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Coastal Cities at Risk (CCaR): Generic System Dynamics Simulation Models for Use with City Resilience Simulator
FINAL REPORT

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EXECUTIVE SUMMARY

It is projected that 67% of global population will be living in urban areas by 2050; an increase of approximately 30% from global urban population in 2011 (United Nations 2012). This anticipated increase may be attributed to the trend of increasing rural-to-urban migration as people abandon agricultural practices to seek out economic opportunities and prosperity in urban cities (Akanda and Hossain 2012; Wenzel et al. 2007). Migration is causing many major cities to rapidly grow into megacities (Akanda and Hossain 2012; United Nations 2008); defined by the United Nations (2008; 2012) as cities with populations greater than 10 million people. A majority of the world's current and projected megacities are located in hazardous low-lying coastal areas, particularly in the developing world. Therefore, millions of people are exposed to coastal climate hazards. In addition, the megacities are often characterized by high population densities, destitute slum settlements and inadequate life-sustaining infrastructure (Wenzel et al. 2007); conditions which exacerbate the impacts of climate hazards.

Coastal cities are particularly threatened by hydro-meteorological climate hazards including: hurricanes, tsunamis, storms, storm surges, flooding and sea-level rise. The climate is changing and so are the spatial and temporal patterns and characteristics (frequency, magnitude, intensity and seasonality) of climate hazards (IPCC 2012). Many coastal cities are already experiencing the consequences of a changing climate and many more can expect an increased frequency of high magnitude events in the future (IPCC 2012). Climate hazards have dynamic and complex impacts on environmental and human systems; which often result in natural disasters. With close to 10% of the global population living in low-elevation coastal zones, there is an increased necessity for estimating and reducing the impacts of coastal disasters (United Nations 2011). Climate change caused hazards will continue to have a significant impact on coastal cities in the future. Therefore, effective adaptation to natural disasters is an essential component of a comprehensive, long-term disaster management strategy.

The work presented in this report is part of an international 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). This report focuses on a system dynamics simulation (SD) approach for understanding the behaviour of complex city systems to climate change caused natural disasters. This approach captures the dynamic characteristics of disaster impacts. A quantitative resilience measure is used to assess a city's capacity to manage climate change disasters. Simulation of resilience in time and space allows for the assessment and comparison of alternative adaptation measures. The project involves a methodology for assessing the impacts of hydro-meteorological disasters on four coastal megacities across the globe: Vancouver in Canada, Lagos in Nigeria, Manila in Philippines and Bangkok in Thailand.

The objectives of this report are to: (i) present an original systems framework for quantifying resilience and introduce a space-time dynamic resilience measure (ST-DRM); (ii) discuss ST-DRM theory and calculations; (iii) introduce Generic System Dynamics Simulation Models (GSDSMs) and provide implementation example; (iv) present a high-level structure of the City Resilience Simulator (CRS); and (v) provide current state of modeling progress for the CCaR project and outline future work.

The report is organized as follows: Chapter 1 introduces the research topic and provides some background information on the CCaR project; Chapter 2 gives more technical and theoretical details pertaining to the development of a City Resilience Simulator (CRS); Chapter 3 provides a description of the Generic System Dynamics Simulation Models (GSDSMs); Chapter 4 provides a detailed description of how to use the GSDSMs to develop unique CRSs for the CCaR project partner coastal cities; Chapter 5 presents a GSDSM implementation example; and finally, Chapter 6 provides a summary of work presented and anticipated future work.

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LIST OF ACRONYMS

AC	Adaptive Capacity
CCaR	Coastal Cities at Risk
CIHR	Canadian Institute of Health Research
CRS	City Resilience Simulator
CRS-N-L	City Resilience Simulator for long duration, continuous hazards
CRS-N-S	City Resilience Simulator for short duration, event-based hazards
CRS-B	City Resilience Simulator for Bangkok, Thailand
CRS-L	City Resilience Simulator for Lagos, Nigeria

CRS-M	City Resilience Simulator for Manila, Philippines
CRS-V	City Resilience Simulator for Vancouver, Canada
GSDSMs	Generic System Dynamics Simulation Models
GSDSM-C	Generic System Dynamics Simulation Model – Combined
GSDSM-E	Generic System Dynamics Simulation Model – Economic
GSDSM-H	Generic System Dynamics Simulation Model – Health
GSDSM-O	Generic System Dynamics Simulation Model – Organizational
GSDSM-P	Generic System Dynamics Simulation Model – Physical
GSDSM-S	Generic System Dynamics Simulation Model – Social
GIS	Geographic Information System
IDRC	International Development Research Centre
IRIACC	International Research Initiative on Adaptation to Climate Change
NSERC	Natural Sciences and Engineering Research Council of Canada
OBD	Overall Burden Disease
SD	System Dynamics
SDRM	Single Dynamic Resilience Measure
SSHRC	Social Sciences and Humanities Research Council of Canada
ST-DRM	Space-Time Dynamic Resilience Measure

1. INTRODUCTION

This report focuses on the design and implementation of Generic System Dynamics Simulation Models (GSDSMs) for use in coastal city resilience quantification and assessment. It should be noted however, that this research is part of a larger, multi-disciplinary, multi-institutional, International Development Research Centre (IDRC) funded project entitled "Coastal Cities at Risk (CCaR)".

The IDRC along with Canadian Institute of Health Research (CIHR), Natural Sciences and Engineering Research Council of Canada (NSERC), and Social Sciences and Humanities Research Council of Canada (SSHRC) awarded funding to the CCaR project under the International Research Initiative on Adaptation to Climate Change (IRIACC). The goals of the CCaR project include:

1. To determine if coastal cities are becoming more (or less) resilient to natural disasters;
2. To identify and understand factors contributing to disaster resilience; and
3. To enhance the capacity of coastal cities to adapt to and cope with the impacts of climate hazards

This project involves an interdisciplinary project team with backgrounds in health science, geography, political science, economics, social science and engineering. The project is also international in scope. The four coastal cities selected as case studies for the project include: Bangkok, Thailand; Lagos, Nigeria; Manila, Philippines; and Vancouver, Canada. These cities were selected based on geography, range of climate-weather and diverse socio-cultural-economic conditions.

This project uniquely selects resilience to analyze various climate change adaptation options and presents an original framework for quantification of resilience through system dynamics simulation to assess the impacts of climate change on coastal megacities (Simonovic and Peck 2013). There is a necessity to move beyond conceptualizations and into actual resilience quantification. Therefore this project considers quantitative, Space-Time Dynamic Resilience Measure (ST-DRM) which combines economic, social, organizational, health and physical impacts of climate change caused natural disasters on coastal megacities. The theoretical background of the ST-DRM is included in Chapter 2 of the report.

1.1 Impacts (*i*)

The five major impacts that are being considered in the ST-DRM calculation include: economic impacts, health impacts, physical impacts, organizational impacts and social impacts (Simonovic and Peck 2013). These impacts require the modification of GSDSMs for the four city models to properly describe the local conditions in each city.

1.1.1 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. These hazards drive the physical sector of the CRS that represents the natural sub-system. 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 changes in the physical system have direct and indirect impacts on economic, social, health and organizational activities.

Hazards are described by climatological variables in the physical sector of the CRS. The physical impacts sector is connected to other sectors in the CRS which affect resilience (Figure 1). For instance, consider the flood hazard. Riverine flooding directly affects water quality, which in turn may affect the health of a population and therefore impact the economy. Some areas within a city may experience larger impacts than others based on the magnitude of hazard (ex. depth of flooding), pre-disaster demographic and economic characteristics and social inequities.

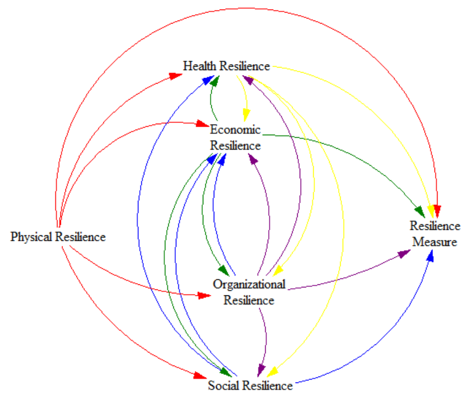

Figure 1: Causal loop diagram of city resilience measure

The CRS is driven by short-term event-based hazards (such as flooding and storm surges) and by long-term, gradual hazards (such as sea-level rise). To accommodate the difference in time scales, there are two CRS developed; CRS-S, for the short duration events and CRS-L, for the long duration events. More details are provided in Chapter 4.

1.1.2 Economic Impacts

Cities are often considered the drivers of national economies. The economic prosperity of coastal cities often depends heavily on the physical coastal environment; an environment which is also a significant contributor to the risk of coastal communities. It is historically recognized that the economic impacts of natural disasters are highly relevant for disaster resilience; particularly when related to the allocation of financial resources. The CRS captures the dynamic impacts of hazard events on local economic activities such as the supply and capacity constraints, GDP, energy and employment.

Economic systems are often complex, comprising of many inter-related variables and exhibiting non-linear behaviour in both information and material flows (Forrester 2009). In this way, economic systems can be well represented in SD modeling. Economic activities of coastal cities that are considered in the CRM 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.

1.1.3 Social Impacts

In affluent communities, people find it desirable to live close to the coast. In poorer communities however, people who have been displaced, or rely on close proximity to water for survival, live closest to the water, which makes them particularly susceptible to impacts of climate caused hydro-meteorological hazards. The relationship between poverty, environmental degradation and hazard vulnerability is a vicious, mutually reinforcing system of feedbacks (Kesavan 2006) especially prevalent in developing countries. The potential impacts of natural disasters on social systems may be very severe.

1.1.4 Health Impacts

Climate related natural hazards can have significant health impacts on a population. Hazards may trigger outbreaks of disease (Paton and Johnson 2006) and hazard debris can cause injury, which may immediately impede mobility and hinder evacuation and response efforts. Hydro-meteorological hazards such as floods, tsunamis and storm surges also carry waste, sewage and bacteria which, through direct contact with drinking water supplies, could spread disease and cause illness for many weeks beyond the duration of a disaster. It is also possible that illness and disease may be spread without direct contact with hazard phenomena through the close proximity of infected people in confined areas. It is therefore important to estimate and anticipate potential health impacts to better prepare for, respond to and recover from climate caused natural disasters.

The present study considers a composite health index to quantify the health effects of climate hazards in coastal cities (Owrangi et al. 2012). This index is used as part of the CRM and considers Disability Adjusted Life Years (DALYs) as a measure of Overall Burden of Disease (OBD) within a city. This time-dependent measure, originally developed for the World Health Organization and World Bank in the 1990s, is used to capture the health vulnerability of a population in the CRM. DALYs are based on health factors that are considered to contribute to premature death; the number of cases of injuries, communicable and non-communicable diseases that are prevalent in a country for a particular year. In the CRS, changes in DALY values reflect the health impacts of natural disasters directly through physical-health sector links and indirectly through economic and social links.

However, there are temporal challenges in using the DALY approach to represent human health in the CRS. For instance, it becomes difficult to accurately assess OBD consequences due to a specific hazard event due to the diverse time scales required to diagnose various health impacts. For instance, injuries often occur immediately during a disaster event, whereas some illnesses and diseases do not display symptoms for weeks, and some may not show any symptoms at all. These afflictions may be left undiagnosed or untreated for years following the initial disaster. Thus, there are difficulties directly linking long-term diseases to a specific hazard event especially considering the potential influences of external environmental factors during a disease's incubation time.

1.1.5 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.

1.2 Adaptive Capacity (*AC*)

The impacts of a disaster exhibit temporal and spatial variability that are caused direct interactions between impacts of a disaster (social, health, economic, and other) and adaptive capacity of the urban system to absorb them. Adaptive capacity is defined using various performance measures. These measures are defined, in terms of four R's (robustness, redundancy, resourcefulness and rapidity).

1.2.1 Properties of Adaptive Capacity (R_i)

The proposed method of resilience quantification (presented in details in Chapter 2 of this report) is based, in part, on the four properties (R_i) of adaptive capacity (*AC*) as identified by Bruneau et al (2003) and adapted by Simonovic and Peck (2013). The adaptive capacity of physical and social systems can be defined using:

i. Robustness (R_1): strength and the ability of elements or systems to resist stress without suffering damages or loss of function;

ii. Redundancy (R_2): the extent to which elements or systems satisfy functional requirements in the event of disruptions, disturbances, or damages;

iii. Resourcefulness (R_3): the capacity to identify problems, establish priorities and mobilize financial and human resources to elements or systems that are threatened by disruption, disturbance, or damage; and

iv. Rapidity (R_4): the capacity to meet priorities and achieve goals in a timely manner to contain losses, minimize damages and avoid future disruptions.

The AC as a function of time and space may therefore be expressed as follows:

$$AC\ (t,s) = f\left[R_j(t,s)\right] \quad j = 1,2,3,4 \tag{1}$$

These 4R's of *AC* will be quantified in the CRS by measuring performance of indicators. These indicators of *AC* will be selected in conjunction with experts and through rigorous research efforts. The remainder of this report discusses *AC* in terms of the 4R properties and indicators in the temporal context only. The resilience model framework has not yet incorporated any spatial dimension into its calculations. Both space-time dimensions are presented in the expressions of resilience, impacts and adaptive capacity to present the comprehensive description, because incorporating the spatial dimension is a part of plans for future work.

1.3 Integration of Impacts

In existing and emerging megacities, the relationship between health, economy, society, and the environment is more complex than ever (Akanda and Hossain 2012). Seemingly unrelated elements may influence each other indirectly through links with other system elements. To capture these dynamic system interactions, this research considers use of a system dynamics simulation tool, called a City Resilience Simulator (CRS). The CRS is intended to determine city resilience in response to a disaster and the ability of the urban system to react, cope and adapt to disaster impacts. The CRS is comprised of multiple systems linked together used to compute the value of the ST-DRM. The CRS framework is introduced in Chapter 4.

2. 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. Vulnerability describes the pre-event, inherent characteristics or qualities of urban systems that create the potential for harm. Vulnerability is a function of whom 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 (Simonovic and Peck 2013). Drawing from resilience literature in the fields of physics, ecology and hazards, some common elements in the definition of resilience 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.

The theory behind developing a CRS is built on a the fundamental concept that 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 consequences; (iii) reducing time to recovery; and (iv) creating opportunity for development and innovation from adverse impacts.

To deal with the shortcomings in existing resilience models and to provide a conceptual basis for establishing baselines for measuring resilience, this project introduces a space-time dynamic resilience measure (ST-DRM). A CRS will capture the process of dynamic disaster resilience simulation in both, time and space.

2.1 Introduction

In this research, a systems dynamics simulation (SD) approach is selected to understand the behaviour of complex city systems subject to climate change caused disasters. This approach was selected in order to capture the dynamic characteristics of disaster impacts and disaster resilience behaviour of coastal megacities. The remainder of this chapter will describe the basic concepts behind the development of a CRS and provide the theoretical basis and the vocabulary used in this report to define disaster resilience. This chapter: (a) introduces a method for *quantifying* disaster resilience; (b) defines disaster resilience as *dynamic* in both time and space; and (c) presents resilience as framework for *integration of impacts* (physical, operational, social, technological, economic and health).

The ST-DRM is defining the level of system performance in time (t) and a particular location in space (s) (Simonovic and Peck 2013). 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, see Figure 2. The area between the initial performance line $P_0^i(t,s)$ and performance line $P^i(t,s)$ represents the loss of system resilience, and the area under the performance line $P^i(t,s)$ represent the system resilience ($\rho^i(t,s)$). In Figure 2, t_0 denotes the beginning of the disaster event, t_1 the end, and t_r the end of the disaster recovery period. Dynamic evolution of system performance may result in one of three possible resilience levels: pre-disruption resilience level $\rho_0^i(t,s)$ - the area under the solid line in Figure 2; level lower than pre-disruption level ($\rho_{e'}^i(t,s)$) - the area under the dashed line in Figure 2; or level higher than pre-disruption level ($\rho_{e''}^i(t,s)$) - area under the dotted line in Figure 2 (Simonovic and Peck 2013).

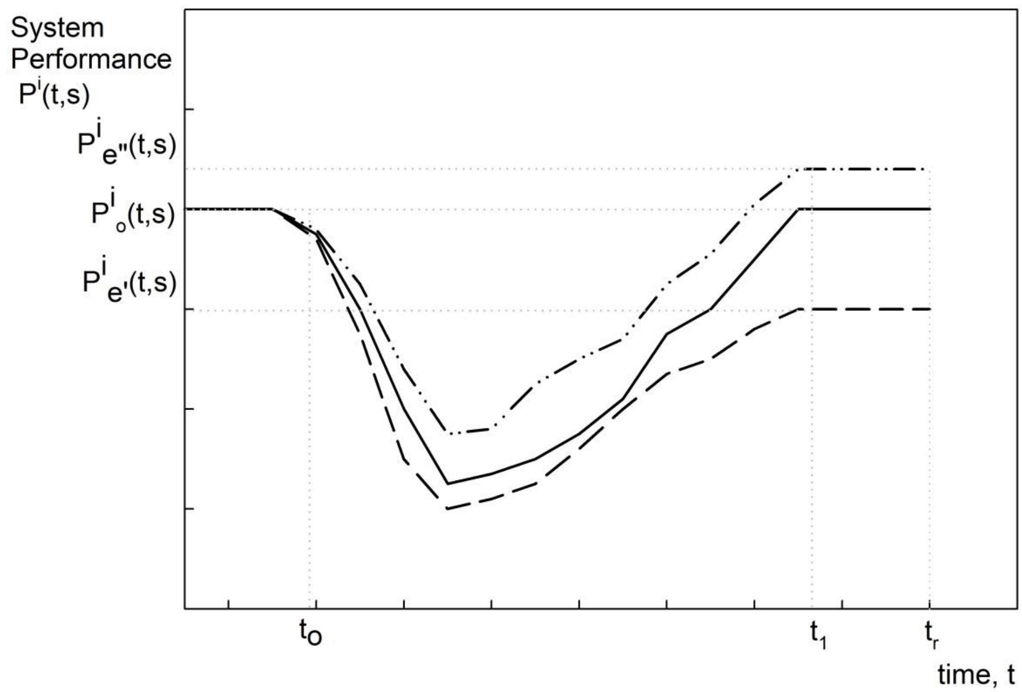

Figure 2: Illustration of system performance subject to a disturbance

2.2 Resilience Quantification

The method of resilience quantification is based on:

(a) Dimensions of resilience;

(b) Impacts and capacities; and

(c) Sectors of resilience.

2.2.1 Dimensions of Resilience

In this study, a resilience measure is selected to capture the dynamic processes and impacts of natural disasters. In reality, the resilience of a system fluctuates in time; before, during and following the occurrence of a disaster. Resilience value is also affected by the location in space. Therefore, the dimensions of resilience measure ST-DRM are time and space:

$$ST - DRM = f(time, space) \tag{2}$$

These dimensions are important to accurately represent real-world dynamic behaviour of urban systems.

2.2.2 Impacts and Capacities

In mathematical form the loss of resilience for impacts (i) represents the area under the performance graph between the beginning of the system disruption event at time (t_0) and the end of the disruption recovery process at time (t_r). Changes in system performance can be represented mathematically as:

$$\rho^i(t,s) = \int_{t_0}^{t} \left[P_0^i - P^i(\tau,s)\right] d\tau \tag{3}$$

$$where \;\; t \in [t_0, t_r]$$

When performance does not deteriorate due to disruption, $P_o^i(t,s) = P^i(t,s)$ the loss of resilience is 0 (i.e. the system is in the same state as at the beginning of disruption). When all of system performance is lost, $P^i(t,s) = 0$, the loss of resilience is at the maximum value.

The system resilience, $r^i\ (t,s)$ is calculated as follows:

$$r^i(t,s) = 1 - \left(\frac{\rho^i(t,s)}{P_o^i \times (t - t_o)}\right) \tag{4}$$

Figure 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 Figure 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. Disturbance to a system causes a drop in system resilience from value of 1 at t_o to some value $r^i(t_1, s)$ at time t_1, see Figure 4. Recovery usually requires longer time than the duration of disturbance. Ideally resilience value should return to a value of 1 at the end of the recovery period, t_r (dashed line in Figure 4); the faster the recovery, the better.

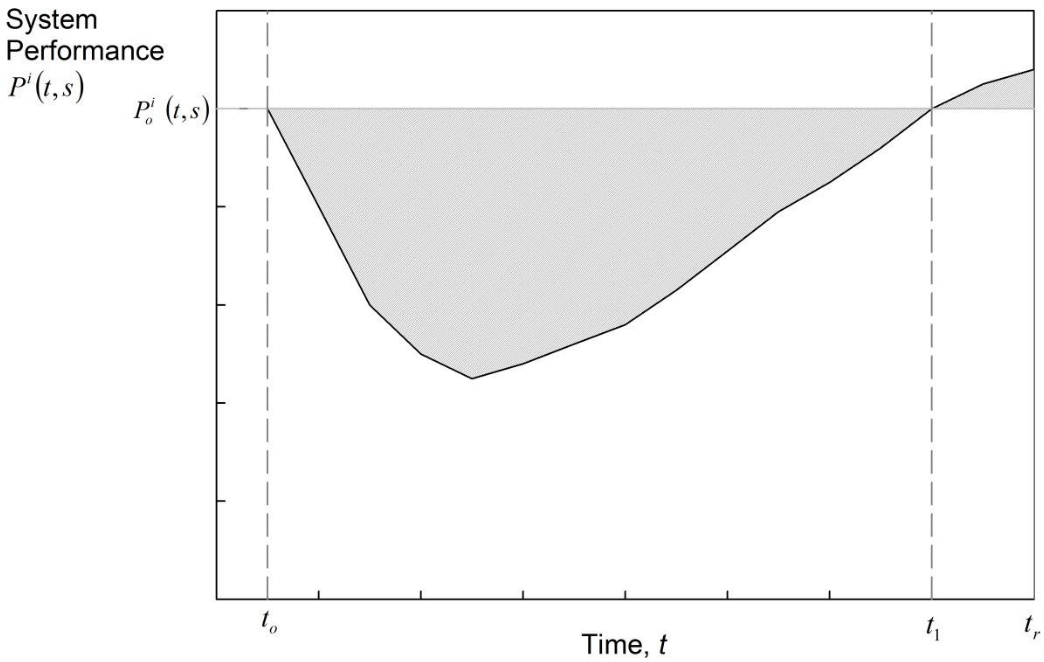

Figure 3: Illustration of system resilience in system performance space

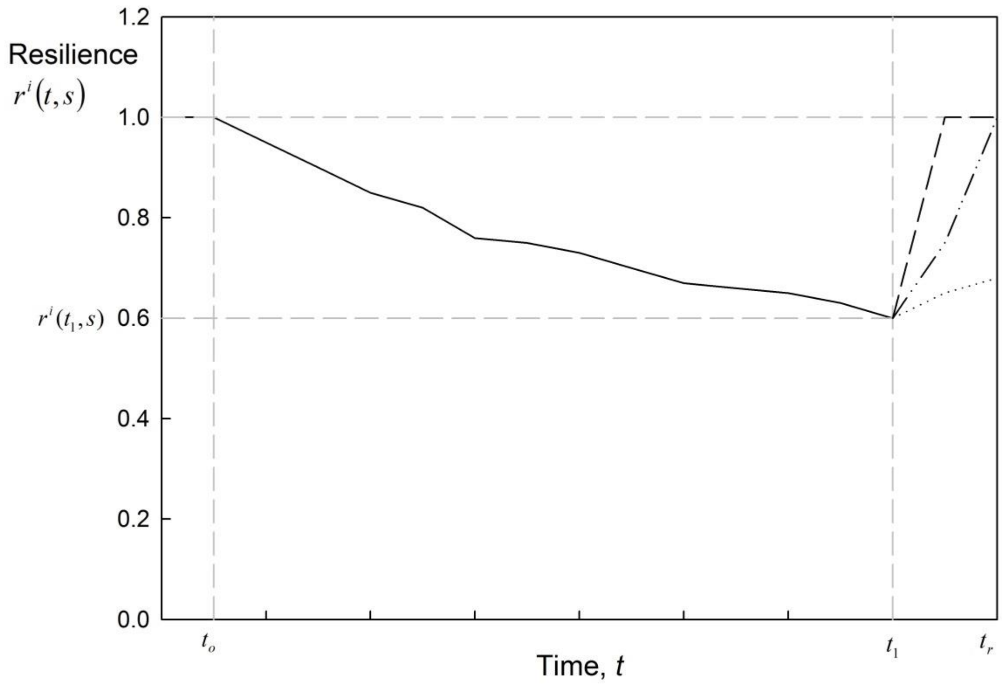

Figure 4: System resilience

There are 3 possible outcomes in resilience simulation: (i) resilience returns to pre-disturbance level (value of 1) – solid line in Figure 4; (ii) resilience exceeds pre-disturbance level (value > 1) – dotted line in Figure 4; or (iii) resilience does not return to pre-disturbance level (value < 1) – dashed line in Figure 4.

For example, if the systems' performance is intensified, it is possible that the time to recovery t_r, can be reduced and/or resilience value may actually surpass the pre-disturbance level (exceed a value of 1). However, it is entirely possible that if system performance is poor and improvement is slow, the recovery period will be longer and in some cases the system may not be able to return to pre-disturbance level (sustain value of less than 1).

The integral ST-DRM (over all impacts (i)) is calculated using:

$$R(t,s) = \{\prod_{i=1}^{M} r^i(t,s)\}^{\frac{1}{M}} \quad (5)$$

$$where\ M\ is\ the\ total\ number\ of\ impacts$$

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. In this report, only time dimension is presented specifically; spatial dimension is still a work in progress.

2.2.3 Resilience Sectors

The present project introduces an integrated resilience measure that builds on the technical-organizational-social-economic integration concept by Bruneau et al. (2003) by considering the resilience measure to be dynamic in both time and space (Simonovic and Peck 2013). The current project modifies this approach by considering the interactions between physical, organizational, social, economic, and health components of resilience in order to estimate disaster impacts and improve disaster resilience (Figure 1).

As an example, improving the capacity of critical lifelines systems during a disaster is important for developing resilience. Table 1 identifies a selection of these critical lifeline systems and provides a description in the context of the 4R *properties* of adaptive capacity. The calculation of ST-DRM for each impact (i) is done at each location (s) by solving the following differential equation:

$$\frac{\partial \rho^i(t)}{\partial t} = AC^i(t) - P^i(t) \tag{6}$$

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

The ST-DRM integrates resilience types, dimensions and properties by solving for each point in space (s):

$$\frac{\partial R(t)}{\partial t} = AC(t) - \prod_i P^i(t) \tag{7}$$

A generic version of a CRS has been developed by implementing this theoretical framework. The GSDSMs are the fundamental building blocks used for the construction of a CRS. The purpose of these generic simulation models is to aid project cities in developing their own CRSs. A description of the Generic System Dynamics Simulation Models (GSDSMs) and how are they applied is in the following Chapter of the report. However, description is limited to temporal dimension of impacts, adaptive capacity and resilience as space dimension has not been incorporated yet.

Table 1: Resilience characteristics of critical lifeline services based on the four R's; adapted from Bruneau et al. (2003)

Lifeline system	Robustness, R_1	Redundancy, R_2	Resourcefulness, R_3	Rapidity, R_4
Water	At least % of commercial buildings maintain water service	Alternative water supplies	Water conservation programs implemented	Re-establish water to commercial buildings in 1 day
Power	At least % of commercial buildings maintain power service	Alternative power supplies	Power conservation programs implemented	Re-establish power to commercial buildings in 1 day
Hospital	At least % ability to maintain services and equipment	Additional alternative hospital arrangements	Arrangements for government reimbursement or insurance	Procurement of new equipment and return to normal operations in 1 day
Emergency Response Services	At least % response vehicles maintain service	Multiple response units with multiple emergency routes	Allocate additional/voluntary emergency responders	Maintain emergency response at all times

3. GENERIC SYSTEM DYNAMICS SIMULATION MODELS (GSDSMs)

The GSDSMs have been developed for the CCaR project. The purpose of the GSDSMs is to provide a starting point for the international research teams for development of their own CRSs. The GSDSMs can be modified to capture specifics of each coastal city in the CCaR project (Bangkok, Thailand; Lagos, Nigeria; Manila, Philippines; Vancouver, Canada), resulting in four separate, unique, CRSs (CRS-B; CRS-L; CRS-M; CRS-V; respectively). This section of the report will describe the basic structure of the GSDSMs.

3.1 GSDSMs: Description

The GSDSMs are a library of generic system dynamics simulation models; six models in total (Figure 5). Five models were created to represent the five resilience sectors described in Chapter 1, which herein will collectively be referred to as GSDSM-5. The GSDSM-5 corresponds to the following GSDSMs:

a.	GSDSM-E:	Economic Simulation Model	Figure 6
b.	GSDSM-H:	Health Simulation Model	Figure 7
c.	GSDSM-O:	Organizational Simulation Model	Figure 8
d.	GSDSM-P:	Physical Simulation Model	Figure 9
e.	GSDSM-S:	Social Simulation Model	Figure 10

There is actually very little difference between each of the GSDSMs; see Figures 6 – 10. The only real difference between the GSDSM-5 models is in the name of the system variables; the system structures are otherwise identical. The reason behind naming the GSDSM-5models differently is to help categorize systems into one of the 5 resilience sectors. It is important to keep track of the resilience sector that each system belongs to because when the overall resilience measure is calculated, the calculation is based on resilience values by sector. Upon simulation, it will also be important to be able to trace the contributions of each resilience sector.

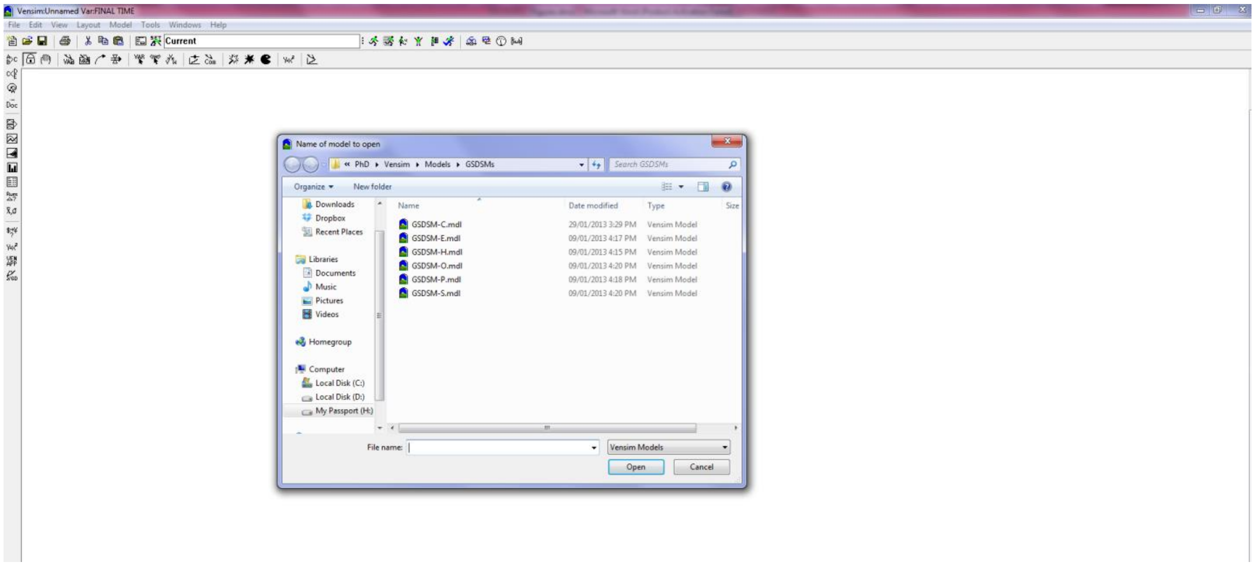

Figure 5: Opening the library of GSDSMs

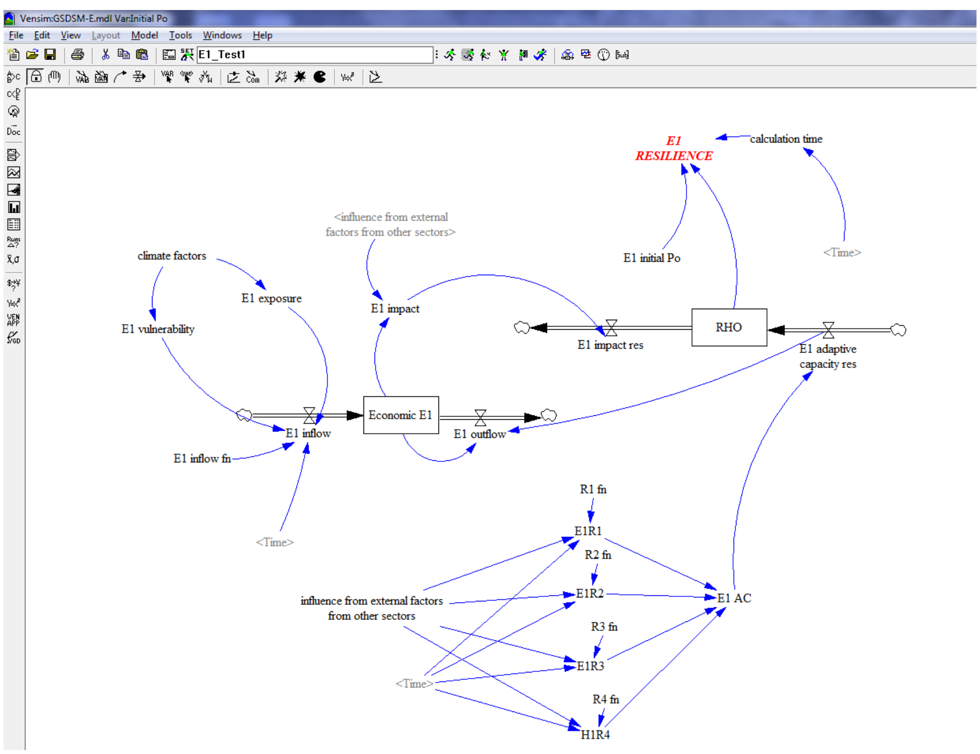

Figure 6: GSDSM-E; economic generic model structure

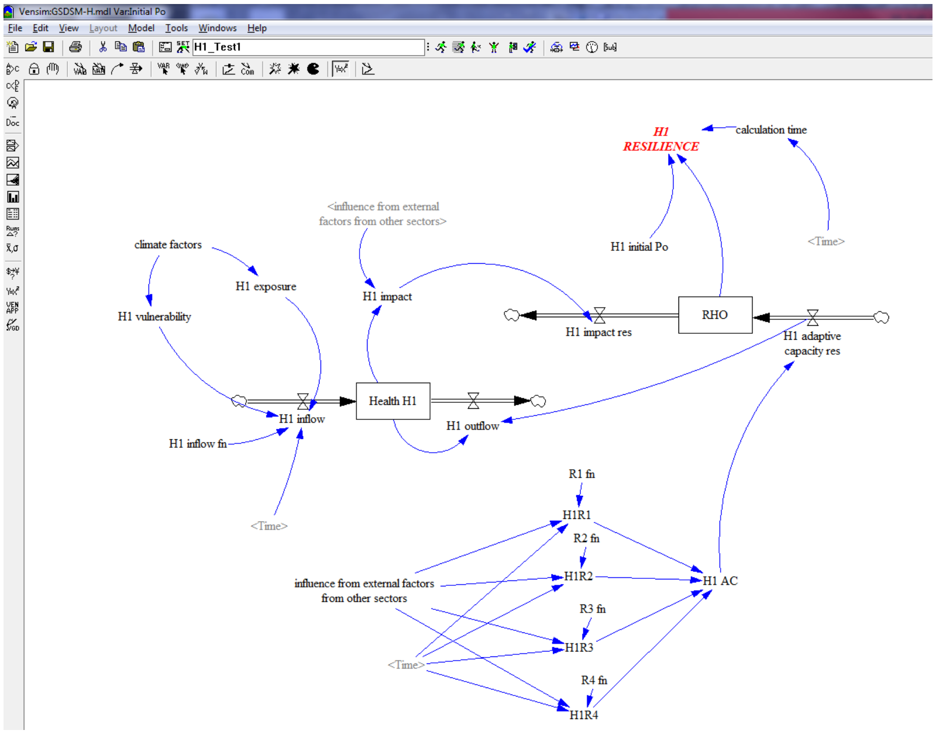

Figure 7: GSDSM-H; health generic model structure

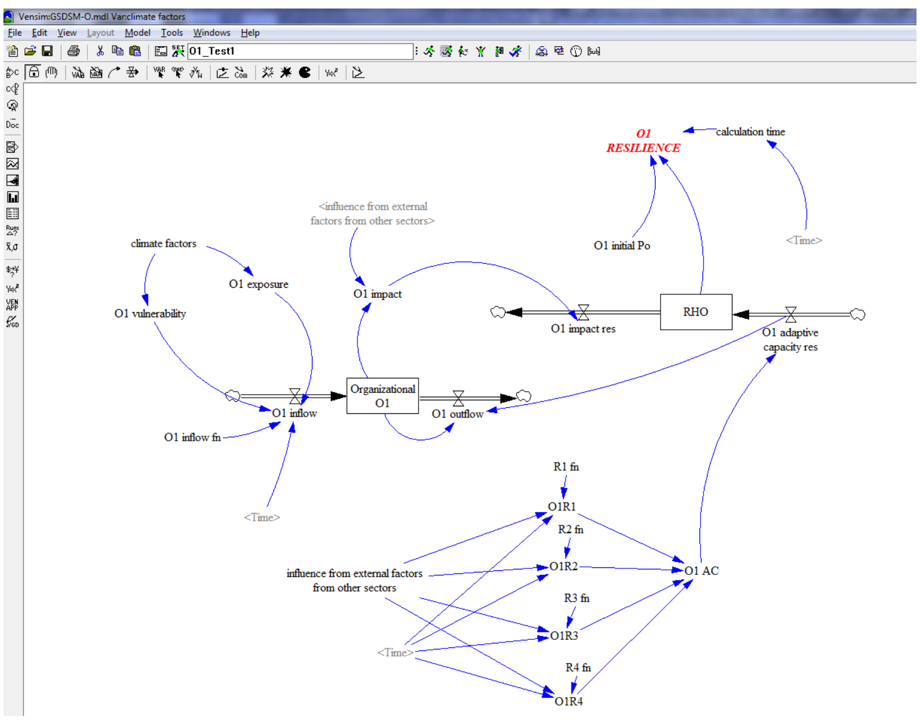

Figure 8: GSDSM-O; organizational generic model structure

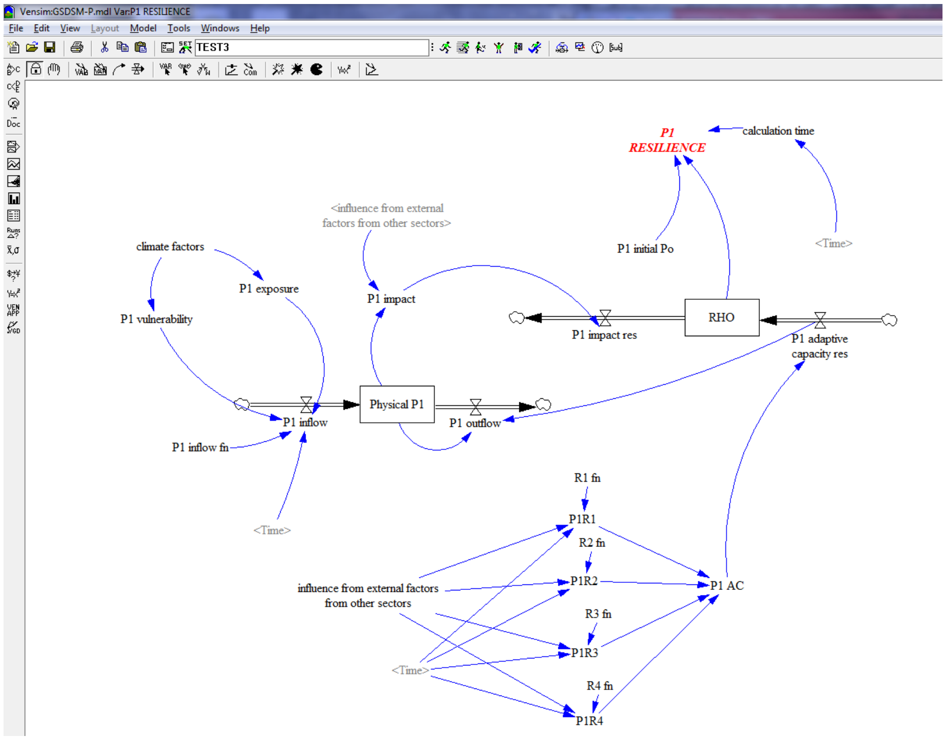

Figure 9: GSDSM-P; physical generic model structure

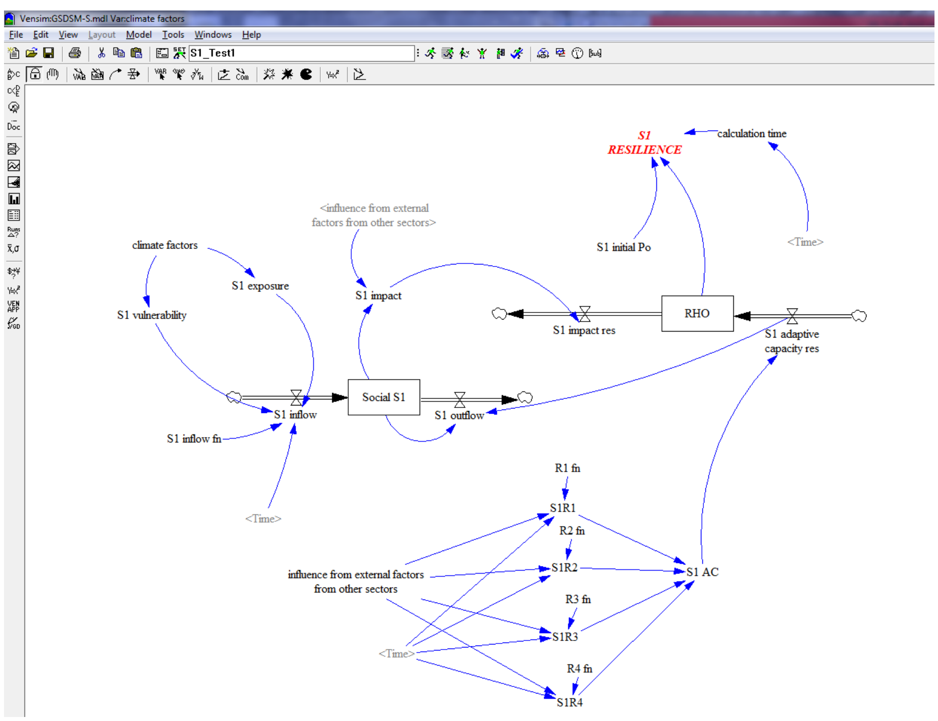

Figure 10: GSDSM-S; social generic model structure

As can be seen in Figures 6 to 10, there are certain variables which are ill defined such as, *climate change, exposure, vulnerability* and *influence from external factors*. These variables are intended to be “placeholders”. That is, they do not relate directly to the resilience sector system, but are meant to be linked to other sectors once the GSDSMs are modified and relationships between the modified GSDSMs have been identified.

The variables *robustness, rapidity, resourcefulness and redundancy* are measured in the GSDSMs by indicators. Every performance measure indicator used in the quantification of impacts and adaptive capacity (the 4 R’s) is compared to a threshold performance indicator value in order to determine the starting point of system disturbance and the ending point. The threshold values may be predefined system impact or adaptive capacity standards. This is how the variables *robustness, rapidity, resourcefulness and redundancy* are quantified in the GSDSMs.

The model settings are just left as default settings when opening Vensim software. A description of these model settings is provided in Table 2.

Table 2: Vensim simulation model settings

Model Parameters	Description
INITIAL TIME	The initial time value for the simulation period
FINAL TIME	The final time value for the simulation period
TIME STEP	The simulation time increment (this is the interval at which calculations will be performed)
Units for Time	The units used in the simulation period (range from seconds to a year)
Integration Type	The integration type used in calculations; in most cases select RK4 option

In addition to GSDSM-5, there is a GSDSM-C which combines output from the five GSDSM-5 models (GSDSM-P; GSDSM-E; GSDSM-H; GSDSM-O; GSDSM-S), into a single dynamic resilience measure (SDRM).This simulation model (GSDSM-C) takes the resilience measure generated from each of the five GSDSMs as input (Figure 11) and uses them to calculate resilience for each sector, and then the overall ST-DRM over time. A generic form of the GSDSM-C can be seen in Figure 12.

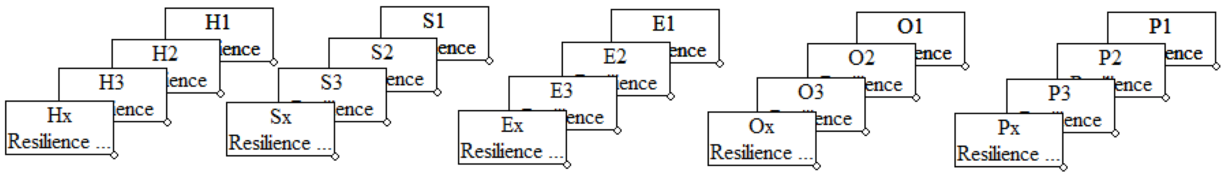

Figure 11: The output of the various GSDSM-5 models; could continue expanding to accommodate any number of GSDSMs

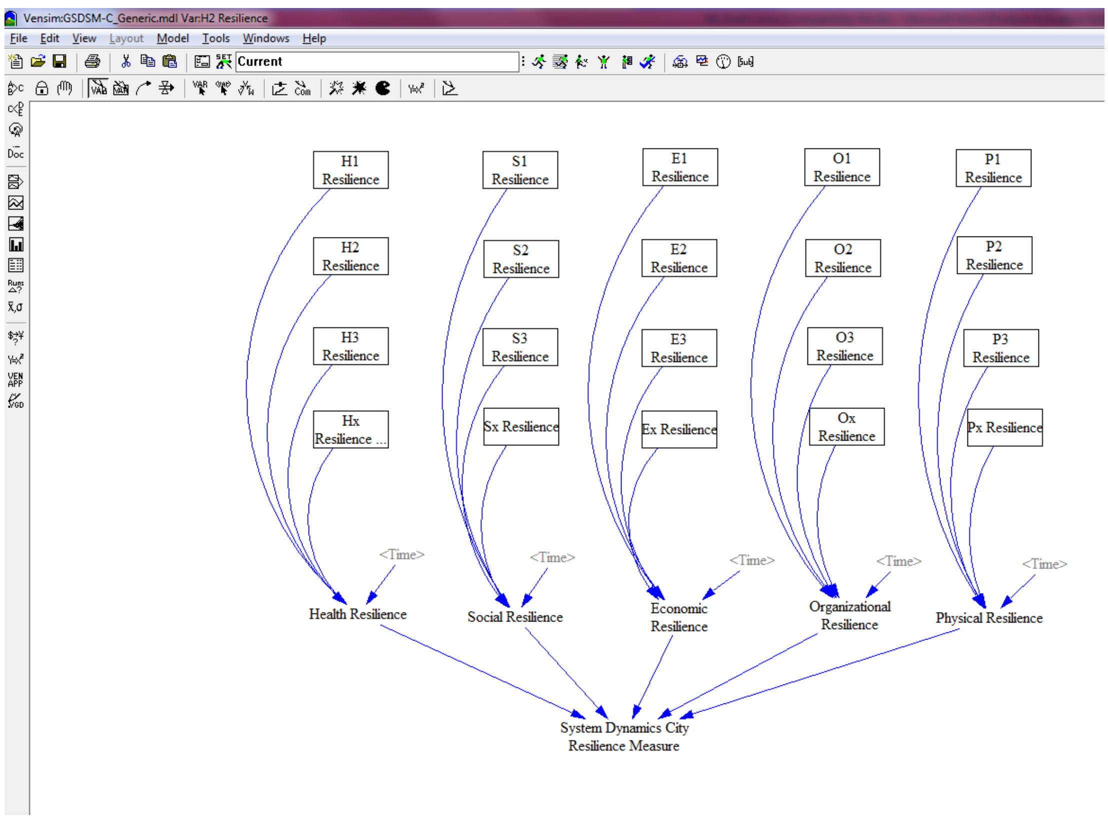

Figure 12: GSDSM-C generic form in Vensim; add as many H, S, E, O, and P variables as necessary

An example implementation of the GSDSM-C can be seen in Figure 13 and model settings provided in Figure 14. A simulation is then run for the GSDSM-C model, where resilience is calculated for each of the five resilience sectors (economic, health, organizational, physical, and social) and results are presented in the form of a graph. Figure 15 illustrates potential simulation results for the five resilience sectors over time. The behaviour of these five resilience sectors is then used in the computation of the overall ST-DRM; Figure 16. The goal of the project is to produce the ST-DRM graph showing behaviour of the entire city system over time. The GSDSM-C presented in this report is intended to be for illustrative purposes only, as this generic model will require expansion to include resilience measures produced from each of the five GSDSM-5 models, based on specific requirements for each city.

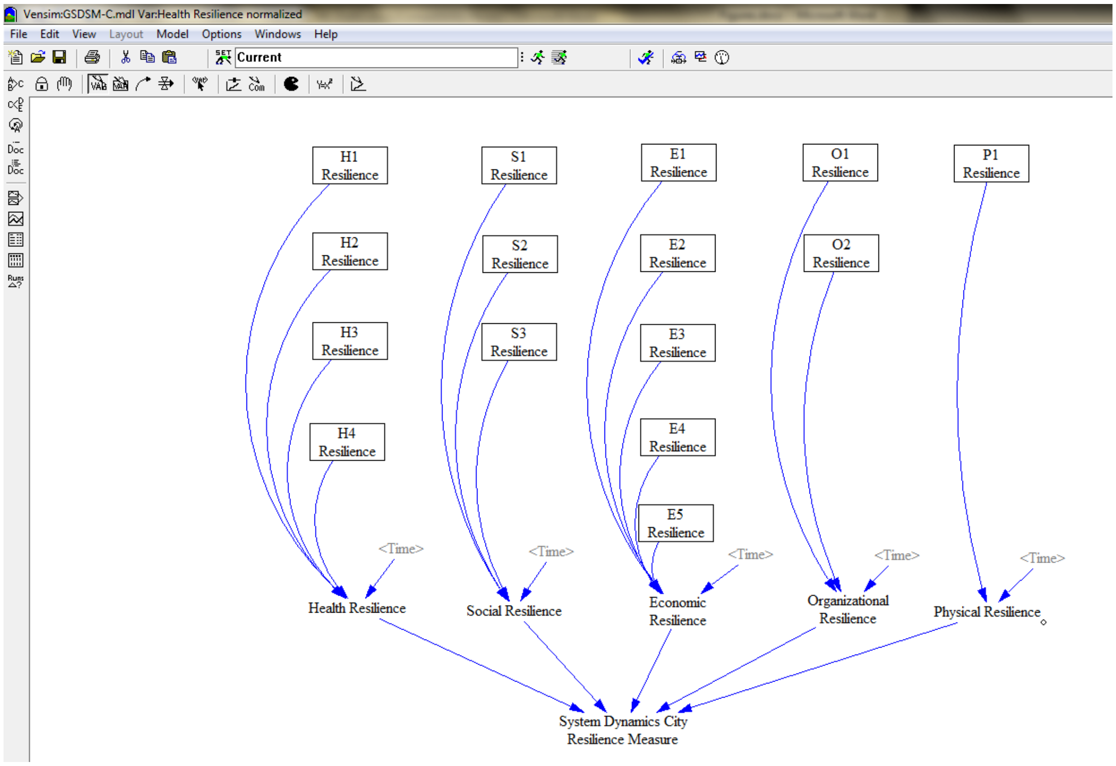

Figure 13: GSDSM-C in Vensim; an illustrative example

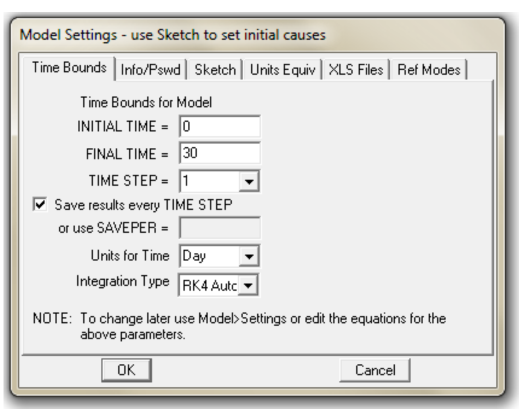

Figure 14: GSDSM-C model settings in Vensim; an illustrative example

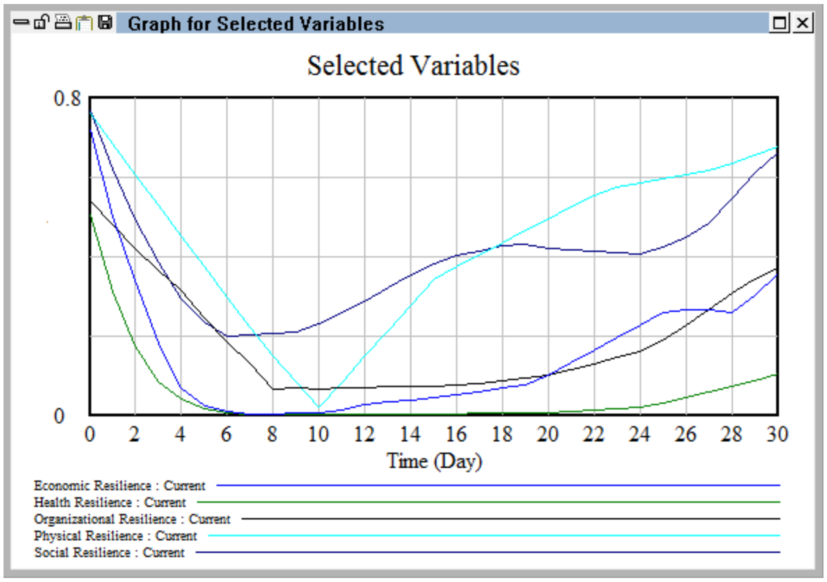

Figure 15: GSDSM-C simulation results for economic, health, organizational, physical and social resilience measures; an illustrative example

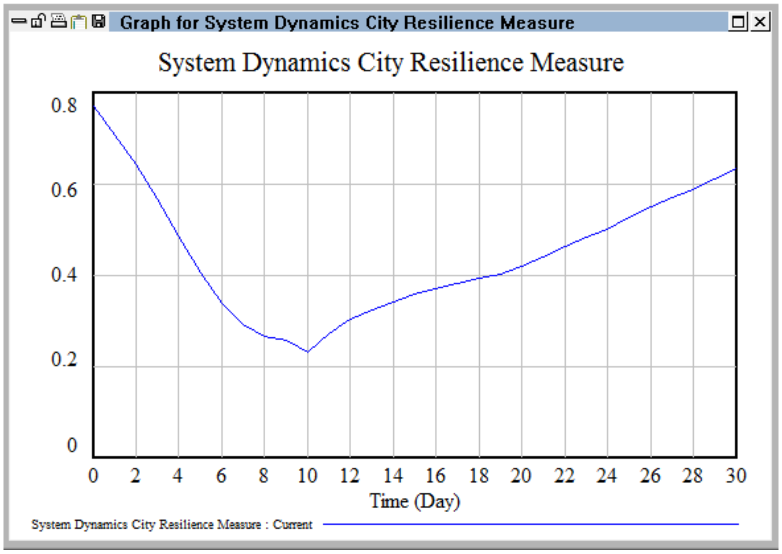

Figure 16: GSDSM-C simulation results for overall city resilience measure; an illustrative example

It is expected that there will be many of each of the GSDSM-5 models in order to construct a meaningful GSDSM-C model and for accurate representation of the ST-DRM. The combination of both the GSDSM-5 models and GSDSM-C model are referred to as the City Resilience Simulator (CRS). The goal of the CRS is to capture dynamic relationships and compute ST-DRM; similar to the GSDSM-C model, but includes the entire system structures of both the GSDSM-5s and GSDSM-C. The CRS is described in more detail later in this chapter. It should be noted that the GSDSMs and CRS currently are not spatially distributed. Incorporating the spatial dimension into GSDSMs will follow in future work.

3.2 GSDSMs: Use

The GSDSMs are generic-structure simulation models created in a Vensim environment to simplify and improve the process of building a CRS. In order to effectively use the GSDSMs to do so, it is recommended to follow the generic steps in Table 3. Ideally, begin the GSDSM process by identifying critical systems; focusing on those services and functional activities that are essential for a resilient community. The continued operation and rapid restoration of these critical lifeline services are a necessary condition for overall community resilience. An example of critical lifeline services is presented in Table 1.

The generic model forms can be modified for the specifics of each coastal city. It is expected that each coastal megacity will require modifications to be made to the GSDSMs structures to best reflect local conditions and available data. It is highly recommended that before using the GSDSMs to develop a CRS, each city develop a high-level causal loop diagram in addition to identifying: major critical systems, potential impacts, capacities and indicators. Taking these initial steps will help improve the effectiveness and successful implementation of the GSDSMs.

Table 3: Suggested steps for successful implementation of GSDSMs

Steps	Description
1	Identify major systems and subsystems related to disaster impacts and adaptive capacity;
2	For each system identified in (1), list potential impacts;
3	For each system identified in (1), list potential capacities in terms of the 4 R's;
4	From library of GSDSMs, select the *sector type* of model which best represents the system identified in (1);
5	Open this GSDSM in Vensim;
6	Choose the "save as" option and give your GSDSM an appropriate new name (as to preserve the original GSDSM files);
7	Modify the generic structure to best represent the system in terms of impacts and adaptive capacities;
8	Select all components in the modified GSDSM;
9	Copy and paste the modified GSDSM structure into the overall CRS;
10	Where appropriate, add/remove relationships and link (using arrows) variables in the newly pasted modified generic model, to other systems in CRS;
11	Follow steps 2 thru 10 for each system identified in step 1, until all major systems have been added to the CRS

Table 4: GSDSM-H health example

Steps	Description
1	Identify major systems and subsystems related to disaster impacts and adaptive capacity: *Hospital, for example*
2	For each system identified in (1), list potential impacts; *No. of injured patients receiving treatment at the hospital, for example*
3	For each system identified in (1), list potential capacities in terms of the 4 R's; *Robustness: ability to maintain treatment services* *Redundancy: alternative hospital arrangements* *Resourcefulness: mobilization of medical personnel* *Rapidity: procurement of equipment to aid treatment*
4	From library of GSDSMs, select the *sector type* of model which best represents the system identified in (1); *A hospital would best be represented by the GSDSM-H (health simulation model); see Figure 17*
5	Open this GSDSM in Vensim;
6	Choose the "save as" option and give your GSDSM an appropriate new name (as to preserve the original GSDSM files); *E.g. H1_Hospital* *Figure 18*
7	Modify the generic structure to best represent the system in terms of impacts and adaptive capacities;

	Figure 19
8	Select all components in the modified GSDSM;
9	Copy and paste the modified GSDSM structure into the overall CRS;
10	Where appropriate, add/remove relationships and link (using arrows) variables in the newly pasted modified generic model, to other systems in CRS; *(Not shown)* *A description of each of the model variables is provided in Appendix A*
11	Follow steps 2 thru 10 for each system identified in step 1, until all major systems have been added to the CRS *(Not shown)*

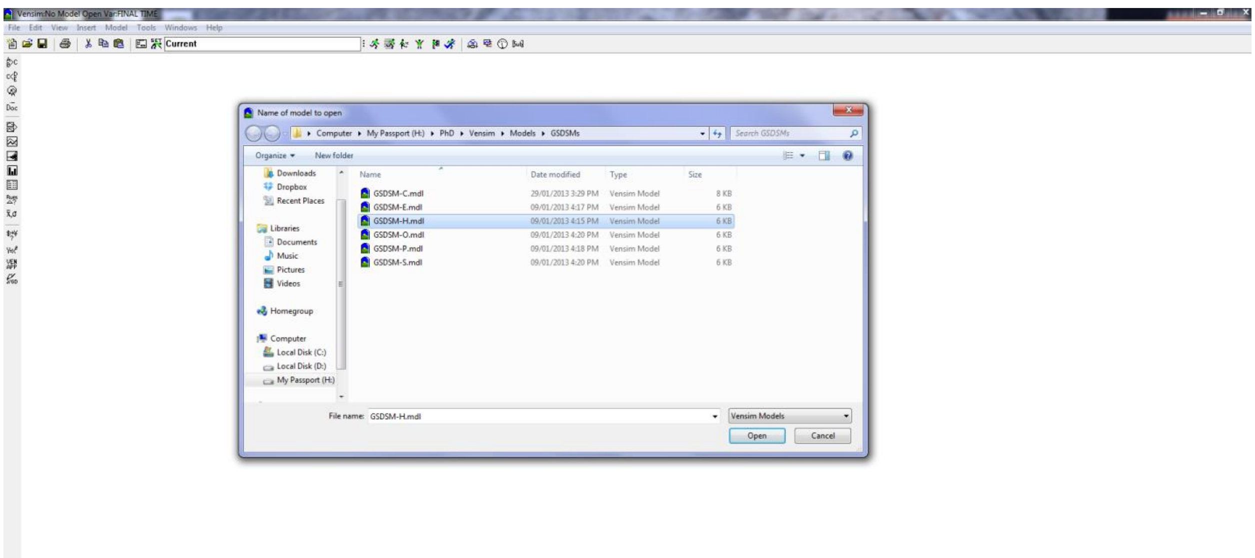

Figure 17: GSDSM-H H1_Hospital example

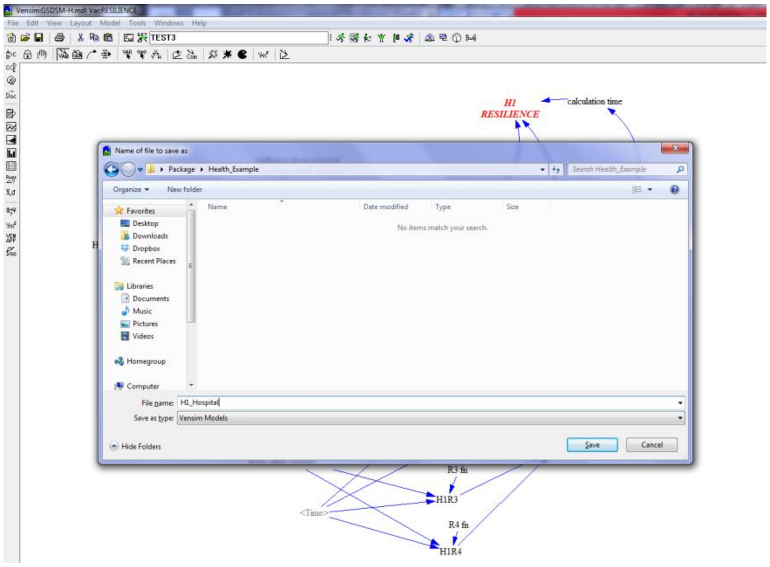

Figure 18: GSDSM-H hospital example; save as a new file name (e.g. H1_Hospital)

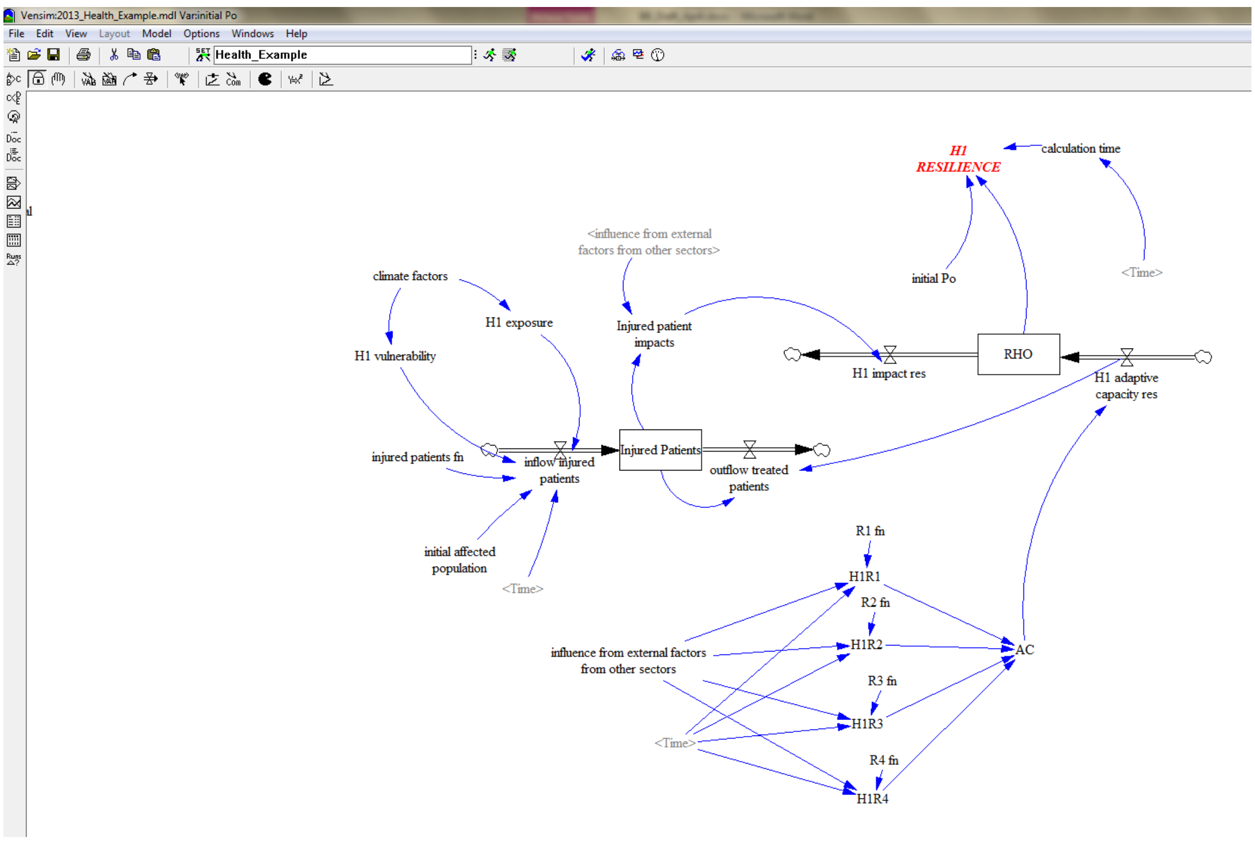

Figure 19: H1_Hospital example; simulation model structure

The final H1_Hospital model structure (Figure 19) has evolved from the GSDSM-H model. The H1_Hospital model provides more detailed system structure and is comprised of more model variables; an explanation of the H1_Hospital model variables is provided in Appendix A. In the H1_Hospital example, it was necessary to select indicators for the 4R's of adaptive capacity as follows:

a. *Robustness R1*: The variable selected as the indicator of robustness is the number of hospital beds available to treat injured patients
b. *Resourcefulness R2*: The variable selected as the indicator of H1 resourcefulness is number of medical personnel available and financial resources to treat injured patients
c. *Rapidity R3*: The variable selected as the indicator of rapidity is the procurement of equipment to treat injured patients and treat all injured patients within reasonable amount of time

   Redundancy R4: The variable selected as the indicator of redundancy is fraction of injured patients for which alternative arrangements have been made for treatment elsewhere

These indicators have been selected by the authors and may therefore not accurately reflect true indicators of the 4R's; better indicator selections may be determined. The selection of these indicators for the H1_Hospital example would ideally be driven by:

- discussions with experts in the field of health science, medicine and local health care system including doctors, nurses, immunologists, surgeons, medical scientists and health administration;
- both scientific and patient-oriented research on injuries, treatments, and decision making; and where appropriate,
- undertaking rigorous performance analysis.

As the current H1_Hospital model is for illustrative purposes, the indicators in the model were arbitrarily selected by the authors. The H1_Hospital example is programmed to run an example simulation, using model settings in Figure 20. This generates H1_Hospital indicator and resilience simulation results in the form of Figure 21 and Figure 22.

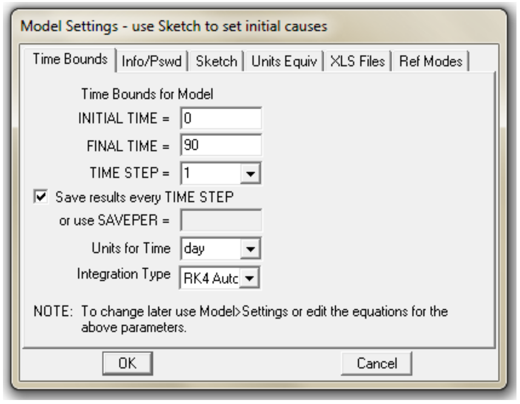

Figure 20: H1_Hospital example; model settings

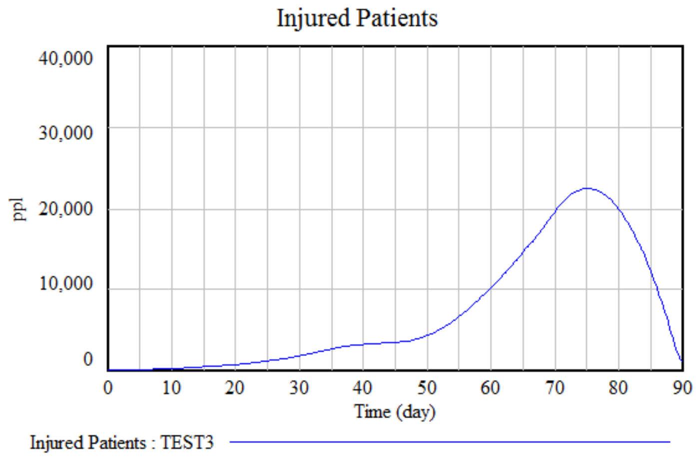

Figure 21: H1_Hospital example; injured patients

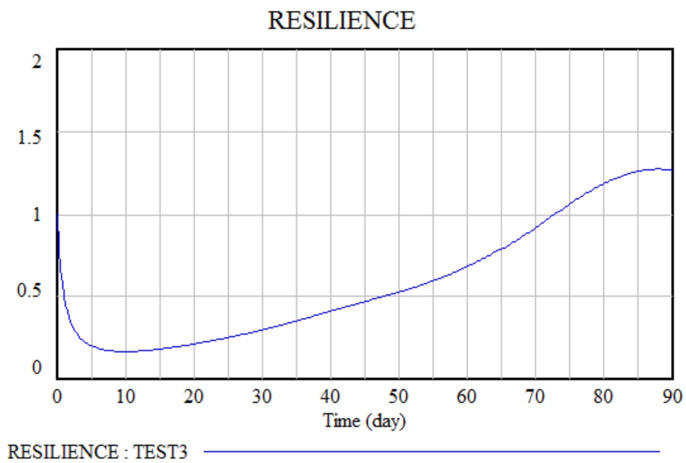

Figure 22: H1_Hospital example; H1 resilience

It would be expected in this example that as the number of *injured patients* and *impacts* increase, the *H1 resilience* would decrease (inverse relationship). Number of *injured patients* per a time step (t_s) can be computed as the difference in the inflow of injured patients and outflow of treated patients. In this example, the *H1 adaptive capacity res* variable captures the systems' adaptive capacity and uses it to control *outflow treated patients*. This *AC* function is described by the 4Rs (robustness, resourcefulness, rapidity, and redundancy). The function is "generic" in terms that it is expressed as a function of these 4Rs, but may require modification based on the selection of the 4Rs and the relationship(s) between them. The 4Rs may be expressed in any units that best describe the capacity of the stock variable. As such, the adaptive capacity function will be different for all variables included int he model. In some instances, perhaps only 3Rs may be considered to be important in describing the adaptive capacity of the system. In this case, the *AC* function may be modified to consider only 3Rs.

This example is developed only to illustrate the calculation of ST-DRM. All input values and variable relationships are assumed in order to execute an example simulation. It demonstrates the way in which each GSDSM-5 model will need to be modified in order to use the same resilience measure as introduced in this report. Currently, this H1_Hospital example is stand alone, that is, it is not connected to other system elements or resilience sectors. The next step would therefore be to connect the H1_Hospital example model to other modified GSDSMs to represent the entire system structure. This system of combined GSDSMs may be referred to as the City Resilience Simulator (CRS). The objective of the CRS is to capture the dynamics of all critical city systems and the intra- and inter-sectoral relationships.

However, the H1_Hospial example demonstrates a few important principles in the approach and understanding the system resilience. This example demonstrates how to use simulation to estimate the period of time required for full recovery of the system (to reach a resilience value of 1; Figure 22). The initial step is the development of the "current level of resilience" of the system. The future adaptation scenarios be implemented (using the same computational principles) through the modification of (a) the 4R functions describing adaptive capacity of the system; and/or(b) the adaptation capacity function.

The 4Rs are describing the *AC* of the system (and therefore they are the input into *RHO* calculation). The modification of any of the 4R variables will modify system performance and ultimately, system resilience behaviour. This is how adaptation scenarios will be effectively implemented into the model simulation.

4. CITY RESILIENCE SIMULATOR (CRS)

The CRS may be considered the main SD model file which contains modified GSDSMs for all economic, health, organizational, physical and social resilience systems. The modified GSDSMs are added to the CRS and the GSDSM model "placeholder" variables (such as "*climate change", "influence from external factors"* and *"exposure"*) are replaced with connections (links/arrows in Vensim) to other sectors within the model. The CRS may therefore be considered the complex, detailed, comprehensive city system simulation model which will simulate the overall city resilience. Progress of CRS development is directly related to the progress of project research in different focus areas: physical modelling, social investigations, economic modeling, health analyses, etc. The results of the work in different impact areas will result in general shape of the CRS model for each city. At this stage of the project research, the focus has been placed on the development of the smaller, subsystems of GSDSMs and general model development procedure. Therefore, there is currently no example of a CRS. The CRS models for each city will develop from GSDSMs as they become defined, refined and added to the main CRS model.

For better understanding of final use of the CRS, a very elementary illustrative example of a CRS is presented in Figure 23.

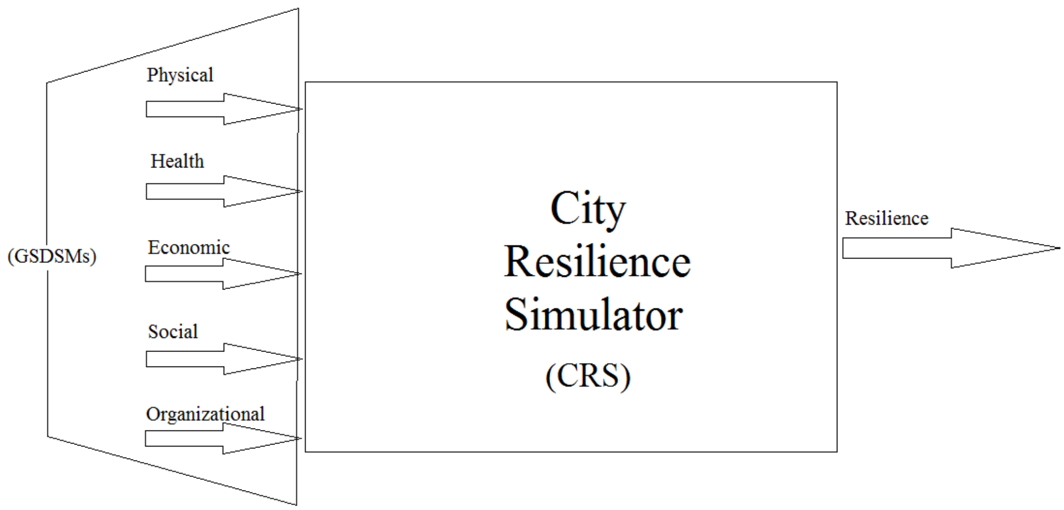

Figure 23: A conceptual diagram of the CRS structure

When the CRS structure is completely developed (all appropriate economic, health, organizational, physical and social systems have been modeled using SD software), the CRS may then be used simulate the change in city resilience as a consequence of various adaptation options. Set of adaptation options will represent one simulation scenario and comparison of city resilience (simulation output) will be used in relative evaluation of each option.

In order to capture both the short- and long- term hazard impacts, the CRS will be used in two different modes:

1. Short term, event, simulation; to capture the more immediate impacts of event-based short and medium duration climate hazards such as flooding, wind gusts, storms, and similar; and
2. Long term simulation; to capture the impacts of more gradual, long duration climate hazards such as sea-level rise.

It is therefore expected that each project city will have both a short- and long- term CRS simulation model (CRS-N-S and CRS-N-L, respectively; where N represents the first letter in the name of the project city, for example CRS-V-S would be the CRS short-term simulation model for the project city of Vancouver, Canada). The SD structure between the CRS-N-Sand CRS-N-L models will be very similar. However, the CRS-N-L may require minor adjustments to system structure to be able to accommodate long-term simulation period. The CRS-N-S and CRS-N-L SD model settings will be different. For example, Figure 24 presents possible model settings for a short term simulation model, where the calculations would be made on a daily time interval over a period of 1 year. In contrast, Figure 25 presents possible model settings for a long term simulation model, where the calculations would be made on a yearly time interval over a period of 50 years. The CRS-N-S and CRS-N-L simulation outputs may then be compared or considered concurrently to determine potential impacts from event-based short term hazards occurring simultaneously with long-term hazards.

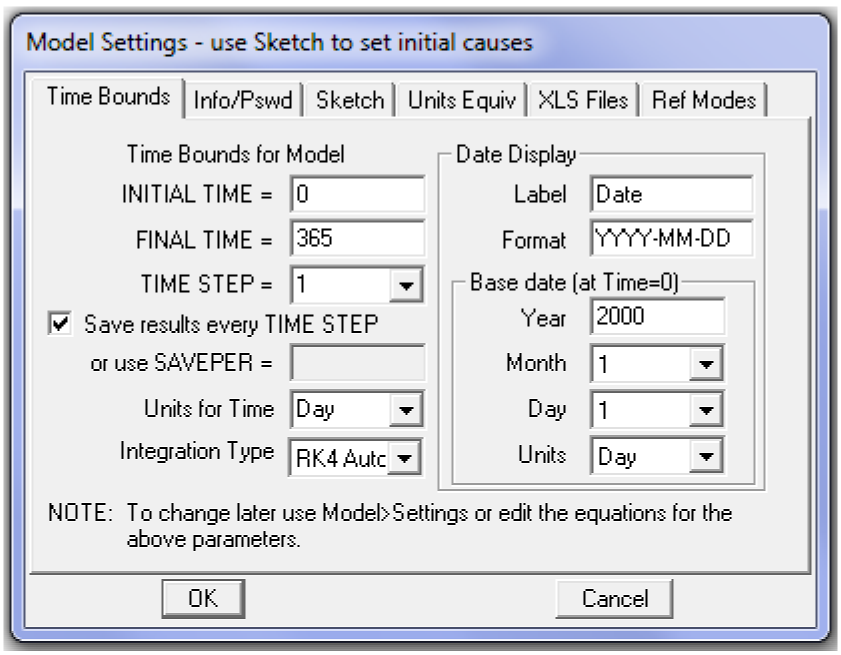

Figure 24: An illustrative example of short term model settings

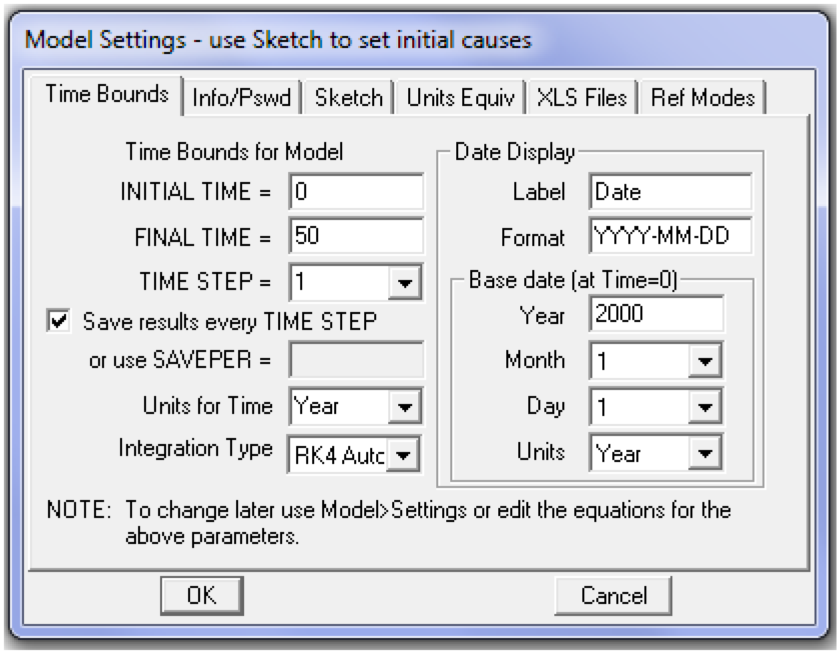

Figure 25: An illustrative example of long term model settings

5. CONCLUSIONS

This report presents the GSDSMs description, use and implementation for simulation of dynamic resilience to climate change caused natural disasters in coastal megacities. The purpose of the GSDSMs is to assist coastal cities in developing their own CRS by using them as a starting point for CRS model structure. GSDSM users may select from a library of generic simulation models which can be added to comprehensive CRS. The number of GSDSMs that may be added to each CRS will depend on each city's individual local conditions.

For the primary case study city of Vancouver, British Columbia, Canada, the data collection for the GSDSMs and CRS model inputs is actively being pursued concurrently with the modeling work through the discussions with local decision makers and other project team members. CRS-V development is underway and model structure is currently being refined and expanded.

This report outlines the system dynamics framework of CRS and is currently only focused on temporal dynamics of the resilience measure. However, the future work includes integration of SD simulation with GIS software so that dynamics of ST-DRM measure will be simulated in both, time and space. The final output will be in the form of dynamic maps which show changes in resilience over space and in time as a response to an adaptation scenario.

The ultimate goal of the CRS is to simulate and assess various climate change adaptation scenarios that will provide for policy development. The assessment process will be based on the analyses of simulated changes in city resilience behaviour over time and space before, during and after the occurrence of a disaster event. The expectation is that using the CRS to simulate behaviour in response to various policy options will help: identify disaster-resilient systems, determine why some systems are more resilient than others, and help prioritize adaptation actions.

Updates on CRS progress and the CCaR project can be found at the project website: coastalcitiesatrisk.org/wordpress.

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APPENDIX A: Description of variables in the H1_Hospital example

The following is a description of the variables *(and units)* used in the implementation of the GSDSM-H example for a hospital (H1_Hospital example).

<Time> (time): This is a shadow variable which provides the current time for each calculation step during simulation. It appears multiple times in the simulation model, but the value of thgis variable at all occurrences is the same.

<Influence from external factors from other sectors> (dmnl): This is a shadow variable which is holding the same name as another variable in the model. Similarly, it is meant to be a placeholder where possible connections to and influences from other sectors within the overall CRS model. This could include connections to the economic, transportation, or other health model sectors. These connections will be different for each system that is being modelled and has therefore been left in a generic form.

AC (people): A function of the 4Rs. Represents capacity of the system to absorb impacts from hazard. The 4Rs create this function. This function will be modified for different impacts; equations will change depending on the relationship between the 4R variables.

Calculation time: This variable is used for the resilience calculation; variable not necessary, could be programmed right into the *H1 Resilience* variable calculation, but for simplicity has been introduced here as a separate variable.

Climate factors (dmnl): This variable represents possible connections to the climate sector; currently a placeholder variable.

H1 adaptive capacity (dmnl): This variable is calculated using the 4R properties of adaptive capacity for an H1_Hospital system, including rapidity, redundancy, resourcefulness and robustness. It is a combination of the normalized 4R properties and will therefore have a solution between [0, 4], as calculated in equation (1).

H1 exposure (dmnl): Represents the degree of exposure to a climate hazard. This variables' value is dependent on the type of hazard; in a flooding situation, this variable may be considered the aerial extent of flooding and depth of water; currently a placeholder variable for future connections to the climate sector.

H1 Resilience (dmnl): The resilience calculation for the H1 system. This variable is calculated using equation (4) as the area under the system performance curve based on the initial performance level, P_o. *H1 adaptive capacity res (people per time):* this variable is actually the inflow rate (per time step) which modifies the *RHO* variable. It is the adaptive capacity value, expressed as a rate, in the same units as the indicator (i.e. *Injured Patients*).

H1 resilience impacts res (people per time): This variable is actually the outflow rate (per time step) which modifies the *H1 Resilience* variable. It is the impacts value, expressed as a rate. It is the impacts value, expressed as a rate, in the same units as the indicator (i.e. *Injured Patients*).

H1R1 (people): (i.e. robustness) This variable calls the *R1 fn* which, for the purposes of this example, is used as an indicator for H1 system robustness. This variable looks up the value of *R1* at time *t*, in the model.

H1R2 (people): (i.e. resourcefulness) This variable calls the *R2 fn* which for the purposes of this example, is used as an indicator for H1 system resourcefulness. This variable looks up the value of *R2* at time *t*, in the model.

H1R3 (dmnl): (i.e. rapidity) This variable calls the *R3 fn* which for the illustrative purposes of this example, is used as an indicator for H1 system rapidity. This variable looks up the value of *R4* at time *t*, in the model.

H1R4 (dmnl): (i.e. redundancy) This variable calls the *R4 fn* which for the illustrative purposes of this example, is used as an indicator for H1 system redundancy. This variable looks up the value of *R4* at time *t*.

H1 vulnerability (dmnl): Represents characteristics that may make a person, place, or thing more susceptible to suffering negative consequences; in the health example case, this could be considered those people who are very young or very old and more prone to injury in the event of a disaster.

Inflow injured patients (people per day): The flow or rate (per time step) at which people are becoming injured and going to the hospital seeking treatment. The rate of people getting injured is dependent on the *Population* and *Injury rate*.

Influence from external factors (dmnl): This variable represents possible connections to and influences from other sector within the overall CRS model. This could include connections to the economic, transportation, or other health model sectors. These connections will be different for each system that is being modelled and has therefore been left in a generic form.

Initial affected population (people): This is the total number of people who are affected by the hazard, who may potentially suffer injuries.

Initial P_0*:* This variable is used in the calculation of *H1 resilience* (equation 4) as the state of the system at the beginning of the disaster.

Injured Patients (people): A stock (accumulation/depletion) of injured population in the hospital for treatment. This stock is determined, in the most basic form, as the difference in people coming to the hospital seeking treatment (*inflow injured patients*) and people who have already obtained treatment at the hospital and are now leaving (*outflow treated patients*).

Injured patient fn (people per time): This is the rate (at a given time) of people getting injured as a result (directly or indirectly) of the hazard.

Injured patient impacts (people): This variable currently just maintains the value of the *Injured Patients* variable, but is used as a placeholder for possible connections to other sectors of the CRS model which may influence the degree of impacts.

Outflow treated patients (people per time): The rate (per time step) that people are being treated for injury and leaving the hospital after recovery. The rate at which people are being treated for injury is dependent on the value of *Injured Patients* and also the *H1 adaptive capacity res*.

R1 fn: The robustness function, currently defined as a function of time, but could also be expressed in other forms. This may be number of beds in hospitals, which indicates how many patients can be treated at the same time.

R2 fn: The resourcefulness function, currently defined as a function of time, but could also be expressed in other forms. This may be financial or human resources that indicate how many patients can be treated.

R3 fn: The rapidity function, currently defined as a function of time, but could also be expressed in other forms. This may be equipment which aids (or takes away from) the ability to treat patients.

R4 fn: The redundancy function, currently defined as a function of time, but could also be expressed in other forms. This could be having alternative arrangements for patients, so they do not need to attend a hospital to receive treatment.

Rho (people): Loss of resilience. Calculated using equation (3).

APPENDIX B: Description of the Distribution Package

The package of models distributed with this report to the project team includes the following:

a. GSDSMs-5

   This sub-folder includes the following five generic system dynamics simulation models:

   a. GSDSM-E

      The generic economics sector system dynamics simulation model

   b. GSDSM-H

      The generic health sector system dynamics simulation model

   c. GSDSM-O

      The generic organizational sector system dynamics simulation model

   d. GSDSM-P

      The generic physical sector system dynamics simulation model

   e. GSDSM-S

      The generic social sector system dynamics simulation model

   *None of these models include equations or even all the links that may be necessary to accurately represent the system. Instead, these generic models are meant to act as a graphical foundation for building sectors that will be modified before being included in a CRS.

b. GSDSM-C

   The Vensim model which would combine all of the city system resiliencies into a single overall resilience measure (ST-DRM) as indicated in Equation (7). The number of systems in each sector (economic, health, organizational, physical and social) will vary for each project city and then be used in ST-DRM calculation. The functions currently used to represent each system (H_1, H_2, H_3,…, H_n) are assumed for illustrative purposes and are not based on real values.

c. Health Example H1

An example in Vensim SD software to illustrate the use of GSDSM-H for a hospital system, defined in this case as a health system H1. Appendix A provides a description of the model and its variables. Please note that the actual values provided in this model are selected by the authors for the purposes of illustrating GSDSM-H model development and simulation. The current assumption in this example is that the disaster event (system disturbance) starts at time 0.

APPENDIX C: List of Previous Reports in the Series

ISSN: (print) 1913-3200; (online) 1913-3219

In addition to 53 previous reports (no. 01 – no. 53) prior to 2007;

(1) Predrag Prodanovic and Slobodan P. Simonovic (2007). Dynamic Feedback Coupling of Continuous Hydrologic and Socio-Economic Model Components of the Upper Thames River Basin. Water Resources Research Report no. 054, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 437 pages. ISBN: (print) 978-0-7714-2638-4; (online) 978-0-7714-2639-1.

(2) Subhankar Karmakar and Slobodan P. Simonovic (2007). Flood Frequency Analysis Using Copula with Mixed Marginal Distributions. Water Resources Research Report no. 055, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 144 pages. ISBN: (print) 978-0-7714-2658-2; (online) 978-0-7714-2659-9.

(3) Jordan Black, Subhankar Karmakar and Slobodan P. Simonovic (2007). A Web-Based Flood Information System. Water Resources Research Report no. 056, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 133 pages. ISBN: (print) 978-0-7714-2660-5; (online) 978-0-7714-2661-2.

(4) Angela Peck, Subhankar Karmakar and Slobodan P. Simonovic (2007). Physical, Economical, Infrastructural and Social Flood Risk – Vulnerability Analyses in GIS. Water Resources Research Report no. 057, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 80 pages. ISBN: (print) 978-0- 7714-2662-9; (online) 978-0-7714-2663-6.

(5) Predrag Prodanovic and Slobodan P. Simonovic (2007). Development of Rainfall Intensity Duration Frequency Curves for the City of London Under the Changing Climate. Water Resources Research Report no. 058, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 51 pages. ISBN: (print) 978-0- 7714-2667-4; (online) 978-0-7714-2668-1.

(6) Evan G. R. Davies and Slobodan P. Simonovic (2008). An integrated system dynamics model for analyzing behaviour of the social-economic-climatic system: Model description and model use guide. Water Resources Research Report no. 059, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 233 pages. ISBN: (print) 978-0-7714-2679-7; (online) 978-0-7714-2680-3.

(7) Vasan Arunachalam (2008). Optimization Using Differential Evolution. Water Resources Research Report no. 060, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 42 pages. ISBN: (print) 978-0-7714- 2689-6; (online) 978-0-7714-2690-2.

(8) Rajesh Shrestha and Slobodan P. Simonovic (2009). A Fuzzy Set Theory Based Methodology for Analysis of Uncertainties in Stage-Discharge Measurements and Rating Curve. Water Resources Research Report no. 061,

Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 104 pages. ISBN: (print) 978-0-7714-2707-7; (online) 978-0-7714-2708-4.

(9) Hyung-Il Eum, Vasan Arunachalam and Slobodan P. Simonovic (2009). Integrated Reservoir Management System for Adaptation to Climate Change Impacts in the Upper Thames River Basin. Water Resources Research Report no. 062, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 81 pages. ISBN: (print) 978-0-7714-2710-7; (online) 978-0-7714-2711-4.

(10) Evan G. R. Davies and Slobodan P. Simonovic (2009). Energy Sector for the Integrated System Dynamics Model for Analyzing Behaviour of the Social- Economic-Climatic Model. Water Resources Research Report no. 063. Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada. 191 pages. ISBN: (print) 978-0-7714-2712-1; (online) 978-0-7714-2713-8.

(11) Leanna King, Tarana Solaiman, and Slobodan P. Simonovic (2009). Assessment of Climatic Vulnerability in the Upper Thames River Basin. Water Resources Research Report no. 064, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 61pages. ISBN: (print) 978-0-7714-2816-6; (online) 978-0-7714- 2817-3.

(12) Slobodan P. Simonovic and Angela Peck (2009). Updated Rainfall Intensity Duration Frequency Curves for the City of London under Changing Climate. Water Resources Research Report no. 065, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 64pages. ISBN: (print) 978-0-7714-2819-7; (online) 987-0-7714-2820-3.

(13) Leanna King, Tarana Solaiman, and Slobodan P. Simonovic (2010). Assessment of Climatic Vulnerability in the Upper Thames River Basin: Part 2. Water Resources Research Report no. 066, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 72pages. ISBN: (print) 978-0-7714-2834-0; (online) 978-0-7714-2835-7.

(14) Christopher J. Popovich, Slobodan P. Simonovic and Gordon A. McBean (2010). Use of an Integrated System Dynamics Model for Analyzing Behaviour of the Social-Economic-Climatic System in Policy Development. Water Resources Research Report no. 067, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 37 pages. ISBN: (print) 978-0-7714-2838-8; (online) 978-0-7714-2839-5.

(15) Hyung-Il Eum and Slobodan P. Simonovic (2009). City of London: Vulnerability of Infrastructure to Climate Change; Background Report 1 – Climate and Hydrologic Modeling. Water Resources Research Report no. 068, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 102pages. ISBN: (print) 978-0-7714-2844-9; (online) 978-0-7714-2845-6.

(16) Dragan Sredojevic and Slobodan P. Simonovic (2009). City of London: Vulnerability of Infrastructure to Climate Change; Background Report 2 – Hydraulic Modeling and Floodplain Mapping. Water Resources Research

Report no. 069, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 147 pages. ISBN: (print) 978-0-7714-2846-3; (online) 978-0-7714-2847-0.

(17) Tarana A. Solaiman and Slobodan P. Simonovic (2011). Quantifying Uncertainties in the Modelled Estimates of Extreme Precipitation Events at the Upper Thames River Basin. Water Resources Research Report no. 070, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 167 pages. ISBN: (print) 978-0-7714-2878-4; (online) 978-0-7714-2880-7.

(18) Tarana A. Solaiman and Slobodan P. Simonovic (2011). Assessment of Global and Regional Reanalyses Data for Hydro-Climatic Impact Studies in the Upper Thames River Basin. Water Resources Research Report no. 071, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 74 pages. ISBN: (print) 978-0-7714-2892-0; (online) 978-0-7714-2899-9.

(19) Tarana A. Solaiman and Slobodan P. Simonovic (2011). Development of Probability Based Intensity-Duration-Frequency Curves under Climate Change. Water Resources Research Report no. 072, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 89 pages. ISBN: (print) 978-0-7714-2893-7; (online) 978-0-7714-2900-2.

(20) Dejan Vucetic and Slobodan P. Simonovic (2011). Water Resources Decision Making Under Uncertainty. Water Resources Research Report no. 073, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 143 pages. ISBN: (print) 978-0-7714-2894-4; (online) 978-0-7714-2901-9.

(21) Angela Peck, Elisabeth Bowering and Slobodan P. Simonovic (2010). City of London: Vulnerability of Infrastructure to Climate Change, Final Report - Risk Assessment. Water Resources Research Report no. 074, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 66 pages. ISBN: (print) 978-0-7714-2895-1; (online) 978-0-7714-2902-6.

(22) Akhtar, M. K., S. P. Simonovic, J. Wibe, J. MacGee, and J. Davies, (2011). An integrated system dynamics model for analyzing behaviour of the social-energy-economic-climatic system: model description. Water Resources Research Report no. 075, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 211 pages. ISBN: (print) 978-0-7714-2896-8; (online) 978-0-7714-2903-3.

(23) Akhtar, M. K., S. P. Simonovic, J. Wibe, J. MacGee, and J. Davies, (2011). An integrated system dynamics model for analyzing behaviour of the social-energy-economic-climatic system: user's manual. Water Resources Research Report no. 076, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 161 pages. ISBN: (print) 978-0-7714-2897-5; (online) 978-0-7714-2904-0.

(24) Millington, N., S. Das and S. P. Simonovic (2011). The Comparison of GEV, Log-Pearson Type 3 and Gumbel Distributions in the Upper Thames River Watershed under Global Climate Models. Water Resources Research Report no. 077, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 53 pages. ISBN: (print) 978-0-7714-2898-2; (online) 978-0-7714-2905-7.

(25) Andre Schardong and Slobodan P. Simonovic (2012). Multi-objective Evolutionary Algorithms for Water Resources Management. Water Resources Research Report no. 078, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 167 pages. ISBN: (print) 978-0-7714-2907-1; (online) 978-0-7714-2908-8.

(26) Samiran Das and Slobodan P. Simonovic (2012). Assessment of Uncertainty in Flood Flows under Climate Change: the Upper Thames River basin (Ontario, Canada). Water Resources Research Report no. 079, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 67 pages. ISBN: (print) 978-0-7714-2960-6; (online) 978-0-7714-2961-3.

(27) Rubaiya Sarwar, Sarah E. Irwin, Leanna M. King and Slobodan P. Simonovic (2012). Assessment of Climatic Vulnerability in the Upper Thames River basin: Downscaling with SDSM. Water Resources Research Report no. 080, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 65 pages. ISBN: (print) 978-0-7714-2962-0; (online) 978-0-7714-2963-7.

(28) Sarah E. Irwin, Rubaiya Sarwar, Leanna King and Slobodan P. Simonovic (2012).Assessment of Climatic Vulnerability in the Upper Thames River basin: Downscaling with LARS-WG. Water Resources Research Report no. 081, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 80 pages. ISBN: (print) 978-0-7714-2964-4; (online) 978-0-7714-2965-1.

(29) Samiran Das and Slobodan P. Simonovic. (2012). Guidelines for Flood Frequency Estimation under Climate Change. Water Resources Research Report no. 082, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 44 pages. ISBN: (print) 978-0-7714-2973-6; (online) 978-0-7714-2974-3.