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CONCEPTUAL FRAMEWORK FOR A SYSTEMS DYNAMICS ADAPTATION MODEL TO CLIMATE CHANGE FOR CHARLOTTETOWN, P.E.I., CANADA[1]

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Abstract: *A benefit-cost analysis is performed on the decision by a small, data poor,coastal community to build a protective dike against anticipated rising sea level due to climate change. The dike decision is zero-one but its height is optimized. The paper offers asystems dynamics methodology, essentially Net Present Value, to estimate its current assets (static model). Future assets are projected to a stationary state according to current population growth (dynamic model). Current and future assets are subjected to five annual maximum water level scenarios provided by the literature, using a Gumbel distribution on water levels (calibrated on historical damage). Annual provisions for assets at risk plus the cost of building the dike are then compared to damage avoided. It is concluded that a dike (about 6 m high) should be built if the community wants to withstand the five scenarios, except the current one for the static model*.

Keywords: climate change, rising sea water level, dikes, systems dynamics, sustainable development, stochastic process.

Introduction

Data can often be found to approximate the revenue or expense value of the services of an asset in a small economy such as the city of Charlottetown, Prince Edward Island (PEI), Canada (fig 1). The value of the assetcan then be obtained by capitalization.Whenever population is kept constant, the method proposed is a simple static net present value (NPV) exercise. When population is allowed to vary over time, the same methodology can be used but is no longer equivalent to NPV because population dynamics turns the static asset economy into a dynamic one. In this case-study, the discount rate overtakes population growth, resulting in a stationary state. As productivity growth has been nil inPEI, it is ignored except for the discount rate which reflects the productivity of capital throughout the Canadian economy.[2]In essence, the model proposed is a capitalized national income/expenditure identity exerciseat the city level and consists in comparing two stationary states, a current one and a future one, under five sea-level rise scenarios to determine whether a dike should be built and at what height.Charlottetown is a city of about 35,000 inhabitants, located on the Atlantic Ocean at the top of a deep bay which is the estuary to three rivers and which opens up on the Northumberland Strait (fig 1).

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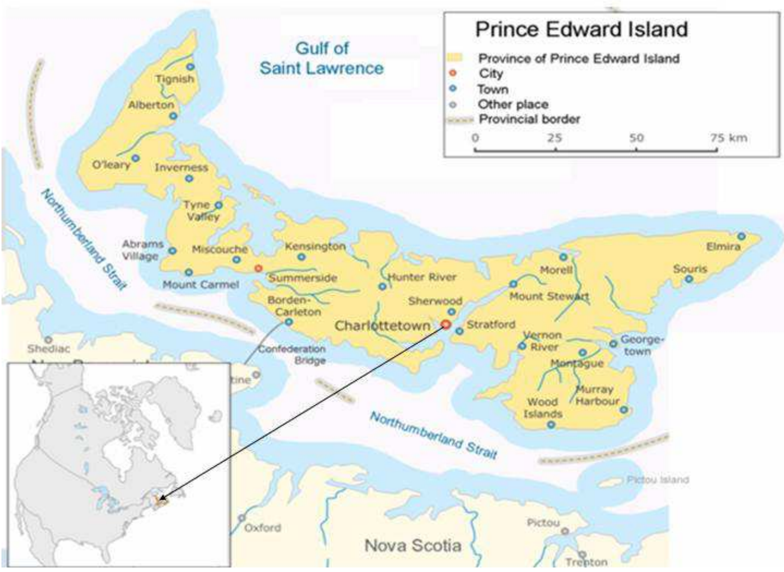
[2]Actually, the real rate of interest (2.9 percent) is an overestimate of total factor productivity in the Canadian economy, which amounts to - .2 percent annually from 1997 to 2010 (CSLS 2012, Table 11a). P.E.I. total factor productivity growth has been 0 over the same period (ibid).

Charlottetown has approximately 23 km of waterfront including the river estuaries.[3] The former is vulnerable to flooding from sea level rise, storm surges and, therefore, from increases in maximum observed water levels (MOWL). Land elevation varies between 0 and 30 m above sea level (fig 2). No spatial consideration or digital elevation is introduced in the models as this information is not publicly available. The shore line is mainly bluff and cliff. High water levels are caused by astronomical high tides and by storm surges. Water levels are measured with respect to local Chart Datum (CD), i.e. the plane of lowest normal tides. Storm surges are defined as the difference between the MOWL and the predicted astronomical tide (Environment Canada (2006)). Large positive storm surges at high tide are events that lead to coastal inundation while maximum observed water levels (MOWL) determine coastal flooding severity. Water levels and damages corresponding to a specific year will be attributed to the highest water level in that specific year (Beigzadeh, 2014**)**. MOWL's can reach 4.2 m, the highest level ever recorded (year 2000). Storm surges vary between .6m and 1.4 m. Storm surge was 1.37 m in year 2000. The current dike which surrounds most of *downtown* Charlottetown is, in places, 4.3 m high and made of armour stone mainly.[4]

Figure 1 Location of Prince Edward Island in Canada and of Charlottetown in Prince Edward Island



Source: Charlottetown, Wikipedia, https://en.wikipedia.org/wiki/Charlottetown

Systems Dynamics (SD) provides a dynamic system organizing framework towards an Integrated Assessment Model (IAM), and a simulation tool for extreme events and adaptive policies. The software used is STELLA 10.0 (ISEE Systems).The current and future stationary statesare obtained after 200 iterations of a simulation needed for the asset values to remain practically constant.Simulation results obtained in these SD models provide a total asset value for Charlottetown of the order of (2013) $ 41.1 billion in the static model and (2013) $ 82.2 billion (with population growth at current rate) in the dynamic model.[5]Valuation information pertinent to specific assets at risk of flooding is exogenous to the model.

The model counts seven inter-dependent sectors or sub-systems: the first four are made of the four forms of capital (natural, manufactured, social and cultural, human) and the fifth one adds

[3] H. Parnham (pers. comm. Jan 20, 2015)
[4] H. Parnham (pers. comm. Jan. 20, 2015)
[5] Details of these computations can be obtained from the author.

up the four forms of capital values to provide the estimate of the total Charlottetown assets. A sixth sector submits these aggregate assets to an empirically estimated destruction stochastic processgenerating MOWL, which yields the aggregate asset damages.[6] These are calibrated to actual damages and water levels recorded in two recent storms (2000 and Juan (1985); Hartt, 2011). Assets at risk in the static model are the current value of assets at risk recorded in 2001 (Milloy and McDonald, 2002). In the dynamic model, assets at risk are obtained by insuring that the damages when the assets reach their corresponding level in the static model do not exceed the corresponding damages at the corresponding MOWL. A seventh sector is a policy one which provides the asset reconstruction policy and the adaptation measures to mitigate the impacts of the stochastic process. This sector also provides the sensitivity of water level damages to reconstruction policies.

The MOWL stochastic process is found to follow either a Dagum (best fit) or a Gumbel (second best fit) density function among five candidate distributions, which provide the best fit to empirical data recorded on an annual basis from 1911 to 2005 whenever MOWL exceeded 1.4 m (Beigzadeh, 2014). The Gumbel distribution was retained because of its linearity property convenient for comparison among several flood scenarios. Total asset damages are related to maximum water levels through a heuristic functional relationship between water levels and destruction coefficients which are based on empirical damages actually recorded for the two historical scenarios mentioned above (Milloy and McDonald, 2002; Hartt, 2011). The time evolution of total assets after asset partial destruction requires a decision about the time path for asset reconstruction. If reconstruction is immediate and costless, asset destruction is immediately compensated by asset reconstruction and total assets are insensitive to damages over the simulation horizon. In the real world, asset reconstruction is not costless and is time consuming. Asset reconstruction costs can be assumed to be equal to the replacement value of the portion of the assets destroyed. Various lag policies for reconstruction are considered as long as they are able to rebuild assets over the simulation horizon to the value the latter would have had without climate change. The benefit of these policies is the damage avoided, i.e. the services of the non-damaged assets, due to the policy adopted.Both the static and the dynamic model are subject of two simulations: One which determines the value of the assets without risk of flooding and one which submits assets at risk to the stochastic process of destruction.

SECTION 2 ASSETS AT RISK, STOCHASTIC PROCESSES FOR MAXIMUM WATER LEVELS, RETURN PERIODS AND EXPECTED INCREASE IN SEA WATER LEVEL OVER THE 21TH CENTURY

2.1 Assets at risk

In the context of this paper, assets at risk are the assets subject to the risk of flooding. Their estimation assumes that, if the risk materializes, the asset is entirely lost (Hartt, 2011). Assets at risk valuation require a spatial model and an elevation model which indicate which specific assets are at risk. A version of such a spatial and elevation model exists but is dated and the aggregate value only of the assets at risk is provided (Milloy and McDonald, 2002).[7]Moreover, the latter's list is incomplete as it does not include human capital and social/cultural capital, except in sketchy qualitative terms.Milloy and McDonald (2002) have provided us with assets at risk for 3 maximum water level scenarios: 4.23 m (highest historical level ever reached on Jan 21, 2000(Canadian Disaster Data Base)), 4.70 m and 4.93 m. Corresponding aggregate asset at risk values were: \$(2013) 224,133,750,\$(2013) 247,623,750, and \$(2013) 263,583,900. This information allows us to check some of our estimates.

[6] Flooding damages are the only ones considered in this paper.

[7]A new digital elevation model dating from 2008 apparently exists but is not publicly available (P. Nishimurah, pers. comm., 2014).

2.2 Stochastic process for Maximum Observed Water Levels (MOWL), return periods and exceedance probabilities

The largest 4.2 m MOWL occurs once in our 200 year simulation, using a statistical distribution (Gumbel) estimated on historical data and de-trended for a secular trend of .3 m. The 3 water level scenarios in Milloy and McDonald are based on observed water level data allowing to recreate: 1) the flood of 2000; 2) one with a .7 m mean sea-level rise, and 3) one intermediate (Milloy et al, 2002, p. 10-11). The Gumbel distribution is a probability distribution widely used in hydrology for modeling extreme events such as extreme MOWLs. It is a two parameter distribution; the first one is a location parameter (μ), which is also the mode of the distribution, while the second one is a scale parameter (β) related linearly to the variance of the distribution. The first one has a value of 2.992 m (for the de-trended data) while the second one has a value of .304 (Beigzadeh 2014). The mean E(y) of the density function f(y) of y, where y is MOWL, is

$E(y) = \mu + .5772 * \beta = 3.168$ m (1)

The mean, therefore, exceeds the mode. This means that the distribution is asymmetric with most of the probability (63 percent) in the tail on the right of the mode. Both statistics, mode and mean, are linear in the random variable MOWL. Moreover, if x is a random variable defined on the closed interval [0-1] such that $y = \mu - \beta.\ln(-\ln x)$, where ln stands for Neperian logarithm, the return period T of the water level x is

$T = x/(1-x)$ or $x = T/(T+1)$ (2)

1/T is the exceedance probability or the probability that a water level x will be exceeded. Both the return periods and thus the exceedance probabilities are invariant to a change in the parameters of the Gumbel distribution.

The Dagum distribution (Type I) is another candidate for fitting the historical data on maximum water levels. It is a three parameter distribution: one scale parameter β, and two shape parameters, αand κ. Unfortunately, the Dagum distribution parameters and statistics are not linearly related to water levels.

2.3 Expected increase in mean, total and extreme sea water level over the 21th century for Charlottetown

The Atlantic Ocean mean level is expected to increase between either .3 m and 1.2 m during the 21th century (US National Climate Assessment, 2014, Sea Level Rise) or about between .3 m to 1 m (IPCC, AR 5, WG I, c. 13, Table 13.5, 2014). Subsidence amounts to a drop of about .002 m yr^{-1} in Charlottetown (Richards and Daigle, ACASA 2011, p. 20-1).[8]According to a (seeded) simulation of the Gumbel distribution with a range of values for the μ parameter between 2.992 m and 4.492 m (increase of 1.2 m at the end of the 21rst century plus the 20th century trend of .3 m near Charlottetown), this would mean that 5.70 m will be the maximum water level ever reachable in Charlottetown during the 21st century.[9]According to the report from the Atlantic Climate Adaptation Solutions Association (Richards and Daigle, ACASA 2011, Table A5, p.45) based in part on IPCC AR4, the *extremetotal* sea level *rise*expected over the 21st century are as follows:

[8]The subsidence phenomenon is well illustrated in Richards and Daigle, ACASA 2011, fig. 9, p. 20. It is as if a piece of plywood had been laid on two two-by-fours at each of its eastern and western side and a large weight had been applied in its middle; the sides east and west would have a tendency to move upward. As the weight is progressively removed (glaciers are melting), the same sides have a tendency to move downward; this is subsidence.

[9]The range of the distribution would be shifted by 1.2 m to the right to which one would add the secular trend for the 20th century, .3m, i. e. by 1.5 m altogether in 2100. So 4.2 m maximum would become 5.7 m.

Table 1: Extreme Total Sea Level (metres CD) – Charlottetown

Return Period	Residual*	Level 2000	Level 2025	Level 2055	Level 2085	Level 2100
10-Year	1.13 ± 0.10	4.14 ± 0.10	4.29 ± 0.13	4.57 ± 0.25	4.97 ± 0.58	5.20 ± 0.58
25-Year	1.30 ± 0.10	4.31 ± 0.10	4.46 ± 0.13	4.74 ± 0.25	5.14 ± 0.58	5.37± 0.58
50-Year	1.42 ± 0.10	4.43 ± 0.10	4.58 ± 0.13	4.86 ± 0.25	5.26 ± 0.58	5.49± 0.58
100-Year	1.55 ± 0.10	4.56 ± 0.10	4.71 ± 0.13	4.99 ± 0.25	5.39 ± 0.58	5.62± 0.58

Source: Richards and Daigle, ACASA 2011, Table B17, p.73. Extreme Total Sea Levels are meant to represent the worst case flooding scenario resulting from the simultaneous occurrence of a significant storm-surge event for the respective return-periods and the highest astronomical tide possible at a given location (Richards and Daigle, ACASA 2011, p. 24-26).

Not only will the mean sea water level rise but the frequency of flooding, aggravated by expected increase in precipitation, will rise as well. “As sea level rises, local flood conditions are reached more often, to a greater extent, and for longer time periods just from simple high tides” (UCS, 2014, p. 7)

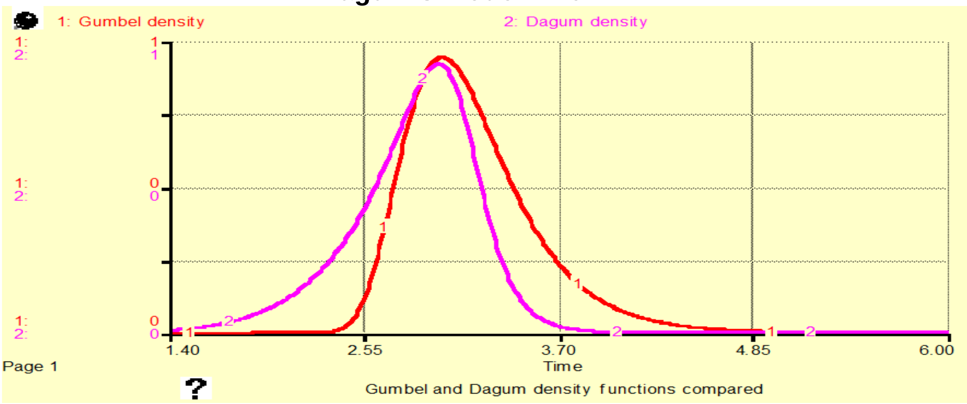
The surges mostly occur during extra-tropical storms in the fall and winter.Rise in sea level would allow storm surges to reach further inland. The consequence of rising sea levels will be far greater than that of increased storms. The impact of sea level rise is so important that extreme water levels with a current return period of 100 years, as during hurricane Juan, are expected to become regular events by the end of the 21stcentury. The increase in tidal range may be in the order of 10 percent of the sea level rise over the next century (The 2009 State of Nova Scotia’s Coasts Technical Report, 2009, section 7.3).

SECTION 3 MAXIMUM OBSERVED WATER LEVELS (MOWL)

3.1 Comparison of the Gumbel and the Dagum distributions

MOWL (detrended) were shown to follow either a Gumbel distribution with a mode of 2.992 m or a Dagum distribution (Type I) (Beigzadeh, 2014). The mode of the Dagum density function is 2.972 m, thus slightly smaller than Gumbel’s. At the end of the 20th century, the mode of the MOWL, including the trend, is 3.292 m for Gumbel; MOWL’s reach their simulation maximum of 4.5 m only once and are above 4.2 m ten times over a 200 year simulation period. For Dagum, if one wants the mode, including the trend, to shift to 3.272 m, the scale parameter β must be adjusted as well to become 3.455.[10] There is no reason for the shape of the distribution to change unless one wishes to increase the frequency of extreme events. Therefore, the other parameters of the Dagum distribution are left unchanged.

Graph 1: Gumbel and Dagum density functions for de-trended data, i.e. μ = 2.992 m and Dagum’s mode = 2.972 m

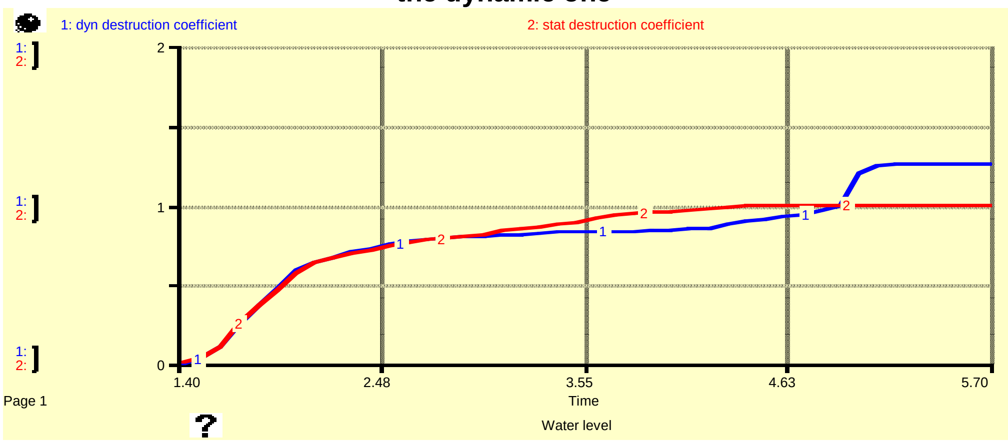


[10]The mode of the Dagum is determined according to the following equation: $x_{mode} = \beta[(\alpha\kappa-1)/(\alpha+1)]^{1/\alpha}$

3.2 Destruction coefficients

A destruction coefficient corresponds to the proportion of assets at risk which are damaged (and assumed lost) through flooding. For the static model, the destruction coefficients were selected from Hartt's(2011, table 4.31, p. 134; table 4.5, p.84-6).[11] The corresponding destruction coefficient for assets at risk at 4.2 m is 96 percent. Assets at risk were estimated at (2013) $238,228,349 by M. Hartt (2011, Table 4.24, p. 126), i.e. the largest estimated loss under the highest maximum water level (between 4.5 m and 5 m). 96 percent of these assets at risk amount to (2013) $ 228.7 M. M. Hartt's analysis of the actual damages led to a figure of about $(2013) 38,622,990 million (M. Hartt, 2011, p.142). As $(2013) 38.6 million is about 16.2 percent of (2013) $238,228,349, asset destruction in the static simulation model for damages was calibrated accordingly.Since 4.5 m is the extreme maximum water level in the simulation, the corresponding destruction coefficient is practically 1.Milloy and McDonald (2002) estimate assets at risk for a 4.23 m maximum water level to be $(2013) 224,133,750; for a 4.7 m, $(2013) 247,623,750; for a 4.93 m, $(2013) 263,583,900. The destruction coefficient becomes for 4.23 m, 85 percent; for 4.7 m, 94 percent; and for 4.93 m, 100 percent. Our simulation generates water levels up to 5.7 m in the worst case scenario for year 2100. A linear regression was conducted on the damages estimated by M. Hartt (2011, p.142) and used to forecast the damages for water levels higher than 5 m, yielding destruction coefficients of 1.248 for 5.5 m and 1.256 for 5.7 m. The destruction coefficients for the dynamic model with population growth were selected from the paper by Milloy and McDonald (2002), which used a spatial and an elevation model, thus more precise than the one used by M. Hartt. On the other hand, their analysis is less comprehensive in terms of assets included. For 4.23 m, the destruction coefficient is .85, thus lower than the one provided by Hartt. For 4.7 m, it is .94, and for 4.93 m, it is 1 (all assets at risk are damaged). For the lower levels, they were selected from M. Hartt to the extent they are compatible with Milloy and McDonald (2002).

Graph 2: Destruction coefficients as a function of water levels for the static mode and for the dynamic one

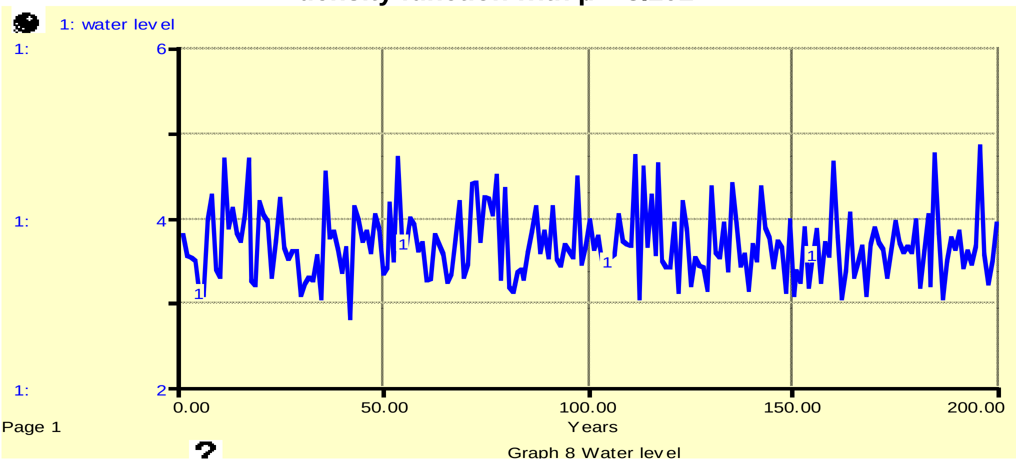


To replicate the three Milloy and McDonald water level scenarios, we can use, for the first scenario, the Gumbel distribution for maximum water levels at the end of the 20th century, including the secular trend of .3 m. The mode would thus be 3.292 m at the beginning of the 21rst century and the MOWL would be 4.5 m for the first scenario (4.23 m). Richards and Daigle estimate the extreme total sea level to be between 4.46 m to 4.66 m with a 100 year return period for this scenario occurring in year 2000. The Gumbel distribution, which has a fatter right-tail than the Dagum's, underestimates somewhat the return periods identified by Richards and Daigle (2011).However, there is complete agreement - our simulation results fall within the appropriate confidence interval - between the Gumbel return periods and the ones of Table 1 except for 2025 (μ= 3.592 m) for the return periods 25 and 50 years. A 100 year return period never occurs in our

[11] **Note these coefficients are not adjusted for the duration of the storm.**

simulations. Each column of table 1 corresponds approximately to our five scenarios, 25 years apart.

Graph 3: 200 year simulation of maximum water level drawings from a Gumbel density function with μ = 3.292



SECTION 4 PROJECTED DAMAGES WITHOUT ADAPTATION OR PROTECTION POLICIES

4.1 Static model

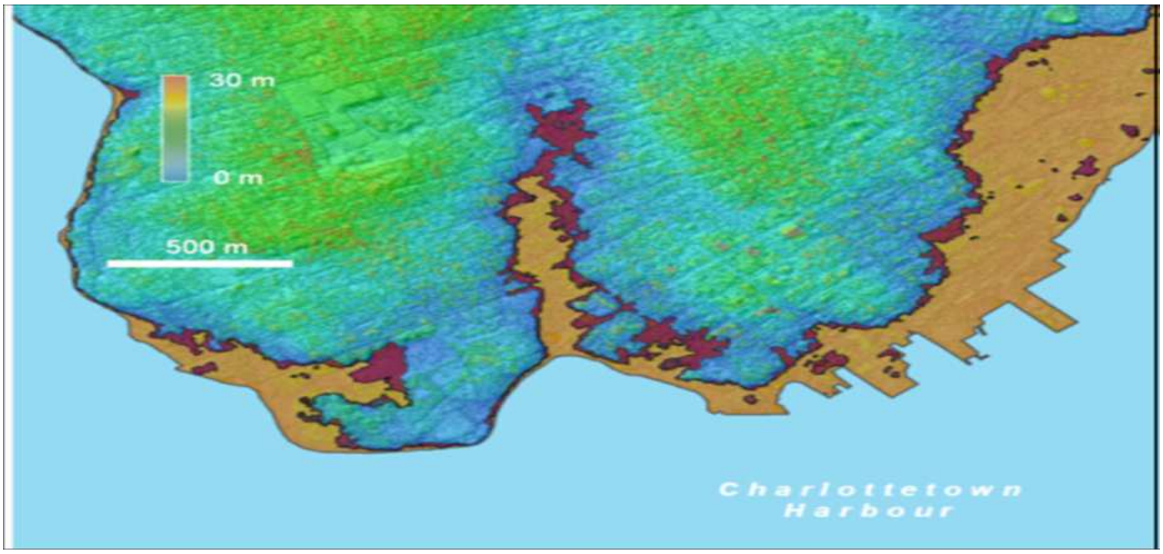
One of the purposes of policy is to rebuild the assets at risk to their initial level after the simulation is completed. According to the simulation model for year 2000 (μ = 3.292 m), the assets at risk are reduced to $ .01 million in about 180 years without any reconstruction. If asset reconstruction is set equal to asset destruction in the same year, the value of assets at risk remain constant. At 4.5 m, the highest MOWL simulated for year 2000, damage is set at $ 38.6 M, the figure obtained from Hartt (2011). Annual damages are thus calibrated accordingly by the use of a calibration constant (.162). The lowest annual damage is obtained at 2.71 m and is $ 30.1 M. However, we know that Charlottetown does not flood if the MOWL is lower than 3.6 m (Webster et al., 2002). Therefore, any damage occurring below a water level of 3.6 m is set to 0. For year 2100, when μ = 4.492 m, assets at risk are reduced to about .01 million dollars in 66 years without reconstruction. No distributed lag structure is able to restore assets obtained without climate change at the end of the simulation. One has to remember that the simulated destructions occur with a return period. While the lowest return period occurs annually (return period =1), the largest recurs in the simulation about every fifty years. The *annualized destruction* is thus the destruction corresponding to a given water level divided by its corresponding return period. Therefore, the *minimum annualized destruction* is the minimum destruction to occur every year over the corresponding return period.The return periods and corresponding exceedance probabilities were borrowed from Table 1 and applied to our static model. Note that the return periods are not mutually exclusive in Table 1 as there is overlap among the confidence intervals for the extreme total sea levels. There is some arbitrariness, therefore, in making them mutually exclusive. Fortunately, there is a way of comparing the mutually exclusive confidence intervals arbitrarily obtained (and thus the corresponding return periods) with the return periods obtained directly from the Gumbel distribution.The correlation coefficient between the two is .884 (s.e.: .051).[12]

Applying this schedule of water levels and corresponding destruction coefficients to the static model with Gumbel μ = 3.292 m whenever reconstruction follows a one year lag with a .95 coefficient, i.e. 95 percent of the destructed assets are rebuilt after one year, an expected damage occurs every year over two hundred years unless the water level is less than 3.6 m. The *mean annualized loss* over the simulation period, i.e. the ensemble average over 200 years, is $ 6.0 M. It would, therefore, be reasonable for the municipality of Charlottetown (or for P.E.I.), to build an

[12]For the worst scenario, the correlation is much smaller.

annual contingency fund for at least $6 M if it is risk neutral.According to the Gumbel distribution with μ = 3.292 m, the 2000 storm with a MOWL of 4.23 m would have a 23 year return period. The corresponding flooding is illustrated by the following picture of Charlottetown (fig 2):

Figure 2 Flooded zones under the 2000 flood (MOWL 4.23 m) and under a projected 7m sea-level rise



The actual zone flooded in 2000 is in brown. Projected additional flooding with a 70 cm sea-level rise is in red (Source: Richards and Daigle, 2011).

4.2 Dynamic model

Assets are never wiped out by destruction (without reconstruction) over the simulation horizon – as they were in the static model - since assets, despite being damaged, keep increasing because of population growth. Since assets increase all the time, we can no longer use assets at risk from Milloy and McDonald (2002). This is why assets are now replaced by aggregate capital. In the static model, assets reach $ 41.1 billion, their NPV, at the end of the simulation. Asset destruction due to flooding in the static model is calibrated in such a fashion that asset destruction corresponds to the damage figure from Hartt (2011). In the dynamic model, whenever assets reach the level they reached in the static model, i.e. $ 41.1 billion, the destruction damage should be $ 38.7 million if the destruction coefficient were 1. Accordingly, the calibration coefficient for the dynamic model should be .00094 when μ= 3.292 m.The reconstruction policy (rebuilding the asset entirely with a one year lag) is able to restore approximately the remaining assets to their un-destructed terminal level for any value of the Gumbel parameter μ. When μ= 3.592 m, the Gumbel density underestimates the high return periods (50 and 100) according to Table 1.

Table 2 Values of Gumbel μ corresponding to the recurrent extreme total sea level rises in table 1 whenever lagged reconstruction policy isadopted

Year	μ (m)	# Flood events ➢ 4.04 m	Maximum Water level m 50 year return period	Maximum destruction $(2013) M	Minimum yearly Destruction $(2013) M	Mean loss $(2013) M
2000	3.292	62	4.5	69.5 (35.6)*	0 (0)	8.7 (6.0)
2025	3.592	137	4.8	74.0	0	20.8
2055	3.892	185	5.1	95.5	0	29.2
2085	4.192	162	5.4	95.6	66.4	33.0
2100	4.492	199	5.7	95.6 (38.6)	66.1 (36.8)	35.2 (24.3)

*The figures in parentheses correspond to static model results.

4.04 m is the minimum extreme total sea level rise anticipated for year 2000 according to Table 1, i.e. our first scenario. The figures for the lagged model are not very different from the ones when reconstruction occurs immediately.

SECTION 5 PROTECTION POLICY IN BOTH THE STATIC AND DYNAMIC MODELS

5.1 Protection with dikes

"…Protecting against flooding and erosion is considered economically rational for most developed coastlines in many countries under all socio-economic and sea level rise scenarios analyzed, including for the 21st century GMSL [Global Mean Sea Level] rise of above 1 m (*high agreement, low evidence*)"(IPCC, 5th Assessment, WGII, 2014, c.5, p.3). "…the global costs of protection through dikes (levees) are much lower than the costs of damages avoided through adaptation" (ibid, p. 35-36).Dikes are a provincial responsibility in Canada and, for harbours,a federal one.

5.2 Dike length

The marginal cost of protection against MOWL increase for Canada was estimated at $(2013) 12.4 million km^{-2} (Delft Hydraulics, Table F.1 Incremental protection cost per km^2 per country), placing Canada in the high cost category (ibid). Applying this marginal cost to the City of Charlottetown area, the total cost of protecting it would amount to $(2013) .548 billion. The cost of building stone protected sea dikes or sand dunes of variable height up to 5 m was estimated at (2013) $ 7.2 million km^{-1} (ibid, p. 41). Annual maintenance costs are assumed to be 1 percent of this amount or $72,000 (Hinkel et al, 2014; capitalized value: $ 2.5 million).[13] Twenty-three km of dikes would thus cost $(2013) 223.1 million.[14]The breakeven annual benefit must be at least 7.24 M over 50 years for dike construction to be undertaken. As the annual contingency fund should be currently of the order of either $ 6 M or $ 6.9 M for Charlottetown (in the static model according to whether reconstruction is lagged or immediate), the capitalized value of this fund over 50 years is $ 184.8 M (lagged reconstruction) or $ 212.5 million (immediate reconstruction) and thus fails the benefit/cost test. The total net benefit of building a 23 km dike (up to 5 m) lasting about 50 years is positive in the dynamic model for all MOWL scenarios under either reconstruction policy, as well as in the static model for future sea level scenarios. The threshold costkm^{-1} for which the benefit/cost test fails is about $21 M$km^{-1}$ for all scenarios.

5.3 Dike height

With 1 m sea level rise, the conservative rule of thumb is that dike heights should be increased by 2 m to avoid annual flooding in Eastern Canada (Delft Hydraulics, p.40; Table A.2 Design water levels and Table A.1 Hydraulic conditions). To avoid decadal flooding dikes should be 3.5 m high, for century floods, 4.4 m high (medium protection) and, for millennial floods, 5 m high (high protection) (ibid).Thus, given that the highest MOWL occurs only once over a 200 year simulation period with a return period of about fifty years, a height of at least between 3.5 m and 4.4 m ought to be recommended. In case of overtopping, which may cause drainage problems because of marsh subsidence, dikes are built .3 to .6 m above maximum water levels (ibid.). Following this advice, dikes should be between 3.8 m and 5 m high.The optimal amount of protection, i.e. the optimal return period for a flood – and thus the corresponding MOWL -, is determined by equating the marginal benefit of protection to its marginal cost. We adopt Hinkel et al (2014) benefit and cost functions:

$$B/Y = \alpha\,(1+S)^{\chi} y^{\lambda} P^{\varepsilon} F^{\theta} \quad (3)$$

Where:B is benefit

S is maximum sea-level rise, 1.2 m

Y is PEI GDP, $ 6.5 billion

y is Charlottetown per capita income, $ 31,516

P is Charlottetown population density, 779.7

F is the return period

[13]The average cost km^{-1} was estimated at $(2012) 37.9 M for the whole of B.C. (British Columbia, 2012)

[14] Assuming existing partial lower dikes have to be torn down.

Thus benefits grow with the return period but grow less than proportionately.
The cost function is:

$C/Y = \beta H_{100} (1 + S)^{\gamma} y^{\mu} F^{\varphi}$ (4)

Where H_{100} is the 100 year extreme maximum water level (5.7 m for Charlottetown in the worst case scenario).[15]The Greek letters are all empirically estimated parameters from other work. (Hinkel et al (2014))

Equating the first derivatives with respect to F and solving for F, we find F^* = 127.23 years (exceedance probability .0079), which, in turn, corresponds to 5.97 m above CD with our Gumbel distribution (μ =4.492 m).[16]

Since the highest MOWL in the worst water level scenario (2100) amounts to 5.7 m., an event which occurs once about every fifty years,the actual increase in height should, therefore, be to 5.97 m from CD. The current dike, where it exists around downtown Charlottetown, is 4.3 m high above CD, thus about 1.7 meter too low for the worst case scenario (Stantec, 2011). If marsh subsidence is an issue, the former may require an additional height increase of between 30 to 60 cm. to a maximum of 6.57 m from CD.

Conclusion

A large-scale dike building decision model has been developed for a data poor community. While this model is a first approximation for a benefit /cost analysis, four improvements should be made. First, though the Gumbel distribution is widely used in hydrology, it seems to underestimate the high return periods and thus to overestimate the corresponding high MOWL probabilities if one is to trust Table 1. The Dagum distribution, which performs better statistically than Gumbel when applied to historical (de-trended) water levels, may be preferable in the range of the parameters considered despite its analytical disadvantages.Second, it was assumed in this paper that MOWL's occur only once within the course of a year while damages are discrete events which occur several times a year and whose frequency is expected to increase. Only a few of these occurrences give rise to "dangerous" floods but the frequency of the latter is expected to increase over the same time period. Their occurrence (the occurrence of large storms giving rise to large storm surges) should be modelled through some kind of killed process and related to tides. This means that the shape parameters of the statistical density functions will have to be adjusted as well. Alternatively, storm regimes and storm surges could be modelled directly through climate and hydrodynamic modeling (Savard et al, 2014). Third, storm surges have been given short shrift in this paper. The B.C. dike design manual (2011) seems to indicate that storm surges increase water crest requirements for dikes above the ones required by maximum water levels. Finally, one should have a better handle on the engineering requirements in terms of length, location and type of dikes required by protection against sea level rise, information which currently seems not to be publicly available for Prince Edward Island.

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[15]Actually 5.7 m is the 50 year return water level in 2100 in our model but it lies within the confidence interval for the 100 year mean flood for 2100 according to Table 1.

[16]This MOWL with a return period of 115 years was obtained by running the simulation for an additional 100 years.

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