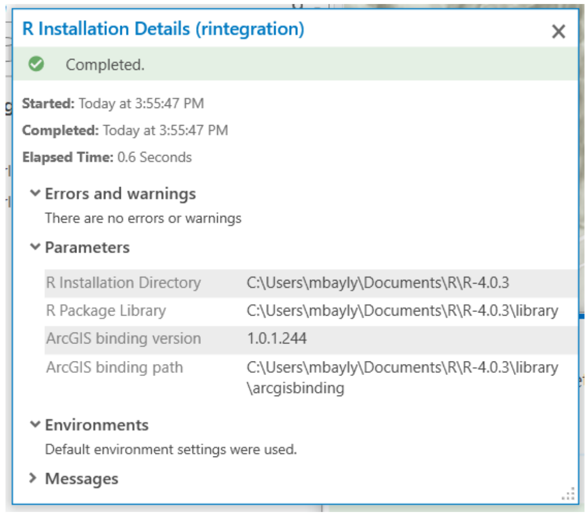


- **** If the above installation fails (red error message), try running ArcGIS Pro in administrator mode; ensure that you can access R outside of ESRI software and ensure that you have read/write permissions to your install directory. Review additional details on the readme page here: https://github.com/R-ArcGIS/r-bridge-install.****
- (Optional) Verify the installation was successful by going back to the R Integration.pyt toolbox and run R installation details. If you encounter issues after and ArcGIS Pro software update try reinstalling the Coastal Toolbox.

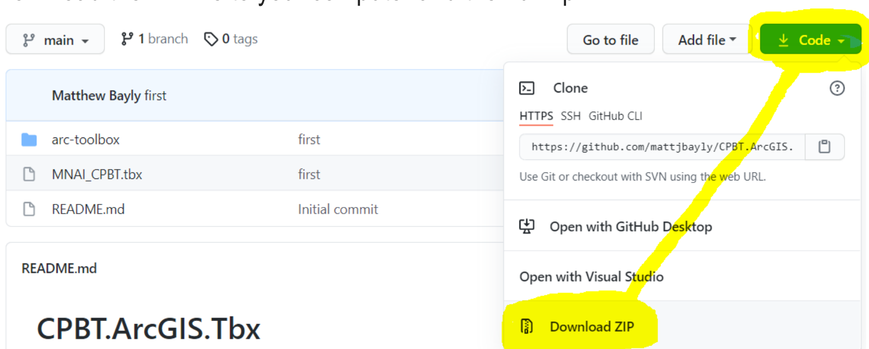




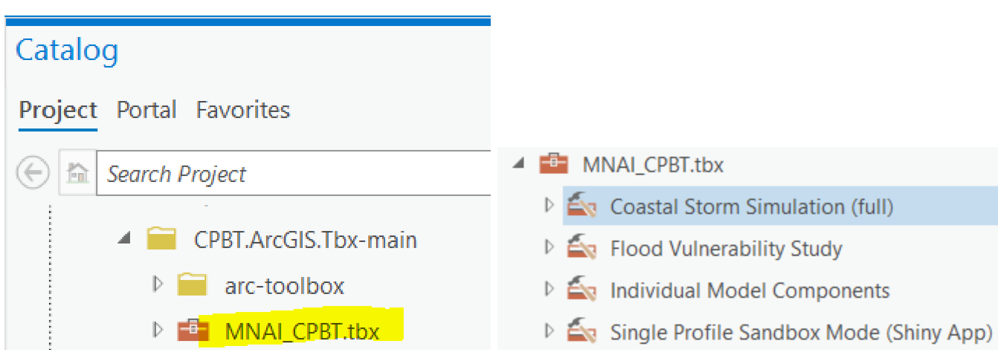
- (Optional) You should see something like this, but version numbers may differ.



- **Download the MNAI CPBT ArcGIS Toolbox.**
  - Navigate in your web browser to the project download page and download the toolbox: https://github.com/essatech/CPBT.ArcGIS.Tbx.
    **** If this link is broken, please contact MNAI for a zip file copy.*
  - Click the green code button and then click "Download ZIP."
  - Download the ZIP file to your computer and then unzip.

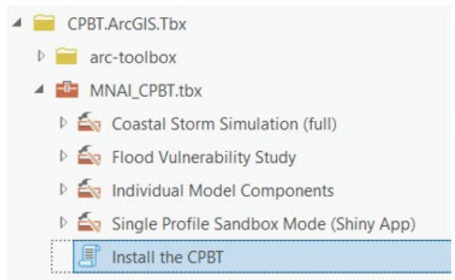


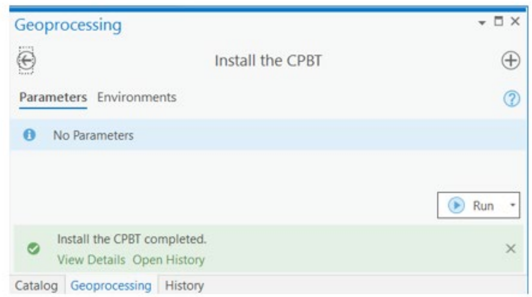
  - Go back to ArcGIS Pro and then go to the Catalog pane. Right click on the Folders icon and click refresh. Click add folder connection and add the unzipped CPBT.ArcGIS.Tbx folder that you just downloaded (this is the Coastal Toolbox for ESRI).



- **Install the MNAI.CPBT Package**

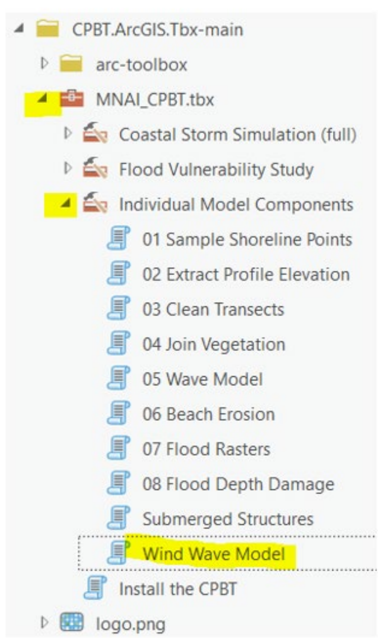
- In the toolbox CPBT.ArcGIS.tbx catalog pane you should see a blue script icon (tool) named *Install the CPBT.* Click on this and run this tool.
- This starts the installation (may take 1 – 2 minutes). Wait until this function finishes for installation to finalize. You should see a screen like this:

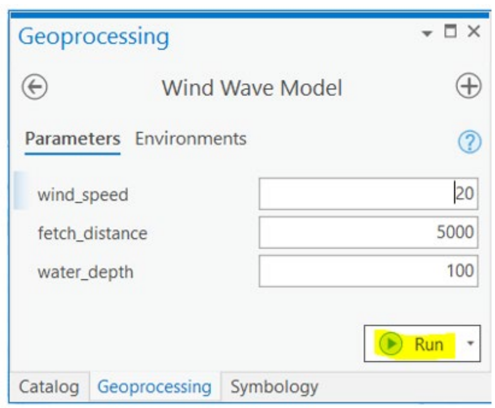


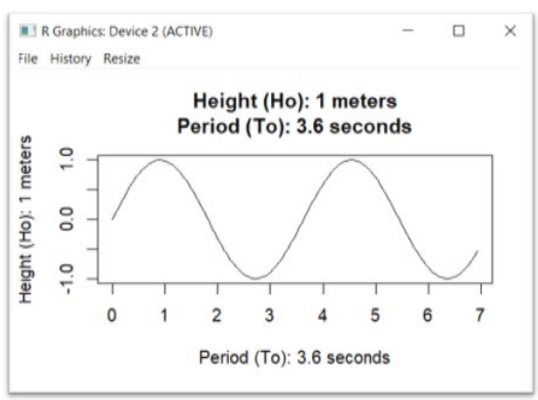


- **** If the above installation step fails, you can manually install the toolbox by opening R (outside of ArcGIS) and running the following lines of code in the R console install.packages("remotes"); library(remotes); remotes::install_github("essatech/MNAI.CPBT", upgrade ='always', force = TRUE); be sure to close out of all other programs and try running R in administrator mode.*

Congratulations! You are now ready for coastal modelling! As a quick check you can try running the Wind-Wave calculator just to ensure everything is working properly (optional).







Function documentation:

Coastal Storm Simulation Toolbox

This toolbox runs the complete CT analysis along a coastline for a given storm simulation. After users click “run” with all necessary inputs arguments an output results folder will be created at specific directory. This output folder will contain all results organized into a single HTML page for simple viewing and interpretation. This is considered the full or complete model since all components from raw data through to economic valuation are bundled into a single function.

Coastal Storm Simulation Toolbox Arguments

simulation_name: Simulation name for current storm and conditions.
Output Folder: Local output directory for CT simulation results. *An output folder*.
Coastline: Spatial line feature layer. Coastline spatial line segment for modelling. The coastline should roughly trace the water edge along the beach at the mean sea level. It is recommended to keep the coastline geometry simple and avoid sharp corners.
ShorelinePointDist Numeric. Spacing between cross-shore profile lines (metres). Note that it is recommended to keep this number as large as possible for your area of interest to speed up processing time. For processing efficiency, the model should have no more than 20 to 30 cross-shore profiles. A general recommendation to define the spacing between cross-shore profiles can be obtained by dividing the coastline length (in metres) by 20. Additionally, cross-shore profile distribution should consider changes in coastal orientation.
BufferDist: Numeric. Buffer search distance (metres) used to identify the perpendicular angle of each cross-shore profile line from the coastline (recommended values are 10-50). Users should not need to change default settings unless cross-shore profiles are irregular and not perpendicular to coastline.
RadLineDist: Numeric. Radial line distance (in kilometres) of the cross-shore profiles. This value determines how far offshore (and how far onshore) the cross-shore profiles should extend (recommended values are one to three kilometres).
TopoBathy: TopoBathy digital elevation model of class RasterLayer.
SmoothParameter: Numeric, smoothing window length as a percentage of the total cross-shore profile length (0-100). A value of zero means no smoothing (recommended values are 5-20). If waves heights increase shoreward and show bizarre unrealistic behaviour, try adjusting this value from one to 30 per cent.
MaxOnshoreDist: Numeric. Maximum radial line distance onshore in kilometres. Note that in some instances the onshore extent should be truncated significantly for the wave evolution model. It is recommended to keep this value below one kilometre.
Trimline: (Optional) spatial line feature class back-shore trim line used to restrict the onshore extent of the cross-shore profiles. The default value is none (blank — not used). If used, the back-shore trim line should run parallel to the coastline but be set back onto land. A back-shore trim line may be required in cases where cross-shore profiles are generated along the coastline of a narrow peninsula or in instances where there is a back-shore lagoon. A back-shore trim line should be provided as a simple line feature class.
Vegetation: A feature layer polygon class of submerged vegetation patches. Ensure geometry has no errors, there are no overlapping polygons and attribute fields are complete.

hc - Numeric, Blade height in metres.
N - Numeric, shoot density as number of shoots per metre squared.
d - Numeric, blade width in metres (e.g., 0.015).
Type – Character, either “eelgrass,” “kelp” or “marsh.”
Cd - Numeric, drag coefficient as per Guannel et al 2015. If unsure use a value of 0.1 for eelgrass.

mean_high_water: Numeric, mean high tidal water elevation above the chart datum (metres) referenced to the TopoBathy DEM.
mean_sea_level: Numeric, mean average tidal water elevation above the chart datum (metres) referenced to the TopoBathy DEM.

tide_during_storm: Numeric, tidal elevation in metres during the storm referenced to the chart datum (metres) of the TopoBathy DEM.
surge_elevation: Numeric, additional elevation from storm surge (in metres) during the storm.
sea_level_rise: Numeric, additional elevation from any local sea-level rise (in metres) during the storm.
Ho: Initial (starting) offshore wave height in metres.
To: Initial (starting) offshore wave period in seconds.
storm_duration: Numeric. Storm duration in hours.
BeachAttributes Feature class spatial polygon layer of foreshore beach attributes. Polygons should be drawn around each beach and populated with the following attributes:

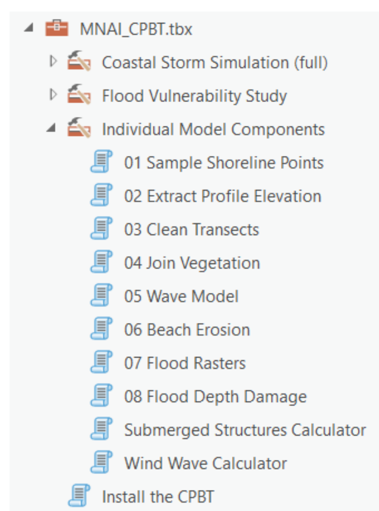
slope: the foreshore slope (slope) as rise over run (min 0.02 and max is 0.20).
W: Numeric, the berm width in metres (W).
B: Numeric, berm height in metres (B).
D: Numeric, dune height (D) in metres.
sediment: Numeric, the sediment grain size in millimetres (sediment) (min 0.12 mm for fine sand and max is 0.15 mm for coarse sand).
V: Numeric, the beach value per metre squared in dollars (V).

Tr: Numeric. Return period (frequency) of the simulated storm (in years).
PropValue: General land value in dollars per square metre of beach. (not used if beach polygon property values are provided).
disc: Annual valuation discount rate over the time horizon (0 - 1).
TimeHoriz: Time horizon (in years) for long-term cumulative valuation given a storm return frequency. Typically, 100-year horizons are used.
Bldgs Spatial polygon of building footprints as a feature class. Mandatory attributes include:

1. DDID: Numeric, the HAZUS depth-damage curves IDs populated for each structure (column name: DDID e.g., RES1-147).
2. VAL: Numeric, estimates of the replacement value cost for each structure in dollars (VAL).

Output folder contents: After the function has run, navigate to the output folder directory. The output folder will contain a file called SimulationResults.html and www. Open the HTML file to view the summary report. Spatial data export are located in the ./www/data path. Individual cross-shore profiles are exported to www\data\profile_csv.

Individual Model Components Toolbox

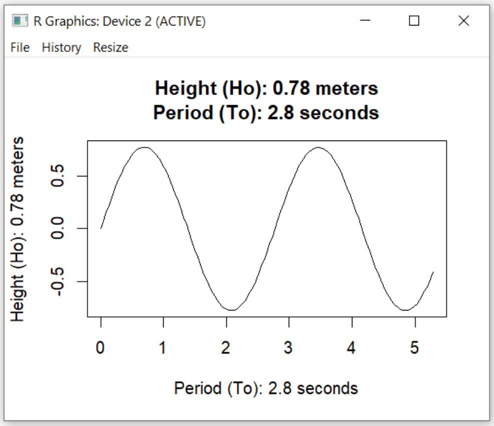


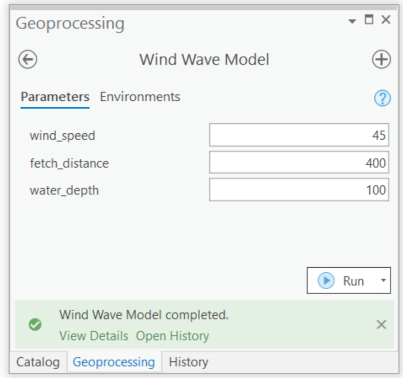
The Individual Model Components is a sub-toolbox of specific functions to help users with special applications or custom extensions to their communities. Many users may not need the full Coastal Storm Simulation and output report, but instead may only require a specific sub-model of the assessment framework. This toolbox isolates specific functions for convenience to help with specific applications, and is also a good way to get to know the CT better by understanding how its sub-models operate.

Wind Wave Model Calculator

This function acts a simple calculator to estimate wave height and period from a fetch distance, wind speed and average depth. The CT uses wave height and wave period rather than wind speed and fetch for storm simulations. In many cases users are unlikely to have accurate estimates of local wave height and period for their area of interest. Wind speeds are more likely to be available in local archives and can therefore be used to estimate wave parameters. We encourage uses to utilize values from Environment Canada Marine Weather (https://weather.gc.ca/mainmenu/marine_menu_e.html) and apps such as Windy (https://www.windy.com/) where possible. Arguments for the wind wave model include:

wind_speed: Wind speed in units of metres per second.
fetch_distance: Fetch distance in units of metres.
water_depth: Average offshore water depth in units of metres.
Returns an estimate of the wave height and period to the console. Note that this function does export any data.





Submerged Structures Calculator

Simple calculator to estimate the reduction in wave height as a wave passes over a submerged structure. The submerged structures model is a very simplified evaluation of these features. User inputs include wave height, period and water depth at the structure's location as numeric values and the model returns a fractional reduction in wave height due to the structures influence. The final wave height after passing over a submerged structure is reported as a fraction (0 to 1) or the original wave height. This function does not make use of spatial data.

1. **Hi** Initial wave height (m) at the seaward margin of a submerged structure.
2. **To** Initial wave period (s) at the seaward margin of a submerged structure.
3. **hi** Total water depth (m) at the seaward margin of a submerged structure.
4. **hc** Height of the submerged structure (m) above the surrounding seabed.
5. **Cwidth** Crest width (m) at the top of the submerged structure.
6. **Bwidth** Base width (m) at the bottom of the submerged structure.
7. *Returns: The final wave height after passing over a submerged structure is reported as a fraction (0 to 1) or the original wave height (e.g., a value of 0.6 would indicate a 40 per cent reduction in wave height from the submerged structure).*

Depth-Damage Reference Curves

Note that there are over 10,000 unique depth-damage curves in the original HAZUS database to choose from for each structure. These curves are embedded inside the tool if users wish to explore that level of detail (e.g., assigning different depth-damage curves for law firms versus accounting firms). However, it is expected that most users may simply choose between 1 – 4 curves for to characterize structures in their area. In Table E-1 we have listed the most common and useful curve IDs:

Table E-1. HAZUS DDID depth-damage reference curve IDs for the building footprint layer.

DDID	Description
RES1_151	one storey, structure, salt water, short duration
RES1_147	one storey, slab foundation, structure, salt water, short
RES1_167	two storey, structure, salt water, short duration

RES1_163	two storey, slab foundation, structure, salt water, short
RES2_195	mobile home, structure, salt water, short duration
RES2_199	mobile home, structure, salt water, short duration
COM1_307	gas station, structure, salt water, short duration
COM1_312	large grocery, structure, salt water, short duration
COM1_317	neighbourhood grocery, structure, salt water, short duration
COM1_322	home-repair store, structure, salt water, short duration
COM1_327	liquor store, structure, salt water, short duration
COM1_300	department store, structure, composite water and duration
COM1_292	convenience store, structure, salt water, short duration
COM1_297	department store, structure, salt water, short duration
COM2_365	warehouse, structure, salt water, short duration
COM3_390	auto repair, structure, salt water, short duration
COM3_400	beauty salon, structure, salt water, short duration

Sub-model 1. Sample Shoreline Points

This function samples shoreline points along a defined area of interest and then generates perpendicular cross-shore profile lines. A shoreline section is provided by the user (by manually tracing or digitizing the mean tidal height) and points are sampled along the shoreline at specified distance intervals. These points are then used to generate perpendicular shoreline transects. Arguments:

1. **Shoreline Section** Spatial line of the coastline (keep the geometry simple and avoid sharp corners).
2. **Perpendicular Search Distance:** Numeric, Buffer search distance (metres) used to identify the perpendicular angle of each cross-shore profile line from the coastline.
3. **Max Radial Line Distance Numeric:** Numeric, Radial line distance (kilometres) of the cross-shore profiles. This value determines how for offshore (and onshore) the cross-shore profiles should extend (recommended values are one to three kilometres).
4. **Shoreline Point Distance:** Numeric, Spacing between cross-shore profile lines (metres). Note that it is recommended to keep this number as large as possible for your area of interest to speed up processing time.
5. *Returns cross-shore profile lines (Output Lines [feature class]) and shoreline points (Output Points) to the layer panel.*

Sub-model 2. Extract Profile Elevations

This function takes the cross-shore profiles generated from the Sample Shoreline Points function and extracts elevation values from an underlying TopoBathy DEM. Arguments:

1. **S01_Profiles:** Spatial lines, cross-shore profiles lines that were output from the previous function (01 Sample Shoreline Points).
2. **Bathy Topo Bathy DEM:** digital elevation model (in meters) of type Raster Layer.
3. *Returns cross-shore profile lines (S02_PointElevations) as spatial points along each line with elevation values to be used in the next function.*

Sub-model 3. Clean Transects

A helper function to clean, QA and verify cross-shore profiles. This utility function cleans transects and remove anomalies that may break the wave-evolution model. This function also ensures that transects are pointing in the correct direction and fixes them if they are not.

1. **S02_PointElevations**: Spatial points, Cross-shore point elevations spatial points object returned from the previous

function (S02 Extract Profile Elevations).

2. **Radial Line Distance:** Numeric, Maximum radial line distance (onshore and offshore) in kilometres of the cross-shore profiles. Note that this value must be the same value used in S01 Sample Shoreline Points.
3. **Max Onshore Dist**ance: Numeric, Maximum radial line distance onshore in kilometres. Note that in some instances the onshore extent should be truncated significantly for the wave-evolution model. It is recommended to keep this value below 1 km. If transects are getting lost (omitted through the function) we suggest reducing this number to a value close to zero.
4. **Trim line:** Spatial line. Optional back shore trim line used to restrict the onshore extent of the cross-shore profiles. The default value is NA (not used). If used, the back-shore trim line should run parallel to the coastline but should be set back onto land. A back-shore trim line may be required in cases where cross-shore profiles are generated along the coastline of a narrow peninsula or in instances where there is a back-shore lagoon. A back-shore trim line should be provided as a simple features line object.
5. *Returns cross-shore finalized spatial points along each cross-shore profile ready for modelling.*

Sub-model 4. Join Vegetation

This function joins data from the underlying vegetation polygons to the spatial points object returned from S03 Clean Transects. Note that this function must be run before the wave-evolution and erosion models can be run. Even if your project has no vegetation, running this function is still necessary to format the data frame with appropriate columns.

1. **S03 Clean Points:** Spatial points. Cross-shore point elevations spatial points object returned from S03 Clean Transect.
2. **Vegetation**: A feature layer polygon class of submerged vegetation patches. Ensure geometry has no errors, there are no overlapping polygons and attribute fields are complete. If you have no submerged vegetation, then simply leave this field blank.
    a. hc - Numeric, blade height in metres
    b. N - Numeric, shoot density as number of shoots per metre squared.
    c. d - Numeric, blade width in metres.
    d. Type – Character, either ”eelgrass,” “kelp” or marsh.”
    e. Cd - Numeric, Drag coefficient as per Guannel et al 2015. If unsure use a value of 0.1 for eelgrass.
3. *Returns spatial points feature class updated with vegetation data attributes and ready for the wave-evolution and erosion model.*

Sub-model 5. Wave Model

This function models wave evolution and propagation along a cross-shore profile with input storm parameters. Wave-attenuation model originally developed by Greg Guannel for the Coastal Natural Capital InVEST project (https://invest-userguide.readthedocs.io/). This function models wave attenuation along a cross-shore elevation profile.

1. **S04 Join Veg:** A spatial points feature class of cross-profiles returned from sub-model 4. Join Vegetation.
2. **Total Water Surface Elevation:** Numeric. Total water surface level (in meters) above the chart datum. Recall that the chart datum and TopoBathy DEM are referenced to a value 0 at low water. It is therefore suggested to set this value at the mean sea level above chart datum or a specific tidal elevation of interest.
3. **Waver Height, Ho:** Numeric. Initial offshore wave height in metres.
4. **Waver Period, To:** Numeric. Initial offshore wave period in seconds.
5. **Force Bad Transects Through Model:** Boolean TRUE/FALSE. should transect be forced even if there are error codes.
6. *Returns a spatial points object updated with wave data along each cross-shore profile saved to the layer panel.*

This function models wave attenuation along a cross-shore elevation profile. Input parameters include a pre-processed cross shore profile dataset (S04 Join Veg)developed through the sequence of functions shown in the example, the total water surface level of still water (adjTotal Water Surface Elevation) above the chart datum, the wave height (Ho) and wave period (To). After running, the function populates the original input dataset with the follow data attributes wave setup with vegetation (Eta), wave setup without vegetation (Etas), bottom orbital velocity (Ubot), wave height with vegetation (H_veg), wave height without vegetation (H_noveg) and wave dissipation (Dis1). If you receive a message stating Transect failed — bad sort order, we suggest decreasing the MaxOnshoreDist, adding a trim line or decreasing the water level.

Sub-model 6. Beach Erosion

This function takes runup from the wave model and foreshore characteristics from the beach polygons to predict shoreline retreat and estimates for the erosion indices.

1. **S05 Wave Model:** Spatial points. Cross-shore profile spatial points object returned from the previous S05 Wave Model function.
2. **Beach Attribute Polygons:** Spatial polygons draw around each beach section (see mandatory beach foreshore attribute fields).
3. **Ho** Initial offshore wave height in metres.
4. **To** Initial offshore wave period in seconds.
5. **Total Water Surface Elevation:** Total water surface level above the chart datum. Recall that the chart datum and TopoBathy DEM are referenced to have 0 at low water. It is recommended that the erosion model is run with mean sea level.
6. **Storm Duration** Numeric. Storm duration in hours. Six to 12 hours is normally representative, but six hours can be used as a preliminary default value.
7. **Shoreline Point Spacing:** Numeric. Use default values or keep this value the same as the value used in Sub-model 1. Sample Shoreline Points.
8. **Beach Value ($/m2):** Numeric. General land value in dollars per square metre of beach (Not used if beach polygon property values are provided).
9. **Strom Return Period Tr (Years):** Numeric. Return period (frequency) of the simulated storm (in years).
10. **Annual Discount Rate (0 – 1):** Numeric. Annual valuation discount rate over the time horizon (0 - 1).
11. **Time Horizon For Evaluation (years)**: Numeric. Time horizon (in years) for long-term cumulative valuation given a storm return frequency. Typically, 100-year horizons are used.
12. *Returns a table with erosion estimates for each cross-shore profile (Output erosion summary table) and a spatial points object (S06_BeachErosion) showing the erosion estimate for each beach section. Data columns are referenced by suffix _NoVeg is estimated without submerged vegetation and _Veg is an estimate with submerged vegetation. Consider using the Higher High Water Large Tide (HHWLT) for this input*.

The coastal erosion model was originally developed by Greg Guannel for the Coastal Natural Capital InVEST project. This function estimates lateral beach erosion and wave runup for each cross-shore profile. Foreshore parameters for berm width, height, etc. are provided as spatial polygons for each beach section. These are then linked to underlying cross-shore profiles for erosion estimates. The return object is a data frame showing erosion estimates for each cross-shore profile.

1. retreat_: Lateral beach retreat distance in metres from the storm (single storm event).
2. runup_: Vertical wave runup elevation at a profile.
3. damage_: Total erosion damage at a cross-shore profile section from beach loss due to retreat and storm return period over the time horizon.
4. transect_id: Cross-shore profile transect ID (to link back to previous data sets).
5. area_loss_: Beach loss area m2 from the storm (single storm event).
6. vol_loss_: Beach loss volume m3 from the storm (single storm event).
7. retreat_pct_: Beach retreat percentage (lateral retreat distance divided by berm width).
8. retreat_index_: Beach retreat index score 1-5.

Sub-model 7. Flood Rasters

This function generates flood raster and water depth surfaces from the storm event and flood contours.

1. **S06_BeachErosion:** Spatial points object returned from S06 beach erosion.
2. **TopoBathy DEM (m):** TopoBathy digital elevation model of class RasterLayer.
3. **High Tide Elevation (m):** Numeric, Mean high-water tidal level above the chart datum.
4. **Total Water Surface Elevation (m):** Numeric. Total water surface level above the chart datum. Recall that the chart datum and TopoBathy DEM are referenced to have 0 at low water. It is therefore suggested to set this value at the mean sea level above chart datum or a specific tidal elevation of interest.
5. *Returns flood rasters and flood contours to the layer panel.*

Sub-model 8. Flood Depth Damage

This function generates flood-damage estimates for a community based on the local wave runup modelled at each profile and the static water level.
(*additional arguments inherit from above functions*)

1. **S06_BeachErosion:** Spatial points object returned from S06 beach erosion.
2. **TopoBathy DEM (m):** TopoBathy digital elevation model of class RasterLayer.
3. **Building Footprint:** Polygon feature class. Spatial polygon object of building structure footprints. This dataset must have HAZUS depth-damage curves IDs populated for each structure (DDID) as well as estimates of the replacement value cost for each structure in dollars (VAL). See Depth-Damage Reference Curves and the sample Buildings.shp dataset as an example.
4. *Returns: Flood damage cost summaries for the storm event with the number of structures flooded, the mean flood depth and the total damage cost. Values are provided for scenarios with and without submerged vegetation.*
    1. nStructure: Number of structures flooded.
    2. MedianDepth: Median depth of flooded structure.
    3. MaxDepth: Maximum flood depth across all structures.
    4. Damage: Total flood structural damage cost in dollars.

Flood Vulnerability Study

Flood Vulnerability Study

The “flood vulnerability” is a computationally intensive yet simple tool to allow communities to better understand the vulnerability of their communities to coastal flooding. The function works by gradually raising the water level by a fixed amount and then recalculating the structural damage cost of a flood at that water level. Users define a range of elevation (e.g., zero to five metres above chart datum) and a step size for incremental water level increases (e.g., 0.15 m) and then the function calculates total damage cost at each 0.15 interval. An HTML report is exported with three plots showing the depth-damage curves used in the assessment, the number of affected structures at each water level and the total damage cost at each water level (Figure E-1). The intent of this tool is to look at overall damage costs of different storms. If the number of affected structures and total damage costs quickly climb upward at low-water levels, users can assume that the area is highly vulnerable to coastal flooding. Conversely, if damage costs do not show any significantly values until the water level reaches extreme levels, users can conclude that the community is naturally resilient to flooding. Users can also evaluate tipping points at which the damage costs climb significantly for a given water level. For example, if a community is expected to have no structural damage below flood water levels of 2.1 metres CD, but then experiences millions of dollars in damages between water levels of 2.1 to 2.5 metres, users can conclude that any forces pushing the water levels above two metres represent a significant concern for their communities.

output_dir Output file directory for the report.

start_elev Numeric. Starting input elevation in metres — usually the elevation of the high-water line (mean high tide).

end_elev Numeric. End elevation in metres — how far the function should search. Usually, this value is below 10 metres. The lower the better to speed up processing time.

step_size Numeric. Step size for the cumulative assessment in metres (granularity). Usually this

value is set at 0.2 metres, although it should be as large (coarse) as possible to speed up processing time.
Bldgs spatial polygon object of building structure footprints. This dataset must have HAZUS depth-damage curves IDs populated for each structure (DDID) as well as estimates of the replacement value cost for each structure in dollars (VAL). See data(Bldgs) for an example input.
TopoBathy digital elevation model of class RasterLayer.
Outputs a file folder with csv files of results.

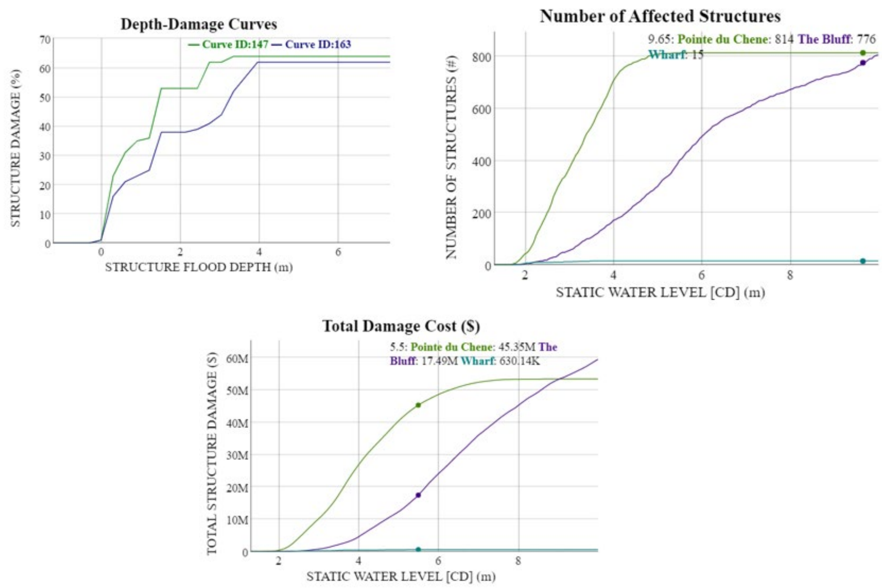


Figure E-1. Plots showing depth-damage curves, number of affected structures and total damage cost at each water level.

Exploration in Sandbox Mode

Single-Profile Sandbox Mode (R-Shiny App)

The single-profile sandbox mode can be used to quickly view and manipulate conditions along a single profile. All that is needed to use the tool is a csv file of a single cross-shore profile from any scenario output. Users can find csv outputs in each of the output folders from running the full CT function (www\data\profile_csv). The Single Profile Sandbox application can be accessed at the following url in a Chrome web browser:

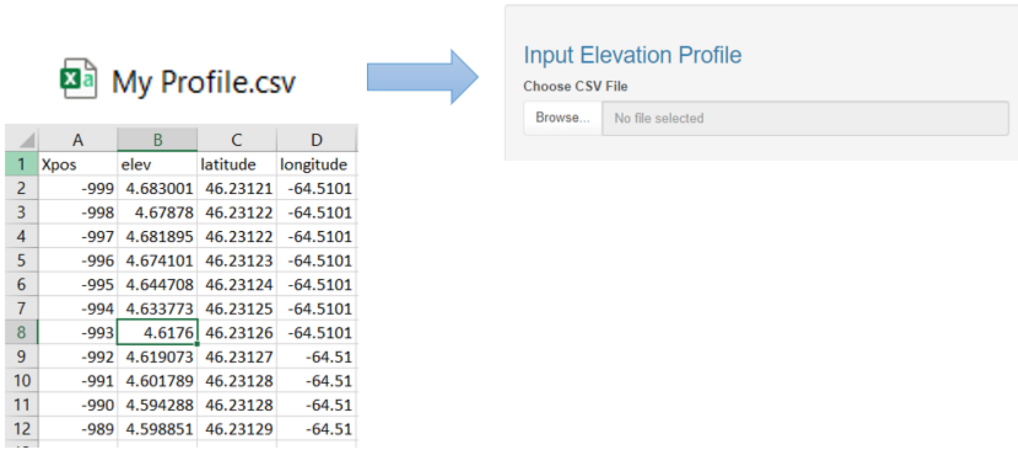
https://essa.shinyapps.io/ProfileSandboxExplorer/

If you wish to access the source code to this Shiny application to modify or run it on your own computer, please download content from the repository here: https://github.com/essatech/CPBTProfileSandboxExplorer.

The input cross-shore profile csv file must have the following columns (see example below):

Xpos Cross-shore profile horizontal distance in metres from the shoreline. 0 is the water's edge and negative values are distance onto land while positive values are distance seaward away from the shoreline (e.g., Xpos of 200 is 200 metres offshore and Xpos of -200 is 200 metres on land away from the shoreline).
elev Elevation in metres referenced to the chart datum where a value of zero is the lower low-water line.
latitude and longitude columns are optional (but recommended) to show the extent of flooding. They should be included as decimal degrees for each point with longitude values being negative in North America.

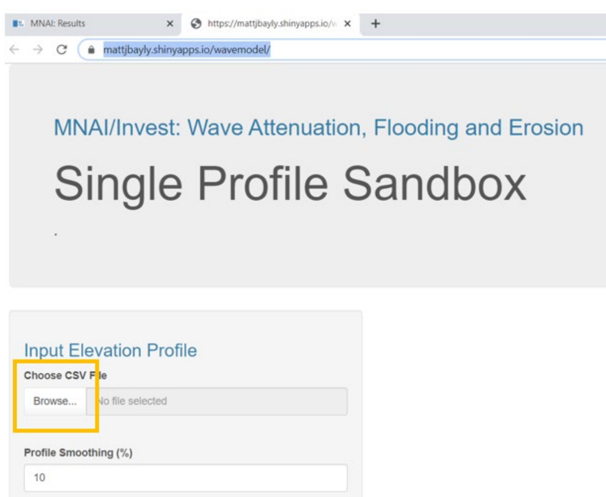
This data can be exported from sub-model 2, Extract Profile Elevations, but each csv file must only contain data for a *single profile.*



	A	B	C	D
1	Xpos	elev	latitude	longitude
2	-999	4.683001	46.23121	-64.5101
3	-998	4.67878	46.23122	-64.5101
4	-997	4.681895	46.23122	-64.5101
5	-996	4.674101	46.23123	-64.5101
6	-995	4.644708	46.23124	-64.5101
7	-994	4.633773	46.23125	-64.5101
8	-993	4.6176	46.23126	-64.5101
9	-992	4.619073	46.23127	-64.51
10	-991	4.601789	46.23128	-64.51
11	-990	4.594288	46.23128	-64.51
12	-989	4.598851	46.23129	-64.51

Instructions for use:

1. Choose an output csv from the CT function (www\data\profile_csv) or prepare a csv file for a single cross-shore profile according to the above format (note that latitude and longitude columns are optional).
2. Click the "Browse" button below "Choose CSV file" and upload your csv cross-shore profile of interest.
3. Then update the default values for tidal elevations and foreshore parameters to match the baseline conditions for your area of interest. *It is not recommended to keep default baseline conditions since tidal ranges may vary considerably for your local area.*
4. Submerged vegetation patches such as eelgrass meadows can be added at specified distances along the profile. Simply define start and stop Xpos distances for each meadow. Multiple patches can be added or removed for a single profile.
5. Finally, when you are satisfied with the input parameter, click the blue "Update Predictions" button to run the storm simulation.

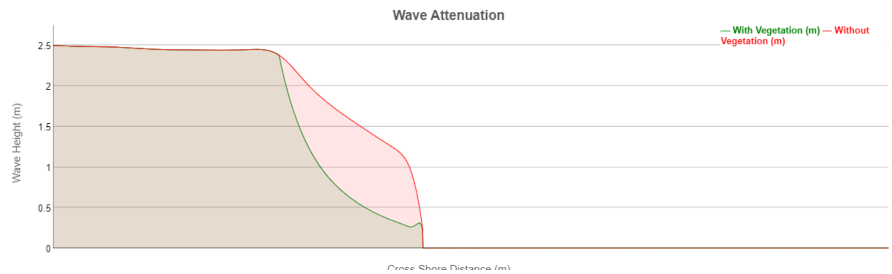


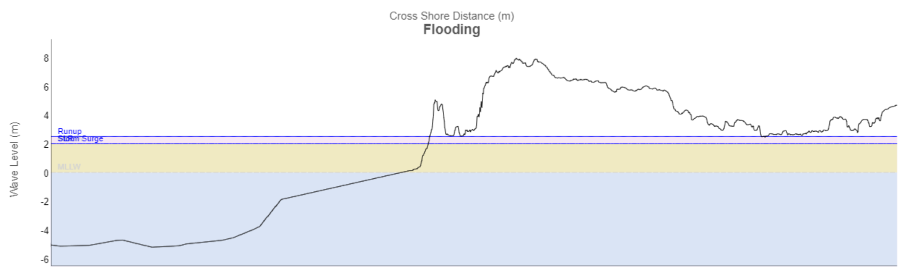
6. The first output plots show wave attenuation along the distance of the profile from the storm. The model is run twice with and without submerged vegetation to show potential differences. As waves

get closer to shore, they are attenuated, and their wave height reduces. In the example below an unrealistically dense vegetation patch was added to the profile to highlight the differences.

7. The next plot shows the cross-shore elevation profile of the current profile. The mean lower low-water line represents the chart datum (0 m elevation – low tide). The additional horizontal lines show the cumulative still-water level as a result of storm surge, wave runup and any sea-level rise.
8. The last plot shows the distribution of user-defined submerged vegetation along the profile.

Wave Attenuation





9. The summary table provides estimate of the horizontal beach retreat, wave runup and erosion damage with and without submerged vegetation.

Horizontal Beach Retreat (m)

Without Vegetation	With Vegetation
2.6m	2.2 m

Vertical Wave Runup (m)

Without Vegetation	With Vegetation
0.7m	0.6 m

Erosion Damage ($)

Without Vegetation	With Vegetation
$206,028.0	$170,938.0

10. A map is also included to allow the user to see where the profile is located along the coastline. The blue line will extend shoreward to the maximum flood extent.

Invest in Nature

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The David Suzuki Foundation (DSF) is a national, bilingual non-profit organization working to conserve and protect the natural environment and help create a sustainable Canada through evidence-based research, education and policy analysis. DSF is exploring and promoting the services that nature provides to our societies. Learning to understand, measure and manage nature-based solutions can help people make better decisions about how we interact with nature and can provide new justifications for protecting and restoring natural spaces.

The Municipal Natural Assets Initiative (MNAI) is changing the way municipalities deliver everyday services, increasing the quality and resilience of infrastructure at lower costs and reduced risk. The MNAI team provides scientific, economic and municipal expertise to support and guide local governments in identifying, valuing and accounting for natural assets in their financial planning and asset management programs, and in developing leading-edge, sustainable and climate-resilient infrastructure.

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