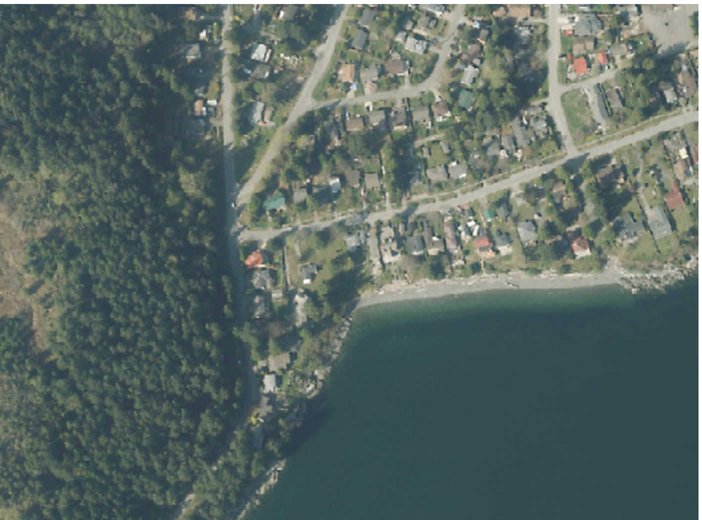
DAVID SUZUKI FOUNDATION
One nature.

Managing Natural Assets
to Increase Coastal Resilience

Town of Gibsons

British Columbia



Pilot Study June 2021

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This work is supported by the David Suzuki Foundation, which is a member of the Municipal Natural Assets Initiative. The two organizations are collaborating on this project.

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 make better decisions about how we interact with nature and 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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PHOTO: WIKI COMMONS - NOTHING EATS YOU

SUMMARY

PHOTO: WIKI COMMONS - MIKE

Communities all along Canada's coasts are facing infrastructure challenges. The structures that people originally built to protect their settlements from storm surges are showing their age, especially as they try to protect against bigger and more frequent storms that climate change is causing.

To address these challenges, the David Suzuki Foundation and the Municipal Natural Assets Initiative piloted the Coastal Resilience project in the Town of Gibsons, B.C. and Pointe-du-Chêne, New Brunswick. This report focuses on the Town of Gibsons. The project developed and tested a Coastal Toolbox (CT) model to determine how enhancing coastal natural assets like subtidal eelgrass, coastal vegetation or beach sediments could reduce flood and erosion impacts, especially if used alongside conventional grey infrastructure.

The Town of Gibsons is situated along the perimeter of the Salish Sea at the entrance to Howe Sound or Átl'ka7tsem (Figure 1). As of the 2016 federal census, the town was home to 4,605 residents. Because of its coastal vulnerability, the Town of Gibsons is actively pursuing climate adaptation planning to help mitigate future damages from forecasted sea level rise and increased storm severity and frequency.

The Coastal Resilience project's two objectives were to:

1. Provide the Town of Gibsons with a quantitative assessment of the benefits that coastal natural assets can offer for flood and erosion protection from coastal storms.
2. Develop and pilot a modelling tool (the Coastal Toolbox, or CT) that coastal communities can further refine so they could understand and compare alternative natural asset management solutions to storm surge and coastal erosion.

The project areas in the Town of Gibsons were along two main shorelines: (1) the South Side - the southern coastline with three beaches used for recreation, and (2) the Marina Side - the shoreline in and around the marina. The South Side is exposed to large storm waves and tidal forces from the Salish Sea (Strait of Georgia), and the Marina Side is exposed to significant storms from Átl'ka7tsem (Howe Sound) in the northeast.

With input from a stakeholder group, the project team developed a list of 15 natural asset management options and assessed them against a set of criteria. Based on those considerations, the team identified four options for modelling:

- Shoreline planting
- Beach nourishment
- Eelgrass planting
- Submerged structures

The project team then took the following five steps:

1. Identified and selected coastal protection options for modelling
2. Incorporated coastal protection options in Coastal Toolbox
3. Specified sea level rise assumptions and constructed design storms
4. Developed simulation modelling using the Coastal Toolbox
5. Evaluated results and estimated benefits

The model evaluated the performance of the four natural asset management options with an assumed sea level rise of 0.24 metres (based on the current RCP 8.5 mid-point scenario for Gibsons), and across a range of storm frequencies/intensities to provide a basis for short- and long-term planning.

Erosion reduction benefits

While the CT can assess erosion protection, the original InVEST model it was based on was designed for sandy beaches and therefore it could not estimate direct erosion amounts for the cobble/gravel beaches around the Town of Gibsons. To deal with this challenge, the project team developed two supplementary, or proxy, indicators for erosion. The first proxy was based on how well natural assets could reduce erosion-causing wave action. The second proxy, called the erosion index score, simulated beaches as being sandy even though they were not. It thus represented the ability of a natural asset to attenuate waves given a particular beach elevation profile. This approach provides a comparison of the relative differences between beach sites and the extent to which they might benefit from natural assets.

Results using these two proxy indicators suggest natural asset options like beach nourishment, shoreline planting and eelgrass planting have the potential to reduce erosion vulnerability on the South Side. On the Marina Side, eelgrass planting and sediment improvement hold the greatest promise of erosion reduction benefits.

Flood protection benefits

Flood estimates from the CT indicate that buildings along the South Side are not at risk of flooding due to their higher elevations, even under extreme storms, high tides and surge scenarios. On the Marina Side, flood risk is potentially much costlier with 14 to 52 buildings at risk of flooding (depending on the storm size). Storms affecting the Marina Side could result in flood damages estimated at up to $3.4 million for a single storm, or $16.2 million cumulatively for multiple storms over a 100-year time horizon. However, since the major contributing factor for flooding in the Town of Gibsons is tide levels, not wave run-up, the CT results suggest minimal impact. A combined option (beach nourishment + shoreline planting/sediment improvement) provided only minimal protection against flooding, with avoided costs of no more than one per cent. The Town of Gibsons could consider adding more natural asset options such as lagoons, and/or pairing natural assets with grey infrastructure such as retaining walls and large dikes to deal with flooding from tide levels. It could also consider raising the backshore dune height or crest height combined with a managed retreat strategy.

Overall, this pilot project demonstrated that:

1. Natural assets would provide protection against wave energy and water run-up, but not against storm surges and high tides.
2. The CT is a rapid and easy-to-use tool that is sufficient for high-level initial screening and for quantifying the benefits associated with coastal natural assets.
3. There are challenges associated with applying a generic tool to different types of coastlines; at its current stage of development, the CT will be most applicable to areas with sandy shores.
4. There's a need for a whole systems approach including exploring the role of watersheds in flood management.

Local governments wishing to consider using the CT should review the full technical guidance document as well as the results from the New Brunswick pilot. Current applications of the CT will likely still require combining local knowledge with professional expertise for some key modelling steps. The resulting screening will help determine whether to proceed with more detailed investigation and research related to natural asset approaches.

PHOTO: TOWN OF GIBSONS

NATURAL ASSETS

What are municipal natural assets

The term *municipal natural assets* refers to the stock of natural resources or ecosystems that a municipality, regional district or other form of local government could rely on or manage for the sustainable provision of one or more local government services[i].

Why manage natural assets

A growing number of local governments recognize that it is as important to understand, measure, manage and account for natural assets as engineered ones. Doing so can enable local governments to provide *core* services such as stormwater management, water filtration and protection from flooding and erosion, as well as *additional* services such as those related to recreation, health and culture. Outcomes of what is becoming known as *municipal natural asset management* can include cost-effective and reliable delivery of services, support for climate change adaptation and mitigation, and enhanced biodiversity.

How to manage natural assets

Local governments have numerous ways to manage natural assets. The Municipal Natural Assets Initiative (MNAI) uses methodologies and tools rooted in standard asset management, and provides a range of advisory services to help local governments implement them. MNAI has developed the methods and tools with significant investments, piloting, refinement, peer review and documentation of lessons in multiple Canadian provinces. MNAI's mission is to make natural asset management a mainstream practice throughout Canada, and in support of this, for local governments to accept and use the methodologies and tools in standard ways across the country.

i mnai.ca/media/2018/02/finaldesignedsept18mnai.pdf

Many MNAI tools to-date have focused on surface water quality and quantity. A newly developed tool called the Coastal Toolbox (CT) is a first attempt to extend the natural assets methodology to coastal issues. The CT was piloted in Pointe-du-Chêne, New Brunswick, and in the Town of Gibsons, B.C. Results from the latter are the subject of this report.

CT development was made possible with funding and project support made available through the David Suzuki Foundation; overall project coordination by MNAI; and technical support from a technical team.

TOWN OF GIBSONS, BRITISH COLUMBIA

The Town of Gibsons is situated along the perimeter of the Salish Sea at the entrance to Howe Sound or Átl'ka7tsem (Figure 1). As of the 2016 federal census, the town was home to 4,605 residents. The complex topography surrounding the community results in different areas being either exposed to or protected from storms, with each area facing unique vulnerabilities and risks.

For this pilot study, the project team organized study sites into the "South Side" and "Marina Side" for analysis and reporting (Figure 1). The South Side beach segments include Atlee Beach, Pebbles Beach and Georgia Beach. These beaches are exposed to large storm waves and tidal forces from the strait to the south. They are somewhat protected at low tide by the large shallow reaches of the Gibsons Shoals (Figure 1) but have experienced coastal erosion (Figure 2a). Concrete blocks have been installed along Atlee and Pebbles Beach for protection. The Marina Side includes the inner harbour, Armours Beach (North and South) and the Bluff. This area is protected from southern storms by the peninsula, Keats Island and two large jetties. However, the area's exposure to Átl'ka7tsem and storms from the northeast mean it is still vulnerable to coastal flooding and sea level rise. Riprap has been placed in some areas to protect against coastal erosion (Figure 2b).

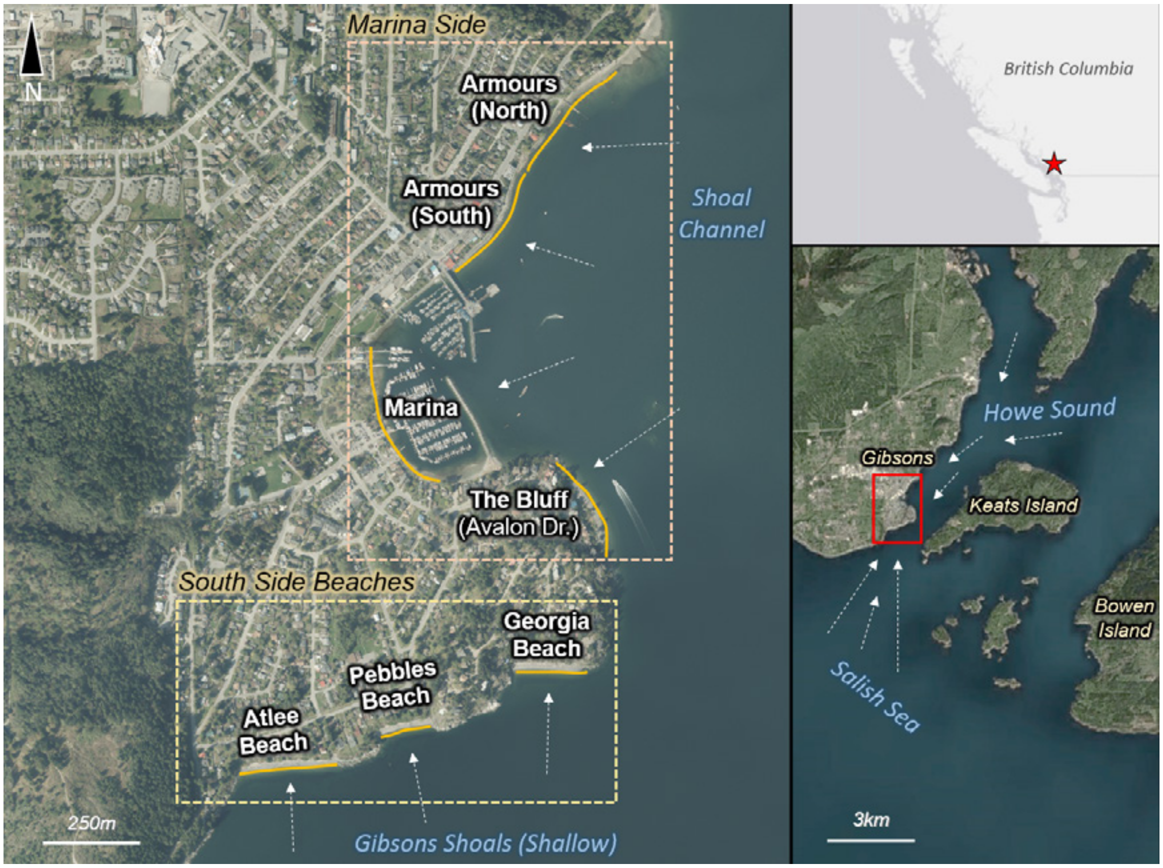


Fig. 1: Project area overview, Gibsons, British Columbia.
Source: Bing Imagery & SCRD Imagery.

Fig. 2: Examples of (a) coastal erosion
on Georgia Beach, (b) the use of riprap to protect the shoreline north of the marina

and (c) flooding at Hyak Marine properties, and d) storm surge at Armours Beach. Source: photos taken by Erica Olson (a, b) and John Roper (c, d) [images from 2020-05-11 Gibsons Council Readings (Gibsons 2020)]

Policy/governance context

Because of its coastal vulnerability, the Town of Gibsons is actively pursuing climate adaptation planning to help mitigate future damages from forecasted sea level rise and increased storm severity and frequency. As a pioneer in natural asset management, the town recognizes the importance of understanding, measuring, managing and accounting for coastal natural assets. They know these assets have the potential to provide significant economic benefits by mitigating floods and erosion, reducing long-term maintenance costs compared to hard/grey alternatives and providing co-benefits such as habitat conservation or improvements to local recreation areas.

Canadian coastal management for flood and erosion mitigation overlaps with multiple marine/coastal jurisdictions. In addition to the Town of Gibsons, which sets and enforces bylaws related to coastal development, provincial and federal governments set relevant regulations and laws (e.g., B.C. Environmental Land Use Act, Canadian Environmental Assessment Act, etc.) and can contribute important resources, data and expertise to support adaptation planning. Other community groups and organizations also play important roles. For an overview of jurisdictional considerations relevant to marine and coastal planning in Canada, see Section 3.1 and Appendix C of the Technical Guidance Document.

Natural asset of interest

The main natural assets that the Town of Gibsons identified as being of interest for flood and erosion protection along the South Side and on the Marina Side are the natural topography and components of the beaches (e.g., berms, existing vegetation). These have shifted over time and may require restoration. The expansion of eelgrass beds was also identified as being of interest. In addition to flood and erosion protection, all beaches in the town provide co-benefits like aesthetic appeal, recreation opportunities and habitat for various marine and terrestrial species. The project team considered several alternatives to enhance beach characteristics like foreshore slope, berm dimensions and shoreline vegetation in scenario modelling, as well as different eelgrass planting alternatives.

Project Objective(s)

The project team set out to develop an initial screening and quantification tool, called the Coastal Toolbox (CT) that could, with the accompanying Technical Guidance Document, be used independently by any community before deciding to invest in more detailed studies. Coastal processes are complex, and at its current stage of development the tool will be more applicable to some communities than others. Current applications of the CT will likely still require combining local knowledge with professional expertise for some key modelling steps. Regardless, the tool provides useful high-level screening and offers a valuable learning and assessment framework for coastal communities interested in exploring natural assets alongside conventional grey infrastructure projects and other strategies to promote coastal resilience.

The two primary objectives of this pilot are to:

1. Provide the Town of Gibsons with a quantitative assessment of the benefits coastal natural assets can offer for flood and erosion protection from coastal storms.
2. Develop and pilot a modelling tool that can be refined for further use in coastal communities that wish to understand and compare alternative natural asset management solutions to storm surge and coastal erosion.

METHODS

PHOTO: WIKI COMMONS - MIRANDA.KOPETZKY

OVERVIEW

As part of this project, the project team identified and inventoried coastal natural assets near the Town of Gibsons, linked these to ecosystem service provision and then quantified the supplied flood and erosion benefits over a 100-year time horizon using the CT to capture a typical coastal planning time horizon. The tool examined how natural assets such as shoreline vegetation, subtidal eelgrass and beach topography can provide flood and erosion protection under different management scenarios and climate change considerations (e.g., sea level rise).

Methods focused on comparing modelled storm and erosion protection benefits of natural asset management options with and without those management options applied.

The project team made comparisons using avoided damage costs to flooded structures (in 2020 CDN $) and a non-monetary erosion index score. The latter compares the hypothetical beach retreat from erosion given beach elevation profiles, and a wave attenuation estimate that evaluates how much subtidal features like eelgrass will mitigate waves.

As a high-level assessment and learning tool, the model is based on one-dimensional transects (or lines that are drawn on maps that extend from offshore to the coastal floodplain). It does not consider cross-cutting effects from wind and waves that are more complex and computationally intensive than a two-dimensional model would provide, nor does it consider dynamic effects like sediment transport over time, which might replenish the eroded volumes indicated by the CT. The Town of Gibsons should consider these characteristics when interpreting results from the model. The CT was designed as a rapid first-pass assessment that minimizes processing time while still permitting a general indication of coastal protection benefits from natural assets and supporting community learning about how those assets can affect coastal processes.

Five main steps were taken in the project:

1. Identification and selection of coastal protection options for modelling
2. Incorporation of coastal protection options in Coastal Toolbox
3. Specification of sea level rise assumptions and construction of design storms
4. Simulation modelling using the Coastal Toolbox
5. Evaluation of results and estimation of benefits (addressed in Section 3)

Each step is summarized below; a more detailed description is in the Technical Guidance Document.

STEP 1: IDENTIFICATION AND SELECTION OF COASTAL PROTECTION OPTIONS FOR MODELLING

Natural asset management strategies require a multidisciplinary, team-based approach. The MNAI process therefore begins with an initial engagement session with community representatives from a range of disciplines. In 2020, the project team held a series of multi-stakeholder workshops to discuss, identify and prioritize existing coastal natural assets, and to isolate the most promising candidate management options that would both reduce damages from storms and provide co-benefits such as habitat conservation or improvements to local recreation areas. Workshops included employees from the Town of Gibsons municipal office and the District of Sechelt, as well as local residents and experts from the Nicholas Sonntag Marine Education Centre and University of British Columbia. This larger group is referred to hereafter as the stakeholder group.

Workshop outputs included:

- Identification of the geographic region of interest and important areas of focus
- A detailed understanding of the flood and erosion problems faced by the Town of Gibsons and important coastal processes
- Itemization of existing coastal natural assets in the Town of Gibsons and identification of asset management alternatives for modelling
- Itemization of available data and identification of outstanding data needs and knowledge gaps

The stakeholder group assisted the project team in identifying 15 options for modelling; five for the South Side and 10 for the Marina Side. To shortlist four options from this longlist, the project team used selection criteria co-developed with the Town of Gibsons that considered 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 (Figure 3). In evaluating the options based on these criteria, the project team considered whether reliable precedents exist, whether the option supplies specific co-benefits of interest 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. Based on those considerations, the four selected options were:

- shoreline planting
- beach nourishment
- eelgrass planting
- submerged structures

Managed retreat was shortlisted as a fifth option, but the project team did not model it as it does not involve a natural asset component.

		Other Benefits		Feasibility			Modelling	
	Flood & Erosion Protection	Co-Benefits	Climate Change Adaptability	Community Implementability	Asset Policy & Planning Relevance	Achievable Cost	Modelling Feasibility	
Beach Segment Baselines								
1. Georgia Beach								X
2. Pebbles								X
3. Atlee Beach								X
4. Armours Beach (South)								X
5. Armours Beach (North)								X
6. Marina								X
7. The Bluff (Avalon Drive)								X
Public Safety, Recreation, & Habitat Protection (South Side)								
S1. Beach nourishment (Georgia Beach)	H	M		M			H	X
S2. Shoreline planting	M	M		H			M	X
S3. Sub-tidal planting (Eelgrass)	L	M		M			H	X
S4. Submerged structure	M	M		M			M	X
S5. Managed retreat	H	M		L			M	
Flood, Erosion & Habitat Protection (Marina Side)								
M1. Sediment improvement	M	M		M			M	X
M2. Eelgrass protection	L	M		M			H	X
M3. Anchored driftwood placement	M	M		H			L	
M4. Submerged structure	M	L		L			M	
M5. Raised breakwater with greenspace	H	H		L			L	
M6a. Raised breakwater no greenspace	H	M		L			L	

M6b. Additional breakwater no greenspace	H	M	L	L	
M6c. Relocated breakwater no greenspace	H	M	L	L	
M7. Additional armouring	H	M	M	M	
M8. Managed retreat	H	M	L	M	

Fig. 3: An example of the criteria-based selection matrix
used to identify a shortlist of top priority natural asset management alternatives. H = Criterion is met; M = Criterion is somewhat met; L = Criterion is not met.

STEP 2: INCORPORATION OF OPTIONS INTO COASTAL TOOLBOX

Evaluating each natural asset option for the Town of Gibsons varied depending on the type of natural asset. Some options could be easily assessed using the CT by simply varying the standard parameter settings (e.g., dune height[ii], beach width). Other options required the use of proxies like increasing the grain size parameter to represent added stability from shoreline planting. To capture a range of cost estimates, the project team used multiple variants of the same management option using a set of tunable model parameter settings. Figure 4 illustrates the main parameters that are tunable in the CT and locates each of the five options (five including managed retreat) from offshore to inland along a schematized profile. Table 1 provides the full list of parameter settings to represent each natural asset option.

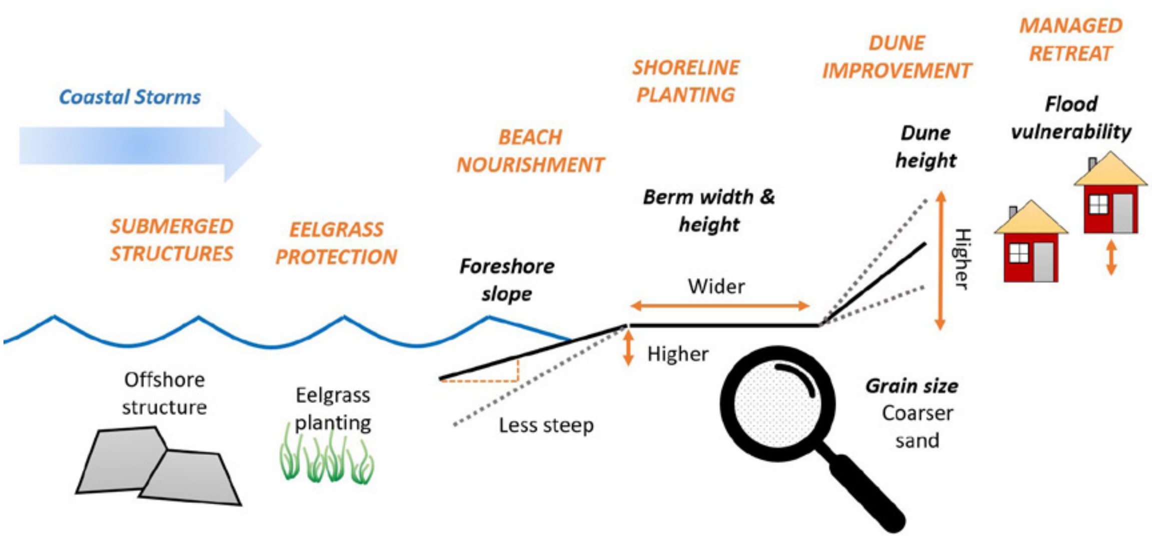


Figure 4: A schematic locating natural asset options along a cross-section from offshore to inland.
Tunable parameters in the CT that can be modified to evaluate flood and erosion impacts are also shown (e.g., foreshore slope, berm width, berm height, grain size, dune height)

ii Note: Dunes are not present in Gibsons; however, this language is used within the model to denote the height of upland areas and so we have retained the language in this report to be consistent with the model parameters.

Table 1: Parameter settings used for baseline simulation modelling and a range of model variants.
Settings in black font represent baseline conditions, while settings in red font represent different variants of the natural asset options the project team explored. The beach nourishment and combined options are unique since they involve multiple tunable parameters. For this option, the project team tested all possible combinations of the parameter settings shown (i.e., foreshore slope, berm height, berm width, grain size).

	Shoreline Planting / Sediment Improvement *	Beach Nourishment	Combined Beach Enhancement ll	Eelgrass Planting	Submerged Structures
Foreshore slope†	1.5%-5%	1.5%-5% 1%, 3%, 5%	1.5%-5% 1%, 3%, 5%	1.5%-5%	1.5%-5%
Berm height†	0.9-1m	0.9-1m 1m, 1.5m, 2m	0.9-1m 1m, 1.5m, 2m	0.5-1m	0.5-1m
Berm width†	5-20m	5-20m	5-20m 5m, 10m, 20m	0.9-1m	0.9-1m
Dune height†, ‡	5m	5m	5m	5m	5m
Grain size	200 µm § 100µm, 2mm	200 µm §	200 µm § 100µm, 2mm	200 µm §	200 µm §
Eelgrass patch distribution	Unmodified	Unmodified	Unmodified	Unmodified Loss, Gain	Unmodified
Structure distance offshore	NA	NA	NA	NA	No structure 100-300m
Structure depth	NA	NA	NA	NA	No structure 3-4m Chart Datum
Structure height	NA	NA	NA	NA	No structure 1.5, 5m
Structure width	NA	NA	NA	NA	No structure 5, 10m
Land value (erosion)	NA – model not capable of handling cobble/gravel shores; proxy indicators used instead				
Structure value (flood)	Total assessed value less assessed land value, distributed proportionally by footprint-area in cases with multiple structures				
Depth-damage estimates (flood)	US HAZUS – filtered for salt water, short duration flooding from USACE – New Orleans. We used curves for one- and two-storey buildings only				
Discount rate (flood)	5% annually				

* Shoreline planting at the South Side, sediment improvement at the Marina Side. We use changes in grain size as a proxy to represent beach stability benefits provided by shoreline planting.

† Baseline parameter values vary by beach segment. For example, the foreshore slope is ~1% at the marina and ~5% at Armours Beach.

‡ Gibsons beaches do not have dunes but since this is a required input for the erosion component of the original inVEST model, we use a default 5m dune height. By holding this value constant across beaches, we can still compare the changes in other parameter settings to evaluate relative differences, but absolute erosion values (which we do not report) are less meaningful.

§ The baseline grain size represents a default of "fine sand" for erosion index calculations. Note that the beaches around Gibsons are cobble/gravel so this indicator is used only to develop the proxy index, which represents the erodibility of the beach given its elevation profile when applied to a hypothetical sandy beach. It does not produce absolute erosion values. See Section 2.3 for further details about how to interpret the erosion index score.

ll A combined option achieved by modifying the foreshore slope, berm dimensions and substrate grain size. For South Side beach segments this option represents shoreline planting + beach nourishment, and for the Marina Side beach segments, it represents sediment improvement + beach nourishment. The same parameter settings are used to represent shoreline planting and sediment improvement.

STEP 3: SEA-LEVEL RISE AND DESIGN STORMS

The project team evaluated the performance of the four selected natural asset options with an assumed sea level rise of 0.24 metres, based on current RCP 8.5[iii] mid-point scenario for Gibsons (including tidal levels, and using different design storm scenarios). Coastal flooding and erosion in the study areas are primarily driven by a combination of "still water levels" and wave impacts, where the former term is used to describe average water surface elevation inclusive of contributions from tides, storm surges and sea level rise. It is therefore important to conduct simulations across a range of storm frequencies/intensities to provide a stronger basis for short- and long-term planning. The design storm scenarios included the following parameter settings:

Table 2: Storm scenarios.

Parameter	Settings			
Sea-Level Rise (constant across all scenarios)	+0.24m* (2070 RCP8.5)			
Tides	Lower low-water large tide	1.2m Chart Datum		
	Mean sea level	3.1m Chart Datum		
	Higher high-water large tide	5.1m Chart Datum		
		1-year storm	**10-year storm**	**100-year storm**
Storms (South Side)	Recurrence frequency	Annual	Decadal	Centennial
	Significant wave height	2.3m	3.1m	4.2m
	Peak wave period	6s	7.1s	8.6s
	Storm surge elevation	0.73m	0.90m	1.20m
		1-year storm	**10-year storm**	**100-year storm**
Storms (Marina Side)	Recurrence frequency	Annual	Decadal	Centennial
	Significant wave height	0.85m	0.97m	1.02m
	Peak wave period	3.3s	3.5s	3.6s
	Storm surge elevation	0.73m	0.90m	1.20m

* Based on RCP 8.5 for 2070 for Gibsons Harbour from the Canadian Extreme Water Level Analysis Tool (EWLAT). We selected the 2070 sea level rise horizon because 50 years (2020-2070) is a typical lifespan for a coastal infrastructure project and it is also a strategic mid-point for our modelling, which covers a 100-year time horizon.

Please refer to the Appendix and the Technical Guidance Document for further details about these parameters and their settings.

iii The RCP8.5 Representative Concentration Pathway for the global high-emissions climate change scenario adopted by the International Panel on Climate Change. RCP8.5 was chosen in this study as a more conservative benchmark for mitigation and planning.

STEP 4: SIMULATION MODELLING WITH THE COASTAL TOOLBOX

Using the Coastal Toolbox, each design storm was simulated over 100 years with and without each of the four natural asset options across all natural asset parameter combinations. The CT was built by modifying the open source InVEST Coastal Protection Module from Stanford University's Natural Capital Project with the assistance of the model's original architect, Greg Guannel.

The InVEST Coastal Protection Model runs as a tool within ArcGIS to estimate how different habitats reduce nearshore wave energy and coastal erosion. The model accepts a baseline scenario and a proposed scenario to facilitate comparison. Unfortunately, this model has been discontinued by the InVEST team as of 2017 due to its dependence on ArcGIS, but they intend to migrate the tool to its standalone platform. As this model was best suited to allow interested municipalities to assign credible values to flood and coastal erosion protection provided by their shoreline and nearshore vegetated ecosystems without needing to outsource any aspect of the analysis, it was adapted to the Canadian environment.

The finished tool is a package of ESRI toolboxes built for use in ArcGIS Pro with some supplementary R Shiny functionality (a web application that allows the user to build interactive web apps). The CT calculates wave propagation, beach retreat and flood levels, and allows users to develop a first-pass estimate of damages from flooding and erosion.

The toolbox comprises six main components (Figure 5) including: a) a cross-shore profile generator that creates a set of transects (or cross-sectional slices, perpendicular to the coast at specified intervals), b) the natural/built asset scenario, which can be constructed uniquely for each profile, c) a wave/storm simulator, d) a flood estimator that builds a two-dimensional flood extent by interpolating flood depths between profiles, e) a coastal erosion estimator, and f) an avoided costs and damages estimation for floods and erosion.

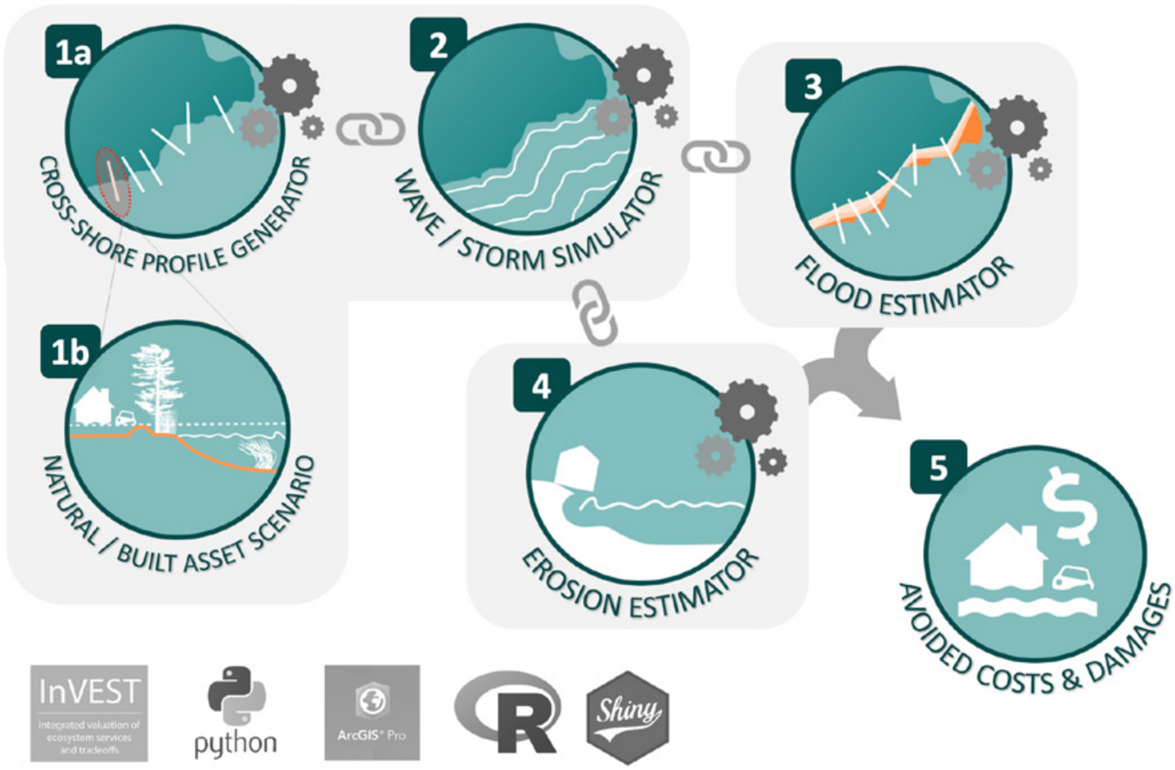


Figure 5: Conceptual diagram of the main components and workflow of the Coastal Protection Benefits Toolbox. Built using the open source InVEST Coastal Protection Module and adapted for use in ESRI ArcGIS Pro with supplementary tools using R Shiny. The steps in this model workflow are described in more detail in the Technical Guidance Document.

Several input datasets are required for application of the CT, many of which will vary in terms of quality and availability depending on the community. For this pilot, the project team prepared input data shown in Table 3 in collaboration with the Town of Gibsons and other project partners. Further details about the compilation of these datasets are available in Appendix A, as well as the Technical Guidance Document.

Table 3: Input datasets for application of the Coastal Protection Benefits Toolbox

Dataset	Details
Coastline	A spatial polyline demarcating the Gibsons coastline. Model runs were separated for South Side and Marina Side beach segments. All areas with rocky shores, infrastructure and riprap were excluded.
Seamless Topographic-Bathymetric Digital Elevation Model	A continuous water-free elevation surface created by merging existing Canadian Hydrographic Service non-navigation bathymetry data with municipal Light Detection and Ranging (LiDAR) data. See Appendix A for more details.
Building footprints	Spatial polygons of all structures in Gibsons with attributes including footprint area, assessed value and building type. Note that individual properties ("households") will often have more than one structure. See Appendix A for more details.

Dataset	Details
Depth-damage curves	Mathematical functions representing the relationship between flood depth and structure damages for different building types. Used for estimating flood damage costs. For this pilot we used US HAZUS depth-damage curves for USACE New Orleans. See the Technical Guidance Document for more details.
Shoreline/foreshore beach attributes	Foreshore slope, berm width, berm height and dune height. Estimated from LiDAR data and site photos. See Appendix A for more details.
Sectionalized representation of Parlee Beach	Gibsons shoreline divided into seven areas (Armours North, South, Marina Backshore, the beach below The Bluff (Avalon Dr.), Georgia Beach, Pebbles Beach and Atlee Beach) based on breakpoints and natural features. See Appendix A for more details.
Historical storms, water levels, wind and wave conditions and sea-level rise scenarios	Static water levels, stormwater levels and sea level rise levels from various data sources. Used to derive design storm parameters. See Appendix A for more details.

Table 4 lists the final indicator outputs available from the CT, including main and supplementary indicators. For erosion, the cost of beach loss ($) is calculated using the beach retreat distance (m). For the Town of Gibsons pilot, it was not possible to calculate the main indicators for coastal erosion or beach loss/damage volumes due to the original InVEST tool's inability to handle cobble/gravel beaches, so the wave attenuation indicator and the erosion index score were used as proxies. For flooding, the costs of flood damages ($) are calculated using the number of buildings inundated and the depth of inundation (m), which is derived from total flood levels (m) approximated using wave run-up levels (m).

Table 4: Indicator outputs from the CT

Hazard	Main Indicators	Supplementary Indicators
Erosion	• Beach retreat distance (m) • Cost of beach loss ($)	• Beach loss/damage (m3) • Wave attenuation (%) • Erosion index score (0-5)*
Flooding	• Wave run-up levels (m) • Total flood levels (m) • Buildings inundated (#) • Cost of flood damages ($)	

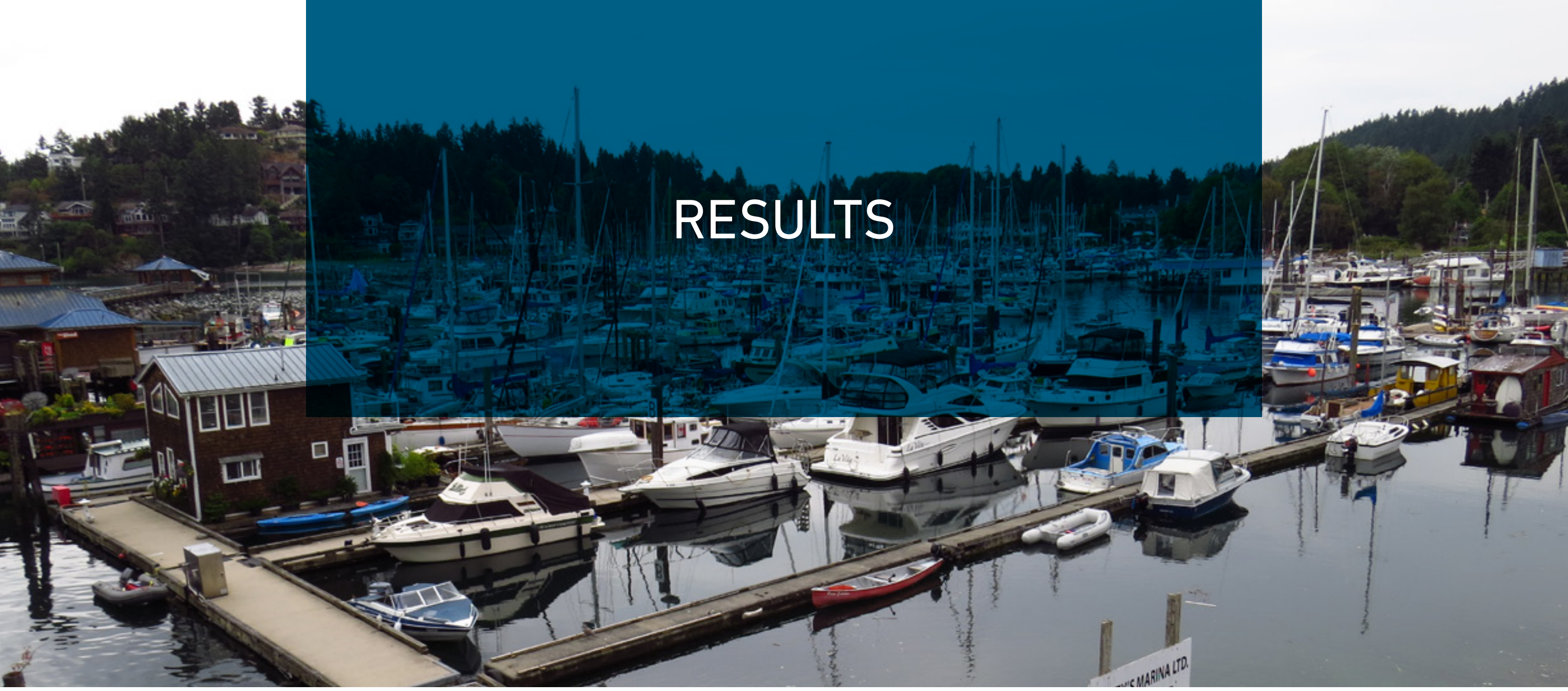
* The erosion index score is calculated as the beach retreat distance relative to the beach size. **0** (<1%), **1** (1 – 25%), **2** (25-50%), **3** (50-75%), **4** (75-100%), **5** (>100%).

For each natural asset option, indicators over a 100-year time horizon for both high and low tides (to capture a range of storm tides) across all tunable parameter settings and combinations were calculated, omitting any settings that produced an asset condition worse than the baseline (e.g., we did not propose actions that would increase erosion such as reducing the berm size at a given beach). Because the project team used a 100-year time horizon, each design storm occurs 100 (one-year storm), 10 (10-year storm) and one (100-year storm) times during the simulated period. These return periods represent storm intensities along a probability distribution and are not actual storm occurrence frequencies in any given year. For indicators that provide outputs in dollar values ($), the CT provides cost outputs in "present value," which means they are discounted annually (five per cent discount 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.

As noted above, it was not possible to estimate damage costs from beach loss. The original InVEST model was developed for sandy coastlines, so the sediment transport equations and theory are not applicable to cobble/gravel beaches like the ones in the Town of Gibsons and other coastal areas on the Pacific coast of Canada (see Study Limitations). This limitation was too complex to adapt within the scope of this pilot project. Therefore, following supplementary indicators were used as proxies to provide insights about erosion:

- The project team used wave attenuation (%) as an indicator of "erosion reduction potential," since it does not estimate actual erosion amounts, but it does indicate how much erosion-causing waves would be reduced with/without a natural asset option. The value reported is the percent wave height reduction after the wave passes over an offshore feature like eelgrass or a submerged structure.
- The erosion index score (0 – 5) is a relative score that uses the ratio between the width of a beach (m) at the mean sea level and the estimated beach retreat caused by a storm (m), then categorizes this ratio from 0-5 across all results (i.e., all natural asset variants) [0: 0%, 1: 1-25%, 2: 25-50%, 3: 50-75%, 4: 75-100%, 5: > 100%]. To estimate this score for the Town of Gibsons, the CT assumes the beaches are sandy even though they are not. It represents the ability of natural asset options to reduce wave run-up given the beach's elevation profile applied to a hypothetical sandy beach. Because the score is scaled by beach size, it permits comparisons of erosion benefits from natural asset options across studies and beach sites regardless of their size. Using this index, "0" indicates lowest erosion potential and "5" indicates highest erosion potential — if the beach were sandy. Given the cobble/gravel nature of the Town of Gibsons beaches, this is obviously an imperfect indicator, but the project team felt it still provides useful comparison information as an interim result until coarser beach types can be integrated into the CT.

To estimate flood damage costs, the project team relied on 2020 assessed building values and ran the model across all parameter variants for each natural asset option (Table 2.1), as well as for low tide and high tide to capture a range of tide-dependent storm impacts. For reporting purposes, the project team used the average of these damage estimate outputs and report a range to communicate the minimum and maximum estimates across all natural asset management variants. The final avoided cost outputs are simply the difference in costs between the baseline condition (without action) and a given natural asset option (with action). This value represents the long-term (100-year) flood protection advantage, if any, from implementing the natural asset alternative.



RESULTS

PHOTO: WIKI COMMONS - MIKE

EROSION-REDUCTION BENEFITS

Erosion reduction estimates using the proxy wave attenuation indicator and the erosion reduction index suggest potential to reduce erosion vulnerability along the South Side beach segments using beach nourishment, shoreline planting and eelgrass planting, and on the Marina Side using eelgrass planting and sediment improvement. The project team reports results for eelgrass planting and submerged structures first since both of these natural asset options are assessed using the wave attenuation indicator. Next, results for beach enhancements (beach nourishment, shoreline planting and sediment improvement) are reported, all of which require the use of the erosion reduction index.

Eelgrass planting: The project team assessed potential wave attenuation (wave height reduction) offered by eelgrass under three scenarios: i) hypothetical loss of all eelgrass arising from a failure to protect the natural asset, ii) current eelgrass extent, and iii) hypothetical eelgrass planting and restoration within available eelgrass habitat (Figure 6). Comparing the first two scenarios provides an estimate of wave attenuation benefits supplied by the current distribution of eelgrass (see Figure 6 for an example), and comparing the last two scenarios provides an estimate of benefits that could be supplied by an eelgrass enhancement program.

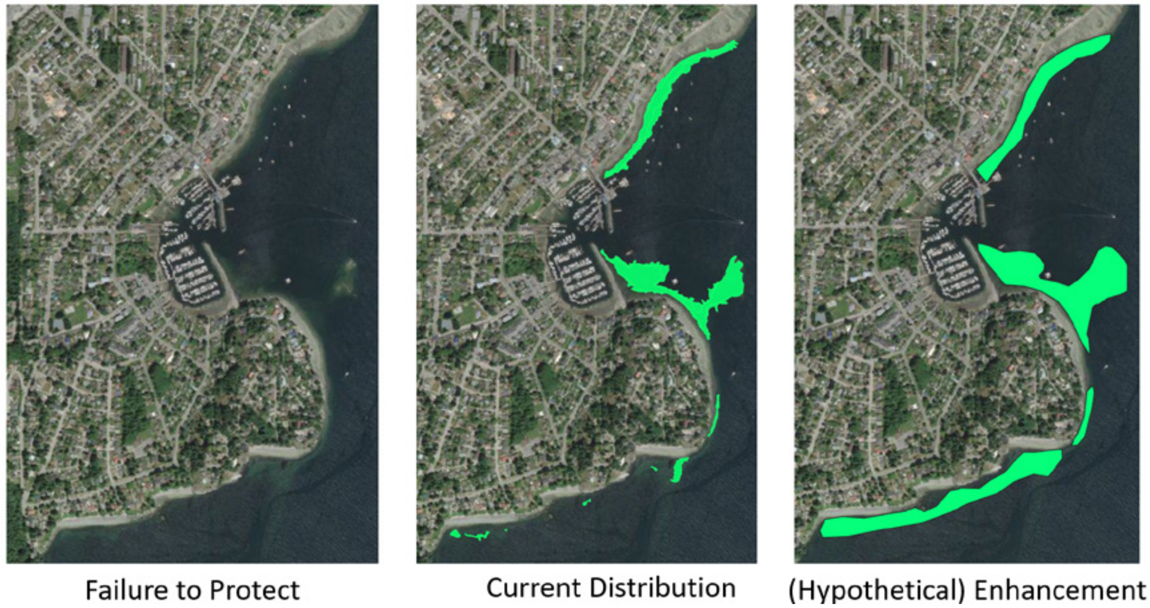


Figure 6: Eelgrass current distribution (middle panel)
hypothetical eelgrass planting/enhancement project (right panel) and hypothetical eelgrass loss scenario (left panel).

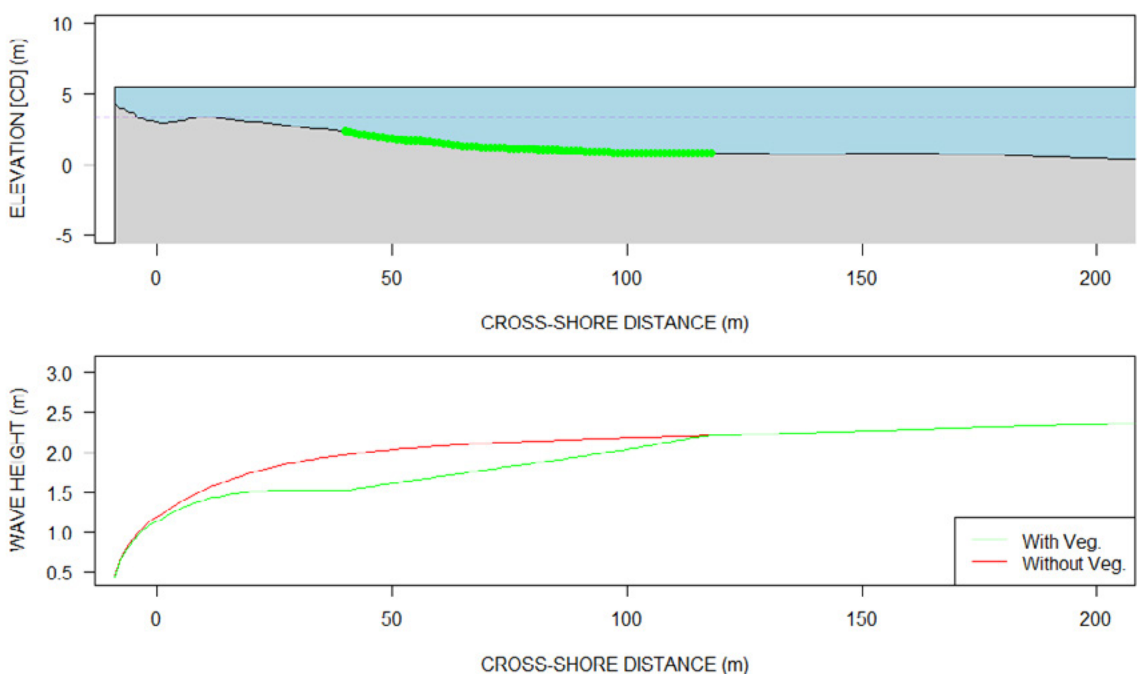


Figure 7: Visualization of a cross-shore bathymetric elevation profile at Georgia Beach (top panel).
The green highlighting represents the distribution of eelgrass (along the profile), the blue shading represents the water level at mean sea level and the purple line is the chart datum (low tide). The bottom panel shows the wave height attenuation along the profile with eelgrass (green) and without eelgrass (red).

Outputs suggest that the current extent of eelgrass only provides significant wave attenuation benefits for The Bluff (Avalon Dr.) and Armours Beach (Table 5). However, if a large restoration and planting project were undertaken, these benefits could be increased by seven to 10 per cent along the South Side beach segments and up 14 per cent in front of the Marina (Table 5).

Table 5: Eelgrass wave attenuation results for each beach segment
(current extent and enhanced extent of eelgrass)

	Wave Attenuation Index (%) protection from eelgrass*	
Beach Segment	**Wave attenuation from the current eelgrass distribution** protection	**Potential wave attenuation achievable from a large eelgrass enhancement program** enhancement†
South Side		
Georgia	0.1%	7.2%
Pebbles	0.0%	0.2%
Atlee	1.0%	10.5%
Marina Side		
Armours (South)	6.4%	9.9%
Armours (North)	6.2%	9.7%
Marina	2.0%	13.9%
The Bluff (Avalon Dr.)	10.4%	10.6%

* The eelgrass wave attenuation index measures the % wave height attenuation at the shoreward margin of the eelgrass patch. We averaged values between low and high tides for all parameter combinations and then took a weighted average across the 1-, 10- and 100-year storms (based on frequency) over a 100-year time horizon. The final values therefore show percent attenuation from a single weighted average storm.

† An enhancement project where eelgrass is planted in large quantities from a chart datum elevation of 0m to 3.75m.

The effectiveness of eelgrass patches in protecting the coast during extreme storm events may be over- or under-represented by the CT in different ways as follows:

- The CT only estimates reductions in wave height along a perpendicular transect assuming a permanent patch of eelgrass with constant parameter settings over time. In reality, the ways storms interact with eelgrass are more dynamic.
- During highly energetic storm events, eelgrass can be damaged or fully removed (uprooted), reducing its capacity to attenuate waves.
- Elevated water levels from high tides and surges can decrease the bottom friction from eelgrass that is felt by the waves. Due to the high turbulence during these events, the drag coefficient caused by the vegetation is also significantly reduced, leading to less wave attenuation (Pinsky et al., 2013).
- Eelgrass patches can decrease bottom velocities and bed-shear stresses, playing an important role in sediment stabilization (Widdows et al., 2008; James et al., 2019). During calmer conditions, these patches can also capture eroding sediment that is retreating seaward from a beach, thus reducing erosion and allowing for beach recovery over time.

Submerged structures: Based on the analysis, a 1.5-metre tall, five-metre wide at its base, submerged structure positioned approximately 100 to 300 metres offshore from the South Side beach segments in water depths of two to three metres (CD – low tide) would only provide wave attenuation benefits at low tides and no noticeable effects at mean sea level or high tides. If this hypothetical structure's size were increased to five metres tall and 10 metres wide at its base, which are similar dimensions to a large breakwater, then the structure would reduce wave heights by over 50 per cent at low to moderate tides. For a submerged structure to provide wave attenuation benefits at high tide it would need to be over five metres high and placed no more than 150 metres offshore of the South Side beach segments. In addition to being a massive infrastructure undertaking, such a structure would protrude from the water at low and mean tides. Figure 8 displays the shape of the submerged structures and where they were located for the model assessment.

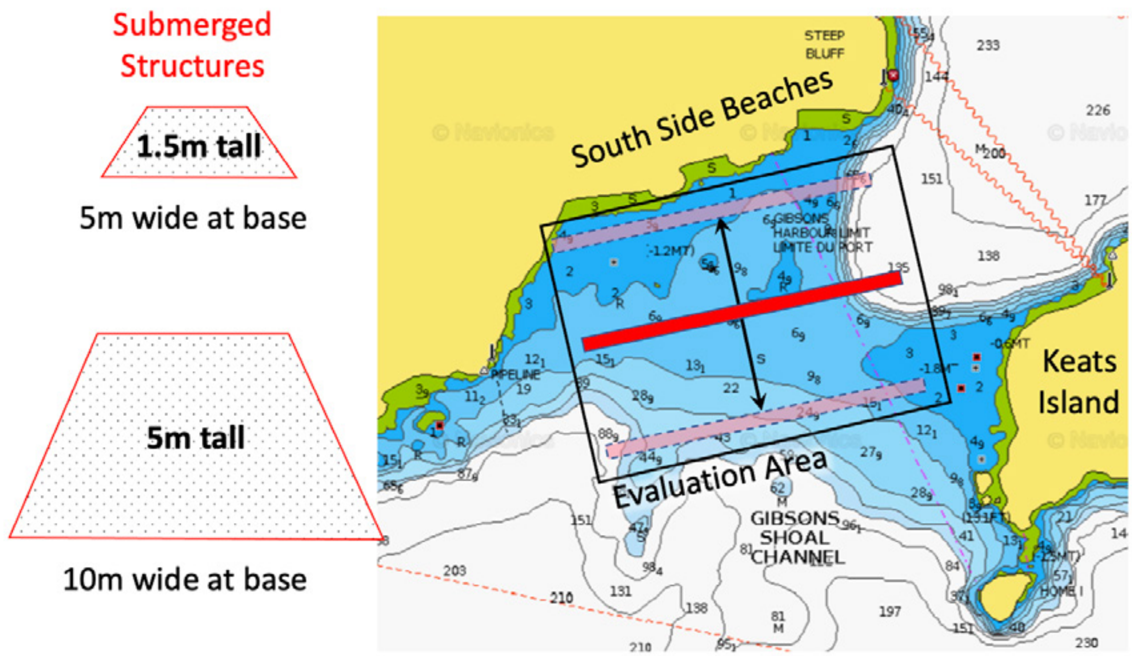


Figure 8: Hypothetical offshore submerged structures
positioned in the shallows at Gibsons Shoal Channel to reduce wave heights. Source: basemap from Navionics Chart Viewer: webapp.navionics.com

Beach enhancement: Table 6 provides erosion index scores for the South Side and Marina Side beach segments for beach nourishment, shoreline planting, sediment improvement and combined natural asset options. Results are displayed separately for each natural asset option and storm return period (one-, 10-, and 100-year storm), both with and without the natural asset option applied ("with action", "without action"). The "with action" results show the median value and the minimum to maximum range for each option, which is the range of results across all variants tested (see Table 6).

"Without action" erosion index scores vary considerably across storm severities and beaches. Not surprisingly, results suggest that a larger, less frequent storm would generate more erosion than a smaller, more frequent storm, with scores for most beach segments increasing one to two points as the storm intensity increases from a one-year to a 100-year storm. Exceptions include Amours (North) and The Bluff (Avalon Dr.). Scores for these beach segments remain at 5 regardless of the storm intensity, suggesting high erosion potential across all storm types. Differences across beach segments arise due to the existing beach morphology (the shape of the beach). Short and steep beaches such as Armours Beach are more vulnerable to erosion than shallow sloped beaches such as Georgia or Atlee beach. With its long, shallow foreshore slope, the Marina beach segment is least prone to erosion with scores of 0, 2 and 2 respectively for one-, 10- and 100-year storms. This estimate does not account for the offshore breakwater that currently protects the marina, so these are overestimates. If the CT model were able to capture the effects of the breakwater, it is expected these scores would be 0 across all storm types.

In addition to varying across storm severities and beaches, "with action" erosion index scores also vary across natural asset options. Scores suggest the South Side beach segments would benefit most from these enhancements, with very little potential for erosion protection on the Marina Side. At the South Side, the median variants for shoreline planting are predicted to be more beneficial than those for beach nourishment. This difference is not very detectable for smaller storms. Only Pebbles Beach would see an advantage from shoreline planting over beach nourishment for one-year storms. But as storm size increases, the advantage becomes clearer with the median variants for shoreline planting reducing the erosion index score by at least one point (Georgia and Atlee) and up to three points (Pebbles), and the median variants for beach nourishment having no effect against 100-year storms. Note that Pebbles and Atlee beaches already have lock-block barriers in place, but these barriers are not considered in the CT. For these beach segments, results should be interpreted as reflecting the advantage of natural asset options *if the barrier were not present*.

The CT erosion model characterizes beaches as being less erodible when the foreshore slope is shallower (flatter), berms are taller (and wider) and when the substrate grain size is increased (made coarser) (Table 6). A beach will be predicted to have the lowest erosion index score when these conditions are met in a simulation. Based on the range of values tested for each parameter, any modifications to the substrate grain size resulted in the largest erosion reductions potential (highest sensitivity); however, this parameter was only used as a proxy sediment improvements and shoreline planting. In reality, grain size modifications are not recommended for the Town of Gibsons beaches. These conditions are only simulated to overcome limitations of the erosion model and provide a relative comparison of beach nourishment against sediment improvement/shoreline planting.

Table 6: Summary of erosion index scores
… for three natural asset options for beach enhancement across all South Side and Marina Side beach segments and storm intensities.

	Natural Asset Option & Implementation Beach Segment	Erosion Index (0-5)					
		Without Action (baseline)			With Action		
		1-yr storm	10-yr storm	100-yr storm	1-yr storm	10-yr storm	100-yr storm
	Beach Nourishment						
South Side	Georgia	2	2	3	1 [0 - 2]	2 [2 - 2]	3 [3 - 3]
South Side	Pebbles	4	5	5	3 [2 - 4]	4 [3 - 4]	5 [4 - 5]
South Side	Atlee	2	3	4	2 [2 - 2]	3 [3 - 3]	4 [4 - 4]
Marina Side	Armours (South)	4	5	5	4 [3 - 4]	5 [5 - 5]	5 [5 - 5]
Marina Side	Armours (North)	5	5	5	5 [4 - 5]	5 [5 - 5]	5 [5 - 5]
Marina Side	Marina	0	2	2	0 [0 - 0]	2 [2 - 2]	2 [2 - 2]
Marina Side	The Bluff	5	5	5	5 [4 - 5]	5 [5 - 5]	5 [5 - 5]
	Shoreline Planting (south side) **/ Sediment Improvement** (marina side)						
South Side	Georgia	2	2	3	1 [0 - 2]	1 [0 - 2]	2 [0 - 3]
South Side	Pebbles	4	5	5	2 [0 - 4]	2 [0 - 5]	2 [0 - 5]
South Side	Atlee	2	3	4	2 [2 - 2]	2 [0 - 3]	3 [2 - 4]
Marina Side	Armours (South)	4	5	5	4 [3 - 4]	4 [3 - 5]	4 [3 - 5]
Marina Side	Armours (North)	5	5	5	4 [3 - 5]	5 [3 - 5]	5 [5 - 5]
Marina Side	Marina	0	2	2	0 [0 - 0]	1 [0 - 2]	1 [0 - 2]
Marina Side	The Bluff	5	5	5	4 [3 - 5]	4 [3 - 5]	4 [3 - 5]
	Combined Beach Enhancement						
South Side	Georgia	2	2	3	1 [0 - 2]	2 [0 - 2]	3 [0 - 3]
South Side	Pebbles	4	5	5	3 [0 - 4]	3 [0 - 5]	4 [0 - 5]
South Side	Atlee	2	3	4	2 [2 - 2]	3 [0 - 3]	4 [2 - 4]
Marina Side	Armours (South)	4	5	5	4 [3 - 4]	5 [3 - 5]	5 [3 - 5]
Marina Side	Armours (North)	5	5	5	5 [3 - 5]	5 [3 - 5]	5 [5 - 5]
Marina Side	Marina	0	2	2	0 [0 - 0]	2 [0 - 2]	2 [0 - 2]
Marina Side	The Bluff	5	5	5	5 [3 - 5]	5 [3 - 5]	5 [3 - 5]

Table 7: Characteristics of less erodible and more erodible beaches for the Town of Gibsons

Beach Parameter	Least Erosion	Most Erosion	Relative Model Sensitivity (Importance)	Description
Foreshore Slope	1% (shallower)	5% (steeper)	High	Flatter beaches are more resilient to erosion than steep beaches. As part of the Beach Nourishment option, decreasing the foreshore slopes of the Town of Gibsons beach segments from their original values to one per cent reduced erosion.
Berm Height	2m (taller)	1m (shorter)	Medium/Low	As part of the Beach Nourishment option, increasing the berm width reduced erosion, but this parameter was less sensitive than decreases to the foreshore slope within the range of values evaluated.
Berm Width	30m (wider)	5m (narrower)	Medium/Low	As part of the Beach Nourishment option, increasing the berm height reduced erosion, but this parameter was less sensitive than decreases to the foreshore slope within the range of values evaluated.
Beach Stability (via Grain Size)	2mm (coarser)	100μm (finer)	Highest	Increasing substrate grain size to represent stability improvements from sediment improvement or shoreline planting reduces erosion along the hypothetical sandy versions of the Town of Gibsons beaches we assessed. While the erosion model is most sensitive to grain size modifications, these results have limited transferability to the Town of Gibsons beaches which are already dominated by coarser material. Think of these results as a general, but very coarse, indicator that actions like shoreline planting and sediment improvement could provide erosion benefits along the Town of Gibsons beach segments.

FLOOD PROTECTION BENEFITS

Flood estimates from the CT indicate that buildings along the South Side are not at risk of flooding. Even under extreme storms, high tides and surge scenarios, these structures are naturally protected due to their higher elevations. A site visit in May 2019 did indicate that other structures like stairs, lock-blocks and the parking lot at Georgia Beach are vulnerable to flood damages, but the CT is not currently capable of evaluating flood damages to this type of infrastructure. Flood risk is potentially much costlier on the Marina Side. Between 14 and 52 structures are at risk from coastal flooding, depending on the storm type, and based on the CT's coarse estimates, a single storm could result in up to $3.4 million in damages (Table 8). Cumulatively over the 100-year time horizon, damage costs will total $16.2 million in present value (Table 9). For flooding, only the combined natural asset option (beach nourishment + shoreline planting/sediment improvement) is reported, because it provided the greatest contrast in results across all the options. At any of the beach segments, this option will have only minimal impact against flooding, with avoided costs of no more than one per cent (not statistically significant).

Flood levels are a function of sea level rise, tides, storm surge and wave run-up (the landward incursion of waves due to winds). Of these components, the natural asset options considered for the Town of Gibsons are only capable of affecting wave run-up. Since the major contributing factor for flooding in the Town of Gibsons is tide levels, not wave run-up, the CT results will naturally suggest minimal impact. Other natural asset options like lagoons, retaining walls and large dikes could be considered to deal with flood contributions from tide levels. In the Town of Gibsons, for example, raising the backshore dune height or crest height in combination with a managed retreat strategy could be a viable option.

The flood damage costs reported are based on structure values provided by the Sunshine Coast Regional District, structural depth-damage curves (US-HAZUS[iv]) and building elevations extracted from the digital elevation model (DEM). The depth-damage curves approximate the proportion of a building that is damaged given floodwater depths, which were then multiplied by the total assessed value of the structure. Intervals for the one-, 10- and 100-year storms shown in Table 3.4 are based on the use of minimum and maximum possible values for a given storm based on surge, tide elevations, wave run-up and sea level rise. The Town of Gibsons has a comparatively large tidal range of 5.1 metres (the difference between the higher high-water large tide [an annual king tide] and lower low-water large tide [approximately the lowest tidal elevation observed for a given year]), which is a key driver of estimated storm damages. In our example ~ 6.5- to 7.5-metre CD is reported as an extreme water level where high tides are aligned with severe storm and high localized wave run-up heights (a worst-case scenario). While these flood elevations may seem unrealistically high at first glance, a previous report to council described a case where still water levels could reach seven metres above CD even before accounting for wave run-up (Gibsons 2020). Note that in reality, if structure contents and municipal infrastructure such as roads or utilities were included, costs would be higher than those reported but would also be lower if structures are protected by fine-scale protective features not captured by the CT, like elevated foundations or drainage/retaining walls.

iv HAZUS is a U.S. commercial loss and risk assessment software built in GIS

Table 8: Structure damages from a single storm on the Marina Side across a range of storm-induced water levels.
The types of storm (one-yr, 10-yr, 100-yr) that could produce each stormwater level are also shown for reference.

	Floodwater Level		Structure Damage Summaries Single Storm Event				
	Chart Datum (m)	GSC Datum (m)	Flooded Structures (#)	Median Structure Flood Depth (m)	Median Structure Damage ($)	Total Damage Cost ($ Millions)*	Storm Return Frequency†
King Tide‡	5.1 (HHWLT)	1.9	20	0.6	$22,290	$0.4M	
Storms	5.3	2.2	28	0.6	$27,122	$0.8M	1-yr storm 10-yr storm 100-yr storm
	5.6	2.5	30	0.8	$36,410	$1.1M	
	5.9	2.8	31	1.1	$44,965	$1.4M	
	6.2	3.1	40	1.2	$44,487	$1.8M	
	6.5	3.4	41	1.5	$56,752	$2.3M	
	6.8	3.7	45	1.7	$59,795	$2.7M	
	7.1	4	48	1.9	$64,364	$3.1M	
	7.4	4.3	52	2.1	$66,132	$3.4M	
	7.7	4.6	59	2.2	$66,836	$3.9M	
	8	4.9	65	2	$66,521	$4.3M	

* Structural damage estimates are the sum of damages across all flooded structures in Gibsons due to an individual storm event. Damages for a single structure are derived from flood depth, structure value and the depth-damage curve assigned to the building type. Note that at a floodwater elevation of 4.4 metres (typical daily high tide), nine structures were predicted to be wetted. We believe these were due to imperfections in the DEM or buildings that are protected by pier foundations. We therefore subtracted the total damage cost at a water level of 4.4 metres ($62,133) from all other flood summaries as a correction to account for possible DEM imperfections.

† Potential stormwater levels above the highest high tide mark (HHWLT/ king tide). Water levels for a given storm include low to high tides (1.2 – 5.1) + Surge (0.7 – 1.2) + SLR (0.24) + Wave Run-up (0.5 - 1). Upper limits reflect a worst-case scenario where the storm occurs close to or near a high tidal elevation. Lower limits reflect a storm occurrence at mean/low tides.

‡ Note that the HHWLT (king tide of 5.1m) can occur on at any given time in the absence of coastal storms. We do not believe flood damages from a still water level of 5.1 metres are an artefact or data imperfection since flood damages from extreme tides are supported by local reference studies (see Gibsons 2020).

Figure 9: Hypothetical maximum flooding extent
(high tide + storm) for the one- ,10- and 100-year storms. The shaded blue area shows the maximum extent of the still water level while the pink shading on the waterline margin represents additional wave run-up. The wave run-up (pink shading) is the portion that the CT can assess across different natural asset scenarios. Note that these visualizations were generated under extreme conditions with HHWL tidal elevation of 5.1-metre chart datum, storm surge and sea level rise for 2070 representing a maximum possible flood extent. In reality, storms will also occur under less extreme conditions.

Table 9: Summary of flood protection benefits for the combination of two natural asset options (i.e., beach nourishment and armouring) with results reported for each individual beach segment in which the asset option is implemented. Each row represents total damages across the entire community. Dollar values are in millions (CDN 2020), annually discounted at five per cent over a 100-year time horizon.

Natural Asset Option & Implementation Beach Segment	Flood Damage Cost [$ Millions]*			
	Without Action baseline	With Action	Avoided Costs ($)	Avoided Cost Range ($)
Combined Beach Enhancement (beach nourishment + sediment enhancement)				
Armours (South)	$16.2	$16.1	$0.1 (1%)	$0.1 - 0.1
Armours (North)	$16.2	$16.1	$0.1 (1%)	$0 – 0.02
Marina†	$16.2	$16.0	$0.2 (1%)	$0.2 - 0.2
The Bluff (Avalon Dr.)	$16.2	$16.1	$0.1 (1%)	$0 – 0.03

*Assumes an investment frequency for damage repair that is consistent with the design storm return periods (e.g., annual investments for one-year storms, decadal investments for 10-yr storms, centennial investments for 100-year storms). Note that this assumption may result in overestimates of total damage costs because individual homeowners are likely to intervene in structural repairs with mitigative action or retreat.

† The flood run-up adjustments for the Marina segment do not account for the existing offshore breakwater. In reality, we expect the benefit from any natural asset option in the marina to foreshore to be zero.

STUDY LIMITATIONS

PHOTO: WIKI COMMONS - MIRANDA.KOPETZKY

The sub-models comprised by the Coastal Tool make several simplifications and assumptions that limit the representation of various complex coastal processes. The toolbox is well suited to coarse-scale evaluations of the relative value and approximate cost differences of alternative coastal natural asset design scenarios. However, the following key limitations should be taken into account during analysis and interpretation of results:

- Complex hydrodynamic flow structures and wave propagation patterns are not represented, such as the flow around Gibsons Harbour and the effect of the estuary and confluence of Gibsons Creek.
- Wave evolution is modelled along individual profiles (1D), therefore processes such as longshore drift and sediment transport are not accounted for in the outputs. The model assumes target beaches to be longshore-uniform, meaning that complex features such as narrow inlets, estuaries and points cannot be accurately captured. While a large winter storm may indeed produce erosion estimates similar to quantities estimated by the CT, beaches may also regenerate in the summer and possibly show additional accretion from longshore drift and onshore sediment transport driven by smaller waves and tidal currents.
- The 1D shoreline profiles assume that the storm's angle of attack is perpendicular to the shoreline section. Therefore, features adjacent to a profile will not interact with the wave model to provide coastal protection. The modelled storm simulations should be customized for an area of interest to represent the dominant exposure aspect to the beach (e.g., a south-facing beach should be modelled with northerly winds).
- The range of sediment grain size that the model can consider for the erosion estimator is limited and does not encompass cobble/gravel shorelines that exist throughout much of the Pacific coast of Canada, including along the Gibsons shoreline. Despite this drawback, supplementary indicators can be calculated to provide insights about erosion (see Section 2.3). While imperfect, these indicators still provide useful information about relative erosion risk and the impacts natural asset solutions might have on that risk.

- The model represents wave attenuation as a reduction in wave height along a bathymetry profile and submerged vegetation patch. There are other mechanisms by which submerged vegetation such as eelgrass may act to reduce storm damage and erosion. For example, eelgrass will also reduce bottom velocities and bed-shear stress, thereby reducing erosion and the seaward transport of sediment away from a beach. Additionally, turbulence characteristics are not implemented in the model, and we expect these would also reduce wave energy and erosion.
- The model provides a simplified estimate of beach loss (retreat) after a storm for each profile, but it does not estimate sediment accretion, seasonal changes to a beach or any other type of cut/fill sediment transport estimates along a profile.
- The flood maps are based on the "bathtub" model approach that assumes very little spatial variation in the water levels and does not consider the actual flow dynamics. This approach usually provides a conservative estimate of the area flooded (i.e., it represents an underestimate).

CONCLUSION

Proxy indicators from the CT suggests eelgrass protection/planting and beach enhancements would be beneficial in terms of erosion mitigation. In particular, erosion index scores could be reduced by applying beach enhancements like shoreline planting to the South Side beaches. A large eelgrass enhancement program would also have wave attenuation benefits.

Results from applying CT in the Town of Gibsons show relatively limited benefits from implementing natural asset options to protect against flooding. This finding is due to a lack of vulnerability in some areas (e.g., South Side) or because the natural asset options explored are not capable of affecting the main contributors to flooding in the Town of Gibsons (i.e., Marine Side tide levels). Solutions to address high water levels may require establishing and raising the backshore dune height or crest height of the coastal structures, combined with a managed retreat strategy due to the close proximity of existing structures to the shore. Temporary sandbags, a retaining wall or improved drainage pathways in the vicinity of Bay Road and Prowse Road might also help to reduce flood damage, but these options could not be represented in the CT. A separate study in the Town of Gibsons looking at the role of watersheds in flood management will explore if terrestrial natural asset management may also contribute flood mitigation, which may emphasize the need for a systems approach from source to sea when thinking about the role of natural assets in flood mitigation.

This pilot study demonstrated the utility of the Coastal Toolbox as a comparatively rapid and easy-to-use tool that is sufficient for high-level quantification of benefits from coastal natural assets. It also emphasized the challenges associated with developing a generic tool that is applicable across many community contexts where coastlines differ dramatically. The project team set out to develop a coarse, first-pass screening model that could, with the Technical Guidance Document, be used independently by any community before deciding to invest in more detailed studies. But coastal processes are complex, and at its current stage of development the tool will be more applicable to some communities than others. Current applications of the CT will likely still require combining local knowledge with professional expertise for some key modelling steps. Regardless, the tool provides a useful high-level screening and offers a valuable learning and assessment framework for coastal communities interested in exploring natural assets alongside conventional grey infrastructure projects to promote coastal resilience.

NEXT STEPS

Refinements to the Coastal Resilience framework and model should be pursued. The Town of Gibsons and/or MNAI and DSF may refine project results through sensitivity analysis, model adjustments to recognize a wider range of beach types, and expanded economic analysis.

Several assumptions are associated with the baseline parameter estimates, and a useful next step would be to examine the impact of these assumptions on results by performing various sensitivity analyses. For example, the CT sub-models are based on a number of assumptions about physical processes related to storms, waves and erosion. As such, it would be useful to tune a few key variables by ±20% (e.g., wave run-up, beach retreat distance, total flood levels) before performing the final indicator calculations to test the impact of these adjustments on final results. Other storm return intervals could also be explored.

A useful next step would be to further develop the CT to accommodate a wider range of beach types in the erosion model. Additionally, the CT could be applied to other areas of the Sunshine Coast, such as Roberts Creek and Sechelt where large sandy shorelines are well-suited to the current iteration of the toolbox.

Once the CT is more capable of evaluating beach types like those around the Town of Gibsons, cost estimates for erosion will be possible as will flood damage estimates for alternative natural asset options that can protect against high water levels (i.e., not just wave run-up). When this functionality is available, the project team advises performing sensitivity analysis on cost parameters. To get building damage costs, the CT relies on the total assessed value of each property, less the land value, which is then distributed proportionally by area in cases where multiple buildings are present (see Appendix A). Since this proportional distribution may not be fully accurate, and since property prices can fluctuate, a ±20% adjustment would provide an uncertainty range that could be useful, for example, if there is a sudden increase in property values over a short time period. In our experience, the discount rate used to derive present values can also have a significant impact on results and should be varied. The default discount rate in the CT is five per cent, but the Treasury Board of Canada (2007) recommends a "social time preference rate" of three per cent. Feedback from MNAI suggests this latter discount rate is preferred and should be adjusted up and down by two percentage points as a sensitivity analysis. For depth-damage relationships, we rely on U.S. HAZUS depth-damage curves from New Orleans. These relationships might vary in the Canadian context and these flood damage estimates do not consider non-structural damage like that to interior content, vehicles and public infrastructure such as utilities or bridges. Ideally, there will be open access to Canadian-derived depth-damage curves. In the absence of these curves, additional sensitivity analysis can be performed by adjusting the U.S. curves (e.g., steepening or flattening, or selecting curves from different depth-damage ensembles), and by including public infrastructure in the analysis.

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APPENDIX A
DATA ACQUISITION AND PROCESSING

Area of Interest

We relied on community engagement meetings to identify the relevant sections of the Gibsons coastline for this study. Due to differences in wave exposure and topographic characteristics, we organized these segments into the “South Side” and “Marina Side” as two distinct sub-areas. The South Side beach segments include Atlee Beach, Pebbles Beach and Georgia Beach. These beaches are exposed to large storm waves and tidal forces from the strait toward the south. Although they also have some protection at low tides from the large shallow reaches of Gibsons Shoals, these beaches have experienced coastal erosion, and on Pebbles Beach concrete blocks have been installed for protection. The Marina Side includes the inner harbour, Armours Beach and The Bluff (Avalon Drive). These segments are protected from southern storms by the peninsula and Keats Island. The inner harbour is also protected by two large jetties; however, it is still believed to be an area of high vulnerability to coastal flooding and sea level rise. Despite being protected from storms to the south, the Marina Side beaches are exposed to Átl’ka7tsem and experience significant storms from the northeast. Riprap has been placed in some areas to protect against coastal erosion.

Digital Elevation Model

We developed a seamless topographic-bathymetric digital elevation model (DEM) using bathymetric data from the Canadian Hydrographic Service (CHS) and topographic data from municipal LiDAR data. We referenced these datasets to the Canadian Geodetic Vertical Datum 2013 (CGVD2013), then merged and interpolated them to generate a continuous surface model. The LiDAR topographic data covers the higher intertidal region, the bathymetry data covers the submerged area below low tide, and we derived the elevation for the intertidal region (between the datasets) using linear interpolation. We compared the final elevation model with the aerial images, nautical charts and previous regional flood studies to confirm that the derived DEM is representative of the area. We then converted the vertical reference datum of the dataset CGVD2013 to the chart datum (CD) used by Fisheries and Oceans Canada where the lower low water is 0 metres. The spatial resolution of the final raster was one metre by one metre, but we applied additional smoothing parameters in the erosion and wave attenuation models.

Static Water Level and Storm Surge

Coastal static water levels include contributions from the astronomical tide, storm surges and sea level rise. The astronomical tide elevations were obtained from the Tide Tables from DFO-MPO (Fisheries and Oceans Canada), the surge levels were approximated from regional studies and the sea level rise scenarios were obtained from the Canadian Extreme Water Level Adaptation Tool (CAN-EWLAT).

Table A-1: Tide elevations at Pointe-du-Chêne from DFO Tide Tables

Tide Elevations	Chart Datum (m)	CGG2013 (m)
Higher high-water large tide (HHWLT)	5.1	2.0
Higher high-water mean tide (HHWMT)	4.4	1.3
Mean water level (MWL)	3.1	0.0
Lower low-water large tide (LLWLT)	1.2	-1.9
Lower low-water mean tide (LLWMT)	0.0	-3.1

"Storm surge" is an abnormal, non-tidal rise (or fall) in the local water level due to the effect of wind and air pressure. When the air pressure is low and the wind is blowing from the sea to the coast, a rise in the water level is observed. Negative surges can also occur when the atmospheric pressure is higher than normal, or the wind is pushing the water offshore. Since this work is focused on the flooding impact of the storm surges, we only considered positive surge values. Table A2 shows storm surge levels for the area.

Table A-2. Extreme storm surge levels at Gibsons.

Return Period (years)	Residual (m)*
1	0.73
10	**0.90**
Max Measured (RP ~45 years)	1.03†
100	1.20

* Surge values at Point Atkinson from Golder (2012)
† Maximum recorded surge value from British Columbia Storm Surge Forecasting Program

Table A-3: Sea level rise at Gibsons.
Source: Canadian Extreme Water Level Adaptation Tool (CAN-EWLAT)

SLR Scenario	2020	2030	2040	2050	2060	2070	2080	2090	2100
RCP2.6	0.03	0.06	0.09	0.1	0.15	0.18	0.21	0.26	0.29
RCP8.5	0.03	0.05	0.08	0.13	0.19	0.38	0.31	0.38	0.47

Wave Conditions

We obtained representative wind and wave conditions for Gibsons from the Meteorological Service of Canada's (MSC) MSC50 wind and wave model hindcast, which contains hourly time series of wind (speed, direction) and wave (height, period, direction) from January 1954 to December 2015. The dataset is a state-of-the art hindcast; i.e., data are computed from all existing wind and wave measurements, re-analyzed and input to a 0.1-degree resolution ocean wave growth model that includes the effect of depth. The MSC50 hindcast was developed by Oceanweather Inc. and is distributed by Environment Canada (Swail et al., 2006).

We calculated extreme wind and wave conditions for one-, 10- and 100-year return periods using the Peaks over Threshold (PoT) analysis with Generalized Pareto Distribution (GPD) as fitting method. This method is based on the observation that the extreme tail of a distribution often has a rather simple and standardized form, regardless the shape of the central part of a distribution.

We applied extreme wave conditions at the model boundaries for the South Side beach segments. For the Marina Side, we only used wind conditions as our input to the CT. Wave conditions are calculated based on wind growth equations that relate fetch distance (distance along wind is somewhat constant above water) and wind speed with wave height and period. We combined the results of this extreme value analysis with storm surge levels to determine the storm simulation parameters shown in Table A4.

Table A-4: Storm simulation parameters

Conditions for South Side							
Return period (yrs)	Hs (m)	Tp (s)	Wind (m/s)	Tide (CD)	Surge (m)	SLR 2070 (RCP8.5 m)	Total WL
1	2.3	6.0	18.9	5.1	0.73	0.24	6.07
10	3.1	7.1	21.2	5.1	0.90	0.24	6.24
100	4.2	8.6	22.4	5.1	1.20	0.24	6.54

Conditions for Marina Side							
Return period (yrs)	Hs (m)	Tp (s)	Wind (m/s)	Tide (CD)	Surge (m)	SLR 2070 (RCP8.5 m)	Total WL
1	0.7	2.9	18.9	5.1	0.73	0.24	6.07
10	0.8	3.0	21.2	5.1	0.90	0.24	6.24
100	0.8	3.1	22.4	5.1	1.20	0.24	6.54

We split the study area's beaches into sections based on geomorphic differences, natural breaks and wave exposure. For each beach segment, we determined the typical foreshore slope, grain size (D50), berm width, berm height and dune height (Table A5).

The value of a section of beach is needed as an input for the erosion model. Determining the value of a beach is challenging, and many assumptions of the underlying modelling process may favour selecting a higher or lower value. For this pilot, we selected a beach value of \$150/m^2 based on an approximate median value of undeveloped land near the coastline (~\$25/m^2-\$400/m^2). Given that the erosion model could not estimate land loss due to the dominant gravel/cobble substrate, the final selection of the beach land value was not consequential to the results reported in this pilot study.

Table A-5: Beach sections and foreshore attributes

	Beach	Sediment Size (mm)*	Dune Height (m) †	Berm Length (m)	Berm Height (m)	Slope (rise/run)	Longshore Extent (m)
South Side	Georgia	0.2	5	15	0.9	0.015	155
	Pebbles	0.2	5	12	0.9	0.03	123
	Atlee	0.2	5	10	0.9	0.01	228
Marina Side	Armours (South)	0.2	5	5	0.9	0.02	183
	Armours (North)	0.2	5	5	0.9	0.05	300
	Marina	0.2	5	20	1	0.01	300
	The Bluff	0.2	5	5	0.9	0.03	300

* Sediment size is default medium grain sand for all Gibsons Beaches
† Gibsons beaches do not have formalized dunes; instead, they have steep backshores. 5 is max value for dune height

Eelgrass and Submerged Vegetation

Current eelgrass coverage was provided by SCRD/Gibsons as spatial polygons generated from recent field surveys (Beaty and Sanford, 2019). For modelling simplicity, we dissolved overlapping polygons across survey years. We assumed that bed characteristics would broadly follow winter Zostera marina attributes from Pinsky et al. 2013 (Stem height 1.5m, blade diameter 0.015m, blade density 150 shoots/m^2). To represent a hypothetical planting project, we haphazardly extended eelgrass patch polygons to depths of approximately 0-4m (CD). We understand that these data processing steps represent crude approximations of the current eelgrass coverage and enhancement opportunities, but we included these analyses as a proof-of-concept to demonstrate the wave attenuation potential.

Building Footprints and Structure Values

We performed all data analyses at the individual structure level rather than the property level to accommodate the use of depth-damage curves, which estimate percentage flood damages at the structure level. We multiplied these proportional damage estimates by the assessed values for buildings to get damage costs. Building footprints and assessed values were provided by SCRD/Gibsons. We assume that assessed values for all structures were for the year 2020. In many cases a given property had more than one structure on the lot. Therefore, the total structure count should not be compared to the total household count from census data. We defined structure values using census data by subtracting land values from total assessed values. For cases where secondary structures were present, we assigned values using the proportional footprint of each structure on a given property and the total structure value for the property (e.g., if the total structure value was $100k and the property had one 10m^2 structure and one 15m^2 structure, then we calculated the value of these structures as $100k* [10/25m^2] and $100k* [15/25]).

Depth-Damage Curves

We assigned depth-damage curves using U.S. HAZUS records, first filtering the record set for salt water, short duration flooding from the USACE – New Orleans source. We assigned curve IDs to structures as follows: one-storey residential = UUID 147 and two-storey residential = UUID 163. Commercial structures curve IDs were assigned manually for several commercial units with elevations <10m CD (approx. 2.5m greater than the most extreme flood scenario). These included curve IDs 449 for administrative offices and 317 for grocery stores and restaurants. Note that depth-damage curves and flooding cost estimates do not consider structure contents, damage to parked vehicles, landscaping or public infrastructure such as roads, utilities and/or recreation areas.

APPENDIX B
WORKSHOP PARTICIPANTS

Last Name	First Name	Role	Affiliation	Workshop		
				1	2	3
Appelt	Paul	Engineering Technician	District of Sechelt	X	X	X
Beaty	Fiona	Eelgrass Expert			X	X
Brooke	Roy	Executive Director	Municipal Natural Assets Initiative	X	X	X
Camarena	Amaury	Coastal Engineer	CBCL	X	X	X
Forester	Tracy	Administrative Assistant	Town of Gibsons	X		
Lewis	Michelle	Parks Department	Town of Gibsons	X	X	X
Machado	Emanuel	CAO	Town of Gibsons	X	X	X
Molnar	Michelle	Ecological Economist	David Suzuki Foundation / Municipal Natural Assets Initiative	X	X	X
Morton	Cedar	Sr. Systems Ecologist	ESSA Technologies Ltd	X	X	X
Newman	Dave	Director of Engineering	Town of Gibsons	X	X	X
Olson	Erica	Systems Ecologist	ESSA Technologies Ltd	X	X	X
Staats	Lesley-Anne	Director of Planning	Town of Gibsons		X	X
Starsage	Graham	Program Director	Nick Sontaag Marine Education Center Society	X	X	X

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