Adaptation Decision Support: An Application of System Dynamics Modeling in Coastal Communities

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Abstract This research develops and applies a system dynamics (SD) model for the strategic evaluation of environmental adaptation options for coastal communities. The article defines and estimates asset-based measures for community vulnerability, resilience, and adaptive capacity with respect to the environmental, economic, social, and cultural pillars of the coastal community under threat. The SD model simulates the annual multidimensional dynamic impacts of severe coastal storms and storm surges on the community pillars under alternative adaptation strategies. The calculation of the quantitative measures provides valuable information for decision makers for evaluating the alternative strategies. The adaptation strategies are designed model results illustrated for the specific context of the coastal community of Charlottetown, Prince Edward Island, Canada. The dynamic trend of the measures and model sensitivity analyses for Charlottetown—facing increased frequency of severe storms, storm surges, and sea-level rise—provide impetus for enhanced community strategic planning for the changing coastal environment. This research is presented as part of the International Community-University Research Alliance C-Change project “Managing Adaptation to Environmental Change in Coastal Communities: Canada and the Caribbean” sponsored by the Social Science and Humanities Research Council of Canada and the International Development Resource Centre.

Keywords Canada · Charlottetown · Climate change adaptation · Coastal community resilience · Coastal community vulnerability · System dynamics model

1 Introduction

Increased frequency and disastrous severity of coastal storms—Typhoon Haiyan (November 2013), Superstorm Sandy (October 2012), Hurricane Katrina (August 2005)—rising sea levels threatening island states such as the Maldives and the South Pacific atolls, and widespread coastal erosion (IPCC 2013) provide considerable evidence of the global climatic changes currently underway. The predictable and mounting impacts of changing coastal environments require further investigation of coastal vulnerability, resilience, and adaptive capacity toward preparing coastal communities to face the impacts of the changing coastal environments (Adger et al. 2004; Cutter et al. 2009).

The United Nations International Strategy for Disaster Reduction (UNISDR) has documented guidelines for disaster preparedness planning, response, and recovery. The Sendai Framework for Disaster Risk Reduction 2015–2030 (UNISDR 2015, p. 6) was designed to “complete the assessment and review of the implementation of the Hyogo Framework for Action 2005–2015: Building the Resilience of Nations and Communities to Disasters (UNISDR 2007).” The Sendai Framework expresses the need for all communities to improve their understanding of vulnerability to severe environmental impacts, to strengthen disaster risk governance and management accountability, and to enhance resilience and recovery in the face of disastrous storm events. The Sendai Framework also highlights the

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Fig. 1 City of Charlottetown, capital of Prince Edward Island, Canada, situated by the confluence of the West River, North River, and Hillsborough River in the central part of the island's south shore. *Source* Reproduced with permission from Tide-Forecast (2017)

importance of diverse and local citizen engagement and responsibility, and emphasizes the monitoring of indicators to build adaptive capacity (Aitsi-Selmi et al. 2016).

In the spirit of the Sendai Framework to foster disaster risk management and evidence-based decision making (Aitsi-Selmi et al. 2016), and building on the multicriteria decision-making work of Mostofi Camare and Lane (2015), this article develops asset-based measures as objectives in a decision support tool for coastal community planning for the evaluation of strategic adaptation options, and to monitor the management of preparedness planning, response, and recovery with regard to environmental disasters. The article develops and applies a system dynamics (SD) simulation model for the determination of the problem-solving objectives and measures for: (1) vulnerability, (2) resilience, and (3) adaptive capacity in the strategic evaluation of environmental adaptation options for coastal communities. The study defines and estimates these measures with respect to the environmental, economic, social, and cultural pillars and assets of the coastal community profile and their relative importance to the community. The results provide support for coastal community efforts to adapt strategically to the pending environmental changes.

This research is part of the International Community-University Research Alliance (ICURA) C-Change project “Managing Adaptation to Environmental Change in Coastal Communities: Canada and the Caribbean” (C-Change 2013; Lane et al. 2013, 2015). C-Change seeks to raise awareness of coastal climate vulnerability and promote improved adaptive capacity and coastal community preparedness in selected communities in Canada and the Caribbean region through the development of community assets.

The development of asset-based measures for vulnerability, resilience, and adaptive capacity is applied to the C-Change coastal community of the city of Charlottetown, capital of the Province of Prince Edward Island, situated on the Atlantic coastline of Canada (Fig. 1).

The city of Charlottetown is defined by the Greater Charlottetown area of approximately 41 square kilometers and 35,000 inhabitants (Charlottetown 2013). The residential area of approximately 13 square kilometers is allocated according to the Charlottetown residential zone by-law (Statistics Canada 2013; Charlottetown 2015). A proportional amount is assigned to commercial area activity, including for example, storefronts, retail businesses, and shopping malls. The percentage allocation of the Prince Edward Island provincial GDP breakdown by sector is used to estimate the distribution of productive services and initial land allocation by sector for the greater area of the city of Charlottetown (Statistics Canada 2007, 2012; P.E.I. Statistics Bureau 2013), which comprises approximately 25% of the provincial economy. Other parameters for year-over-year system parameters, for example, birth, death, emigration and immigration rates, and sectoral production trends are set based on recent historical values (Charlottetown 2013).

2 Methods

The evaluation of coastal community adaptation strategies to environmental change is a multidimensional dynamic planning problem. The decision support model for this problem uses a strategic system dynamics (SD) model that captures the environmental, economic, social, and cultural

dimensions of the coastal community profile subject to community vulnerabilities induced by the impacts of severe storms, storm surges, and rising seas (Sherwood 2002).

The SD model is constructed as the FACE (Framework for Adaptation and Community Evaluation) of the community. FACE is comprised of three phases:

- Phase I** *Profile & Simulate*. Profile the resources of the coastal community with respect to the community's "pillars of sustainability" identified as: (1) Environmental; (2) Economic; (3) Social; and (4) Cultural dimensions (Ling et al. 2007; Stantec Consulting 2010; Lane et al. 2013). A system dynamics model using STELLA (STELLA® 2012) is defined here (Lane et al. 2017). The impacts of historical coastal storms on the community are used to project simulated storm patterns and storm impacts over the strategic planning period
- Phase II** *Develop & Compare*. Develop community strategic adaptation options for inclusion in

the SD model. Recalculate the simulated impacts of storms over the planning period under the alternative adaptation scenarios

- Phase III** *Measure & Evaluate*. Compute the indicators for Vulnerability, Resilience, and Adaptive Capacity for the community strategic adaptation options and evaluate the trends for ranking the strategic performance of the adaptation options over the planning period

Figure 2 illustrates the model for community adaptation strategy evaluation. The model phases are described and illustrated below.

3 Case Application: City of Charlottetown

The SD model described above is applied to the case of the City of Charlottetown, capital of the Province of Prince Edward Island and coastal community situated in Atlantic Canada.

Fig. 2 Framework for adaptation and community evaluation (FACE)

3.1 Phase I: Community Sustainability Profile and System Dynamics Model Simulation

Charlottetown community status is defined with respect to the community's status quo value-based assets position in terms of its environmental, economic, social, and cultural pillars. These pillars describe the inventory and resources associated with the community's physical and environmental attributes, the membership and involvement in the commercial economic sector, the elements of the social system (for example, community demographics, social and community services, and health care), and the characteristics that identify the unique cultural perspective of the community (for example, churches, community centers, faith-based organizations) (Fisher 2011).

In 2009, the Government of Canada requested that Canadian municipalities define their "pillars of community sustainability" as the communities' status quo capital asset

positions through the associated values of related indicators (Stantec Consulting 2010). These indicators are resource assets measured in nominal monetary units. Selected indicators by pillar are denoted in Table 1.

The SD model for Charlottetown is built around the sustainability pillars that profile community status as an annualized capital stock and flow model (Beigzadeh 2014). Figure 3 presents an overview of the system dynamics model developed using the STELLA modeling software (STELLA® 2012). At the center of Fig. 3, the "Human Capital" sector drives the sustainability pillars. The population flow is modeled by an age-structured set in three predominant age classes: young (ages 0–14), middle (ages 15–65), and old (ages 65+) members. Population dynamics are tracked through the annual process of births and deaths (as well as immigration and emigration) of the community into the population classes. This sector of the model also attributes health, education, and work skills to

Table 1 Pillars of community sustainability in Canadian municipalities

Pillar title, vector	Valued assets	Example pillar indicators
Environmental, $EN(\cdot)$	Land use/value	Land-use assets for: residential, commercial, industrial, greenspace, public works, and social and cultural purposes
Economic, $EC(\cdot)$	Economic goods and services	Built environment assets for: industrial production, commercial services, public works (for example, roads and water), ecosystem services, and social and cultural services
Social, $S(\cdot)$	Social processes	Labor income, safety and well-being resources, schools, hospitals, community collaboration, community well-being, and social networking assets
Cultural, $C(\cdot)$	Cultural services	Community resources, faith-based infrastructure, churches, and community centers

Fig. 3 System dynamics model: high-level STELLA model interfaces output. *Source* Modified output from STELLA® (2012)

Table 2 City of Charlottetown, Prince Edward Island, attributed land value assets

Land use	Space (acres) (2012)	Land value (\$Million/acre) (CAD 2012)	Description/sources
Residential	3225	\$2.855	Housing—average discounted selling value/acre for January 2016 Multiple Listing Service (MLS) Ottawa listings for detached bungalows prorated to 2012 Charlottetown average aggregate valuation (Royal-LePage 2016)
Commercial	2680	\$3.484	Commercial property—average discounted selling value (to 2012) for January 2016 Multiple Listing Service (MLS) Ottawa listings for business and retail properties prorated to 2012 Charlottetown average aggregate valuation (Royal-LePage 2016)
Industrial	1239	\$4.149	Industrial property—average discounted selling value (to 2012) for January 2016 Multiple Listing Service (MLS) Ottawa listings for Industrial and Office properties prorated to 2012 Charlottetown average aggregate valuation (Royal-LePage 2016)
Greenspace	472	\$1.500	Estimated value of city park lands, sports fields, trails, and open recreation space (Charlottetown 2007)
Public Works	2011	\$3.000	Estimated value of infrastructure for water, electrical power, sewage/water treatment, roadways, bridges, and maintenance (Charlottetown 2007, 2013)
Social and cultural	1326	\$2.000	Estimated value of lands for schools, hospitals, community centers, libraries, and arenas (Charlottetown 2007)
Total	10,953	\$16.988	

the population classes. The flows of people between the age classes determine the dynamic requirements for residential housing and commercial spaces in the community. The age class determines the need for residential and commercial spaces—for example, the aging of the population reduces the demand for household space and commercial activity as families age and downsize after children are grown-up and leave home.

The “Environmental: Residential and Commercial” land use sector (Fig. 3, top left) denotes the dynamics of residential housing and commercial spaces. The changing population adjusts the community housing and space needs. The “Environmental: Alternative Land Use” sector (Fig. 3, top right) assigns community greenspace (for example, parks and recreation spaces), industrial land (for example, industrial parks, warehouses, and office space), public works land (for example, infrastructure and public space), and social and cultural land (for example, community services, churches, schools, and hospitals). Adjustment of land use associated with the stock categories of greenspace, public works land, industrial land, and social and cultural land is determined by the population-driven requirements for commercial and residential land. The total community area of land is assumed to be approximately constant over the 50-year planning period so that annual population changes that affect residential housing and commercial area lands, that is, as the population goes up or down, proportionately adjust all other land use categories. Land is valued based on attributed dollars per acre (in 2012 CAD) of use for commercial, residential, greenspace, public works land, industrial land,

and social and cultural land categories as indicated in Table 2.

The land use stocks of commercial, industrial, and public works are the capital inputs to the “Economic: Goods and Services” sector (Fig. 3, bottom left) that tracks sector productivity. This sector articulates the aggregate productive components of the economy: (1) commercial services, (2) industrial services, and (3) public works (Statistics Canada 2007, 2012). The elements included in these aggregates are described in Table 3. In the “Social and Cultural” sector (Fig. 3, bottom right), social and cultural land is the capital input to ecosystem services and social and cultural production services.

Labor supplies to all production and services are provided by the corresponding work skill, education, and health attributes assigned to the population classes—for example, educated segments of the population are assigned to public works services, technically skilled population segments are assigned to industrial and commercial goods and services. Capital and labor are combined using a homogenous Cobb–Douglas production function to model goods and services outputs (Boumans et al. 2002).

The SD model is initialized by setting the population age class membership, the initial distribution of community land use, including the residential land units, that is, average housing unit needs per age class member, and the reported level of production of the sectoral services as per the Charlottetown dataset for 2012 (Charlottetown 2013). Annual Total Community Assets are determined for Charlottetown by summing annual Land Value, Goods and Services, and Social and Cultural Services assets.

Table 3 Goods and services sector aggregate productive components

Services title	Services components
Commercial	Wholesale trade, Retail trade, Transportation, Warehousing, Finance, Insurance, Real Estate, Rental and Leasing, Professional services, Scientific and Technical services, and Management of Companies and Enterprises
Industrial	Mining, Oil and Gas Extraction, Utilities, Construction, and Manufacturing
Public works	Waste Management and Remediation services, Public Administration, Education services, and Other services
Ecosystem	Recreation, Parks, and Greenspace services

3.1.1 SD Simulation and Uncontrollable Variables— Severe Storm Events

Total Community Assets are assumed to grow annually with the adjustments to the population growth. Assets are also negatively impacted by unpredictable storms and storm surges that are simulated in the SD model. The historical time series of storms relevant to selected coastal communities are available through NOAA's HURDAT2 online database tool (Landsea and Franklin 2013; Landsea et al. 2013). The Canadian Tides and Water Levels Data Archive (Fisheries and Oceans Canada 2013) provides maximum water levels at the time of storms from marine observation stations aligned with Canadian coastal communities. Data on historical coastal storm tracks, severity, and water level are the drivers for coastal community impacts. The SD model defines storm events as the single most severe storm event of the year in the community of interest as measured by the single yearly Maximum Observed Water Level (MOWL) that results from severe storms and storm surges in the coastal community. For the case of Charlottetown, the historical annual maximum MOWL data for the period 1911–2005 are used to determine the best fit probability distribution to these data. Beigzadeh (2014) found the best fit, as the Gumbel maximum extreme probability distribution for storm severity with its intuitive left skew and long right tail indicate the diminishing probability of rising MOWL values for Charlottetown. The randomized Gumbel maximum distribution is used to simulate the severe storm event in the SD model as an independent annual random draw from the distribution parameters: (1) the location parameter, MOWL mode, α ; and (2) the scale parameter, β . Changes to the distribution parameters are used to project emergency event futures as alternative simulation model storm severity, including applying the alternative severe storm futures used by the IPCC (2013).

There are four levels of storm severity in the SD model that are applied analogous to the IPCC's Representative Concentration Pathways (RCPs). The RCPs are categories for greenhouse gas concentration trajectories. These uncontrollable variables are designed to project the occurrence of severe storms based on the IPCC Fifth

Assessment Report (AR5) (IPCC 2013), that is, increasing RCP values imply increasing storm severity. The RCPs model a wide range of possible changes in future anthropogenic greenhouse gas (GHG) emissions as CO₂ equivalents. The simulated storm severity levels vary from Low to High severity as measured by the modal parameter, α of the Gumbel maximum distribution that describes the annual MOWL for the city of Charlottetown. These uncontrollable variables model annual Charlottetown storm severity events and are described in further detail in Table 4.

3.1.2 SD Simulation and Storm Impacts on Community Assets

GIS mapping is used in C-Change coastal community storm impact analysis (Lane et al. 2013) to analyze the community assets impacted by storms of different severity. Limited data exist on the impacts of storms to coastal community assets, homes, infrastructure, and businesses, and there are no formal community by community reporting mechanisms for natural storm damage. Accordingly, the impacts of storms on selected coastal communities are estimated based on aggregate values dependent on storm severity. Community severe storm impacts occur in each pillar of the community, that is, the environmental, economic, social, and cultural pillars, and have differential monetary impacts on community assets as a function of the severity of the storm (Hart 2011, 2014; Mohammadi 2014). Severe impacts are modeled by diminishing the land use sector contributions to production and service delivery as a direct function of storm severity. Recovery from storm damage is reflected in the SD model by calculating a flow back to land use capital with an annual recovery rate parameter.

3.1.3 SD Simulation Model Results

Results for the SD model are presented for specific annual state output variables described below. The SD model results summarize the annual asset position of the community for each of the 50-year planning periods. The initial model results presented here assume no controllable

Table 4 System dynamics model uncontrollable variables—city of Charlottetown, Prince Edward Island, annual storm severity levels, maximum observable water levels (MOWL)

Storm severity	Description	Application ^a	IPCC analogy ^b
I. Low (Base Case)	Modal MOWLs signal storms that result in minimal damage to property and infrastructure. This is the assumed storm definition for the Base Case scenario	$\alpha = 2.0$ and $\beta = 0.303$ Max MOWL < 4.0 m	RCP 2.6—GHG emissions peak 2010–2020 then decline substantially
II. Historical	Modal MOWLs signal storms consistent with the historical data values for 1911–2005 and result in occasional appreciable damage to property and infrastructure	$\alpha = 3.0$ and $\beta = 0.303$ Max MOWL < 4.5 m	RCP 4.5—GHG emissions peak by 2040 then decline
III. Medium	Modal MOWLs signal storms consistent with the increasing historical trend since the beginning of the 21st century and result in considerable damage to property and infrastructure	$\alpha = 3.5$ and $\beta = 0.303$ Max MOWL < 5.0 m	RCP 6.0—GHG emissions peak by 2080 then decline
IV. High	Modal MOWLs signal storms predicted with high certainty into the 21st century and result in significant damage to property and infrastructure	$\alpha = 4.0$ and $\beta = 0.303$ Max MOWL < 5.5 m	RCP 8.5—GHG emissions continue to rise throughout the 21st century

^aCity of Charlottetown Gumbel maximum severe storm parameters^bRepresentative Concentration Pathways (RCP), definitions based on IPCC (2013)

variables, that is, no applied adaptation, and no storms. The set of annual state output results is presented in Table 5.

3.1.4 “No Storm” Simulation Output State Results

The SD model results for the case of no storms and no adaptation strategy are illustrated in Fig. 4a–c for a single 50-year trial of simulated annual dynamics of the city of Charlottetown including:

1. Environmental Land Value assets attributed to residential, commercial, industrial, public works, green-space, and social and cultural land use valuation; for Charlottetown, Land Value assets are flat over the planning period;

2. Economic Goods and Services assets for public works, industrial production, commercial, and ecosystem services; these assets tend to grow along with the growth of the total population; and.
3. Social and Cultural Services assets, and social mapping functions attributed to assets for collaboration, social networking, and social well-being valuations; these assets tend to grow faster than the population increases.

Finally, Fig. 4d presents the expected Total Community Asset positions for alternate Storm Severity levels (averages of 10 trials) assuming no adaptation strategy is applied. Figure 4d illustrates how the Total Community Assets (sum of Land Value, Goods and Services, and Social and Cultural Services assets) are affected by

Table 5 System dynamics model Base Case output state results

Annual state	Definition	Description
Total community asset status Quo, $TA^0(t)$	Sum of pillar values (\$): $EN^0(t) + EC^0(t) + S\&C^0(t)$	Total Community Assets value measure assigned to community assets for each pillar indicator; denotes vector of Community Status Quo asset position at time $t = 0, 1, 2, \dots, 50$ and without any severe storm
Post-storm total community asset status, $TA^j(t)$	$TA^j(t)$, $j = \text{I, II, III, IV}$ severe storms, $TA^j(t) < TA^0(t)$ for all j and t	Total Community Assets after severe storm damages reduce the state of Community Profile valued assets; assumes that no previous application of adaptation strategies was put in place to alleviate severe storm damages
Storm damage impacts, $D^j(t)$	$D^j(t) = TA^0(t) - TA^j(t)$	Costs and losses to the Total Community Asset value measures attributed to the indicators in the Community Profile vector; $0 \leq D^j(t) \leq TA^0(t)$ for all j , $j = \text{I, II, III, IV}$ storms

Fig. 4 Charlottetown, Prince Edward Island, No Storm scenario SD model results: **a** Environmental (Land Value); **b** Economic (Goods and Services); **c** Social and Cultural (Services and Social Mapping

Value); and **d** Total Community Assets for Storm Severity Levels (No Adaptation) (averages of 10 trials)

increasing storm severity. While the No Storms and the Low (Base Case) Severity storm cases imply a projection over 50 years of slowly increasing total community assets for Charlottetown, High Severity storms project a sharp decline in total assets with a slight later year recovery over the 50-year planning period.

3.1.5 Population Dynamics

For the city of Charlottetown, and Prince Edward Island as a whole, the population growth over the 50-year strategic planning period (2011–2061) is expected to rise slightly and then decline beyond 2034 (Statistics Canada 2013). The young and middle age groups increase slightly, while the old age group more than doubles over the planning period, consistent with the current trend of a progressively aging population and with recent population growth projections. The model estimates that the population of urban Charlottetown will increase from 34,565 (2011) to 44,765 by 2061, a small rate of increase of +0.5% per annum. The population trend is independent of the storm severity and the alternative adaptation strategies. Alternative community population growth models can be examined by modifying model parameters for predicted growth, death, emigration, and immigration.

3.1.6 Environmental Pillar: Land Value Assets

The SD model trajectory of cumulative Charlottetown land value over the planning period for the No Storms scenario (Fig. 4a) shows relative stability in residential and commercial lands consistent with the slow growth population trend and the aging population. Similarly, land value for public works, industrial lands, greenspace, and social and cultural lands decline slightly (at an annual rate of -0.3%) as illustrated in Fig. 4a.

3.1.7 Economic Pillar: Goods and Services Assets

All production and service components exhibit slow expected growth over the planning period in the No Storms scenario, consistent with the slow population growth over the 50-year planning period. This slow growth is led by ecosystem services (+ 0.5% annual growth rate), followed by commercial (+ 0.4% annual growth rate), public works (+ 0.1% annual growth rate), and a relatively stable industrial production sector (Fig. 4b).

3.1.8 Social and Cultural Pillar Assets

Community social and cultural values are attributed to social and cultural land use with valuation assigned to the social functions of collaboration, well-being (general health), and social networking (Fig. 4c). These attributions show trends that are a function of: (1) the aging population affecting overall population health; (2) increases in the number of total households in the population; and (3) the anticipated rise in social and cultural activity (and value) when severe storm events occur. Social functions for collaboration, well-being, and networking and social and cultural services show a slight increasing trend over the planning period of approximately + 0.5% annual growth rate.

3.1.9 Total Community Assets

Figure 4d presents the summarized results for Total Community Assets under the No Storms and the four alternative severe storm scenarios of Table 4: I. Low (Base Case storms level); II. Historical; III. Medium; and IV. High storm severity. In each of these storm scenarios, it is assumed that no adaptation strategy is applied, that is, the community applies a status quo, “do nothing” strategy throughout the planning period. Figure 4d indicates that relative to the No Storms community asset position, $TA^0(t)$, $t = 1, 50$, the more severe the storm, the more degraded the total community asset position $TA^j(t)$, $j = I, II, III, IV$. The gap $[TA^0(t) - TA^j(t)]$ represents the extent to which the community assets are at risk or “vulnerable” to the simulated series of severe storm events. The vulnerability gap records annual predicted storm damages (assuming no explicit adaptation is in place) in Fig. 4d. This gap represents a key element in the asset-based measures to be discussed in Phases II and III below.

3.2 Phase II: Develop Adaptation Strategies and Compare Scenarios

In this phase of the modeling, local adaptation strategies of the city of Charlottetown are defined to develop simulation model scenarios that include selected controllable (adaptation strategies) and uncontrollable (severe storms) model variables (Table 4). These scenario results require estimations of modified storm impacts as a consequence of the adaptation strategy adopted. The adaptation strategies are defined in terms of their controllable SD model variables and are assumed to be implemented at the outset of the planning period—Year 1 (2012). These are presented in further detail below.

3.2.1 SD Simulation and Controllable Variables: Applied Adaptation Strategies

There are four broad categories of coastal community adaptation strategies: (1) Protection; (2) Accommodation; (3) Retreat; and (4) Status Quo or “Do Nothing” (Pilkey and Young 2009). These are defined in Table 6 for the Charlottetown context. The adaptation strategies, A_i are the controllable components of the simulation model scenarios. The specific applications of adaptation strategies for Charlottetown are designed based on comparable case studies for Atlantic Canada as described in Weissenberger and Chouinard (2015).

3.2.2 Simulation Model Scenarios

Table 7 presents a selected subset of five model simulation scenarios that are applied to the SD model for analysis and evaluation for the city of Charlottetown. These five scenarios differ with respect to their combination of controllable and uncontrollable variables toward examining the effectiveness of alternative adaptation strategies in the face of varying degrees of predicted storm severity for Charlottetown. These scenarios are taken from the larger set of the pairwise combinations (16) of the controllable (4), and uncontrollable (4) variables. The scenario results are examined to determine the robustness of the alternative adaptation strategies with respect to the storm severities and the measures of Vulnerability, Resilience, and Adaptive Capacity defined and evaluated below.

3.3 Simulation Scenario Results

SD model simulation results are presented and different scenarios are compared. Figure 5 presents the SD simulation model average annual Total Community Asset positions for $n = 10$ 50-year trials for the simulation scenarios of Table 7: (a) R1, Worst case (no adaptation/high storm severity); (b) R2, Protect—Worst case storms; (c) R3, Accommodate—Worst case storms; and (d) R4, Retreat—Worst case storms.

Figure 5a illustrates the year-over-year Total Community Assets position under the no adaptation, or Status Quo (Do Nothing) strategy. The average annual differences between the annual nominal total assets of the No Storms case (highest annual assets position, Fig. 4d), and the High Severity case, denote the Worst Case scenario with total average annual vulnerability or expected damages to the community attributable to High Severity ($j = IV$) annual storms (scenario R1). Figure 5a shows a declining assets position in the face of high severity storms compared with an increasing trend of total assets under No Storms. This

Table 6 System dynamics model controllable variables—Charlottetown, Prince Edward Island, adaptation strategies, A_i

Adaptation strategy, A_i	Description	Application: city of Charlottetown, P.E.I.
Protect	Physical coastlines reinforcement; “hard” engineering—seawalls, breakwaters, gabions and groins; “soft” engineering—grading coastal cliffs, planting or maintaining existing vegetation (Ollerhead 2006)	Construct 3.75 m seawalls Labor skills adjustment (professional skills enhancement) Public service increase in cost of \$100 million investment over 5 years
Accommodate	Construction of structures to reduce storm damage (for example, elevated houses), improve land use, zoning plans to restrict permission of coastal constructions; legislation and increasing natural resilience by rehabilitating coastal dunes and wetlands (Pilkey and Young 2009)	Labor skills adjustment for structures Attributed land as public works Public service increase in cost of \$50 million investment over 5 years
Retreat	Abandon areas closest to the coastline, place temporary or dispensable structures only in these areas; avoid direct impact from storms; land swapping, or management strategies such as rezoning, insurance denial, or tax policies (Shaw and CCAF A041 Project Team 2001; Natural Resources Canada 2010)	Adjustment to work skills Attributed increase in land to greenspace Public service increase in cost of \$75 million investment over 5 years
Status Quo (Do Nothing)	Toleration of all storm damages without attempting to mitigate storm impacts; arguably most commonly adopted strategy (McCulloch et al. 2002)	No adaptation strategy (Do Nothing/Status Quo)

Table 7 System dynamics model scenario definitions for the city of Charlottetown, Prince Edward Island

No.	Scenario name	Controllable variables—adaptation strategies, A_i (see Table 6)	Uncontrollable variables—IPCC analogy/storm severity for Charlottetown (see Table 4)
R0	Base case/Benchmark	No adaptation strategy (Do Nothing/Status Quo)	Low severity storms, IPCC, RCP 2.6: $\alpha = 2.0$ and $\beta = 0.303$
R1	Worst case	No adaptation strategy (Do Nothing/Status Quo)	High severity storms, IPCC, RCP 8.5: $\alpha = 4.0$ and $\beta = 0.303$
R2	Protect—worst case storms	Protect with 3.75 m seawalls; Labor skills adjustment for seawalls construction (professional); Public service increase in cost of \$100 million investment in 5 years	High severity storms, IPCC, RCP 8.5: $\alpha = 4.0$ and $\beta = 0.303$ Strategy modification: IF MOWL < 3.75 m then “No Impacts” ELSE “Impacts”
R3	Accommodate—worst case storms	Labor skills adjustment; Attributed land as public works; Public service increase in cost of \$50 million investment in 5 years	High severity storms, IPCC, RCP 8.5: $\alpha = 4.0$ and $\beta = 0.303$ Strategy modification: New MOWL = 0.75 Original MOWL
R4	Retreat—worst case storms	Adjustment to work skills; Public service increase in cost of \$75 million investment in 5 years; Increase in greenspace	High severity storms, IPCC, RCP 8.5: $\alpha = 4.0$ and $\beta = 0.303$

implies that the gap indicating high severity storm annual vulnerability widens over the planning period.

The application of active adaptation is depicted in Fig. 5b–d. Each adaptation strategy is modeled as an investment in the first 5 years of the planning period, that is, $t = 1, 2, \dots, 5$, and is signaled by a corresponding 5-year shift in assets to reflect the operationalization of the proposed adaptation strategy.

In the case of the Protect strategy, and relative to Fig. 5a, b includes the addition of the average annual nominal total assets position when the Protect strategy is applied against high severity storms (scenario R2). The

presence of the protective seawall reduces the impact of the storms of high severity and increases the annual total assets position relative to the No Adaptation (Do Nothing) strategy. The average annual impacts are depicted in the expected assets curve (black line) representing Total Community Assets under the high severity storms—Protect strategy (Fig. 5b). The assets curve (black line) of Fig. 5b improves the assets position relative to the no adaptation assets position with the exception of the first two years of the investment in protective infrastructure. Subsequently, assets under Protect exceed those under No Adaptation. The average annual gap reduction is identified as the

Fig. 5 Charlottetown, Prince Edward Island, simulation High Severity Storms scenario average results for Total Community Assets, Vulnerability, and Resilience over 10 trials assuming: **a** Scenario R1—no adaptation; **b** R2—protect; **c** R3—accommodate; and **d** R4—retreat

resilience attributed to the Protect strategy. Likewise, the reduced vulnerability gap indicates the remaining damages from high severity storms that affect the community.

Figure 5c provides similar information to Fig. 5b, but for the Accommodate strategy under high severity storms (scenario R3). The figure illustrates the Accommodate Resilience as the average annual reduction in total vulnerability over the planning period, and the Accommodate Vulnerability as the remaining vulnerability gap after Accommodate Resilience is removed. The indicator results for Fig. 5b (Protect) and c (Accommodate) are roughly comparable in their ability to reduce the total vulnerability gap of Fig. 5a.

Figure 5d presents the comparable results for the Retreat strategy under high severity storms (scenario R4). In this case, the Retreat option shows inferior average annual nominal total assets to the no adaptation strategy under high severity storms. The Retreat option is seen as being less preferred to the Status Quo or Do Nothing option in this case. For Charlottetown, the transformation of alternative land use into greenspace to represent the removal of activities from the waterfront and the flooding of susceptible areas diminish the attributed land values (as in Table 2 where greenspace land value per acre in the model is appreciably less than the value for other land use alternatives, notably commercial and residential lands). While this shift reduces storm damage, it undermines high land-

use values, leading to a significantly reduced total community asset position, as depicted in Fig. 5d. In this case, Retreat Resilience is expressed as being negative, that is, it adds to increased vulnerability.

3.4 Phase III: Measure Vulnerability, Resilience, and Adaptive Capacity, and Evaluate

The SD simulation model results over the planning period, as depicted in Fig. 5, provide information on the expected consequences for Charlottetown's asset position under various controllable and uncontrollable scenarios.

The evaluation of the controllable adaptation strategies against the risks and impacts of the uncontrollable incidence of severe storms enables the calculation of the asset-based indicators for the comparison of adaptation strategy performance relative to total community assets. For each adaptation strategy, these indicators express Charlottetown's measured vulnerability, strategy resilience, and adaptive capacity over the planning period.

The Sendai Framework defines vulnerability and resilience. Vulnerability is characterized by "the conditions determined by physical, social, economic, and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards" (UNISDR 2015, footnote reference p. 6). Resilience is characterized by "the ability of a system, community or society exposed

to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions” (UNISDR 2015, footnote reference p. 7). Given this foundation, the variables for vulnerability, resilience, and adaptive capacity are defined for Charlottetown through the results of the SD asset model for coastal community adaptation. The asset-based indicators are defined in Table 8.

Consider the set of community adaptation strategies, A_i , $i = 1, 2, \dots$ where A_i represents additional planned strategies designed to reduce the damages expected from severe storms (Table 6). When adaptation strategies, A_i are introduced to moderate the impacts of storm damages, a reduction is expected in the coastal community's level of vulnerability. These strategies are designed to protect community assets from storm impacts, and therefore result in less loss on initial asset values. Thus, applying adaptation strategy A_i means that the new status of the community in the face of severe storm j is given by $TA^j(A_i)$, the modified total community assets position such that the new position is expected to exceed the No Adaptation assets, $TA^j \leq TA^j(A_i)$ and is less than the maximum No Storm assets position, $TA^j(A_i) \leq TA^0$, as noted in Table 5.

Figure 6 illustrates the concepts of vulnerability and resilience to storm scenario $j = I, II, III, IV$, based on the total community asset axis. The rightmost (highest) total community asset value is denoted by the No Storm asset position, TA^0 . The leftmost (lowest) total community asset value, TA^j is the asset value following Storm j when the No Adaptation strategy (or Status Quo) is applied. Vulnerability V_j is shown as the difference between the No Storm asset position, TA^0 versus the Worst Case impact of storm scenario j (high storm severity with no adaptation) asset position of the community indicators, TA^j . When an adaptation strategy A_i is invoked, vulnerability (relative to no adaptation) is expected to be reduced as a result. Resilience $R^j(A_i)$ is depicted as the reduced total

vulnerability as a consequence of the adaptation strategy A_i , that is, $TA^j(t, A_i) - TA^j(t)$.

Community adaptive capacity, $AC^j(A_i)$ is determined for each adaptation strategy, A_i , and relative to all adaptive options of the community, as the ratio of the related resilience to total vulnerability for the specified storm scenario, j , and the adaptation alternative strategy, A_i . $AC^j(A_i)$ is recorded as a ratio value < 1 , or as a percentage, $< 100\%$. Average annual $AC^j(A_i)$ or $\overline{AC}$ is determined by averaging the average annual adaptive capacity results for storm scenario j over the planning period.

Figure 7 illustrates the breakdown of the average annual nominal asset results by pillar for the adaptation scenarios R1 through R4 (Table 7). These results enable the comparative evaluation of the alternative adaptation strategies over the 50-year planning period.

Figure 7a shows the combined graphic of the average annual nominal total community assets position for the No Storm case and the R1 through R4 scenarios. This graph unites the scenario results for Fig. 5a–d. In terms of total assets, the preferred strategy is considered to be Accommodate with respect to its superior asset performance especially in the later years of the planning period. As such, the Protect strategy outperforms the Accommodate strategy, but only in the earlier part of the planning period.

Figure 7b–d break down the adaptation scenario asset performances into their respective pillar components for Environmental (Land Value), Economic (Goods and Services), and Social and Cultural Values (Social Mapping Indicators). These component-wise results are not necessarily compatible with the average annual nominal total assets position by strategy. For example, while the Accommodate strategy may be considered an overall superior adaptation strategy, the Protect strategy has an overall superior Land Value performance compared to the Accommodate strategy (Fig. 7b). However, Accommodate is superior with respect to Protect for both Goods and

Table 8 System dynamics model asset-based indicators: vulnerability, resilience, and adaptive capacity

Asset indicators	Definition	Description
Community vulnerability, $V^j(t)$ (No adaptation)	$TA^0(t) - TA^j(t)$	Estimated difference between pre-storm and post-storm community assets under No Adaptation; equivalent to storm damages, $D^j(t)$ (Table 5)
Community Vulnerability under adaptation, $V^j(t, A_i)$	$TA^0(t) - TA^j(t, A_i)$	Estimated reduced difference between pre-storm and post-storm community assets under adaptation strategy, A_i
Community resilience, $R^j(t, A_i)$	$TA^j(t, A_i) - TA^j(t)$, $0 < R^j(t, A_i) < V^j(t)$	Value-added measure arising from the adoption of specific adaptation strategy, A_i and denoting the reduction in vulnerability loss compared to the Do Nothing strategy, TA^j under storm scenario $j = I, II, III, IV$
Community adaptive capacity, $AC^j(t, A_i)$	$R^j(t, A_i)/V^j(t)$, $0 < AC^j(t, A_i) < 1$	Ratio of the related community resilience under adaptation strategy, A_i to community vulnerability (under No Adaptation) for the specified storm scenario, $j = I, II, III, IV$

Fig. 6 Total community asset indicators for vulnerability and resilience to severe storm j , $j = \text{I, II, III, IV}$. Source Modified from Mostofi Camare and Lane (2015)

Fig. 7 Charlottetown, Prince Edward Island, High Storm Severity scenarios averages for 10 trials: **a** Total Community Assets; **b** Environmental (Land Values); **c** Economic (Goods and Services); and **d** Social and Cultural Values (Social Mapping Indicators)

Services (Fig. 7c) and Social and Cultural Values (Fig. 7d).

Similarly, the Retreat strategy has a markedly weak asset performance for Land Values and Goods and Services as a function of the shift in greenspace land use. However, the Retreat strategy is expected to outperform all other adaptation strategies over the planning period with respect to Social and Cultural Values (Fig. 7d).

Table 9 provides the summary of 50-year average annual indicator values by scenario for the asset-based indicators over the planning period. As indicated in this table, the Accommodate strategy provides a relatively high Total Community Assets position, reduces Vulnerability, and maximizes Adaptive Capacity. Based on this information, further research should investigate the details of defining, funding, operationalizing, and implementing this adaptation strategy relative to the other alternatives.

Figure 8 presents the Annual Adaptive Capacity measures for the 50 years of the planning period under the Worst Case storms and the associated adaptation strategies—scenarios R2 (Protect), R3 (Accommodate), and R4 (Retreat).

The results of the time series of the Adaptive Capacity measure reflect the vulnerability and resilience results of Fig. 5. In the beginning five investment years, the Accommodate and Protect strategies are preferable. The Retreat strategy is not preferred in comparison with at least one other adaptation strategy throughout the entire planning period. Thus, the Retreat strategy is dominated by the alternative Protect and Accommodate strategies. Similarly, the Do Nothing strategy has zero Adaptive Capacity in every period since Resilience is measured as zero, by definition, when no adaptation strategy is adopted (Table 9). Accordingly, as a strategy, Do Nothing is

Table 9 Asset-based indicators for average annual Vulnerability, Resilience, and Adaptive Capacity over the 50-year planning period

Scenario	Storm severity	Adaptation strategy	Average annual total community assets	Average annual vulnerability, $TA^0 - TA^j$	Average annual resilience, $TA^j(A_i) - TA^j$	Average annual adaptive capacity, $R^j(A_i)/V^j$
No storms	None	Do Nothing	\$ 38,787	\$ 0	\$ 0	N/A
R0	Low	Do Nothing	\$ 38,555	\$ 232	\$ 0	0%
R1	High	Do Nothing	\$ 36,775	\$ 2012	\$ 0	0%
R2	High	Protect	\$ 37,948	\$ 839	\$ 1173	58.29%
R3	High	Accommodate	\$ 38,044	\$ 743	\$ 1269	63.09%
R4	High	Retreat	\$ 35,728	\$ 3059	– \$ 1047	– 52.03%

Fig. 8 Annual adaptive capacity for selected high severity storm scenarios: R2—protect, R3—accommodate, R4—retreat

dominated with respect to any strategy that has some positive resilience over the planning period.

4 Discussion

The research developed and applied a system dynamics model in support of the multidimensional evaluation of alternative adaptation strategies over a long-term planning period for coastal communities facing changing environmental conditions from more frequent severe storms and sea-level rise. The procedure determines context-based objectives and measures for coastal community vulnerability, resilience, and adaptive capacity based on the four-dimensional profile of the community pillars of sustainability: environmental, economic, social, and cultural.

The SD model represents a simplification in the determination of dynamic coastal community assets subject to impacts from severe storms over a long-term planning period. For example, the definition of the population into three discrete age classes can be refined with the support of

data that would take into account more detailed age class education, work skills, and health status. Similarly, a more detailed population would enable a refinement of how different age classes are expected to impact land use, housing, and the consumption of goods and services. The determination of storm impacts based on observed water levels does not take into account other storm damage impacts due to high winds, extreme temperature shifts, or other natural hazards. The availability of data on coastal storm impacts in local communities is insufficient and needs to be addressed with mechanisms in place in the local context to account for these negative effects on community assets. Nevertheless, and under the precautionary principle, there is an obligation to provide estimates for information that enables a relative comparison for evaluation and selection purposes of the strategic adaptation alternatives.

This article assumes that the development of the SD model for the local context provides a tool for local decision makers, for example, regional or municipal governments. The transparency and ease of use of the SD model

permit stakeholder involvement. Model development, data collection, and use of strategic results of relevance to key stakeholders and community decision makers require their direct engagement in the modeling exercise that can be easily accommodated in an open process that promotes model verification and viability. Developing examples of “best practices” would provide convincing evidence of the usefulness of the modeling process and encourage further data and model development for the local context.

5 Conclusion

The SD model results indicate preferred adaptation strategies (and the elimination of dominated adaptation strategies) in the context of the coastal community. The preferred strategies can be further developed, compared, and evaluated using the proposed methodology, and the quantitative indicators for vulnerability, resilience, and adaptive capacity calculated to guide alternative selection. The method promotes the need for a longer-term, strategic planning perspective necessitated by the unidirectional trends of the changing coastal climate characterized by rising sea levels, and more frequent and severe storms and storm surges. The strategic view enables differentiation of multidimensional and integrated evaluation of adaptation alternatives that recognize the need for solutions over the longer term. The proposed decision support methodology contributes to the UNISDR Science and Technology Roadmap “key actions” (Aitsi-Selmi et al. 2016) as a concrete initiative of a comprehensive, integrated, multi-disciplinary evidence-based approach to disaster risk reduction for the evaluation of policy options over a longer-term planning period.

The research has exposed the need for improving the amount and availability of local storm impact data, and promotes the monitoring and analyses of these data as the primary means for assessing and evaluating alternative coastal community adaptation strategies at the local community level and in conjunction with decision makers. The imminent creep of coastal climate change, and the urgency of coastal communities to be better prepared to adapt to the changing coastal environment, require further effort in the strategic analysis of adaptation strategies.

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