Brief for GSDR – 2016 Update

Conceptual Framework for a systems dynamics adaptation model to climate change for Charlottetown, P.E.I., Canada

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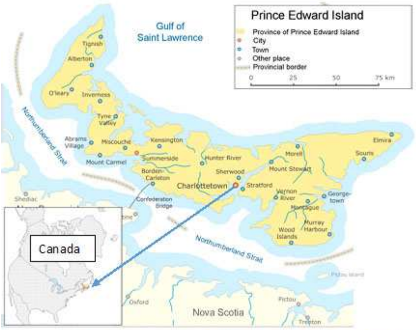
INTRODUCTION

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 paper uses a systems dynamics methodology, in essence Net Present Value (NPV), to estimate its current assets (static model). Future assets are projected to a stationary state according to current population growth (dynamic model). Total assets are decomposed into the four pillars which are customary in sustainable development: natural assets or capital, social and cultural, manufactured and, finally, human capital.

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, population about 35,000 inhabitants (fig 1). The value of the asset can then be obtained by capitalization. Whenever population is kept constant, the method proposed is a simple static 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. As productivity growth has been nil in PEI recently, the former is ignored except for the discount rate which reflects the productivity of capital throughout the Canadian economy. In this case, the discount rate overtakes the population growth rate, resulting in a stationary state. In essence, the model proposed is a capitalized national income/expenditure identity exercise at the city level and consists in comparing two stationary states, a current one and a future one, under five sea-level rise scenarios provided by the literature. These are simulated in order to determine whether a dike should be built and to which height. The time horizon for the simulation, 200 time periods, has been selected heuristically, i.e. until a stationary state is obtained.

Charlottetown is 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). The former has approximately 23 km of waterfront including the river estuaries. It 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. No spatial consideration or digital elevation are introduced in the models as this information is not publicly available. The shore line is mainly bluff and cliff.

Figure 1 Location of Prince Edward Island in Canada (see insert) and of Charlottetown in Prince Edward Island



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

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

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inundation while MOWL determines 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 0.6 m 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 mainly made of armour stone.

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).

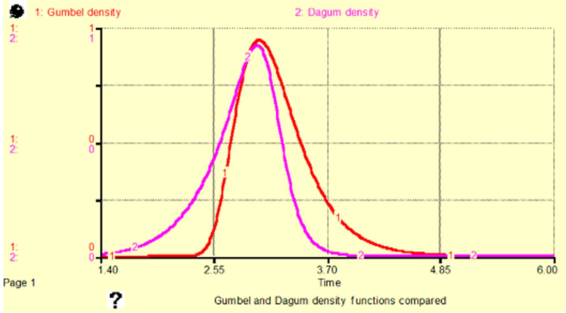
RESULTS

The static model yields a total asset value of Can (2013) $ 41.1 billion. This asset value is split four ways with 3 % (4 %) for natural, 17 % (14 %) for social and cultural, 27 % (37 %) for human and 53 % (45 %) for manufactured capital. The dynamic model yields a value of Can (2013) $ 82.2 billion for total assets and the pillar proportions indicated between parentheses in the previous sentence.

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 (graph 1; Beigzadeh, 2014).

The Gumbel distribution was retained because of its linearity property convenient for comparison among several flood scenarios. According to a (seeded) simulation of the Gumbel distribution with a range of values for the mode between 2.992 m and 4.492 m (increase of 1.2 m at the end of the 21rst century plus the 20th century upward trend of 0.3 m near Charlottetown), this would mean that 5.70 m will be the maximum water level ever reachable in Charlottetown during the 21st century.

Graph 1 Gumbel and Dagum density functions for detrended data; Gumbel's mode = 2.992 m and Dagum's mode = 2.972 m



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 extreme total sea level rise expected over the 21st century are as indicated in Table 1.

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. Residual is the difference between storm surge and predicted astronomical tide. The ± figures are confidence interval limits. The extreme total sea level is thus the sum of the highest predicted tide and of the storm surge net of this tide.

The Gumbel distribution, which has a fatter right-tail than the Dagum's (graph 1), underestimates somewhat the return periods identified in Table 1. 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 (mode = 3.592 m) for the return periods 25 and 50 years. A 100 year return period never occurs in our simulations. Each column of table 1 corresponds approximately to our five scenarios, 25 years apart.

Table 2 Values of Gumbel mode corresponding to the recurrent extreme total sea level rises in Table 1

Year	mode (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 between parentheses correspond to static model results. 4.04 m is the minimum extreme total sea level rise estimated for year 2000 according to table 1.

Total asset damages are related to MOWLs through a heuristic functional relationship between water levels and destruction coefficients, i.e. the proportion of assets at risk which are damaged (and assumed lost), based on both historical and simulated damages (Milloy and McDonald, 2002; Hartt, 2011). Annual provisions for assets at risk (or annual contingency fund) are defined as the mean annualized losses over the simulation period, i.e. the ensemble average over 200 years of the annualized destructions (table 2). The latter are the minimum annual destructions corresponding to a given water level divided by their corresponding return period. Annual provisions are of the order of either Can (2013) $ 6 M or Can (2013) $ 6.9 M depending on the reconstruction policy adopted (lagged or immediate) in the static model.

The breakeven annual benefit must be at least Can (2013) $7.24 M over 50 years for dike construction to be undertaken as the dike's capital cost is estimated at Can (2013) $ 223.1 M for a 5m high dike.

The annual contingency fund plus the cost of building the dike are then compared to damage avoided. It is concluded, using benefit and cost functions developed by Hinkel et al. (2014) that a dike (about 6 m high) should be built if the community wants to withstand the five scenarios corresponding to the columns of table 1, except the current one for the static model.

There is some degree of arbitrariness in what's allocated to the different types of capital. In any case, in our case-study, assets at risk are a relatively small portion of total assets: maximum destruction barely exceeds .1 % of total assets. This consideration does not affect the building of the dike which passes the benefit/cost test.

An important exogenous decision variable in the analysis is the speed of reconstruction of the damaged asset. No lag structure with weights summing up to 1 (except complete reconstruction in one single lag) seems to be able to achieve the objective of restoring the initial assets at risk over the simulation period. The risk (or mean annualized losses), i.e. the probabilities that a certain maximum water level will be exceeded (exceedance probability) times the corresponding damage (or equivalently the damage divided by the return period) averaged over the simulation period, must be determined as well as the speed of reconstruction if one does not want to see assets decrease over time.

It was assumed in this paper that MOWL's occur only once within the course of a year. However, damages are discrete events which occur several times a year and whose frequency is likely to increase with climate change. 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. In stochastic analysis a killed process is a stochastic process that is forced to assume an undefined or "killed" state at some (possibly random) time (Bass, 2011). Storm regimes and storm surges could also be modelled directly through climate and hydrodynamic modeling (Savard et al, 2014). As the frequency of dangerous floods is expected to increase at least threefold over the 21rst century, the shape parameters of the statistical density functions are not stationary.

It is obvious that the robustness of the conclusion depends on the availability of detailed engineering requirements in terms of length, location and type of dikes for protection against sea level rise as well.

REFERENCES

Bass, R.F. (2011). Stochastic Processes, Cambridge University Press.

Beigzadeh, S. (2014), *System Dynamics and Statistical Modeling of Severe Storms: The Case of Charlottetown, P.E.I., Canada*, M. Sc. Thesis, University of Ottawa.

Crabbé, P.(2016), Conceptual Framework for a Systems Dynamics Adaptation Model to Climate Change for Charlottetown, P.E.I., Canada, *Journal of Global Resources*, 2(January): 1-11.

Environment Canada (2006), *Impacts of Sea-level Rise and Climate Change on the Coastal Zone of South-Eastern New-Brunswick*, Ottawa.

Hartt, M. (2011), *Geographic Information Systems and Systems Dynamics- Modeling of Impacts of Storm Damage on Coastal Communities*, M.Sc. Thesis, University of Ottawa.

Hinkel, J., C. Hinkel, D. Lincke, A. T. Vafeidis, M. Perrette, R. J. Nicholls, R. S. J. Tol, B. Marzeion, X. Fettweis, C. Ionescu, and A. Levermann (2014), Coastal Flood Damage and Adaptation Costs under 21st Century Sea-Level Rise", *Proceedings of the National Academy of the Sciences*, 111(9), March 4: 3292-3297.

Intergovernmental Panel on Climate Change (2014), Fifth Assessment Report, WG I, *The Physical Science Basis*, 2014.

Milloy, M. and K. McDonald (2002), c 10 *Evaluating the socio-economic impacts in Coastal Impacts of Climate Change and Sea-level Rise on Prince Edward Island*, M. McCullogh, D. Forbes, R. Shaw and the CCAF A041 scientific team, Ed., Climate Change Action Fund Project A041. Geological Survey of Canada Open File 4261, Ottawa.

Richards, W. and R. Daigle (2011), *Scenarios and Guidance for Adaptation to Climate Change and Sea Level Rise – N.S. and PEI Municipalities*, Atlantic Climate Adaptation Solutions Association.

Savard, J.P., P. Gachon, C. Rosu, R. Aider, P. Martin et C. Saad, *Impacts des changements climatiques sur le régime des tempêtes, les niveaux d'eau et les vagues dans le Nunavik*, Ouranos, Octobre 2014.

US National Climate Assessment (2014), http://nca2014.globalchange.gov/.