



Dynamic Resilience to Climate Change Caused Natural Disasters in Coastal Megacities Quantification Framework

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Authors' contributions

This work was carried out in collaboration between all authors. Author SPS provides the overall guidance for the work presented in this article, developed the conceptual formulation of the resilience measure and wrote the first draft of the manuscript. Author AP is working on the development of CMRS model and provided illustrations and comments on the first draft of the manuscript. All authors read and approved the final manuscript.

Research Article

Received 4th November 2012
Accepted 28th June 2013
Published 15th September 2013

ABSTRACT

Objectives: The framework is designed to provide (i) for better understanding of factors contributing to urban resilience; and (ii) for comparison of climate change adaptation options.

Methodology: Disasters occur at the intersection of hazards and vulnerabilities. As the climate changes, so do the patterns of climate hazards. Coastal megacities are faced with many challenges including (i) increased exposure to natural hazards such as hurricanes, typhoons, storm surges, sea-level rise and riverine flooding; (ii) pressures of increasing urbanization and population growth; and (iii) increased complexity of interacting subsystems. An original method for quantification of resilience is provided through spatial system dynamics simulation. The quantitative resilience framework combines economic, social, organizational, health and physical impacts of climate change caused natural disasters on coastal megacities. The developed measure defines resilience as a function of time and location in space. The framework is being implemented through the system dynamics model in an integrated computational environment.

Conclusion: Data collection for the Coastal Megacity Resilience Simulator (CMRS)

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model input and discussions with local decision makers are actively being pursued concurrent with the model development for the primary case study coastal city of Vancouver, British Columbia, Canada. Future work includes developing policy driven adaptation scenarios, resilience model simulations, transfer of the resilience model to local community and capacity building.

Keywords: Resilience; coastal megacities; climate change; systems modeling.

ACRONYMS

CMRS: Coastal megacity resilience simulator; **DALY:** Disability adjusted life year; **GIS:** Geographic information system; **IDRC:** International Development Research Centre; **ST-DRM:** Space-time dynamic resilience measure

1. INTRODUCTION

Coastal regions are highly dynamic and complex systems, which respond in various ways to extreme weather events [1]. Coastal floods are among the most dangerous and harmful natural disasters. On the other side, the urban areas adjacent to the shorelines are characterized with large and growing concentrations of human population, settlements and socio-economic activities. Currently, 21% of the world's population lives within coastal zones and an average of 46 million people per year experience storm surge flooding. Some 189 million people presently live below the one-in-a-hundred-year storm surge level [2]. Climate change is making natural disasters in coastal areas much more significant. Therefore, there is a need for quantitative assessment of climate change caused natural disaster impacts on coastal regions and analyses of various adaptation options. This paper presents an original resilience assessment framework based on system dynamics simulation. This framework can be used to identify the most significant factors affecting urban resilience (Fig. 1) and to develop climate change adaptation measures for coastal megacities. In this paper, the focus is on large cities in low-lying deltaic environments (Vancouver, Canada; Manila, Philippines; Lagos, Nigeria; and Bangkok, Thailand) selected for consideration under the project "Coastal Cities at Risk: Building Adaptive Capacity for Managing Climate Change in Coastal Megacities" supported by the International Research Initiative on Adaptation to Climate Change of the Canadian International Development Research Centre (IDRC) [3]. These cities experience impacts of flooding both from rivers and the sea, and are therefore very vulnerable to the impacts of climate change.

There are practical links between disaster risk management, climate change adaptation and sustainable development leading to reduction of disaster risk and re-enforcing resilience as a new development paradigm [4]. There has been a noticeable change in disaster management approaches, moving from disaster vulnerability to disaster resilience; the latter viewed as a more proactive and positive expression of community engagement with natural disaster management. As hazard is increasing, at the same time it erodes resilience, therefore climate change has a magnifying effect on disaster risk. In the past, standard disaster management planning emphasized the documentation of roles, responsibilities and procedures. Increasingly, these plans consider arrangements for prevention, mitigation, preparedness and recovery, as well as response. However, over the last ten years substantial progress has been made in establishing the role of resilience in sustainable development [5]. Multiple case studies around the world reveal links between attributes of

resilience and the capacity of complex systems to absorb disturbance while still being able to maintain a certain level of functioning. Building on emergency planning experience, there is a need to focus more on action-based resilience planning to strengthen local capacity and capability, with greater emphasis on community engagement and a better understanding of the diversity, needs, strengths and vulnerabilities within communities. Disasters do not impact everyone in the same way. It is clear that the problems associated with sustainable human wellbeing in urban regions call for a new research approach. Cities may be seen as living systems (systems of systems), constantly self-organizing in many and varied ways in response to both internal interactions and the influence of external factors. Use of resilience as an appropriate matrix for investigation arises from the integral consideration of overlap between: (a) physical environment (built and natural); (b) social dynamics; (c) metabolic flows; and (d) governance networks, as shown in Fig. 1.

This paper provides an original systems framework for quantification of resilience. The framework is based on the definition of urban resilience as the ability of physical and social urban systems to absorb disturbance while still being able to continue functioning. The disturbance in cities depends on spatial and temporal perspectives and direct interaction between impacts of disturbance (social, health, economic, and other) and adaptive capacity of the urban system to absorb disturbance.

The main objectives of this paper include: (i) the introduction of an original systems framework for quantification of resilience; (ii) the procedure for framework implementation through system dynamics simulation; and (iii) a brief discussion of the tool being developed for the implementation of the framework in coastal megacities. The remainder of the paper is organized in the following way: The next section presents the new systems framework for quantification of resilience; the following section focuses on the implementation of the proposed framework through system dynamics simulation; and the paper ends with a brief discussion of current progress on the development of Coastal Megacity Resilience Simulator (CMRS) model and a brief description of its future use.

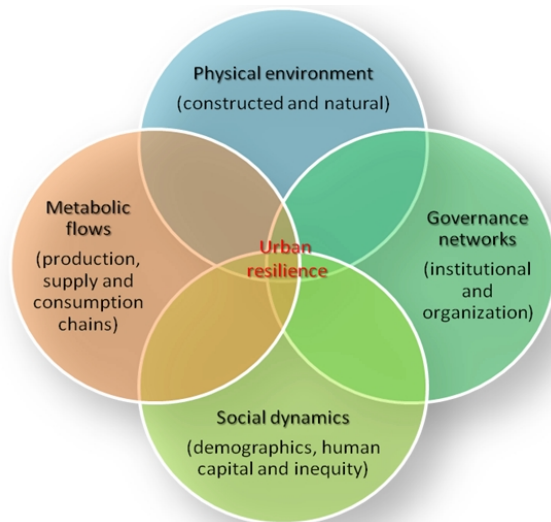


Fig. 1. Four interconnected areas that define urban resilience (modified after [4])

2. A SYSTEMS FRAMEWORK FOR QUANTIFICATION OF URBAN RESILIENCE

The most common approach to urban disaster management is focused on the assessment of vulnerability, which when combined with hazards, provides for disaster risk evaluation. Based on Cutter et al. [11], "vulnerability describes the pre-event, inherent characteristics or qualities of urban systems that create the potential for harm. Vulnerability is a function of who or what is at risk and sensitivity of system (the degree to which people and places can be harmed). On the other side, resilience is the ability of a complex system to respond and recover from disasters and includes those conditions that allow the system to absorb impacts and cope with an event, as well as post-event, adaptive processes that facilitate the ability of the system to re-organize, change, and learn in response to a threat" (paraphrased by the authors).

There are many definitions of resilience, from general [6]:

- (i) The ability to recover quickly from illness, change or misfortune.
- (ii) Buoyancy.
- (iii) The property of material to assume its original shape after deformation.
- (iv) Elasticity.

to ecology-based [7]:

- (i) The ability of a system to withstand stresses of 'environmental loading'.

to hazard-based [8]

- (i) Capacity for collective action in response to extreme events.
- (ii) The capacity of a system, community, or society potentially exposed to hazards to adapt, by resisting or changing, in order to reach and maintain an acceptable level of functioning and structure.
- (iii) The capacity to absorb shocks while maintaining function.
- (iv) The capacity to adapt existing resources and skills to new situations and operating conditions.

The common elements of these definitions include: (i) minimization of losses, damages and community disruption; (ii) maximization of the ability and capacity to adapt and adjust when there are shocks to systems; (iii) returning systems to a functioning state as quickly as possible; (iv) recognition that resilient systems are dynamic in time and space; and (v) acknowledgements that post-shock functioning levels may not be the same as pre-shock levels. Resilience is a dynamic process, but for measurement purposes is often viewed as static phenomena [11].

A resilient city is a sustainable network of physical (constructed and natural) systems and human communities (social and institutional) that possess the capacity to survive, cope, recover, learn and transform from disturbances by: (i) reducing failure probabilities; (ii) reducing failure consequences (for example material damage); (iii) reducing time to recovery; and (iv) creating opportunity for development and innovation from adverse impacts. Numerous institutions, organizations, and elements in the urban environment contribute to community resilience. Let us for the sake of simplicity, focus here only on critical organizations whose functions are essential for community well-being in the aftermath of disasters [9,10]. These critical facilities include water and power lifelines, acute-care hospitals, and organizations that have the responsibility for emergency management at the

local community level. Improving the resilience of critical lifelines such as water and power and critical facilities and functions such as emergency response management is critical for overall community resilience. These organizations are essential for community functioning; they enable communities to respond, provide for the well-being of their residents, and initiate recovery activities when disasters strike [9]. For example, since no community can cope adequately with a flood disaster without being able to provide emergency care for injured victims, hospital functionality is crucial for community resilience. Water is another essential lifeline service that must be provided to sustain disaster victims. Any consideration of resilience must begin with a focus on services and functional activities that are essential for a resilient community. The continued operation and rapid restoration of these services are a necessary condition for overall community resilience.

2.1 A Space-Time Dynamic Resilience Measure

There is a significant literature that covers qualitative conceptualizations of disaster resilience, but very little research that focuses on resilience quantification and its implementation in the management of disasters. Even though [9], [10] and [11] propose conceptual frameworks for resilience assessment, challenges remain in developing standard metrics that can be used in quantifying and assessing disaster resilience. Therefore, there is the necessity to move beyond conceptualizations and into actual resilience quantification. This paper takes the first step in this process by providing a conceptual framework for natural disaster resilience drawn from global change, hazards and systems literature.

The starting point in the development of new system framework for quantification of resilience is an engineering hazard-based definition of resilience as a static measure that reduces the probability of failure [12,13,14,15,16,17]. The main shortcoming of the engineering approach as quoted in [11] "is that it often fails to capture important social and governance factors (presented in Fig. 1) that occur at the most local levels or to account for the vulnerability or resilience of the natural environment". In our approach we follow [11], "resilience has two qualities: inherent (functions well during non-crisis periods); and adaptive (flexibility in response during disasters)" and can be applied to physical environment (built and natural), social systems, governance network (institutions and organizations), and economic systems (metabolic flows), as shown in Fig. 1. To deal with the shortcomings in existing resilience models and to provide a conceptual basis for establishing baselines for measuring resilience, we have developed a space-time dynamic resilience measure (ST-DRM). The ST-DRM is designed to capture the relationships between the main components of resilience; one that is theoretically grounded in systems approach, open to empirical testing, and one that can be applied to address real-world problems in urban communities.

A space-time dynamic resilience measure, ST-DRM, is illustrated in system performance space in Fig. 2. The solid line illustrates the adaptation capacity that leads to system performance level equal to one before the system disturbance. Dashed line is illustrating adaptation capacity that is insufficient to bring the performance level to a pre-disaster stage. The dotted line illustrates the adaptation capacity that brings the level of system performance above the pre-disturbance level.

The ST-DRM is defining the level of system performance in time (t) at a particular location in space (s). The measure integrates various units (i) that characterize impacts of disasters on urban community. At the current level of development the following units of resilience (ρ^i) are considered: physical, health, economic, social and organizational. Measures of performance for physical impacts ($P^i(t,s), i = 1$) may include length [km] of road being

inundated by a flood, or the reduction in water supply [m^3/s] due to pipe break, or the area of the city [km^2] that is under the water during a flood event, or the height of the sea wall [m] that provides the coastal protection, and so on. The health impacts ($P^i(t, s), i = 2$) may be measured using an integral index like disability adjusted life year (DALY), or the number of hospital beds in emergency hospitals, or the number of doctors per capita, and so on. The economic ($P^i(t, s), i = 3$) impacts can be measured using aggregates like GDP, or much more sophisticated expressions of production, supply and consumption chains obtained through input-output modeling. The measure of performance for social impacts ($P^i(t, s), i = 4$) can be expressed using indicators like age, gender, ethnicity, social status, education and household arrangement. The organizational impacts ($P^i(t, s), i = 5$) can be measured using number of disaster management services available to the population, or the time [hr] required under the current regulations to provide assistance or process a damage claim, or similar. This approach is based on the notion that an impact, $P^i(t, s)$, which varies with time and location in space, has been defined for the quality of the resilience component of a community.

Every performance measure indicator used in the quantification of impacts is compared to a threshold performance value in order to determine the starting point of system disturbance (t_0) and the ending point (t_1). The threshold values may be predefined system adaptive capacity standards. We follow [9] and [10] and define adaptive capacity of physical and social systems using: (i) robustness - strength, or the ability of elements, systems, and other indicators of analysis to withstand a given level of disturbance or demand without suffering degradation or loss of function; (ii) redundancy - the extent to which elements, systems, or other indicators of analysis exist that are replaceable, i.e., capable of satisfying functional requirements in the event of disturbance, degradation, or loss of functionality; (iii) resourcefulness - the capacity to identify problems, establish priorities, and mobilize resources when conditions exist that threaten to disrupt a system; and (iv) rapidity - the capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future system disruption.

Fig. 3 illustrates conceptual calculation of SR-DRM. When the loss of system resilience – shaded area between t_0 and t_1 – is equal to the recovery of system resilience – shaded area between t_1 and t_r , then the system resilience is equal to 1 at the end of the recovery period t_r . As illustrated in Fig. 3, performance of a system which is subject to a disruption (disaster event) drops below the initial value and time is required to recover the loss of system performance.

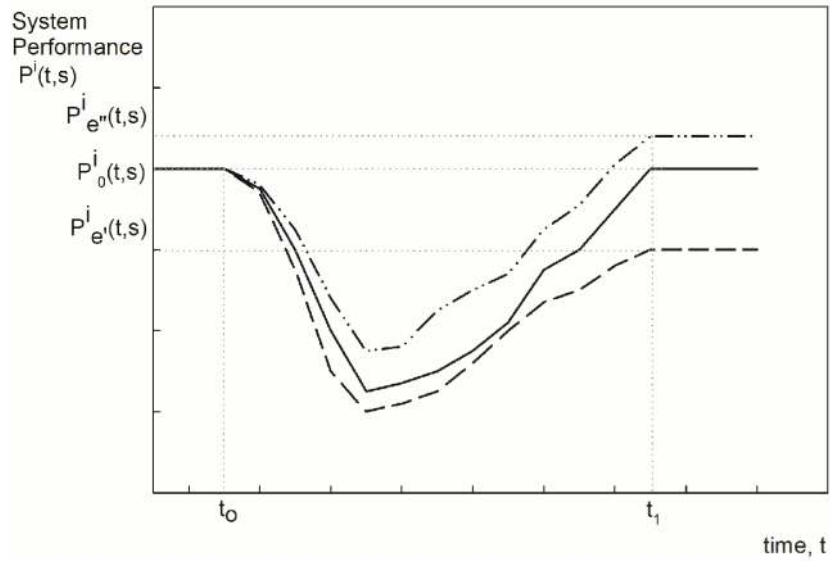


Fig. 2. Conceptual definition of the space time dynamic resilience measure (ST-DRM)

In mathematical form the performance measure for impact (*i*) represents the shaded area in Fig. 3 between the beginning of the system disruption event (t_0) and the end of the disruption recovery process (t_1). It can be represented mathematically as:

$$\rho^i(\tau, s) = \int_{t_0}^t [P_0^i - P^i(\tau, s)] d\tau \quad \text{where } t \in [t_0, t_1] \quad (1)$$

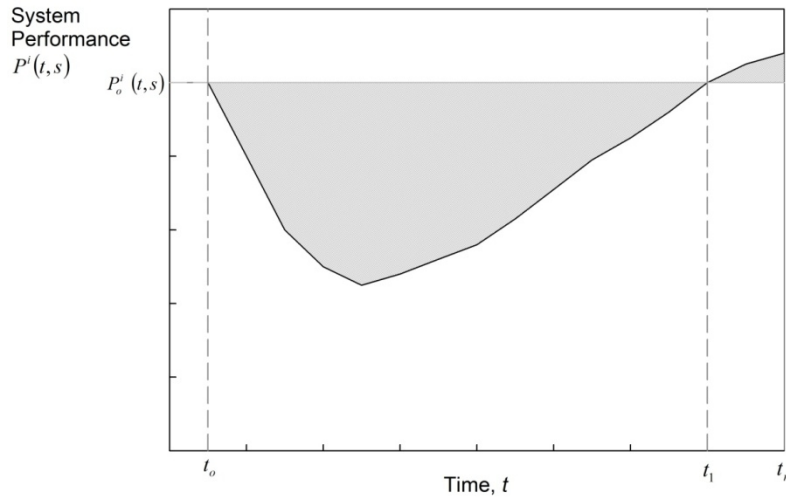


Fig. 3. Illustration of system space time dynamic resilience measure (ST-DRM) in performance space

Equation (1) will have the units of selected impact indicator. In order to allow for the calculation of integral resilience measure across different impacts, the value of $\rho^i(t, s)$ is then used in calculation of resilience for each impact (*i*):

$$r^i(t, s) = 1 - \left(\frac{\rho^i(\tau, s)}{P_o^i \times (t - t_o)} \right) \tag{2}$$

Fig. 4 shows the value of resilience calculated from the change in system performance. There are three possible outcomes in resilience simulation: (i) resilience returns to pre-disturbance level (value of 1) – dash-dotted line in Fig. 4; (ii) resilience exceeds pre-disturbance level (value > 1) – dashed line in Fig. 4; or (iii) resilience does not return to pre-disturbance level (value < 1) – dotted line in Fig. 4.

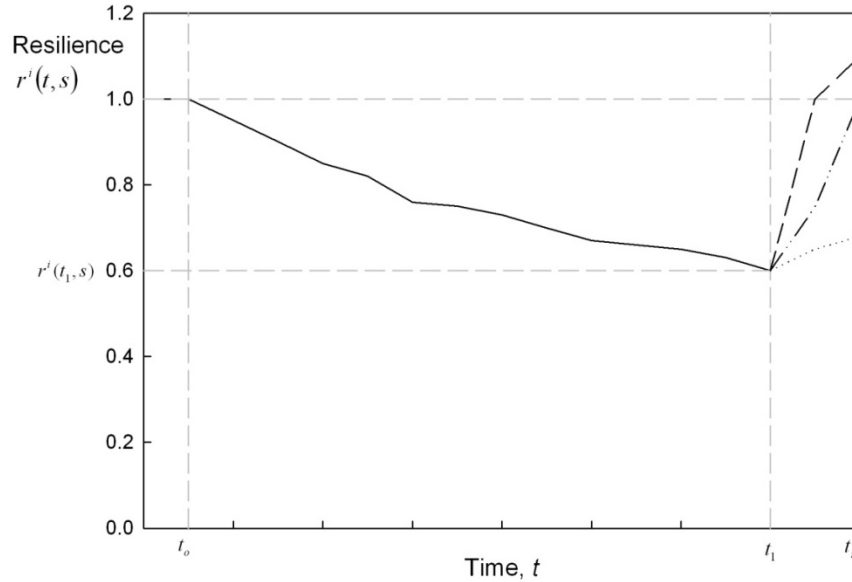


Fig. 4. System resilience

Specifically, the value of $r^i(t, s)$ will range from 0 to 1, where 1 means no degradation in system performance and 0 means no performance is available. If a disturbance (for example flood) occurs at time t_0 , it could cause sufficient damage to infrastructure such that the performance quality is immediately reduced. Restoration of the infrastructure is expected to occur over time, as indicated in Fig. 4, until time t_r when the system resilience is recovered. The integral ST-DRM (over all impacts (i)) is calculated using:

$$R(t, s) = \left\{ \prod_{i=1}^M r^i(t, s) \right\}^{\frac{1}{M}} \tag{3}$$

where M is total number of impacts

Computation of the ST-DRM is performed for each location in space (s). Fig. 5 is the schematic presentation of the ST-DRM computational process. The shades of red colour illustrate different resilience values. Spatial units of the analysis are shown as grid cells for the simplicity of the concept illustration. Since the calculated value of $R(t, s)$ will change with time and location, the final outcome of the ST-DRM computation is a dynamic map that shows change of $R(t, s)$ with time and location. Selected spatial resolution of analysis may require aggregation and/or disaggregation of indicators selected for description of various impacts, (i). One possible scheme for implementation in Canadian cities is the use of

dissemination area as the spatial unit of analysis [18]. This area is defined by Statistics Canada as “a small, relatively stable geographic unit composed of one or more adjacent dissemination blocks. It is the smallest standard geographic area for which all census data are disseminated”.

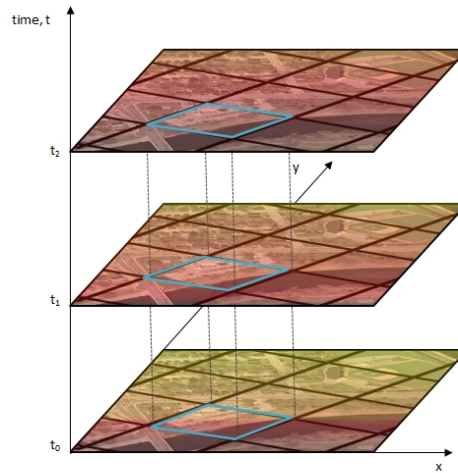


Fig. 5. Illustrative presentation of the space time dynamic resilience measure (ST-DRM) computation process

2.2 Implementation of ST-DRM through System Dynamics Simulation

The implementation of the ST-DRM is proposed to use the system dynamics simulation approach. System dynamics is an academic discipline introduced in the 1960s that has gradually developed into a tool useful in the analysis of social, economic, physical, chemical, biological and ecological systems [15,16,17,18]. In the context of this paper, a system is defined as a collection of elements that continually interact over time to form a unified whole. The underlying pattern of interactions between the elements of a system is called the structure of the system. The term dynamics refers to change over time. If something is dynamic, it is constantly changing in response to the stimuli influencing it. A dynamic system is thus a system in which the variables interact to stimulate changeover time. The way in which the elements, or variables, composing a system vary over time is referred to as the behavior of the system. One feature that is common to all systems is that a system's structure determines its behavior. System dynamics links the behavior of a system to its underlying structure. It can be used to analyze how the structure of a physical, biological, social or any other system can lead to the behavior the system exhibits.

The system dynamics simulation approach relies on understanding complex interrelationships existing between different elements within a system, by developing a model that can simulate and quantify the behavior of the system. The major steps that are carried out in the development of a system dynamics simulation model include: (i) understanding the system and its boundaries; (ii) identifying the key variables; (iii) describing the interactions between variables through mathematical relationships; (iv) mapping the structure of the model; and (v) simulating the model for understanding its behavior.

The ST-DRM is converted into the system dynamics model using the high-level model diagram shown in Fig. 6. The calculation of ST-DRM for each impact (*i*) is done at each location (*s*) by solving the following differential equation:

$$\frac{\partial p^i(t)}{\partial t} = AC^i(t) - P^i(t) \tag{4}$$

where AC^i represents adaptive capacity with respect to impact, *i*

Adaptive capacity is defined using various performance measures. These measures are defined, as presented above, in terms of four R's (robustness, redundancy, resourcefulness and rapidity). Examples of health performance measures for some critical systems (power and water lifelines, hospitals, and emergency response system) are shown in Table 1. It must be noted that these are for illustrative purposes only. Bruneau et al. [9] suggest a distinction between “ends” and “means” dimensions of resilience; robustness and rapidity are essentially the desired “ends” that are accomplished through adaptation resiliency-enhancing measures and are the outcomes that more deeply affect decision makers and stakeholders; and redundancy and resourcefulness are measures that define the “means” by which resilience can be improved.

The integral ST-DRM is calculated at each location (*s*) by solving:

$$\frac{\partial R(t)}{\partial t} = AC(t) - \sum_i P^i(t) \tag{5}$$

Assessment of impacts is driven by the selected performance measures and a set of system disturbance sources (hazards). In other words, traditional concepts of vulnerability and exposure will be used and adapted to each performance measure. Change in climate and non-climate drivers will be affecting vulnerability and exposure of system components. At the same time, adaptation measures under consideration will be modifying them too. Interaction of numerous feedback mechanisms underlining the high level model structure in Fig. 6 will generate system behaviour. In this way, the ST-DRM describes the integral system behavior.

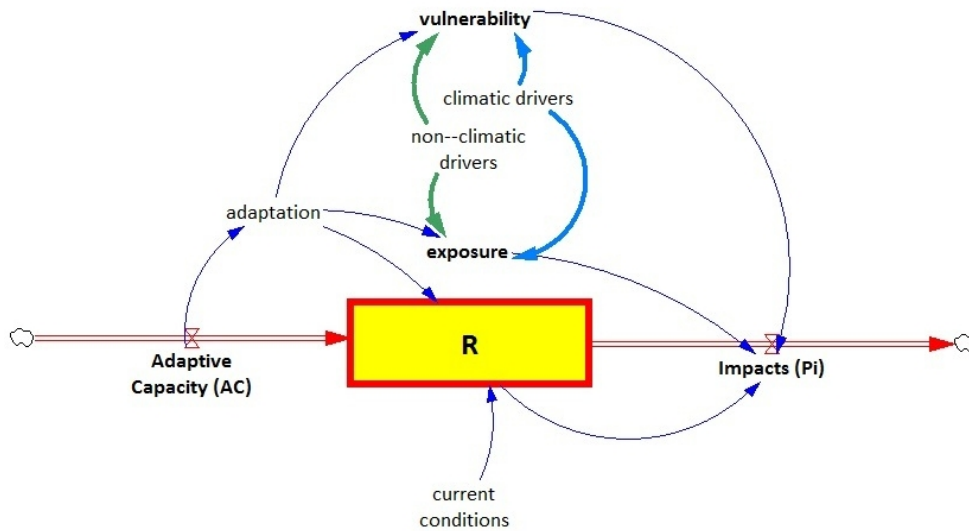


Fig. 6. A schematic system dynamics model for the implementation of ST-DRM

The system dynamics simulation model of ST-DRM can be used to design and evaluate adaptation policies for improvement of system performance that will lead to levels of resilience higher than the pre-disruption levels. Adaptation policy design involves various approaches such as: (a) change of model parameters; and/or (b) creation of new strategies, structures, and decision rules. Regardless of the approach used, the aim of any system dynamics simulation model experimentation is the exploration of model behavior between different simulation runs. The purpose is to observe how the modeled system behaves normally, and then how changes in policies or physical parameters alter that behavior.

It has been shown [17,18] that the feedback structure of a system determines its dynamic system behavior over time. Most of the time high leverage policies involve changing the dominant feedback loops by redesigning the system structure, eliminating time delays, changing the flow and quality of information available at key decision points, or fundamentally recreating the decision processes in the system. The robustness of policies and their sensitivity to uncertainties in model parameters and structure must be assessed, including their performance under a wide range of alternative scenarios. The interactions of different policies must also be considered; because real systems are highly nonlinear, the impact of combination policies is usually not the sum of their impacts alone. Often policies interfere with one another and sometimes they reinforce one another and generate substantial synergies.

Table 1. An illustrative example of health performance measures for a flood disaster

Critical system	Robustness	Redundancy	Resourcefulness	Rapidity
Water	% of residential buildings with safe drinking water service immediately following a flood event	Alternative and secondary drinking water sources	Water conservation programs, boil water advisories, bottled water initiatives implemented	Reestablish safe drinking water supplies in 1 day
Power	% of all residential buildings with power service immediately following a flood event	Alternative power supplies	Power conservation programs implemented	Reestablish power to residential buildings in 1 day
Hospital	% treatment of injured people and ability to provide patient care without transfers	Alternative hospitals and care clinics	Arrangements for temporary hospitals and treatments	Treat all injured persons in 2 days
Emergency Response Services	% of response vehicles that maintain service	Multiple response units with multiple emergency routes	Allocate additional voluntary emergency responders for disaster assistance	Maintain emergency response at all times, provide emergency shelters for displaced residents within 12 hours

3. COASTAL MEGACITY RESILIENCE SIMULATOR

The ST-DRM framework is being applied to the project "Coastal Cities at Risk: Building Adaptive Capacity for Managing Climate Change in Coastal Megacities" supported by the International Research Initiative on Adaptation to Climate Change of the Canadian IDRC [2]. The system dynamics model (Coastal Megacity Resilience Simulator - CMRS) is being developed that implements the ST-DRM framework in an integrated computational environment (as shown in Fig. 3). VENSIM system dynamics simulation software [20] is integrated with ArcGIS software [21]. The CMRS model will have a generic form based on the space-time dynamic resilience framework. The model generic form will be modified to specifics of each coastal city considered in the project (Vancouver, Canada; Lagos, Nigeria; Manila, Philippines; and Bangkok, Thailand) resulting in four specific city models to be used in improving adaptive capacity for managing climate change in coastal megacities.

3.1 The Systems Approach Context of Coastal Megacity Resilience to Climate Change

The evolution of systems approach to cities is progressing very fast. The current view of the city as a "System of Systems" is dominating the European Union [23] and North America [24]. In this view a city is looked as a very large scale integrated system of components that are themselves systems. These components link many constituent systems on a wide variety of temporal and spatial scales. The resulting combined system is able to address problems which the constituent systems alone would be unable to do and yields functionality that is only present as a result of the creation of new, "emergent", behavior.

A coastal megacity can be considered a network of three interdependent subsystems: (i) the natural subsystem; (ii) the socio-economic subsystem; and (iii) the administrative and institutional subsystem. Each of the three subsystems is characterized by its own elements and is surrounded by its own environment. For the purpose of the project, coastal megacity resilience is caused by the interaction between society and climate change caused hazards (e.g. precipitations, floods and cyclones). Some rapid onset hazards are noticeable immediately, such as flooding or hurricane, and may last for relatively short time period ranging from hours to weeks. Continuous hazards, such as sea-level rise, are very slow events that are hardly perceptible by society [25].

The natural system is defined by climate and physical conditions (catchment and coast), the socio-economic system is formed by the demographic, social and economic conditions of the surrounding economies, and the administrative and institutional systems are formed and bounded by the constitutional, legal and political systems. Climate change affects three sub-systems of the coastal megacity system: hydro-geological, socio-economical and administrative-institutional. Their interactions affect the possible short- and long-term damages from climate change caused disasters. The components can be assessed by different indicators to understand the resilience of the system to climate change caused natural disasters. These sub-systems are described in more detail below.

(a) Hydro-geological sub-system. The hydro-geological sub-system is a part of the natural system. It includes hydro-geo-morphological (i.e. sea-level rise, river discharge, soil subsidence) and climatic (i.e. number of cyclones, storm surges) characteristics of the coastal megacities. This sub-system affects disaster exposure (illustrated in Fig. 2). Developments such as land subsidence, storm surge and high river discharge increase

environmental degradation, aggravating effects of climate change and associated sea-level rise, increasing the potential occurrence of floods.

(b) Socio-economic sub-system. This component is part of the socio-economic system; for example, climate change caused flooding affects the day-to-day lives of the population that belongs to the system. The social component relates to the presence of people and includes issues related to it. For example, decreased mobility of people may be associated with gender, age or disabilities. Coastal floods can cause destruction of houses, disruption in communications, disruption in agricultural activities, or even fatalities. The economic component is related to income or issues which are inherent to the economy of the affected area. There are many economic activities that can be negatively affected by coastal flooding. Among them are: tourism, fisheries, navigation, industries, agriculture, availability of potable water, etc.

(c) Administrative-institutional sub-system. To characterize the administrative and institutional system, the relevant institutions at the national, regional and local level must be identified. The approach assumes that one or more institutions have the ability and authority to develop and implement plans that will oversee and manage the coordinated development and actions of the local authorities that affect the coastal megacity.

Understanding the natural processes as well as the economic and social services or functions that coastal megacities fulfill is critical to the successful and sustainable management of these systems. For example, more severe storms will result in a slight decrease of the storm surge levels as a result of increased water depths; storm surge may also increase because of the more severe storm activity; and tidal prisms will increase; etc. As a result, salt intrusion will increase, structures will be more stressed and wetlands will be inundated and adversely affected. All of these will affect the population of the coastal megacity, which is under permanent increase. Damage will also occur to agricultural areas as a result of increased saltwater intrusion. In addition, cultural heritage may be susceptible to flooding. The coastal parts of megacities are affected by human activities such as bank protection, shipping, and construction and operation of hydraulic infrastructure. Coastal cities provide tangible and direct economic benefits; tourism, transport and fisheries depend on the wealth of natural resources that a coastal environment supplies. The protected coastal waters also support important public infrastructure, serving as harbours and ports vital for shipping, transportation and industry.

3.2 The Impacts

The five major impacts that are being considered in the ST-DRM include: physical impacts, economic impacts, social impacts, health impacts and organizational impacts. They will be individually modeled in the modifications of generic Coastal Megacity Resilience Simulator (CMRS) model into four city models (Vancouver, Manila, Bangkok and Lagos) to properly describe the local conditions in each city.

3.2.1 Physical impacts

Coastal cities are exposed to multiple types of hydro-meteorological climate hazards including: storm surges, tsunamis, sea-level rise, hurricanes, and coastal and riverine flooding. Climate change and urbanization will exacerbate the problems associated with these hazards in urban coastal megacities as the frequency and magnitude of events increases. These hazards drive the physical sector of the CMRS model that represents the

natural sub-system. The changes in the physical system have direct and indirect impacts on economic, social, health and organizational activities.

The main hydro-meteorological hazards that threaten the coastal megacities include: riverine flooding, storm surges and sea-level rise. These hazards are described by climatological elements in the physical sector of the system dynamics model. The physical impacts sector is connected to other sectors in the model which describe a community's resilience to various impacts of a disaster. For example, flooding directly affects the health of people, inundates infrastructure and impacts social wellbeing. However, some communities will experience higher levels of impacts than others based on the magnitude of hazard (depth of flooding for example), pre-disaster characteristics of population health, local pre-disaster economy and social inequities.

The physical impacts sector is where the effects of climate change are captured in the projection of hazard events. The CMRS model will be able to simulate a single hazard event (e.g. flooding) but may also simulate multiple hazards which occur simultaneously (e.g. storm surge and riverine flooding) or in series (e.g. back-to-back flooding events). Climate change modifies the physical events which are being used as input into the CMRS model; this is how the effects of climate change are being captured.

3.2.2 Economic impacts

The economic prosperity of coastal megacities often heavily depends on the physical coastal environment. The same environment is a significant contributor to the risk to coastal communities. The economic activities of coastal cities that are being considered in the CMRS model include manufacturing and services, tourism, fishing, export-import trade, transportation, construction and other industries that rely on or are linked to the oceans for operations.

The CMRS model uses an input-output economic model to illustrate pre- and post-disaster economies. A physical hazard (such as a flood) is used as input into the physical impact sector of the model. The model captures the dynamic impacts of the hazard on local economic activities such as the supply and capacity constraints, GDP, energy and employment. This will impact the other sectors of the CMRS model. These other sectors experience changes that then feedback into the economic sector and modify it again. This is the essential system dynamics concept of feedback loops. The economic impacts of climate change caused natural disasters are important for the development of appropriate adaptation policies.

3.2.3 Social impacts

People like to live near the coast. In affluent communities, being in close proximity to water is a desirable place to live for the view it provides. In poorer communities however, it is people who have been displaced or rely on their proximity to water for survival (for example, fishing) who live closest to water bodies, which makes them susceptible to multiple impacts of hazardous events. The relationship between poverty, environmental degradation and hazard vulnerability is a vicious, mutually reinforcing system feedback [26].

Social vulnerability is based on the concept that a population exposed to hazards is susceptible to suffering physical, emotional or psychological distress. The degree to which people may experience these damages is influenced by their tolerance and coping

capabilities in stressful situations. Vulnerable populations exhibit certain characteristics that suggest they are more likely to incur damages in the event of a disaster. The CMRS model being developed includes 21 social indicators of social vulnerability, such as: population under 19 years of age, population whose primary language is not English or French, incidence of low income, population with only high school education, and single parent families. The social impacts sector is linked to the physical, economic and health impacts sectors, creating additional feedbacks in the CMRS model. These sectors influence each other and all contribute to overall city resilience.

3.2.4 Health impacts

Coastal hazards can have significant impacts on the health of individuals and a community. Floodwaters carry debris that can impact people causing injury which may immediately impede mobility. Floodwaters also carry waste, sewage and bacteria which, through direct contact with drinking water supplies, could spread disease and cause illness for many weeks after a disaster. Illness may also be passed from person to person in close quarters.

Disability Adjusted Life Years (DALYs) are used in CMRS to capture the health vulnerability of a population. These values are available for most countries worldwide from the World Health Organization. The DALYs provide the number of cases for injuries, communicable and non-communicable diseases for a particular year. As coastal hazards affect a community, the DALY values will change to reflect the health impacts. However, the time scales for different health impacts are not equal. Injuries usually occur during the disaster, whereas some illnesses may not show for weeks, and some diseases may not show at all or may not be related to a disaster event. The CMRS model is able to handle differences in temporal scales of different health impacts, but is limited by the simulation time horizon of the model and the availability of specific local health data. Health impacts of a disaster are also linked to the economic, physical, organizational and social impacts of a disaster. Together, these sectors contribute to the overall coastal megacity resilience.

3.2.5 Organizational impacts

The effectiveness of climate change adaptation measures must consider the political administrative and institutional framework which affects the functioning of the coastal megacity. This framework defines the overall effectiveness of decision making. It must be framed because the overall implementation and effectiveness of climate change adaptation options depends on political motivation, budgets and climate change policy. The manner in which a city formulates policy decisions is not explicitly represented in the CMRS model structure but it is incorporated as an essential part of adaptation scenarios to be simulated by the model.

3.3 Data Needs

The Coastal Megacity Resilience Simulator (CMRS) is data intensive. A very detailed description of each of the five impacts considered within the tool and detailed temporal and spatial scales require serious data support. Table 2 provides an extensive example list of time series data and Table 3 lists the necessary spatial data.

Table 2. An illustrative example of CMRS time series data needs

Data category	Data type
Physical	<p>Local historical climate data (precipitation, wind, tides, temperature extremes, etc.) Local historical seasonality of hazards Global Climate Modeling (GCM) data and emission scenarios Historical disasters: Data relating to the size and magnitude of greatest observed disaster; Data relating to the most recent disaster and details surrounding it; Damages to infrastructure; Impacts of natural disasters in case study locations</p>
Economic	<p>Economic Accounts (National/Provincial/Regional/ City Levels) - standard tables prepared in all countries according to UN guidelines, including GDP, national income and its composition, expenditure and its composition International trade data - exports and imports by industry and commodity. Input-output "Use", "Make", and final demand matrixes Output by industry Employment by industry Gross Domestic Product (GDP) Household survey micro-data including income and/or consumer expenditure plus other variables (e.g. age, sex, employment status and education of household members, and home ownership); asset and debt variables. Size distributions of income and wealth by age, sex and household type - means, medians, decile shares, Gini coefficients Employment and unemployment numbers and rates Jobs especially related to emergency management and recovery processes Energy production in physical units Valuation of public capital and infrastructure Hospitals, schools, colleges and universities, other public service buildings Roads, railways, ports, airports Local public transit Valuation of private capital and infrastructure: Residential Commercial/Industrial Energy production and distribution system (output or carrying capacity in physical units and value)</p>

	electricity generating stations
	oil refineries and storage facilities
	energy distribution systems (electric power lines, pipelines etc.)
	Estimate property damage for disasters of different magnitudes; damage given by type (residential, commercial, industrial, public buildings, infrastructure etc.); stage-damage curves
Social	Population statistics (e.g. Statistics Canada)
	Culture, religion and behaviour which may influence disaster preparedness, response, recovery and adaptation
	Social networks and service providers
	Identification of isolated individuals
Health	Transportation access
	Local disease data and statistics
	DALY values
	Impact of local diseases on an individual's mobility
	Onset time after infection
	Rate of infection
	Duration of infection
	Vaccination availability for communicable diseases
	Links between diseases and climate change
	Emergency plans for medical service providers and personnel to help during a disaster
	Hospital and aid-center characteristics (i.e. capacity; number of doctors/nurses employed; budget; etc.)
Other	Details related to water infrastructure (structural properties; design specifications; maintenance details; operational requirements; etc.)
	Details related to coastal infrastructure (structural properties; design specifications; maintenance details; operational requirements; etc.)
	Disaster response plans and emergency management provisions; first responders
	Details pertaining to expected disaster aid (historical and otherwise)
	Historical experience in disaster responses
	Emergency and standard communications networks
	Communication requirements for specific groups of people (i.e. no access to internet; First Nations People; etc.)

Table 3. An illustrative example of CMRS spatial data needs

Data category	Data type
Physical	Digital Elevation Models (DEMs) Digital boundary files Water features (rivers, lakes, oceans, ponds etc.) Land cover; (trees, grass, sand, etc.) Land use; (agricultural, industrial, commercial, residential, etc) Hydrological surveys of coast and rivers Coastal infrastructure Geological maps
Economic	Fine resolution economic data; location of particular industries and major facilities Income and wealth data as available Energy distribution systems Roads, railways, airports, bridges, tunnels Number, type, value of structures (residential, commercial, industrial, public) and infrastructure (public, private)
Social	Population characteristics Age % population under 19; % population aged 65 and over; % population who are widows; Gender % population who are female; Ethnicity % breakdown of ethnicities; % population without citizenship; Social status Mean and median dwelling value; Mean and median household income; Incidence of low income; % population who rent their dwelling; % income received from government transfers; % labour force (age > 15) unemployed; % labour force employed in manufacturing; % labour force employed in agriculture;

	Education % adult population whose highest qualification is i): high school diploma, ii) trade certificate, iii) post-secondary qualification other than university degree, iv) university degree
	Household arrangement % single-parent families; % female-headed single-parent families; % private households with one person % private households with > 6 people
	Divisions of power (and therefore independence and vulnerability) within households
	First language % breakdown of first languages spoken
	Clusters
Health	Locations and details of hazardous materials storage facilities Locations of temporary disaster shelters Critical infrastructure (hospitals, bridges, schools, emergency response, daycare centers, seniors homes, prisons, etc.) Specific regions with known, predisposed health hazards
Other	Spatial distributions of hazards Areas exposed to multiple hazards (historical and in the future)Energy providers and energy distribution networks Location of municipal infrastructure Areas of high biological/environmental sensitivity Areas of high cultural significance

The identified data is available from different data sources. The physical data is provided by the national/regional and local hydrometeorological services in each country. The climate change data is accessed from the climate modeling centers. For example, the Vancouver climate data is obtained from the Canadian Centre for Climate Modelling and Analysis which is a branch of Environment Canada. Other physical data is available from the city government sources and regional institutions responsible for various services. Most of the economic, social and health data is available from national statistical services (in Canada Statistics Canada). In the case of local missing data, some international sources (United Nations Department of Economic and Social Affairs, World Health Organization, World Meteorological Organization, and similar) can be considered. A detailed social data require surveys conducted on ground.

3.4 Use of the CMRS for Building Adaptive Capacity of Coastal Megacities to Climate Change

The purpose of the system dynamics model simulation is to focus on behavioural patterns of a system rather than to predict a single value or outcome for a specific event [18]. This means that the CMRS model is in no way predictive, but is instead intended to develop and observe the interactions between elements of model structure, provide for learning and increase the understanding of community resilience. Simulation models may also be thought of as cause-and-effect models that describe the response of the system to a particular input [17]. Various elements of the CMRS model structure will exhibit different behaviour; each contributing to the overall behaviour of the space-time dynamic resilience measure. Simulation makes it possible to test the sensitivity of the system behaviour to changes in system structure.

A simulation scenario represents specific course of action and is created as a particular combination of system input variables. The purpose of simulation scenarios is to provide changes in model output in response to a particular input. Real policy systems are highly nonlinear in behaviour and policies often conflict or reinforce each other. Therefore, the CMRS simulation is providing for comparison of climate change adaptation options using ST-DRM as the measurement matrix. In the current work, adaptation scenarios are used as a way to introduce potential climate change adaptation strategies into the resilience model to observe effects on model behaviour and prioritize the implementation of different adaptation policy options within a coastal megacity.

Adaptation to climate change of coastal megacities will be investigated using CMRS model with a number of adaptation scenarios. These scenarios are a combination of values assigned to a set of CMRS model variables. A scenario may require modification of initial values of input variables, or modification may be implemented during the simulation process. For example, a scenario may include the allotment of additional financial resources to a particular model sector in the period of recovery after a disaster has occurred. This scenario is then simulated using the CMRS model to observe its effect on model sub-systems and on overall city resilience behaviour.

An example adaptation scenario may be to designate additional medical personnel in anticipation of coastal population growth and increased frequency of extreme climate events. The expected system behaviour from this action would be an increase in overall city resilience measure. The addition of medical personnel would decrease disaster health impacts; likely reducing the spread of communicable disease and improving the overall wellbeing of the population. However, this is an example of linear, more obvious thinking that

will not see that there may be other relationships in the system that could be negatively affected by this action. For example, increasing medical personnel requires more funding that will reduce the available budget for other adaptation options, like improvement in the flood protection infrastructure. Lower level of protection increases potential damage and exposes larger number of people to hazards, therefore increasing further the need for more medical personnel. The CMRS model will be able to provide the insights into complex relationships that drive the response to various adaptation scenarios and therefore assist in identification of those adaptation options that will increase adaptive capacity measured by the increase in community resilience. The main purpose of adaptation scenario simulations using CMRS model is to help develop adaptation policy, aid in resource allocation decisions and prioritize disaster management investments. Therefore these scenarios are being developed in close collaboration with local decision makers.

4. CONCLUSION

The paper presents an original framework for quantification of resilience through spatial system dynamics simulation, ST-DRM. The quantitative resilience measure combines economic, social, organizational, health and physical impacts of climate change caused natural disasters on coastal megacities. The framework is designed to provide for: (i) better understanding of factors contributing to urban resilience; and (ii) comparison of climate change adaptation options using resilience as a decision making criterion.

The developed measure defines resilience as a function of time and location in space. The framework is being implemented through the system dynamics model (Coastal Megacity Resilience Simulator - CMRS) in an integrated computational environment (system dynamics simulation software is integrated with GIS software). The CMRS model will have a generic form based on the space-time dynamic resilience framework [27]. The generic model form will be modified to specifics of each coastal city considered in the project (Vancouver, Lagos, Manila and Bangkok); this will result in four specific city models to be used in improving adaptive capacity for managing climate change in coastal megacities.

Data collection for the CMRS model input and discussions with local decision makers is actively being pursued concurrently with the model development for the primary case study coastal city of Vancouver, British Columbia, Canada. Future work includes developing policy driven adaptation scenarios, resilience model simulations, transfer of the resilience model to the local community and capacity building.

ACKNOWLEDGEMENTS

The authors are thankful for the research financial support provided by IDRC to the first author and the NSERC CGS doctoral scholarship provided to the second author. Prof. J. Davies and anonymous reviewers contributed to the improvement of the manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:

The peer review history for this paper can be accessed here:
<http://www.sciencedomain.org/review-history.php?iid=267&id=10&aid=2034>