Greening the Fight against Sea Level Rise: The Value of Ecosystem-based Approaches to Coastal Flood Resilience in the City of Vancouver

by

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Ethics Statement

Abstract

This paper addresses the issue of sea level rise; contributing a multi-criteria trade-off analysis of five coastal flood resilience investments that could be undertaken in Vancouver, Canada, at the case study site of Kitsilano Beach. The analysis uses mixed methodology (primary expert interviews and secondary benefit transfer valuations) to assess the relative merits and trade-offs between soft, hard, and hybrid approaches to coastal flood resilience. Results suggest that while hybrid infrastructure may require 2 to 3.5 times the capital costs of hard infrastructure, it is equally effective at providing flood-related damage protection from sea level rise, and many times more effective at enhancing aesthetic, amenity, and ecological values. In the near term, it is recommended that the City of Vancouver invest in soft-shore armouring at Kitsilano Beach, as well as commence a technical feasibility assessment for the implementation of a sand dike with sediment fill for future preparedness.

Keywords: Sea level rise; coastal flood resilience; ecosystem-based adaptation; hybrid infrastructure; benefit transfer valuation; multi-criteria trade-off analysis

Dedication

This work is dedicated to Michelle Sarrazin (May 25, 1941 – March 27, 2017)

The depth of your love will never be forgotten, and I am proud to carry the best of you in my heart as I make my way through life

Acknowledgements

First and foremost I would like to thank my parents, Carole and Don, for never failing to offer anything short of unwavering support towards my life and educational endeavours; as well as my brother, Eric, for inspiring me to be a better person every day. I would like to thank Dr. J. Rhys Kesselman for tirelessly supervising and guiding my Capstone work, Dr. Benoit Laplante for being helpful and encouraging through my defence examination, Deb Harford at ACT for bringing this important topic to my attention, and Tamsin Lyle at Ebbwater Consulting for providing analytical scope and invaluable on-going consultation. I would also like to extend a personal thank you to MPP Director Doug McArthur and to Dr. Nancy Olewiler for their unparalleled dedication to my (and each of their students') educational outcomes, personal well-being, and future life successes. Finally, I would like to thank my wonderful partner for providing me with the patience, emotional support, and late night study sessions needed to keep me sane throughout this trying process.

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List of Acronyms

AEP	Annual exceedance probability
BC	British Columbia
CFRA	Coastal Flood Risk Assessment
CGVD	Canadian Geodetic Vertical Datum
CoV	City of Vancouver
CPI	Consumer price index
EbA	Ecosystem-based adaptation
EGS	Ecosystem goods and services
MoFLNRO	Ministry of Forest, Lands and Natural Resource Operations
PV	Present value
SLR	Sea level rise
WTP	Willingness to pay

Executive Summary

Policy problem

Global mean sea level is projected to increase between a “low-end” scenario of 0.3 meters and a “worst-case” scenario of 2.5 meters by the year 2100 (National Oceanic and Atmospheric Administration, 2017a, p.21), rendering the residents, assets, and habitats of coastal cities such as Vancouver, Canada at risk of flood-related damage. As identified by two *Coastal Flood Risk Assessment* (CFRA) reports (Northwest Hydraulic Consultants, 2014; Compass Resource Management & Ebbwater Consulting, 2015), coastal flood resilience in the City of Vancouver (CoV) is inadequate to provide safety and security against the threat of sea level rise (SLR).

Purpose and scope

The purpose of this paper is to investigate the relative merits and trade-offs between soft (green), hard (grey), and hybrid (mixed green and grey) approaches to coastal flood resilience for use by decision-makers in the CoV, with a focus on Kitsilano Beach (one of the flood-prone areas identified in the CFRA). The options considered are: beach nourishment, soft-shore armouring, a traditional dike, a green dike, and a sand dike with sediment fill. Results from the analysis may be informative to other flood-prone areas outside Kitsilano, where investment decisions for coastal flood resilience are to be faced by the CoV and neighbouring municipalities in the coming decades.

Methodology

This study follows a multi-criteria trade-off framework, using inputs from a mixed methodology. I conduct primary interviews with academic, industry, and NGO experts to guide option selection, design, and (to a lesser extent) evaluation; and I use secondary economic valuation literature to estimate willingness to pay (WTP) for aesthetic and amenity values with benefit transfer techniques. The analysis aims to maximize the triple-objective of enhancing outcomes for people, the environment, and the economy/government, by systematically comparing the options against a set of criteria.

Research findings

Primary expert interviews reveal insight into the costs, benefits, technical feasibility, and implementation hurdles associated with innovative soft and hybrid adaptation designs undertaken internationally. Notably, wide green dikes (7:1 slope) along the Wadden Sea in Germany support biodiversity, while integrated dike-in-dune designs in the Netherlands preserve beach ecosystem and recreational functions—both designs contributing successfully to the mitigation of flood-related damages. Secondary economic valuation studies from other countries reveal a higher social WTP for green than for grey infrastructure, and a higher social WTP for beach than for park area.

Analysis

The present values (presented in 2015 Canadian dollars) of the capital costs for each option over a 100-year period are as follows: Beach nourishment ($4.1 to $15.4 million); Soft-shore armouring ($0.81 to $2.0 million); Traditional dike ($5.7 million); Green dike ($5.9 million); Sand dike with sediment fill ($11.2 to 19.2 million). Overall, soft-shore armouring performs the best on criteria under the objectives of “environment” and “economy/government”—a result that is expected to be widely transferable to other areas in the CoV. A sand dike with sediment fill performs the best on criteria under the objective of “people.” This result is largely due to the high-volume use of Kitsilano Beach as a recreational destination, and so, may not be transferable to other areas in the CoV.

Recommendation

I recommend that the CoV consider soft-shore armouring in the short term, which inexpensively enhances coastal resilience against erosion and storms without precluding the introduction of complementary future measures. In the event that the CoV opts for a “protect” strategy in future decades, I recommend commencing a technical feasibility assessment for the implementation of a sand dike with sediment fill at Kitsilano Beach. This innovative hybrid design combines the flood protection of a traditional dike with the aesthetic, amenity, and ecosystem benefits of softer options. While the design may require 2 to 3.5 times the capital costs of a traditional dike, the amenity value gained by preserving a large portion of the beach may be sufficient to cover this cost differential.

Chapter 1. Introduction

1.1. Policy problem

Global mean sea level is projected to increase between a “low-end” scenario of 0.3 meters and a “worst-case” scenario of 2.5 meters by the year 2100 (National Oceanic and Atmospheric Administration [NOAA], 2017a, p.21), rendering the residents, assets, and habitats of coastal cities such as Vancouver, Canada at risk of flood-related damage. Even without sea level rise (SLR), the areas of Kitsilano, Jericho-Spanish Banks, False Creek and Flats, Southlands, and Fraser River Foreshore in the City of Vancouver (CoV) are at risk of flooding from king tides and storm surges today (Northwest Hydraulic Consultants [NHC], 2014). It is clear that coastal flood resilience in the CoV is inadequate to provide safety and security against the threat of SLR.

1.2. Kitsilano Beach and Park

One area within the CoV under threat of flood-related damages is Kitsilano. Kitsilano (known locally as “Kits”) is a vibrant residential and commercial area located along the south shore of English Bay between Granville Island and Point Grey, and is internationally recognized for its beautiful beach of the same name. According to the 2011 Census and National Household Survey (CoV, 2013), more than 41,000 people live in Kitsilano, in average household sizes of 1.8 persons. The median household income is approximately $60,000 ($4,000 above the CoV average), and the majority of residents (77%) are adults aged 20 to 64, with children and seniors underrepresented compared to the CoV average.

Kitsilano Beach (Figure 1) and adjacent Kitsilano Park provide many public amenities such as: on-duty lifeguards from May to September, playing courts for tennis, basketball, and beach volleyball, raised seawall paths, off-leash areas for dogs, and a children's playground (CoV, 2017). Along with some waterside residences, the beach and park are under threat of permanent inundation from 1 meter of SLR (explored further in subsection 2.3). Investing in costal resilience in this area is expected to generate benefits not only for Kitsilano residents, but for anyone in Metro Vancouver (or beyond) who enjoys the vast array of recreational opportunities that are currently offered.

Figure 1. Kitsilano Beach

Vancouverites enjoying Kitsilano Beach, off-season. Author's photograph: taken March 29, 2013.

1.3. Purpose, scope, and structure

The purpose of this paper is to assess the relative merits and trade-offs between soft (green), hard (grey), and hybrid (mixed green and grey) approaches to coastal flood resilience for use by municipal decision-makers. To achieve this, I first explore the scientific, legal, and policy context pertaining to SLR in British Columbia (BC) and the CoV (Chapter 2). I then conduct a literature review of climate change adaptation strategies (Chapter 3), develop a mixed qualitative and quantitative research methodology (Chapter 4), and interpret primary interview and secondary benefit transfer valuation data (Chapter 5). Next, I systematically evaluate five potential adaptation options (Chapter 6) across common criteria (Chapter 7) in a multi-criteria trade-off analysis (Chapters 8 and 9). Finally, I develop a set of recommendations and implementation considerations for coastal flood resilience in Kitsilano and the CoV more broadly (Chapter 10).

1.4. Knowledge contribution

On the basis of the aforementioned analysis, I recommend that the CoV consider implementing soft-shore armouring at Kitsilano Beach in the short term, which inexpensively strengthens coastal resilience against storms while not precluding the introduction of complementary hard structures in the future. I also recommend that the CoV commence a technical feasibility assessment for the implementation of a sand dike with sediment fill at Kitsilano Beach, in the event that a “protect” strategy is opted for in the future. While a sand dike may require 2 to 3.5 times the capital costs of a traditional dike, it is equally effective at providing flood-related damage protection from 1 meter of SLR, and many times more effective at enhancing aesthetic, amenity, and ecological values. These results may be informative for areas outside Kitsilano, where investment decisions for coastal flood resilience are to be faced by the CoV and neighbouring municipalities in the coming decades.

Chapter 2. Background

2.1. Climate change and SLR

Since 1880, the 10 warmest years on record have all occurred within the last 2 decades (NOAA, 2017b). 2016 marked the warmest year to date, with annual average temperature across global land and ocean surfaces reaching 0.94°C above the 20th century average (NOAA, 2017b). Such warming of the planet has induced reduction in the volume of glaciers and ice caps, reduction in the volume of polar ice sheets, and thermal expansion in oceans; all of which contribute to global mean SLR (Domingues et al., 2008; Golledge et al., 2015; King et al., 2012). Like temperature, the rate at which global mean sea level is rising has increased over time. Between 1901 and 2010, the average rate of global mean SLR was 1.7 millimetres per year, increasing to 3.2 millimetres per year between 1993 and 2010 (Intergovernmental Panel on Climate Change [IPCC], 2013). The most recent science projects that global mean sea level will rise between a "low-end" scenario of 0.3 meters and a "worst-case" scenario of 2.5 meters by the year 2100 (NOAA, 2017a, p.21), at a rate that some scientists predict may be exponential instead of linear (e.g. Hansen et al., 2015).[1]

Many studies have attempted to quantify the expected economic and social implications of SLR in the absence of resilience for BC and the CoV. The National Round Table on the Environment and the Economy (2011) estimates that 8,900 to

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[1] There is an important distinction between "absolute" SLR (sea level change relative to the center of the Earth) and "relative" SLR (sea level change relative to the solid surface of the Earth) (Geological Survey of Canada [GSC], 2014, p.4). Regionally—when faced with the same absolute SLR—an area with land uplift may experience a reduced rate (and perhaps even a fall) in relative SLR, while an area with land subsidence may experience an increased rate in relative SLR (GSC, 2014, p.4). Highlighting a few projections from the 2014 GSC, the rate of land uplift (millimetres per year) relative to the center of the Earth throughout the 21st century is estimated to be 0.58 in Victoria, 0.00 in Vancouver, and -0.15 in Surrey (p.29). As such, SLR in the CoV is expected to remain similar to the absolute global mean value.

18,700 dwellings in BC—the most of any province—will be at risk of flooding by the year 2050 (p.69). This impact is largely concentrated within Metro Vancouver, where households built at or below sea level are protected by 127 kilometers of dikes that were not designed to accommodate SLR (Walker & Sydneysmith, 2008, p.341). As of 2015, it is estimated that nearly 13 square kilometers of CoV lands are located in the floodplain for 1 meter of SLR, with a total assessment value (land and buildings) of $7 billion (Compass Resource Management [CRM] & Ebbwater Consulting [EC], 2015, p.8).

2.2. Relevant liability and legislative provisions in BC

In 2003, the Government of BC passed the *Flood Hazard Statutes Amendment Act*, amending the *Local Government Act* [RSBC 2015] to delegate the responsibility of managing flood hazards to local governments. To aid municipalities with this transition and with future construction and maintenance planning, the Ministry of Water, Land and Air Protection (now called the Ministry of Environment) published the *Flood Hazard Area Land Use Management Guidelines* (2004). While the Guidelines are extensive, they are not legally binding and have been criticized with regard to their effectiveness in fostering sufficient municipal flood risk management (e.g. Stevens & Hanschka, 2014). The Guidelines now fall under the Ministry of Forest, Lands and Natural Resource Operations (MoFLNRO), which proposed a draft amendment in 2013 based on 3 commissioned reports (Ausenco Sandwell 2011a, 2011b, 2011c). The draft amendments call for an adjustment of flood construction levels and building setbacks to account for SLR (Government of BC, 2013), but have yet to be formally adopted.

As defined by the *Dike Maintenance Act* [RSBC 1996], a dike is “an embankment, wall, fill, piling, pump, gate, floodbox, pipe, sluice, culvert, canal, ditch, drain or any other thing that is constructed, assembled or installed to prevent the flooding of land.” In 2003, the Ministry of Water, Land and Air Protection published the *Dike Design and Construction Guide: Best Management Practices for British Columbia*. This Guide now falls under the MoFLNRO, and was amended in 2011. The Guide allows for dikes to be locally widened—where adjacent land is available—to provide space for amenities (e.g. benches, picnic tables) on the landward side of the dike, ensuring that the full width of the original dike crest is left “unobstructed” for maintenance and emergency vehicles (p.2–11).

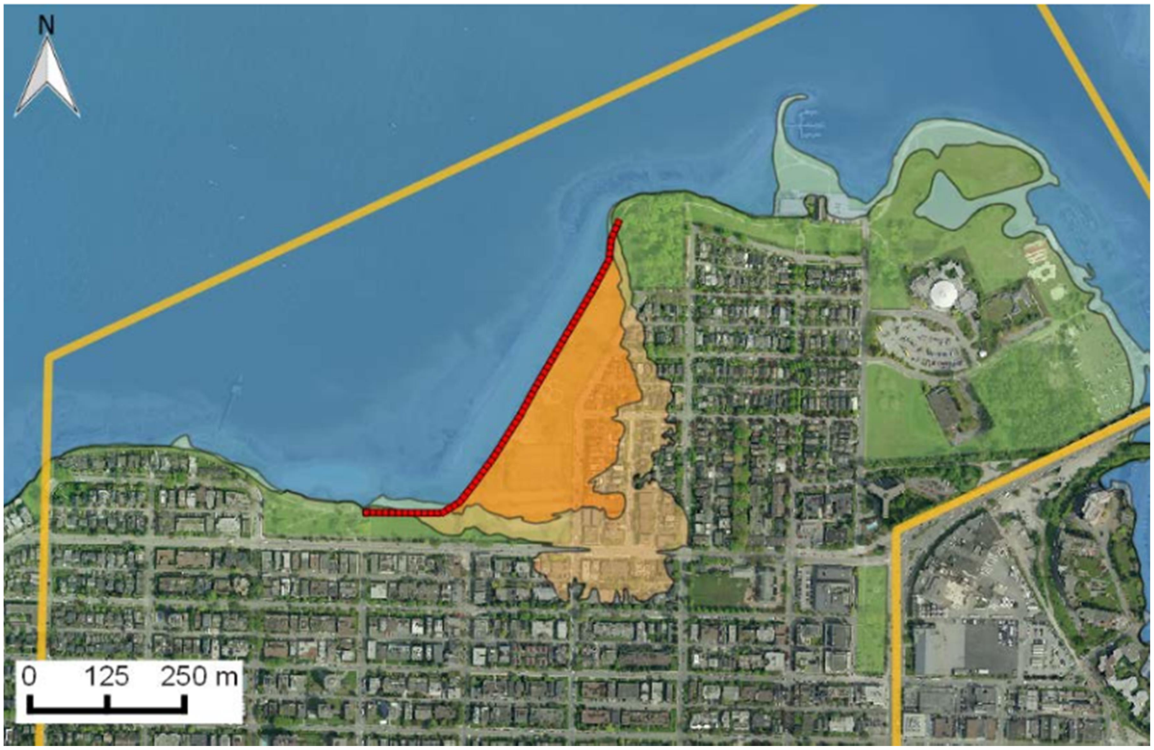
The only vegetation allowed on most dike crests is trimmed grass, since trees and shrubs “detrimentally affect dike fills by root penetration causing cracking, loosening, wind throw holes and seepage (Government of BC, 2003, p.2–56). However, vegetation clumps and trees are acceptable on, or adjacent to, certain “overwidth” dike designs with the understanding that “vegetation between flood protection works and the watercourse are recognized for their dike safety, environmental and aesthetic values” (Government of BC, 1999, p.2). The Guide requires that sea dike crest elevations be determined by considering the contribution of tidal fluctuations, storm surge, and wave run-up only (p.2–37). However, newer guidelines recommend that sea dike crest elevations be determined by considering the contribution of designated flood level, wave run-up, and freeboard; where “designated flood level” leaves buffer space for SLR, tidal fluctuations, and storm surges (Ausenco Sandwell, 2011b, p.12).

2.3. SLR in the CoV and Kitsilano

The Province of BC recommends that municipalities make policy decisions based on 1 meter of SLR by 2100 (Ausenco Sandwell, 2011a, p.5). To this end, the CoV has named SLR a priority for action in its 2012 *Climate Change Adaptation Strategy*. The Strategy endorses a specific objective to “increase the resilience of Vancouver’s infrastructure and assets to coastal flooding and erosion” (p.21), which has since been informed by two Coastal Flood Risk Assessment (CFRA) reports. Phase I of the CFRA identifies Kitsilano, Jericho-Spanish Banks, False Creek and Flats, Southlands, and Fraser River Foreshore as areas in the CoV at high risk of inundation from 1 meter of SLR, or from high tide combined with a 1-in-500 annual exceedance probability (AEP) extreme weather event today (NHC, 2014).

Phase II of the CFRA performs a multi-criteria trade-off analysis of potential adaptation options that could be undertaken at each of the at-risk areas (CRM & EC, 2015). For Kitsilano, the report highlights a potentially preferred option titled “park dike,” which would be a 690-meter dike constructed along an established path between the beach and the park (CRM & EC, 2015, p.70). The park dike is projected to generate the inundation avoidance depicted in Figure 2.

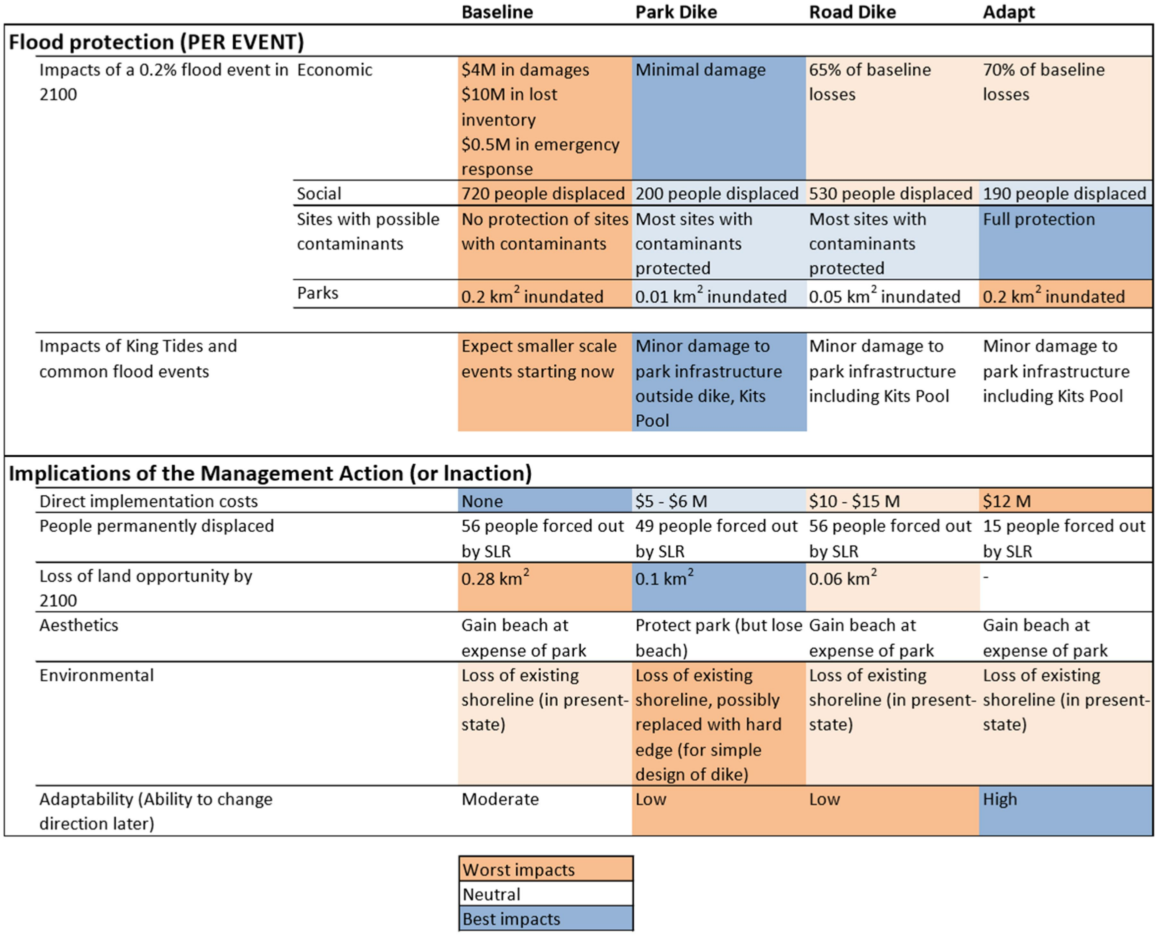
Figure 2. Projected inundation avoidance with “park dike” in Kitsilano



Source: CRM and EC (2015), p.67, *reprinted with permission*. The location of the proposed dike at Kitsilano Beach is indicated in red. The mitigated flood extent granted by the dike for a 1-in-500 AEP flood event today (0 meters SLR) or high tide with 1 meter SLR is indicated in dark orange. The mitigated flood extent from the dike for a 1-in-500 AEP flood event with 1 meter SLR is indicated in light orange. The remaining flood extent for a 1-in-500 AEP flood event today (0 meters SLR) or high tide with 1 meter SLR is indicated in blue (i.e. the ocean profile; note full beach inundation).

The trade-offs associated with the park dike relative to other “protect,” “accommodate,” and “retreat” strategies are assessed in the Phase II report (Figure 3).

Figure 3. Impact analysis for responses to SLR (from CFRA Phase II)



		Baseline	Park Dike	Road Dike	Adapt
Flood protection (PER EVENT)					
Impacts of a 0.2% flood event in 2100	Economic	\$4M in damages \$10M in lost inventory \$0.5M in emergency response	Minimal damage	65% of baseline losses	70% of baseline losses
	Social	720 people displaced	200 people displaced	530 people displaced	190 people displaced
	Sites with possible contaminants	No protection of sites with contaminants	Most sites with contaminants protected	Most sites with contaminants protected	Full protection
	Parks	0.2 km^2 inundated	0.01 km^2 inundated	0.05 km^2 inundated	0.2 km^2 inundated
Impacts of King Tides and common flood events		Expect smaller scale events starting now	Minor damage to park infrastructure outside dike, Kits Pool	Minor damage to park infrastructure including Kits Pool	Minor damage to park infrastructure including Kits Pool
Implications of the Management Action (or Inaction)					
Direct implementation costs		None	\$5 - \$6 M	\$10 - \$15 M	\$12 M
People permanently displaced		56 people forced out by SLR	49 people forced out by SLR	56 people forced out by SLR	15 people forced out by SLR
Loss of land opportunity by 2100		0.28 km^2	0.1 km^2	0.06 km^2	-
Aesthetics		Gain beach at expense of park	Protect park (but lose beach)	Gain beach at expense of park	Gain beach at expense of park
Environmental		Loss of existing shoreline (in present-state)	Loss of existing shoreline, possibly replaced with hard edge (for simple design of dike)	Loss of existing shoreline (in present-state)	Loss of existing shoreline (in present-state)
Adaptability (Ability to change direction later)		Moderate	Low	Low	High

Worst impacts
Neutral
Best impacts

Source: CRM and EC (2015), p.70, *reprinted with permission*. “Baseline” indicates no action against SLR. “Park Dike” indicates a 690 meter dike along an established trail, constructed 1.4 meters higher than the established pathway. “Road Dike” indicates elevating 600 meters of established roadways (Arbutus St. and Cornwall Ave.), constructed 1.4 meters higher than the existing grade. “Adapt” indicates structure retrofits, by-laws, and education to slowly render the area more resilient to flooding over the course of the natural building cycle. Since “Park Dike” is associated with the best impacts (i.e. the most blue boxes), it is potentially the preferred approach to coastal flood resilience in Kitsilano.

While the park dike is well-equipped to mitigate flood-related damages, it is likely to introduce damage to habitats, as well as aesthetic and recreational losses to society (as highlighted in the Figure 3 trade-offs table). To mitigate these social harms, an opportunity exists for the CoV to align coastal flood resilience with the aims of the *Greenest City 2020 Action Plan* (2016) by considering ecologically-based actions alongside physical infrastructure in its investment planning.

Chapter 3. Literature Review

3.1. Adaptation versus mitigation

Climate change mitigation is defined as an "anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases" (IPCC, 2001, p.379), and is commonly achievable through processes such as new technology, renewable energy, structural retrofit, and behavioural change (United Nations Environment Program [UNEP], 2016). Climate change adaptation, on the other hand, functions on the premise that climate change impacts will occur even if mitigation is successfully undertaken. Adaptation is thus defined as an "adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities" (IPCC, 2001, p.365). In other words, adaptation is the creation of proactive plans to prepare for the expected impacts of climate change.

The case for adaptation and for investing in local adaptive capacity is strong. Even if greenhouse gas (GHG) emissions were to be reduced to zero today, impacts such as SLR would continue to occur from emissions that have already been released (Leverman et al., 2012); a phenomenon that has been coined Earth's "climate change commitment" (IPCC, 2013, p.1102). Despite this commitment, aggressive mitigation is still an important contributor to reducing the expected rate of SLR (Körper et al., 2012; Washington et al., 2009; Yin, 2012) or to increase the time horizon over which adaptation measures can be implemented (Meehl et al., 2012). In support of this hypothesis, Zickfeld, Solomon, and Gilford (2017) model a counterfactual which suggests global mean SLR projections for 2100 would be 13.8 centimeters higher if the internationally-adopted Montreal Protocol were not adhered to (p.662).

While mitigation and adaptation were considered policy alternatives historically, the prevailing norm is to consider both approaches in tandem (Ayers & Huq, 2009; Swart

& Raes, 2007; Tol, 2007; Willbanks & Sathaye, 2007). The 2015 *Paris Agreement* asks constituents to “consider methodologies for assessing adaptation needs” and to “strengthen regional cooperation on adaptation” (United Nations Framework Convention on Climate Change [UNFCCC], 2016, p.7). This goal is taken in tandem with UNFCCC’s overall mitigation strategy to limit the increase in global mean temperature to 2°C above pre-industrial levels.

3.2. Adaptive strategies to SLR

The literature on climate change adaptation commonly references four general strategies: retreat, avoid, accommodate, and protect (Ausenco Sandwell, 2011c, p.19). “Retreat” involves withdrawing, relocating, or abandoning assets in areas susceptible to SLR; “avoid” involves restricting or disallowing development in susceptible areas; “accommodate” involves changing human behaviour through education or changing physical buildings through zoning and retrofit to allow for the continued occupation of susceptible areas; and “protect” involves constructing structural (hard) or non-structural (soft) mechanisms to armour susceptible areas against impacts (The Arlington Group Planning + Architecture [AGPA], EBA a Tera Tech Company [EBA], De Jardine Consulting [DJC], & Sustainability Solutions Group [SSG], 2013, p.21-22).

Soft protect mechanisms are often referred to as ecosystem-based adaptations (EbAs). Three possible conditions for assessing whether an adaptation is ecosystem-based are to determine if it reduces a community’s vulnerability to climate change, if it directly or indirectly increases the resilience of biodiversity and the flow of ecosystem goods and services (EGS), and if it sustainably uses biodiversity and EGS without harm or with enhancement (UNEP, International Union for Conservation of Nature [IUNC], & United Nations Development Programme [UNDP], 2015, p.8). Common soft protect mechanisms include coastal wetlands, living shorelines, dunes, beach nourishment (AGPA et al., 2013, p.29), barrier islands, sea grasses, coral and oyster reefs, and mangrove forests (Sutton-Grier, Wowk, & Bamford, 2015, p.138); while common hard protect mechanisms include dikes, floodwalls, sea gates, storm surge barriers, and breakwaters (Delcan, 2012, pp.9-10).

Hard infrastructure is initially effective in preventing damage from climate change impacts, but it has a set lifetime, is weakened with age, and is generally constructed to parameters that cannot easily (or cheaply) adapt to changing sea levels and other climate conditions (Sutton-Grier et al., 2015, p.142). Hard infrastructure also imposes negative impacts on habitat development and species diversity (Bilkovic & Mitchell, 2013; OSPAR Commission, 2009). By contrast, some EbAs are self-maintaining, self-repairing after damaging events, and may have the potential to physically grow as SLR occurs (Sutton-Grier et al., 2015, p.142). While the primary benefit derived from EbAs is a reduction in expected damages from climate change impacts (UNEP, 2015), this is often coupled with a multitude of co-benefits such as habitat creation, biodiversity, public health, aesthetics, recreation, carbon sequestering, air quality, pollination, education and knowledge, water purification, and nutrient cycling (Wamsler et al., 2016; Barbier at al., 2011); as well as the protection of livelihoods, and poverty alleviation in developing economies (UNEP, 2010, pp.3-8). Unsurprisingly, coastal flood resilience is more cost-effective in jurisdictions that are EbA-rich, relative to jurisdictions that must construct hard infrastructure to achieve the same level of protection. For example, the natural buffers against erosion and wave damage provided by coral reefs in the Turks and Caicos Islands provide $16.9 million (2012 US dollars) of benefits per year with virtually zero cost, contrasted against constructed dikes and levees which return fewer benefits at a cost of $223 million (Jones, Hole, and Zavaleta, 2012, p.505).

To remedy the disadvantages of hard infrastructure, some municipalities have adopted hybrid approaches to coastal resilience, which incorporate EbAs into hard structures. For these hybrid approaches, Sutton-Grier et al. (2015) express a call to action for greater innovation, ease of implementation, and monitored field experimentation to better understand which approaches to coastal resilience perform best “in different locations and under different circumstances” (p.146). Given this present uncertainty, policy debate persists over both the application of integrated ecosystem assessments (Borgström, Bodin, Sandström, & Crona, 2015; Tallis et al., 2010), and EbA operationalization by local governments (Wamsler et al., 2016).

3.3. Valuing non-market goods and services

The use of economic valuation techniques to estimate marginal and total willingness to pay (WTP) for non-market attributes has become increasingly popular in cost-benefit analysis and urban infrastructure policy debates. While methodologies to obtain economic valuations for non-market attributes are vast and non-standardized, most studies follow the same general four-step approach: conduct stakeholder consultations to determine impacts and understand aspirations, develop a socio-economic profile of the potential beneficiaries, assess the adequacy of current infrastructure or programs (determine the status quo), and estimate the costs and benefits (in monetary terms) of the impacts determined in the stakeholder consultations (Mekala, Jones, & MacDonald, 2015, p.1357).

For estimating the marginal costs and benefits of a project or policy, location-specific valuation studies are often preferred. However, “benefit transfer” has become increasingly accepted in practice as a legitimate valuation technique. Benefit transfer utilizes results from pre-existing primary research to predict value estimates for impacts of significance in other jurisdictions, applying value estimates from a “study site” with data to a “policy site” without data (Rosenberger & Loomis, 2000, p.1097). Such valuations are widely performed when primary estimates for the policy site are unavailable (Johnston & Rosenberger, 2010, p.479), or when resources such as timeframes and budgets are constrained (Mekala et al., 2015, p.1357).

Though convenient, benefit transfer methodology is not without weakness. In a comprehensive literature review, Johnston and Rosenberg (2010) find that protocols for appropriate and accurate benefit transfer lack consensus, that important methodological questions have yet to be answered, and that benefit transfer results remain at least somewhat unreliable (p.480). In the literature, the “accuracy” of benefit transfer valuation is tested by comparing transfer values to estimates derived from site-specific contingent valuation. For example, Ready et al. (2004) find that the majority of benefit transfer estimates (more than three-quarters) commit transfer errors of less than 50% (with an average transfer error of 38%), though the range of this error is -77% to 230% (Ready et al., 2004, pp.79-80).

The most commonly used (and most scrutinized) form of benefit transfer is unit value transfer (Mekala et al., 2015, p.1357). Unit value transfer takes the (inflation-adjusted) value estimate from one study site (or the average of value estimates from several study sites) and directly transfers the value to the policy site (Richardson, Loomis, Kroeger, & Casey, 2014, p.54). To reduce transfer error, Boyle and Bergstrom (1992) propose three "idealistic technical criteria": homogeneity of the nonmarket good in question, homogeneity of characteristics among the affected populations, and homogeneity in the assignment of property rights (p.53). Refining these criteria, it is widely agreed that site similarity on characteristics such as geography, demography, size, resources, and the state of the market are vital to increase benefit transfer validity and reliability (e.g. Colombo & Hanley, 2008; Johnston, 2007; Rosenberger & Phipps, 2007; Piper & Martin, 2001).

Chapter 4. Methodology

4.1. Multi-criteria trade-off analysis

I use a mixed methodology in an iterative process to conduct a multi-criteria trade-off analysis (Chapter 8). To do this, the relative merits and trade-offs of different adaptation options (Chapter 6) are systematically compared using criteria and specific measures for assessment (Chapter 7). Inputs into the analysis stem from primary expert interview data and secondary economic valuation literature.

Primary expert interviews

Primary semi-structured telephone and in-person interviews (conducted between November 2016 and March 2017) with academic, industry, and NGO experts are used to gain critical insight on the costs, benefits, technical feasibility, and implementation hurdles of various options. Interviewees were selected by credentials and recruited through publicly available email addresses. The interviews were mainly informational, serving to guide option selection, design, and (to a lesser extent) evaluation.

Secondary benefit transfer valuation

Publicly available economic valuation literature is used to assess dimensions of human use value (aesthetics and recreation) across the options. Estimates of WTP for these non-market goods are transferred to Kitsilano using benefit transfer method.

4.2. Limitations

My analysis makes use of the best available information I could collect on a topic that has not yet diffused into wide literature circles. By necessity, my analysis has made many assumptions, which may change under alternative perspectives. The interviewees contacted for this study were few and selected through targeted email recruitment based on credentials or expertise. As such, no rigorous qualitative techniques such as content analysis could be performed. I use the interview results to fill information gaps or to add perspective to the analysis, not to provide statistical certainty. Unavoidably, relying on expert opinion to fill knowledge gaps leaves room for individual biases to impact the results. I also acknowledge the many limitations of benefit transfer methodology. To mitigate these limitations, I use benefit transfer mainly as a method to rank options against each other in a relative manner (i.e. to determine which option generates *the most* benefit, not to determine the exact value of that benefit). While I do offer some numerical estimates, I do not suggest that these be used in a cost-benefit analysis without careful consideration of their validity.

Chapter 5. Data Investigation

5.1. Primary expert interviews

Throughout my study, I consulted with three expert interviewees: Tamsin Lyle, a Vancouver-based flood specialist, consultant, and principal author of the CFRA Phase II report; a representative from a non-profit grant-making organization for living shorelines in Maryland’s Chesapeake region; and Dr. Jantsje van Loon-Steensma, a climate change, flood protection, and adaptation expert at Wageningen University in the Netherlands. The interviews were used to identify potential adaptation options for coastal flood resilience at Kitsilano Beach, as well as to identify some of the key trade-offs.

To begin, I was informed that barrier islands “came off the table very early on” as a viable option in English Bay due to technical constraints such as the dominant wind direction and presence of shipping lanes (Lyle, personal communication, November 29, 2016). Extrapolating, other structures that are built in the water (such as breakwaters and jetties) would be subject to the same constraints, and so are not assessed in the analysis. Beach nourishment, though popular on the east coast of the US in the 70s and 80s, is criticized for being short-term, expensive, and reliant on a shrinking world sand supply (Lyle, personal communication, November 29, 2016). Despite these trade-offs, beach nourishment holds the potential to reduce rates of beach inundation, and so is retained in the analysis. For soft-shore armouring (also known as living shorelines), I was informed that there is “a little bit of a misinterpretation of the role of living shorelines in sea level rise;” namely, that they “do a great deal of good in certain situations,” but “can’t protect against sea level rise” (NGO representative, personal communication, January 10, 2017). Regardless, soft-shore armouring holds the potential to be a worthwhile investment in the short term, since it enhances resilience against erosion and storms without precluding the introduction of complementary future measures.

Finally, I collected rich information on Dutch sea dikes from Dr. van Loon-Steensma (personal communication, January 24, 2017). Most sea dikes in the Netherlands are built at a slope ratio of 4:1—determined based on wave attack—which cannot be built steeper without compromising effectiveness (i.e. preventing dike breaches caused by water overflow and landward slope erosion). In the 60s and 70s, dikes covered in asphalt were "really an innovation at the time," designed to look modern, save money, and require less maintenance. However, some decision-makers and citizens "regret that we have covered [dikes] with asphalt" and "are looking for other solutions like green dikes," which are prevalent along the Wadden Sea coast in Germany. At minimum, green dikes have grass coverage on the seaward slope, though most also have grass coverage on the landward slope. Green dike pilot projects in the Netherlands are built at a slope of 7:1, since it had been assessed that 4:1 is "not good enough" to withstand wave attack. Typically, green dikes are used only in locations "where there is a lot of silt, where there is no beach… salt marsh area with a lot of tidal flats." For beach areas, dune nourishment is the preferred adaptation approach since it is "nicer, cheaper, [and] more effective in an area where you have natural dunes to use the dunes as protection." However, in some urban areas where nourishment is not possible, governments "might decide to build a dike and cover it [with] sand." Additionally, in urban areas where little beach existed before, sand coverage over hard infrastructure is sometimes used to improve aesthetic quality and to create new recreation areas, as was the case with closure damns built in the southwestern delta area of the Netherlands.

5.2. Secondary benefit transfer valuation

I selected three economic valuation studies estimating willingness to pay (WTP) for infrastructure aesthetics, beach amenities, and park amenities. The studies were selected based on soundness of statistical methods and sample size, as well as on the degree of economic similarity between the study location and Vancouver (only wealthy, urban, western locations were selected). My analysis assumes that preferences across the three attributes follow the same distributions in Vancouver as they do in the study locations. All monetary values are presented in 2015 Canadian dollars. This is done for ease of comparison against the dollar figures presented in the CFRA Phase II report, as well as to ensure that consumer price indexes (CPIs) from different countries (used in the benefit transfer estimates) could be obtained from the same reliable source (World Bank, 2017—which has not yet released data for 2016).

Each WTP estimate is presented in per-household present value (PV) terms. This number is sufficient to make relative comparisons between options (i.e. to deem one option "better" than another). However, for greater usefulness in comparing these values against capital costs, I also perform an estimation of the PV of total WTP by aggregating the per-household value across the 400 households that benefit most directly from coastal flood resilience investments in Kitsilano.[2] For simplicity, these households are assumed to be homogeneous (same income and preferences), and spatial considerations such as distance from the ocean are not taken into account. Since Kitsilano Beach and Park are popular destinations for numerous people in Metro Vancouver, many times more than 400 households enjoy the goods and services offered by these amenities (though, presumably, to a lower degree than those who live nearby). Since my estimations ignore other users of the beach and park, the PVs of total WTP are extreme lower bounds (if the benefits to all CoV taxpayers are considered).

5.2.1. Infrastructure aesthetics

WTP for a view of different combinations of grey and green flood-resilience infrastructure is estimated in Mell, Henneberry, Hehl-Lange, and Keskin (2016), which analyzes 510 contingent valuation survey responses completed from April to May 2013 in The Wicker (a residential-commercial area of Sheffield, United Kingdom). The paper finds that people base their WTP on an "integrated assessment" of social, ecological, and economic factors, where "the greener and more functional an investment appears to be in terms of access and availability of amenities and services, the greater their WTP

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[2] The CFRA Phase II report estimates that if a 1-in-500 AEP flood event were to occur with 1 meter of SLR, 720 people in the Kitsilano area would be temporarily displaced from their home (CRM & EC, 2015, p.70). To determine the approximate number of households affected, 720 people divided by 1.8 persons per household (average persons per household in Kitsilano; CoV, 2013) equals approximately 400 households at risk of temporary displacement (loss of physical access and/or in need of dwelling repairs).

for it" (p.258). Respondents were given three 3D visualizations (virtual landscape models) featuring different proportions of green and grey flood-resilience infrastructure along an urban canal, and asked how much they would be willing to pay in permanent increased monthly rent to obtain a *view* of the landscape presented in the image. Likely, however, other factors such as greater flood protection or some recreational values (from walking paths) are included in this WTP. As such, these estimates likely over-capture the effect of aesthetics alone (an inconvenience which is not expected to affect the rank between options, only the absolute numerical value). Since the study location is an urban canal, the estimates are not expected to include WTP for beach and park amenities.

Results from the benefit transfer are presented in Table 1. The initial point estimates are annualized, inflated and exchanged to 2015 Canadian dollars, adjusted for cost of living differences,[3] extended to perpetuity in present value terms, and totalled over the 400 households that are threatened by temporary displacement.

Table 1. WTP for green and grey infrastructure

Infrastructure proportion	WTP/mo 2013 GBP[a]	WTP/yr 2013 GBP[b]	WTP/yr 2015 GBP[c]	WTP/yr 2015 CAD[d]	Adj. WTP 2015 CAD[e]	PV WTP 2015 CAD[f]	Ttl. PV WTP 2015 CAD[g]
Mostly grey	4.28	51.36	52.14	101.87	152.05	1,900	0.76 M
Mixed green and grey	8.00	96.00	97.45	190.42	284.20	3,600	1.4 M
Mostly green	10.56	126.72	128.63	251.35	375.15	5,000	1.9 M

[a] Initial point estimates; Mell et al. (2016), p.263

[b] Annualized point estimates (multiply by 12)

[c] Inflate using United Kingdom CPI 2013=110.177, 2015=111.842; World Bank (2017)

[d] Exchange GBP to CAD using average exchange rate 2015=1.953984; Bank of Canada (2016)

[e] Adjust for cost of living, 23% less in Sheffield than in Vancouver (divide by 0.23); Expatistan (2017)

[f] Calculate PV in perpetuity, 8% real discount rate (divide by 0.08); Government of Canada (2011), p.37

[g] Scale by 400 households (times 400)

[3] Household income, property value (or rental rate), and purchasing power between Sheffield and Vancouver are not identical. To adjust for this difference, I used a cost of living index calculated by the website Expatistan (2017). The index compiles price observations for food, housing, clothes, transportation, personal care, and entertainment as submitted by users of the site. Between Sheffield and Vancouver, the cost of living comparison was calculated using 2,598 prices submitted by 448 different people.

5.2.2. Beach amenities

WTP for greater beach area is estimated in Gopalakrishnan, Smith, Slott, and Murray (2011), which analyzes the effect of beach area on 1,555 house and condominium sale prices from 2004 to 2007 along 10 beaches in North Carolina using hedonic price estimation. The paper finds that beach area is positively correlated with beachfront house prices, and that this effect is smaller the further from the ocean the property is located (p.303). In the double-log specification of the model (R^2=0.683), a 1% increase in beach area is associated with a 0.08% increase in beachfront house sale price, significant at the 1% level (pp.302-303). In theory, this result can be reversed to indicate that the economic cost to households from losing 1% of beach width is a decrease in property price by 0.08%.

Results from the benefit transfer are presented in Table 2. Different levels of permanent beach inundation are translated into dwelling price discounts (already in PV terms to perpetuity), and totalled over the 400 households threatened by temporary displacement. To simplify the analysis, all dwellings are considered "beachfront" (no discount based on distance from the park is accounted for).

Table 2. WTP to avoid permanent beach loss

Beach loss	Price discount [a]	PV WTP 2015 CAD[b]	Ttl. PV WTP 2015 CAD[c]
25%	2.00%	19,000	7.6 M
50%	4.00%	38,000	15.2 M
75%	6.00%	57,000	22.8 M

[a] Percent beach loss multiplied by 0.08; Gopalakrishnan et al. (2011), pp.302-303

[b] Price discount multiplied by the average 2015 house benchmark price (detached, townhouse, and apartment) in "Vancouver West" region ($952,041.67); Real Estate Board of Greater Vancouver (2017)

[c] PV WTP multiplied by 400 households

5.2.3. Park amenities

WTP for greater urban park area is estimated in Poudyal, Hodges, and Merrett (2009), which analyzes the effect of park area on 11,125 house sale prices near 46 parks between 1997 and 2006 in Roanoke, Virginia. The paper finds that park area is positively correlated with house sale price, and that this effect is smaller the further from the park the house is located (p.980). In the semi-log specification of the model (R^2=0.64), a 1% increase in park area is associated with a 0.03% increase in house sale price, significant to the 1% level (pp.979-980). Again, this result can be reversed to indicate that the economic cost to households from losing 1% of park area is a decrease in property price by 0.03%.

Results from the benefit transfer are presented in Table 3. Different levels of permanent park loss are translated into dwelling price discounts (already in PV terms to perpetuity), and totalled over the 400 households threatened by temporary displacement. All dwellings are considered “parkfront” (no discount based on distance from the park is accounted for).

Table 3. WTP to avoid permanent park loss

Park loss	Price discount [a]	PV WTP 2015 CAD[b]	Ttl. PV WTP 2015 CAD[c]
25%	0.75%	7,000	2.9 M
50%	1.50%	14,000	5.7 M
75%	2.25%	21,000	8.6 M

[a] Percent park loss multiplied by 0.03; Poudyal et al. (2009), pp.979-980

[b] Price discount multiplied by the average 2015 house benchmark price (detached, townhouse, and apartment) in “Vancouver West” region ($952,041.67); Real Estate Board of Greater Vancouver (2017)

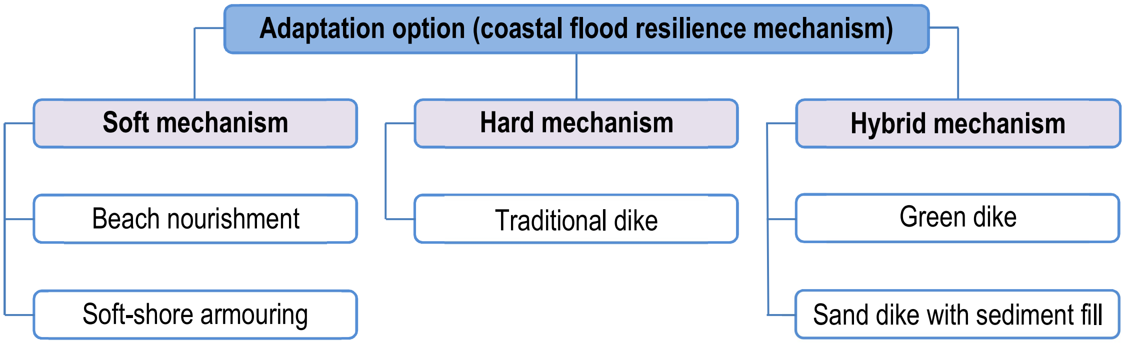
[c] PV WTP multiplied by 400 households

The benefit transfer results derived in Tables 1, 2, and 3 are used to assess aesthetic (landscape) and amenity (recreation) values in the analysis of options (Chapter 8). The purpose of the estimates is mainly illustrative, as there are many limitations to the extent of their usefulness. The key takeaway is within the broad results (green infrastructure is valued higher than grey infrastructure; beaches are valued higher than parks), rather than within the accuracy of these values.

Chapter 6. Adaptation Options

The adaptation options selected for analysis are: beach nourishment, soft-shore armouring, a traditional dike, a green dike, and a sand dike with sediment fill (Figure 4).

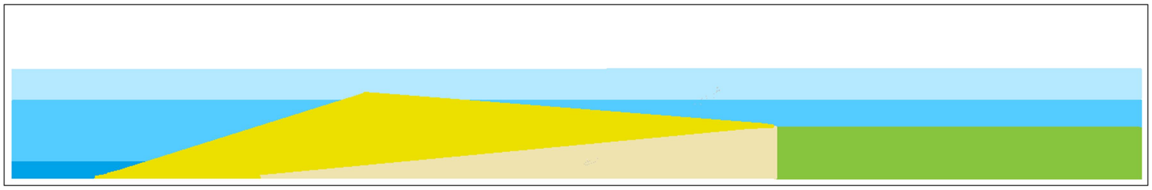
Figure 4. Options for analysis



6.1. Beach nourishment

Beach nourishment (Figure 5) involves digging or dredging sediment from another site, then transporting, dumping, and spreading the sediment at a target site. Beach nourishment is often employed as a response to erosion (maintaining a critical level of sediment through time), but it can also be used proactively to build a beach higher, or to alter the gradient of a beach's slope into the sea. Depending on site-specific rates of erosion and SLR, re-nourishment is typically required every 2 to 10 years.

Figure 5. Beach nourishment

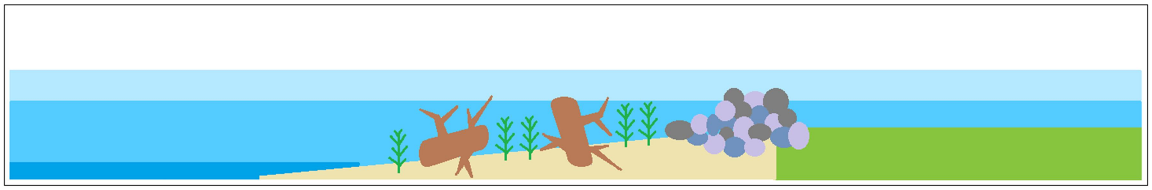


For each diagram illustrating an adaptation option: 0m SLR is indicated in dark blue, 1m SLR—or a 1-in-500 AEP extreme weather event with 0m SLR—is indicated in medium blue, and 1m SLR with a 1-in-500 AEP extreme weather event is indicated in light blue. The initial beach profile is indicated in tan, new sediment is indicated in yellow, grass is indicated in green, and hard structures are indicated in grey.

6.2. Soft-shore armouring

Soft-shore armouring, also known as “living shorelines” (Figure 6), involves the use of vegetation, wood, boulders, and other natural riprap to protect the coastal edge from erosion and storm surge damages, and can be defined as “a way to protect properties from erosion through erosion control mechanisms that provide as many habitat elements and habitat values as possible” (NGO representative, personal communication, January 10, 2017). While soft-shore armouring does not explicitly prevent or delay beach inundation from SLR, it can be incorporated as part of a broader strategy by enhancing storm-surge resilience.

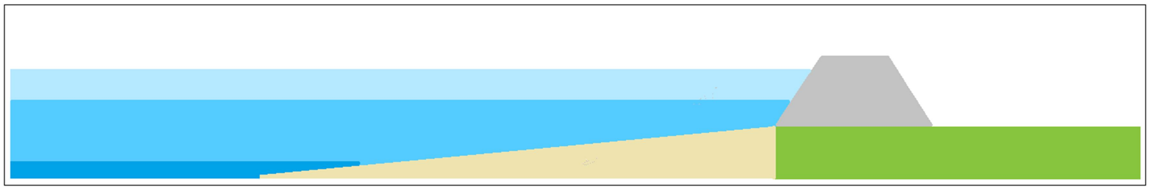
Figure 6. Soft-shore armouring



6.3. Traditional dike

A traditional dike (Figure 7) is a hard engineered impermeable core with sloped sides that is covered with asphalt or rock revetment.

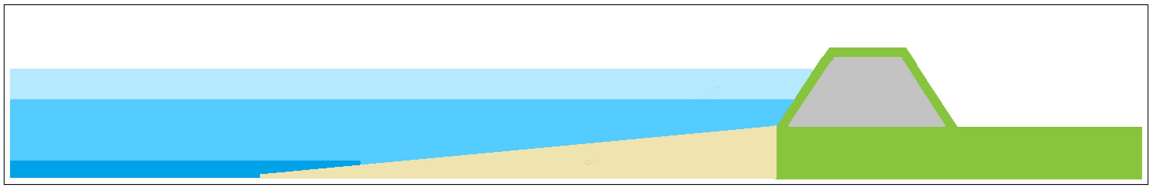
Figure 7. Traditional dike



6.4. Green dike

A green dike (Figure 8) is a hard engineered impermeable core that is covered with grass along (at minimum) the seaward slope. In this analysis, it is assumed that the grass coverage does not change the slope of the dike relative to the traditional dike (though the implications of widening this slope are later discussed).

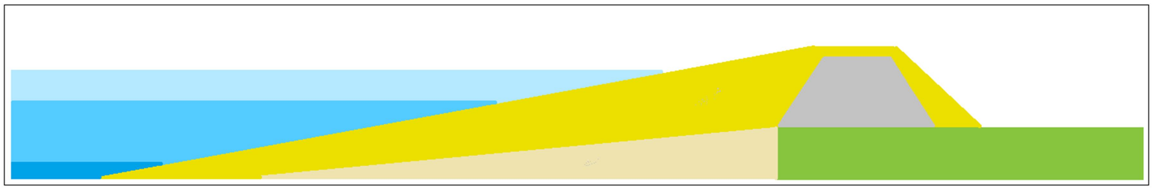
Figure 8. Green dike



6.5. Sand dike with sediment fill

A sand dike (Figure 9) is a hard engineered impermeable core that is covered with sand on both sides. To better integrate the dike into the surrounding ecosystem, this option includes a sediment fill from the crest of the dike out toward the sea. The sediment fill operates similarly to beach nourishment; however, in this case, the current highest point on the beach is raised significantly.

Figure 9. Sand dike with sediment fill



Chapter 7. Criteria and Measures

The CFRA Phase II report emphasizes a "triple bottom line" objective to maximize outcomes for people, the environment, and the economy/government, using criteria developed through community consultations (CRM & EC, 2015, p.20). Drawing from the CFRA and Wamsler et al. (2016) (which uses survey data to determine the most commonly cited co-benefits to climate change adaptations by industry and municipal decision-makers), I identify 9 criteria and specific measures for their assessment (Table 4). Each criterion is explained in detail in the subsections below.

Table 4. Criteria and measures definitions, by objective

Criteria	Definition	Measure	Index
People			
Long-term SLR protection	Does the option protect people, the environment, and the economy from 1 meter of SLR?	Impenetrable barrier separating people and properties from the coastal edge	Yes or no
Aesthetic / landscape value	Does the option impact the beauty of the surrounding landscape?	Economic value (WTP for aesthetics)	Numerical calculation
Amenity / recreation value	Does the option impact recreational opportunities?	Economic value (WTP for use of beach and park)	Numerical calculation
Environment			
Carbon co-benefits	Does the option impact GHG emissions (or sequestration)?	Net carbon emissions during construction and operation	Relative position (H,M,L scale)
Ecosystem co-benefits	Does the option impact the health or functionality of ecosystems?	Biocentric impacts during construction and operation	Relative position (H,M,L scale)
Erosion co-benefits	Does the option impact the rate or intensity of erosive forces?	Reflectivity of wave attack and slope of parallel structures	Relative position (H,M,L scale)
Economy / government			
Ease of implementation	How easy will implementation of the option be for the CoV?	Degree to which examples of implementation are localized	Relative position (H,M,L scale)
Capital cost	How much will it cost to construct the option?	Projected capital expenditure needed (PV over 100 years)	Numerical calculation
Maintenance cost	How much will it cost to maintain the option?	Projected routine and post-storm maintenance needed	Relative position (H,M,L scale)

7.1. Long-term SLR protection

Long-term SLR protection refers to flood-related damages that would be incurred by people, the environment, and the economy/government if a 1-in-500 year AEP flood event were to occur with 1 meter of SLR. The quantification of these impacts is reported in the CFRA Phase II report (CRM & EC, 2015, p.70) and includes: property damage, lost inventory, emergency response, number of people temporary displaced from their dwellings, protection of sites with environmental contaminants, and square kilometers of parkland inundated. In quantifying these impacts, it is assumed that the current distribution of people and properties persist to the year 2100. The long-term effectiveness of each option is measured by the presence (yes or no) of an impenetrable barrier separating people and properties from the coastal edge.

7.2. Aesthetic / landscape value

Aesthetics are found to be an important co-benefit to adaptation, cited 14% of the time (Wamsler et al., 2016, p.311). Aesthetic value refers to how visually pleasing an option is, and increases the more that an option integrates with its surrounding ecosystem features (i.e. the landscape). This criterion is measured by reporting the PV of WTP for the aesthetics of the option in perpetuity, as determined by the benefit transfer estimates in Table 1 (Subsection 5.2.1). To define a starting point, soft options are deemed “mostly green,” hard options “mostly grey,” and hybrid options “mixed green and grey,” with additional nuance discussed in the analysis.

7.3. Amenity / recreation value

Wamsler et al. (2016) finds recreation (11%) to be another frequently cited co-benefit to climate change adaptation (p.311). Two high-profile public amenities located at the case study area that are subject to inundation or damage from SLR are Kitsilano Beach and Kitsilano Park. In the absence of a hard barrier between the beach and the park, some proportion of the beach ecosystem is likely to migrate upland as SLR occurs, overtaking some proportion of the park (CRM & EC, 2015, p.70)—though the exact amount of beach loss relative to park loss is unknown. This criterion considers the impact of the option on the area and lifetime of the beach and park amenities (largely characterized by changes to recreational opportunities). Tables 2 and 3 (Subsections 5.2.2 and 5.2.3) estimate the PV of the marginal economic cost to society associated with reducing beach and park area (assumptions regarding the specific percentages of reduction induced by each option are discussed in the analysis). The criterion is measured by the summation of value losses from the beach and the park.

7.4. Carbon co-benefits

Carbon sequestration (8%) and air quality (8%) are both frequently cited co-benefits to adaptation (Wamsler et al., 2016, p.311). This criterion considers the overall carbon footprint the option. It is measured through a qualitative discussion of net carbon emissions (emissions net of sequestration) over the project lifetime, scored on the following scale:

High	Low net carbon emissions during construction; low during operation
Medium	High net carbon emissions during construction; low during operation
Low	High net carbon emissions during construction; high during operation

7.5. Ecosystem co-benefits

Habitat creation and biodiversity (25%) is the most frequently cited co-benefit to adaptation in Wamsler et al. (2016, p.311). This criterion considers the impact of the option on ecosystem health and functionality over the project lifetime. It is measured through a qualitative discussion of biocentric (as opposed to anthropocentric) impacts on ecosystems both at the beach and adjacent areas, scored on the following scale:

High	No negative impact during construction; positive impact during operation
Medium	Negative impact during construction; positive impact during operation
Low	Negative impact during construction; negative impact during operation

7.6. Erosion co-benefits

Any hard or soft structure that alters the natural movement of waves is likely to have an impact on the rate or intensity of erosive forces. This is especially true for structures constructed parallel to the sea. This criterion is measured by a qualitative discussion of localized (to the beach itself), and adjacent (to land masses adjacent the beach) erosion impacts, scored on the following scale:

High	No hard barrier that reflects wave energy
Medium	Hard barrier that reflects wave energy; softened by material composition or widened slope
Low	Hard barrier that reflects wave energy

7.7. Ease of implementation

This criterion considers the ease of option implementation by the CoV, measured by the degree to which examples of successful implementation are localized (assuming the more local the precedent, the easier implementation will be). While imperfect, this is a proxy measure to encapsulate many elements of implementation ease such as the time needed to acquire authorizations, perform community consultations, approve blueprint designs, obtain confirmation of technical and legal implementation aspects, and build infrastructure. The assessment is scored on the following scale:

High	Examples of use in British Columbia
Medium	Examples of use in other Canadian provinces or the United States
Low	Examples of use outside North America

7.8. Capital costs

Capital costs are the budgetary dollar amount needed for construction (materials and labour) of the option over its lifetime. The criterion is measured in 2015 Canadian dollars, informed by engineering assessments. It is assumed that hard infrastructure options have a useful life of 100 years. For options that require repeat investments, the PV of costs over the 100-year period are calculated using a real discount rate of 8%

(weighted average cost of capital) as suggested by the *Canadian Cost-Benefit Analysis Guide* (Government of Canada, 2011, p.37).

7.9. Maintenance costs

Maintenance costs are the budgetary dollar amount needed for upkeep (materials and labour) of the option on an annual basis. These are considered separately from capital costs because of the budgetary implications that on-going costs may have over a long time-horizon. Due to information constraints, this criterion is measured qualitatively by the degree of routine and post-storm maintenance required, scored on the following scale:

Low	Minor routine maintenance; minor maintenance after storms
Medium	Minor routine maintenance; major maintenance after storms
High	Major routine maintenance; major maintenance after storms

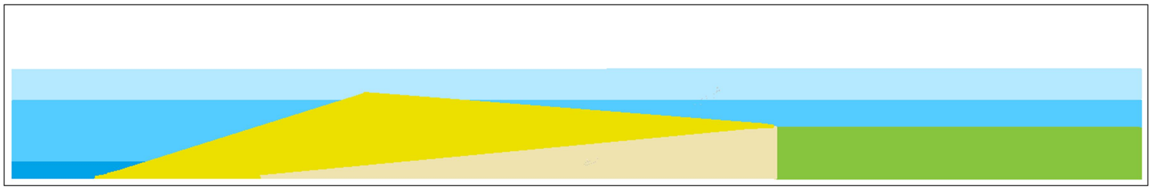
Chapter 8. Analysis of Adaptation Options

The adaptation options set out in Chapter 6 are assessed against the criteria and measures defined in Chapter 7. A visual summary of the final assessments is presented in Table 5, with rationale for each assessment detailed in the subsections below. Because of the differences in subject and magnitude between the impacts (e.g. millions of dollars of damages from SLR versus a qualitative discussion of implementation ease), numerical tallies across each criteria are not performed. Instead, the "best" option for pursuit by the CoV is deemed to be the one (or ones) that best enhances outcomes across the 3 objectives (people, environment, and economy/government), as determined in a broad discussion of trade-offs (Chapter 9).

Table 5. Analysis summary table

Criteria / Option	Beach nourishment	Soft-shore armouring	Traditional dike	Green dike	Sand dike / sediment
People					
Long-term SLR protection	No	No	Yes	Yes	Yes
Aesthetic / landscape value (PV perpetuity)	Value gain >$1.9 M	Value gain ~ $1.9 M	Value gain <$0.76 M	Value gain $0.76-1.4 M	Value gain $1.4-1.9 M
Amenity / recreation value (PV perpetuity)	Value loss $16.2 M	Value loss $20.9 M	Value loss $22.8 M	Value loss $22.8 M	Value loss $7.6 M
Environment					
Carbon co-benefits	L	H	M	H-	L+
Ecosystem co-benefits	M	H	L	M	H-
Erosion co-benefits	H	H-	L	L+	M
Economy / Government					
Ease of implementation	M	H	H-	H-	L
Capital costs (PV 100 years)	$4.1-15.4 M	$0.81-2.0M	$5.7 M	$5.9 M	$11.2-19.2M
Maintenance costs	L	M	L+	M	H-

8.1. Beach nourishment



Long-term SLR protection

Beach nourishment is a soft defence mechanism that does not provide an impenetrable barrier separating people and properties from the coastal edge. Historically, beach nourishment has been employed by jurisdictions as a response to erosion, not SLR. However, since beach nourishment raises the height of the shoreline, some protection against SLR is granted (contributing to an increased time-horizon over which high capital cost decisions regarding hard or hybrid infrastructure can be made). The extent of SLR protection offered by beach nourishment depends greatly on the scale of the project undertaken (i.e. how much new sand is being introduced), and the rate of erosion due to waves and storm surge. While beach nourishment can be expected to protect against small increases in mean sea level (over the next, say, 50 years), it is not likely to be effective in preventing damage to people and properties from 1 meter of SLR to the year 2100. In the absence of an impenetrable barrier, the extent of damages in Kitsilano following a 1-in-500 AEP flood event with 1 meter SLR is estimated to be: $4 million property damage, $10 million lost inventory, $0.5 million emergency response, no protection of sites with contaminants, 720 people temporarily displaced, and 0.2 square kilometers of parkland inundated (CRM & EC, 2015, p.70).

Aesthetic / landscape value

Beach nourishment not only maintains but enhances the open sandy landscape currently enjoyed at Kitsilano Beach. As determined in Mell et al. (2016), the greener that an option looks, the greater people are willing to pay to have a view of it (p.385). Using the benefit transfer value derived in Table 1 (Subsection 5.2.1), aesthetic / landscape value for options that are “mostly green” is estimated to be $1.9 million among households threatened by temporary displacement. Since this option introduces no hard elements (i.e. is not just “mostly green,” but rather, only green), the economic benefit may be higher than this estimate.

Amenity / recreation value

With no hard barrier, some proportion of the beach ecosystem is expected to move inland and overtake some proportion of the park as SLR occurs. Since sediment volume is increased under beach nourishment, a greater beach area is expected to be preserved than under soft-shore armouring. Assuming that 75% of the current beach area is able to move inland from inundation (overtaking 75% of the park area), total amenity value loss among households threatened by temporary displacement (using the benefit transfer values derived in Tables 2 and 3 in Subsection 5.2.1) is estimated to be $16.2 million ($7.6 million from the beach, $8.6 million from the park).

Carbon co-benefits

Since beach nourishment involves transferring truckloads of sediment from other locations, high levels of carbon are emitted. Backhoes are needed to scoop sediment from an established site into dump trucks, which then drive to and unload at the beach where front-end loaders spread and shape the sediment. Alternatively, sediment can be dredged by special boats at a site away from the beach, and transferred by boat or barge to the new location, which, too, is a carbon-intensive process. These impacts are repeated each time the beach is re-nourished.

Ecosystem co-benefits

Beach nourishment moderately contributes to biocentric processes. Depending on the compatibility of the sediment introduced, beach nourishment can create, restore, and protect habitats in the long term (NOAA, 2010, p.82). Since no hard structures prevent foreshore movement, beach nourishment can also aid in the landward migration of organisms as SLR occurs. Despite these benefits, careful site-specific ecological consideration must be taken into account. At the target site, burying and smothering the top layer of sediment destroys habitats in the short term. The use of bulldozers may permanently destroy primary dune vegetation and increase the compactness of sediment, negatively impacting vascular plants and arthropods living on dry portions of the beach (OSPAR Commission, 2009, p.18). Re-colonization of flora and fauna is species-specific, and depends on dispersal and migration capacities, as well as on habitat demands and tolerances (Speybroeck et al., 2006, p.426). Negative impacts can also accrue to the site where the sediment is being dug or dredged (such as damage or mortality to the established benthos), or waterside slopes may become too steep—impacts that are repeated each time the beach is re-nourished. In the event of option termination, no foreseeable reclamation efforts would be needed.

Erosion co-benefits

Beach nourishment is generally considered to be "a better alternative than the construction of hard structures to protect against detrimental erosion" (OSPAR Commission, 2009, p.19). Rather than refracting wave energy (as hard structures do), sediment absorbs it. Since new sediment is introduced into the entire tidal system, adjacent beaches may also benefit (NOAA, 2010, pp.81-82). However, new surface sediment may take several days to settle, rendering it susceptible to blowing off the beach and into the park or adjacent properties if windy.

Ease of implementation

Beach nourishment has been explored to a small degree in BC (with the majority of these examples from Vancouver Island). Canadian jurisdictions on the east coast (such as New Brunswick), as well as numerous jurisdictions in the US (such as California and Florida) use beach nourishment. Its technical feasibility is site-specific, depending on the availability of sediment, as well as beach access for trucks, barges, and other equipment. Given the positioning of Kitsilano Beach, it is likely that trucks (if used) would need to drive through the park in order to access the shoreline, which may cause an implementation hurdle if a designated access point through the park is not easy to establish.

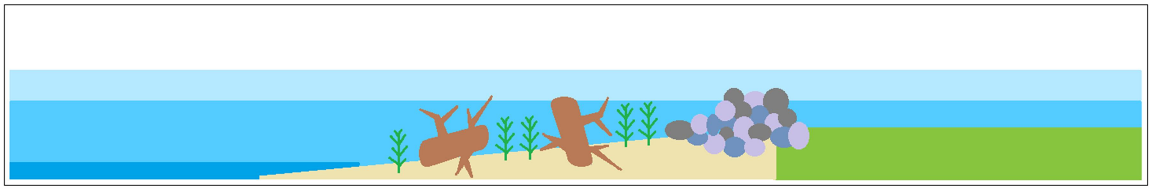
Capital costs

Beach nourishment requires a capital cost investment each time it is performed. To estimate the first-period investment, capital costs for a traditional dike (Subsection 8.4) are subtracted from the capital costs of a dike with sloped sand fill (Subsection 8.5). The difference ($6,000 in 2012 dollars) represents the costs of sloped sand fill without the dike along a 70-meter gradient length. However, for beach nourishment, less sand is needed than would be the case to fill a gap in front of a hard structure. Assuming beach nourishment requires 50% less sand, the cost is $3,000 (2012 dollars) per meter of width. Applying this cost along 690 meters of beach and inflating to 2015 prices produces a capital cost estimate of $2.2 million. Beach nourishment is typically undertaken every 2 to 10 years, depending on the degree of nourishment desired and the rate of natural erosion (site-specific assessment needed). Over a 100-year timeframe, this option in present value terms could cost $4.1 million (if performed every 10 years), $6.8 million (if every 5 years), or $15.4 million (if every 2 years).

Maintenance costs

Between re-nourishment periods, the beach requires little to no routine or post-storm maintenance. If desired, however, some re-shaping or re-sloping of the beach could be performed between re-nourishment periods (enhancing resilience) for a slight increase in on-going costs.

8.2. Soft-shore armouring



Long-term SLR protection

Soft-shore armouring (also known as “living shorelines”) does not provide an impenetrable barrier separating people and properties from the coastal edge. As such, the same damages listed for beach nourishment would occur under soft-shore armouring following a 1-in-500 AEP flood event with 1 meter SLR. Historically (as with beach nourishment), soft-shore armouring has been employed by jurisdictions as a response to coastal erosion, not SLR. Undertaken on its own, soft-shore armouring is likely to be ineffective at preventing flood-related damages from 1 meter of SLR (see discussion in Subsection 5.1). However, since soft-shore armouring helps to protect and anchor the coastal edge, it may contribute to enhanced short-term resilience against erosion and storm surge. Depending on the extent of this resilience, soft-shore armouring may also increase the time horizon over which hard or hybrid infrastructure decisions can be made. As such, this option maintains flexibility while adding robustness to the CoV's coastal resilience strategy.

Aesthetic / landscape value

Soft-shore armouring enhances the sandy landscape currently enjoyed at Kitsilano Beach, but may reduce some of its openness by taking up beach space with natural riprap. Using the benefit transfer value derived in Table 1 (Subsection 5.2.1), aesthetic / landscape value for options that are "mostly green" is estimated to be $1.9 million among households threatened by temporary displacement. This estimate may be high or low depending on the proportion of harder natural elements used (e.g. boulders) in comparison to softer natural elements (e.g. logs or sea grasses).

Amenity / recreation value

With no hard barrier, some proportion of the beach ecosystem is expected to move inland and overtake some proportion of the park as SLR occurs. Assuming 50% of the current beach area is able to move inland from inundation (overtaking 50% of the park area), total amenity value loss among households threatened by temporary displacement (using the benefit transfer values derived in Tables 2 and 3 in Subsection 5.2.1) is estimated to be $20.9 million ($15.2 million from the beach, $5.7 million from the park).

Carbon co-benefits

Soft-shore armouring requires a very low level of carbon emissions since it involves manually building up the shoreline with vegetation, wood, boulders, and other natural riprap. Some soft-shore armour elements even have the ability to "accrue their own sediment and are therefore more self-sustaining [than beach nourishment]" (Lyle, personal communication, November 29, 2016). Depending on the mix of elements used, opportunities to enhance carbon sequestration and nutrient cycling also exist.

Ecosystem co-benefits

Soft-shore armouring can contribute greatly to biocentric processes at the site where it is implemented. The most prominent of these benefits include: maintaining natural shoreline dynamics and sand movements, trapping and retaining sediment, providing shoreline habitat, reducing wave energy and coastal erosion, absorbing storm surge and flood waters, filtering water pollutants, sequestering atmospheric carbon dioxide, and—importantly—allowing for the eventual landward migration of organisms as SLR occurs (NOAA, 2010, p.81). The success of landward migration, however, depends on the proximity of the shore to hard infrastructure (such as dikes, streets, or buildings). As cautioned by a representative from a non-profit grand-making organization in Maryland's Chesapeake Bay region, if a living shoreline is "in an area where there is infrastructure right behind your coastal system… by definition then it's going to be hard for your wetlands to migrate inland" (NGO representative, personal communication, January 10, 2017). Given the presence of a park separating the beach from the street, it is not anticipated that organisms will be impeded along an inland migration. While most of the environmental impacts are localized (contained within the beach ecosystem), consideration should still be given to where the soft armour materials are originating to insure that an established habitat is not being disrupted. In the event of option termination, no harm is caused to the surrounding ecosystem if the natural riprap is simply left on the beach. The only foreseeable reclamation efforts needed would be to remove chains from anchored elements such as logs.

Erosion co-benefits

Soft-shore armouring is unlikely to introduce hard structures which redirect wave energy sideways. The only exception to this is if rock revetment is used, and piled parallel to wave action somewhere along the beach. Assuming that rock revetment is not used (or at least, used much later as a line of last defense), soft-shore armouring is not expected to increase the rate of erosion to the beach or to adjacent areas.

Ease of implementation

Soft-shore armouring is already being widely used in BC. The Stewardship Centre for British Columbia has an established Green Shores program, which includes implementation and landscape guidelines for building green shores on private property. As there is already a precedent for this type of action in BC, no major implementation hurdle is expected.

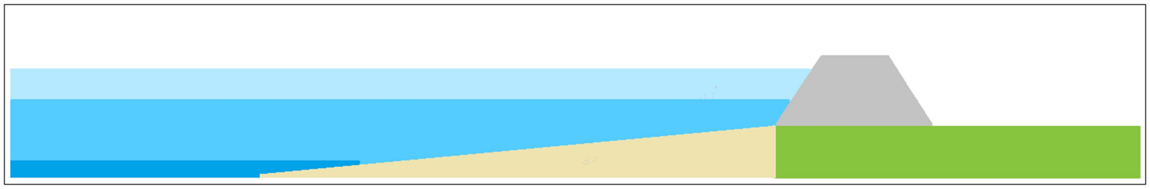
Capital costs

The cost of constructing a soft-armoured shore varies around the type of soft armour selected and the density with which elements are placed. To provide a range, The City of Seattle's Department of Planning and Development estimates an average cost of $200 to $500 per foot (2008 US dollars) for "bioengineered" shorelines (2008, p.25). Inflating these values to 2015, converting to Canadian dollars, and multiplying over 690 meters, a capital cost estimate of $0.64 to $1.6 million is produced. If the extent of soft-shore armouring performed at Kitsilano Beach is light (e.g. simply adding more anchored logs), capital costs are expected to fall beneath this range. Though many soft-armour elements are self-regenerating, some have finite lifetimes (which are difficult to pinpoint). Assuming a general lifetime of 20 years, soft-shore armouring over a 100-year timeframe in present value terms could cost $0.81 million to $2.0 million.

Maintenance costs

Once established, soft-shore armouring is relatively self-sustaining and requires little to no routine maintenance. However, soft armour elements that have been destroyed, buried, or blown away during storms may require some maintenance to fix. If the damage is such that replacement is needed, new capital costs will be required. Post-storm maintenance costs are expected to increase with the softness of the mix of elements selected (e.g. logs and sea grasses, relative to boulders).

8.3. Traditional dike



Long-term SLR protection

A traditional dike—a dike covered in asphalt or rock revetment—provides an impenetrable barrier separating people and properties from the coastal edge. As such, it is highly effective in preventing flood-related damages from 1 meter of SLR. With an impenetrable barrier, the extent of damages following a 1-in-500 AEP flood event with 1 meter of SLR is estimated to be: low to no property damage, low to no lost inventory, low to no emergency response, 200 people temporarily displaced from their dwellings, and 0.01 square kilometers of parkland inundated (CRM & EC, 2015, p.70).

Aesthetic / landscape value

A traditional dike at Kitsilano Beach would not integrate well with the natural, open aesthetics granted by the beach and park. Using the benefit transfer value derived in Table 1 (Subsection 5.2.1), aesthetic / landscape value for options that are “mostly grey” is estimated to be $0.76 million among households threatened by temporary displacement. As explained in Subsection 7.2, this estimate includes WTP for flood protection. Some evidence suggests that the pure aesthetic effect of traditional dikes may be negative. For example, in Westerland (along the North Sea coast in Germany), a 1-kilometer increase in dike length is correlated with a decrease in hotel fares of €0.52 per night, B&B fares of €0.21 per night, and private accommodation fares of €0.17 per night (Hamilton, 2007, p.599). Multiplying these values by the patronage at each type of accommodation per year, the economic losses for Westerland are estimated to be €392,329 (2002 EUR) per kilometer of new dike (Hamilton, 2007, p.600). Inflating this value to 2015, converting to Canadian dollars, adjusting for cost of living, and multiplying across a 0.69 kilometer dike, an estimated economic loss of $0.73 million per year (or $9.1 million in perpetuity) is generated. However, since Kitsilano Beach is more of a local than tourist destination, the economic losses are expected to be lower than this transfer estimate. Regardless, the $0.76 million benefit among households threatened by temporary displacement is likely to be a high estimate.

Amenity / recreation value

With a hard barrier, no proportion of the beach ecosystem can move inland with SLR, thereby preserving the full area of the park. However, some proportion of the beach (likely large) will be permanently inundated by SLR. Assuming that 75% of the beach and 0% of the park is lost, total amenity value loss among households threatened by temporary displacement (using the benefit transfer values derived in Tables 2 and 3 in Subsection 5.2.1) is estimated to be $22.8 million.

Carbon co-benefits

High levels of carbon are emitted in the process of constructing a traditional dike, both in terms of its material composition and usage of heavy machinery. Once built, however, the continued carbon impact of the structure is only the low level generated from routine maintenance. No opportunities for carbon sequestration are generated.

Ecosystem co-benefits

The ecological impacts generated by hard coastal defenses vary site to site. During construction, negative temporary impacts accrue to birds and fish from construction-based vibrations. In the location where the structure is built, permanent impacts of disturbance and area loss accrues to natural sedimentary habitats, including assemblages of animals and plants (soft substrate benthos), and in some cases, the surrounding soft seabed environment (OSPAR Commission, 2009, p.16). Depending on how close the structure is built to the sea, algae and epibenthic fauna may colonize the surface of the structure, contributing to some biodiversity over the long term. However, this biodiversity lacks in comparison to that found on natural rocky shores and houses mostly only opportunistic species (OSPAR Commission, 2009, p.17). Furthermore, many European studies (e.g. Bacchiocchi & Airoldi, 2003; Martin et al., 2005; Moschella et al. 2005) have found only juvenile species to live on hard built structures; generating evidence that built structures cannot support stable communities of adult flora and fauna. The steepness and height of a traditional dike is likely to disrupt the movement of organisms between the upland and the foreshore (SNC-Lavalin, 2010, p.28), rendering the retreat of coastal systems difficult to impossible as SLR occurs. In the event of option termination, some land under the structure is likely to remain permanently irremediable.

Erosion co-benefits

Hard structures redirect wave energy sideways, and have a well-known negative impact on areas adjacent to the protected zone in the form of accelerated erosion. Accelerated erosion has also been observed on beaches in front of hard structures. A longitudinal study in Quebec finds that beaches backed by reflective structures are 2 to 5 times narrower than unmodified beaches of the same type, for which encroachment (reduction in beach width due to the structure itself) is only accountable for 19 to 27% of this loss (Bernatzchez & Fraser, 2012, p.1559). The intensity of beach loss depends on the natural rate of sediment transit. Beaches with strong long-shore drift currents are increasingly vulnerable to “rapid and significant evacuation of sediment in front of hard defence structures since the reflection of waves on the structures stops sediment in transit from accumulating” (Bernatzchez & Fraser, 2012, p.1559). To avoid undesired consequences at Kitsilano Beach, assessments of both erosion effects (adjacent and localized areas) should be conducted before a hard structure is built.

Ease of implementation

Well over 100 kilometers of sea dike have already been constructed in Metro Vancouver. This suggests high technical feasibility for constructing these structures in the area (though the CoV itself does not currently operate any of these dikes). One potential implementation hurdle may derive from various stakeholder interests. Since

Kitsilano Beach and Park is located in a high-traffic urban area with both residential and commercial zoning, many stakeholders will be affected by decisions to build hard infrastructure. After extensive community consultation is undertaken, implementation as directed by the *Dike Design and Construction Guide* is expected to be straightforward.

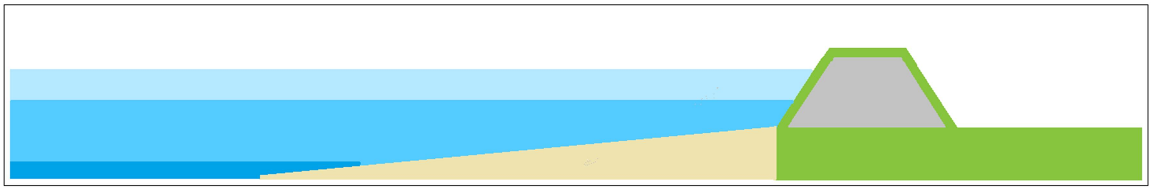
Capital costs

SNC-Lavalin conceptualized a concrete dike with a crest constructed approximately 5 meters above the Canadian Geodetic Vertical Datum (CGVD) for a private property located on the east coast of Vancouver Island (2014, p.23). The option is estimated to cost $8,000 (2012 dollars) per meter width (SNC-Lavalin, 2014, p.30). Applying this cost to a 690-meter dike at Kitsilano Beach and inflating to 2015 prices produces a capital cost estimate of $5.7 million. By contrast, the CFRA Phase II report estimates a base dike cost of $3.2 million excluding ground improvements ($9.4 million if ground improvements are undertaken) (CRM & EC, 2015, p.D–75). Forgoing ground improvements, a dike with greater use value (e.g. one that has a walking path) is estimated to cost $5 to $6 million (CRM & EC, 2015, p.70), corroborating the $5.7 million estimate. It is assumed that this investment is required only once in a 100-year period.

Maintenance costs

Assuming the dike is constructed at the appropriate slope-ratio to withstand wave attack, only a minor amount of routine maintenance is expected. The CFRA Phase II report estimates this cost to be $7,000 per year (CRM & EC, 2015, p.D–75). Since the dike is armoured with asphalt or rock revetment, little to no maintenance is expected to be required after storms.

8.4. Green dike



Long-term SLR protection

A green dike provides an impenetrable barrier separating people and properties from the coastal edge. As such, it is highly effective in preventing flood-related damages from 1 meter of SLR. A green dike is expected to provide the same level of damage mitigation as a traditional dike.

Aesthetic / landscape value

A green dike at Kitsilano Beach would clash with the aesthetic of the beach ecosystem but would integrate with the aesthetic of the park. Using the benefit transfer value derived in Table 1 (Subsection 5.2.1), aesthetic / landscape value for options that are “mixed green and grey” is estimated to be $1.4 million among households threatened by temporary displacement, while that for options that are “mostly grey” is estimated to be $0.76 million. Since a dike covered in grass is visibly still a dike, aesthetic benefit is likely to fall somewhere in between these two values.

Amenity / recreation value

As with a traditional dike, no proportion of the beach ecosystem can move inland as SLR occurs. As such, the full area of the park will be preserved while some proportion of the beach (likely large) will be inundated by SLR. Assuming that 75% of the beach and 0% of the park is lost, total amenity value loss among households threatened by temporary displacement (using the benefit transfer values derived in Tables 2 and 3 in Subsection 5.2.1) is estimated to be $22.8 million; the same as with a traditional dike.

Carbon co-benefits

The initial construction of a green dike emits the same level of carbon as a traditional dike, assuming the core of the structure is the same. However, since a green dike is covered in grass, some carbon sequestration benefits accrue year to year. For a narrow-sloped dike, sequestration benefits are expected to be minor. If a wider dike is constructed, however, sequestration benefits will increase proportionally to surface area.

Ecosystem co-benefits

Constructing a green dike is subject to the same immediate negative ecological impacts of disruption and habitat loss as a traditional dike. The difference, however, is in the level of biodiversity supported by the structure upon completion. An ecological survey conducted at 26 wide green dike locations along the Wadden Sea coast in Europe counted an average of 11.3 different vegetation species along the lower, middle, and upper zones of the dikes (van Loon-Steensma & Huiskes, 2016, p.19). The dikes profiled in that survey are wider than traditional dikes and located in mostly rural areas. True green dikes "consider the whole dike;" meaning full grass coverage is implemented along the top and both sides of the dike (van Loon-Steensma, personal communication, January 14, 2017). However, in urban environments, a paved walking path or other structure is typically constructed along the top or landward side of the dike, reducing the area for biodiversity to accrue (van Loon-Steensma, personal communication, January 14, 2017). While biodiversity on a green dike built at Kitsilano Beach is expected to be much lower than what was found along the Wadden Sea, it is still greater than what would be found on a traditional dike. The steepness and height of the dike is likely to impede organism retreat inland as SLR occurs, as is the case with a traditional dike (though this negative impact can be mediated by constructing a dike with a wider slope). In the event of option termination, some land under the structure is likely to remain permanently irremediable.

Erosion co-benefits

Since green dikes are constructed parallel to wave action, they are likely to generate negative erosion impacts to local and adjacent areas. However, depending on the thickness and slope of the grass cover, some wave energy is absorbed rather than reflected. Many sea dikes in BC have been built with a seaward slope of 3:1. Green dikes along the Wadden Sea, however, are built at a seaward slope of 7:1, which better dampens wave energy along the slope and reduces the level of wave attack on the top of the dike (van Loon-Steensma, personal communication, January 14, 2017). A longitudinal study in Quebec finds evidence that structures with broader slopes contribute significantly less to erosion than structures with steeper slopes (13% reduction in beach width from sloped rock armour versus 39% reduction in beach width from straight seawall) (Bernatzchez & Fraser, 2012, p.1557). By trading off increased construction costs for a wider-sloped dike, less local and adjacent erosion—as well as more surface area for greater biodiversity—are expected to be gained.

Ease of implementation

Green dikes are not in danger of violating the *Dike Maintenance Act*, which allows for trimmed grassed coverage. While they have not been explored to the same degree as concrete dikes in Metro Vancouver, the City of Surrey is in the process of conceptualizing green dikes as per their broader green infrastructure strategy. Likely, opportunities to share design elements and costing data between municipalities exists. Despite the presence of grass coverage, a permanent hard structure is still being built in an urban area with many stakeholders, thus much community consultation is expected to be necessary.

Capital costs

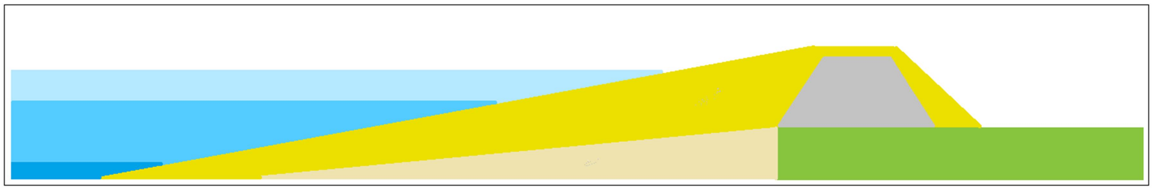
The core of a green dike is expected to cost the same as a traditional dike. The unit cost of topsoil and grass cover is estimated in the CFRA Phase II report to be $25 per square meter (CRM & EC, 2015, p.D–76). With a traditional dike slope ratio of 3:1 (and assuming the top of the dike has a concrete path), only the landward and seaward slopes (6110 square meters) require grass coverage (CRM & EC, 2015, p.D–77). Multiplying over the unit cost for grass and topsoil, grass coverage is expected to increase capital costs by $0.15 million, to a total of $5.9 million. This cost increases at a rapid rate the wider the seaward slope constructed. In the Netherlands, a 7:1 slope on prototype green dikes is constructed using a thick layer of clay covered in grass (van

Loon-Steensma, personal communication, March 13, 2017). Notably, if the clay can be dredged nearby (forgoing costly transport), "[a green dike] is not really more costly than an asphalt covered dike;" though this may not be the case in urban areas where the land needed to construct a wider dike is expensive (van Loon-Steensma, personal communication, January 24, 2017).

Maintenance costs

Maintaining the grass cover on a green dike is paramount for preventing landward side erosion by water overflow and the threat of subsequent dike breaches. Specifically, grass coverage must be maintained to withstand wave attack on the seaward side, and water overflow on the landward side (van Loon-Steensma, personal communication, January 24, 2017). This requires a greater level of routine maintenance than a traditional dike. During storms, it is likely that wave attack and water overflow will intensify, increasing wear and tear on the grass cover. As such, post-storm maintenance is also higher for green dikes than for traditional ones.

8.5. Sand dike with sediment fill



Long-term SLR protection

A sand dike with sloped sediment fill provides an impenetrable barrier separating people and properties from the coastal edge. It is therefore highly effective in preventing flood-related damages from 1 meter of SLR. A sand dike with sediment fill is expected to provide the same level of damage mitigation as a traditional or green dike.

Aesthetic / landscape value

If done well, a sand dike at Kitsilano Beach could integrate seamlessly into the aesthetic of the beach ecosystem. Since the option involves a sediment fill from the crest of the dike out to sea, there would be no visibility of the dike itself. Using the benefit transfer value derived in Table 1 (Subsection 5.2.1), aesthetic / landscape value for options that are “mostly green” is estimated to be $1.9 million among households threatened by temporary displacement. If the dike is masked poorly, however, the benefit may fall towards the “mixed green and grey” level of $1.4 million.

Amenity / recreation value

With a hard barrier, no proportion of the beach ecosystem can move inland as SLR occurs, preserving the full area of the park. Additionally, since the sediment fill raises the height of the beach significantly, some proportion of the beach area is expected to remain free from inundation, even with 1 meter of SLR. Assuming that 25% of the beach and 0% of the park is lost, total amenity value loss among households threatened by temporary displacement (using the benefit transfer values derived in Tables 2 and 3 in Subsection 5.2.1) is estimated to be $7.6 million.

Carbon co-benefits

The carbon emitted to construct the initial dike core is the same as the concrete dike. Additional high carbon emissions are needed to locate, dig or dredge, transport, and spread the sand fill (as is the case under beach nourishment). Since this option builds the beach significantly higher than its current highest point, more sediment is needed initially than is the case under beach nourishment. Likely, however, greater initial volume also means increased time lapse between re-nourishment periods.

Ecosystem co-benefits

A sand-covered dike and sloped sediment fill can positively contribute to biocentric processes. Unlike traditional or green dikes, sand-covered dikes maintain the functions of a beach ecosystem, and, in some cases, may even mimic the functions of a natural sand dune. These functions may include: soil formation, nutrient cycling, water recycling, carbon sequestration, and—importantly—the provision of habitat (Everard, Jones, & Watts, 2010, p.481-483). During construction, the ecological impacts for the beach and for the site where the sediment is dug or dredged are expected to be negative (as they are under beach nourishment). However, since a greater volume of sediment is brought in at once, the frequency with which habitats need be disturbed is lessened. In addition, due to the stable nature of the beach crest line and the wide slope at which the beach gradient climbs, the movement of organisms landward is not expected to face impediment as SLR occurs (SNC-Lavalin, 2010, p.25). In the event of option termination, flora and fauna in the sediment above the dike core face habitat destruction when the dike is unearthed. As with a traditional dike, some land underneath the sand dike footprint is likely to be permanently irremediable.

Erosion co-benefits

Since the sediment fill is soft and widely sloped, wave energy is absorbed and spread rather than reflected. This protects the dike core from direct contact with waves, and prevents increased erosion to local and adjacent areas. The introduction of new sand into the tidal system may also benefit adjacent beaches (NOAA, 2010, p.81-82). However, loose sediment on the beach or dike may take days to settle, resulting in sand blown into the park or adjacent properties if windy. Loose sediment blown off the dike may become an ongoing issue, but could perhaps be mitigated by implementing dune stabilization techniques such as planting dune grasses or using sand fences.

Ease of implementation

A dike core integrated into a sloped sand fill has not been implemented in BC before. However, a similar concept has been conceptualized (including costing figures) by engineering firm SNC-Lavalin (2014) along a portion of Qualicum Beach on Vancouver Island. In addition, integrated dike-in-dune designs have been implemented on beaches in the Netherlands along the North Sea. For implementation in the CoV, it is possible that the current legal provisions set out in the *Dike Maintenance Act* restrict this option. If law reform is required, then implementation is expected to be a lengthy and difficult process.

Capital costs

SNC-Lavalin considered a concrete dike with a crest constructed approximately 5 meters above the CGVD covered by seaward sand fill extending for 70 meters along a sloped gradient, with the dike position lying 30 meters away from the current high tide sea level (2014, p.17). A dike constructed between Kitsilano Beach and Kitsilano Park would be similarly distanced from the sea edge, rendering the SNC-Lavalin cost estimates transferable to this case. The option is estimated to cost $14,000 (2012 dollars) per meter width (SNC-Lavalin, 2014, p.30). Applying this cost to 690 meters of dike with sloped land fill and inflating to 2015 prices produces a capital cost estimate of $10.0 million. Of this cost, $5.7 million is attributed to the dike core and $4.3 million is attributed to the sand fill. Given that a large volume of sand used (relative to beach nourishment), re-nourishment periods are expected to be further apart. Assuming that re-nourishment is required every 5 to 20 years (site-specific assessment needed), the total capital costs of the option over a 100-year timeframe (in PV terms) could be $11.2 million (if performed every 20 years), $13.7 million (if every 10 years), or $19.2 million (if every 5 years).

Maintenance costs

Since the dike core is covered in sand, it is not exposed to waves and other erosive elements. This reduces routine maintenance costs to the core dike. However, the sediment covering the dike core must be routinely maintained (to preserve effectiveness), as well as re-shaped or replaced if lost to windy storms.

Chapter 9. Discussion of Trade-offs

As depicted in Table 5 (Chapter 8), there are strengths and weaknesses to each of the adaptation options analyzed. To begin, while beach nourishment retains a soft shoreline for relatively high aesthetic / landscape value, it is unlikely to prevent the majority of flood-related damages from 1 meter of SLR. Instead, shorter-term erosion and storm resilience is enhanced since new sediment is repeatedly introduced into the coastal system and no hard barriers are in place to redirect wave energy. While beach nourishment requires low routine and post-storm maintenance, it requires high carbon emissions at both the dump and dredge or dig site over the project lifetime. Capital costs for the option have the potential to be relatively low ($4.1 million) over a 100-year period. However, there is a risk that these costs may more than quadruple (to $19.2 million) if re-nourishment periods are short.

Soft-shore armouring also retains a soft shoreline for relatively high aesthetic / landscape value. Like beach nourishment, however, it is unlikely to prevent the majority of flood-related damages from 1 meter of SLR, but may be used to enhance shorter-term erosion and storm resilience. Since the process is largely self-sustaining and ecosystem-based, high co-benefits to carbon, ecosystems, and erosion are generated. An additional strength is its implementation ease, as determined by the precedent and wide use of soft-shore armouring techniques throughout BC. Though moderately expensive to maintain, the capital costs required over a 100-year period are relatively low ($0.81 to $2.0 million).

Unlike the soft approaches, a traditional dike is likely to prevent the majority of flood-related damages from 1 meter of SLR. The option requires relatively moderate capital costs ($5.7 million), and a low level of routine and post-storm maintenance. However, co-benefits to ecosystems and erosion are expected to be low (even negative) since permanent habitat destruction and wave energy deflection is introduced. In addition, a traditional dike is expected to reduce amenity / recreation value by a relatively large extent (due to high levels of beach loss), as well as generate little aesthetic / landscape value (due to its engineered appearance). Though a traditional dike is easy to implement and relatively inexpensive for the level of flood protection granted, the magnitude of negative impacts it is expected to generate warrants investigation into potential alternatives.

A green dike is also likely to prevent the majority of flood-related damages from 1 meter of SLR. While a green dike does not greatly mitigate the negative impact on amenity / recreation value nor the low erosion co-benefits of a traditional dike, it offers greater co-benefits to carbon (through sequestration opportunities) and ecosystems (through habitat generation). These co-benefits can be further enhanced by widening the dike slope. Widening the slope, however, increases the physical footprint of the dike, which may be an expensive endeavour on urban Vancouver land. A green dike is as easy to implement as a traditional dike, and the difference in capital cost requirements between the two designs is negligible ($0.2 million). The only significant trade-off of a green dike relative to a traditional dike is increased routine and post-storm maintenance costs.

A sand dike with sediment fill is also likely to prevent the majority of flood-related damages from 1 meter of SLR. Since the hard dike structure is masked by the fill, greater aesthetic / landscape value is generated than is the case for a traditional or green dike. Though carbon co-benefits suffer (due to repeat re-nourishment), ecosystem and erosion co-benefits are greater relative to the other dike designs. However, the option introduces low implementation ease, high routine and post-storm maintenance costs, and relatively high (and uncertain) capital costs in the range of $11.2 to 19.2 million ($5.3 to $13.2 million more than a green dike). Despite these negatives, a sand dike with sediment fill is expected to preserve the park along with a significant portion of the beach. This impact is expected to reduce losses to amenity / recreation value (relative to a traditional or green dike) by $15.2 million among households threatened by temporary displacement. Combining these findings, it is possible that the addition to amenity / recreation value generated by a sand dike with sediment fill can offset its greater cost requirements.

Chapter 10. Recommendation

Given the long time scale of the analysis (with impacts considered to the year 2100), both short-term and long-term considerations should factor into coastal flood resilience investment decisions. Based on the analysis of options (Chapter 8) and examination of the trade-offs (Chapter 9) for a case assessment of Kitsilano Beach, I recommend that the CoV consider: (i) implementing soft-shore armouring in the near term (within the next 5 years), and (ii) commencing a technical feasibility assessment for the implementation of a sand dike with sediment fill. If the sand dike is deemed technically feasible, the CoV might then consider determining a “trigger level” of SLR (rather than a time frame) to guide the point of commencing dike construction.

Though soft-shore armouring is unlikely to prevent the majority of flood-related damages from 1 meter of SLR, it may enhance coastal resilience against erosion and extreme weather events in the shorter-term. These are two important aspects of a holistic coastal defense strategy, which may increase the time horizon over which decisions regarding higher-cost hard or hybrid infrastructure can be made. Importantly, this reserves flexibility for the CoV to change policy directions should new science, new technology, or new preferences among residents emerge, altering the parameters that impact the course of best action. Some implementation aspects or next-step considerations may include:

- Developing a communications strategy, and conducting media outreach in Kitsilano (and the rest of Vancouver) to convey the message that coastal flood resilience is a priority
- Engaging in community consultation with residential and commercial stakeholders to facilitate communication channels and to canvas what types of soft-shore armouring elements would be well-received at Kitsilano Beach

- Formalizing opportunities to build social capital in the operation process (e.g. recruitment of volunteers such as local school groups to help plant and maintain sea grasses, arrange natural rip-rap, collect debris after storms, etc.)

A sand dike with sediment fill is an innovative hybrid design that combines the flood protection of a traditional dike with the aesthetic, amenity, and ecosystem benefits of softer options. While a sand dike with sediment fill may require 2 to 3.5 times the capital costs of a traditional or green dike, the amenity (or recreation) value gained by preserving a large portion of Kitsilano Beach may be sufficient to cover this cost differential. Proactively, the CoV could initiate a technical feasibility assessment for a sand dike with sediment fill at Kitsilano Beach in the event that it opts for a “protect” strategy in the decades to come. The assessment could draw from experts in coastal engineering, coastal geomorphology, and coastal biology to ascertain technical feasibility along with more precise (site-specific) costing figures. Implementation aspects or next-step considerations may include:

- Engaging in community consultation with residential and commercial stakeholders

- Conducting a site-specific contingent valuation survey estimating the amenity value of Kitsilano Beach relative to Kitsilano Park (to confirm that a high amenity value can offset the greater cost of a sand dike relative to a green dike)

- Identifying potential dig or dredge sites for sediment supply (e.g. drift sediment caught by the breakwaters at the Royal Vancouver Yacht Club, or sediment dredged from shipping lanes in the Fraser River)

- Identifying and overcoming potential legal constraints as set out in the *Dike Maintenance Act*

- Determining a “trigger level” of SLR (e.g. 0.3 meters) to guide when dike construction should commence

Chapter 11. Concluding Remarks

Earth's climate is changing. While mitigation remains a worthwhile goal for environmental policy, it can no longer be sought divorced from adaptation since the best available science shows that some climate change impacts are too rooted to avoid. One of these impacts is a rise in global mean sea level. The Province of BC recommends that municipalities prepare for 1 meter of SLR by the year 2100. Phases I and II of the CFRA identified and modeled damages to five residential areas in the CoV that are vulnerable to SLR. In selecting the path towards policy solutions, an opportunity exists for the CoV to align coastal flood resilience as prioritized in the *Climate Change Adaptation Strategy* (2012) with the aims of the *Greenest City 2020 Action Plan* (2016) by incorporating ecologically-based actions alongside physical infrastructure in its investment options.

Drawing on a mix of primary expert interviews and secondary economic valuation literature, I assessed the relative merits of implementing beach nourishment, soft-shore armouring, a traditional dike, a green dike, and a sand dike with sediment fill in Kitsilano (one of the vulnerable areas identified) using a multi-criteria trade-off framework. Based on the analysis results, I recommend that the CoV invest in soft-shore armouring in the short term. This option inexpensively enhances coastal resilience against erosion and extreme weather events, while potentially increasing the time horizon over which higher-cost hard or hybrid infrastructural decisions can be made. For investment in the long term, my analysis displays the potential of a sand dike with sediment fill in preventing flood-related damages from 1 meter of SLR while enhancing the value of aesthetics, public amenities, and ecosystem processes (relative to a traditional dike).

This study could be improved by incorporating greater precision into my benefit transfer estimates (for example, by differentiating between "zones" of households instead of assuming homogeneity—especially in considering distance from amenities). These estimates are subject to many assumptions and should not be used in a formal cost-benefit analysis without careful consideration of their limitations, as they may suffer from significant transfer error. However, my assessment of the options relative to each other is more contingent upon broad characteristics (e.g. green infrastructure valued greater than grey infrastructure; beaches valued greater than parks) than upon the accuracy of the estimates. Given my reliance on primary expert interviews to fill information gaps, a greater array of voices could have been sought to increase confidence in the interview results. While outside the scope of this project, it would have been illuminating to canvas views among Kitsilano residents and among a representative sample of Kitsilano Beach and Park users. Community consultation of this magnitude is delegated as next steps in the research process.

The use of hybrid infrastructure for SLR protection is a new and highly innovative global discussion. For any municipality wishing to join the conversation, it is important to keep watch for current and future projects, technologies, and policies as they become adopted and fine-tuned worldwide. Ideally, more information should be collected on the costs, benefits, technical feasibility, and implementation details for sand dikes (and other innovations) before investment decisions are made. By greening the fight against sea level rise, the City of Vancouver can retain its role as a climate leader while enhancing the safety and security of residents.

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