An innovative technique for modelling impacts of coastal storm damage

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A spatial–temporal model is developed to model the impacts of simulated coastal region storm surge and flooding using a combined spatial mapping and system dynamics approach. By coupling geographic information systems and system dynamics, the interconnecting components of the spatial–temporal model are used with historical data to evaluate storm damage. The model examines the component-wise changes to the physical environment, community infrastructure and socioeconomic resources from simulated storm surges. To illustrate this model, the research is applied to the case of Charlottetown on Prince Edward Island, Canada, a vulnerable coastal city subject to considerable impacts from increasingly frequent severe storm surges.

Keywords: spatial system dynamics; coastal vulnerability; geographic information system (GIS); system dynamics

Introduction

Despite the increased ability and capacity to forecast severe storm surges and predict coastal vulnerabilities to sea level rise (Lane & Watson, 2011), there is growing anxiety that there is a lack of connections between current scientific knowledge and the institutions responsible for the response planning and adaptation of coastal regions (Lemmen, Warren, Lacroix, & Bush, 2008). This knowledge gap needs to be bridged in order for actors in coastal regions to understand properly and prepare for intense storm activity. Considering the immense monetary and social costs associated with storm surges and that the frequency, intensity and duration of severe surges has increased (Barnett & Campbell, 2010; Mimura et al., 2007; Tita, 2014), it is imperative that vulnerable sites are identified and research pertaining to community and government preparedness and their response to storm surges be conducted in order to limit the impacts from future storm damage. This paper presents an innovative approach to capturing storm system impacts and an interactive tool for decision-makers to assist in storm planning preparedness and adaptation.

Currently, available models and tools do not produce relevant and useful storm damage assessments (Merz, Kreibich, Schwarze, & Thieken, 2010). Storm damage reporting available to the public, whether by government, insurance agencies or media, remains inconsistent, minimal and vague – especially outside large urban areas (Hartt, 2011). Insurance companies’ assessments often undervalue damage, whereas government
agencies and academics endeavour for a more accurate assessment of total damage, although the latter concentrate heavily on economic losses (Jongman et al., 2012). The social and environmental costs of storm surges in coastal regions cannot be overlooked, nor can the impact on the rich cultural heritage often found in these regions. Due to the complex nature of systems and storm surge modelling, decision-makers need robust, easy-to-explain and easy-to-execute tools to aid in the identification and preparation of vulnerable areas.

In order to assess, rank and evaluate aspects of regional storm surge vulnerability and to estimate storm damage impacts, the region’s spatial–temporal interactions with its environment must be taken into account. This research presents a model that builds on Ahmad and Simonovic’s (2004) concept of spatial system dynamics, wherein system dynamic and geographic information system (GIS) techniques are coupled together to model feedback-based dynamic processes in space and time. This spatial–temporal approach can be applied to a range of natural processes such as disaster management, water resource systems and natural resource management. This paper proposes a practical application of the spatial system dynamics approach to a vulnerable coastal region. The goal of this model is to capture the storm impacts on all aspects of the region through a series of simulations. These include impacts to the biophysical, socioeconomic and infrastructural components of the region. One of the key objectives of this model is to provide a powerful tool for decision-makers and citizens of coastal regions to assist in storm response planning preparedness, and adaptation to the changing coastal climate. In order to illustrate the model, the case of Charlottetown on Prince Edward Island, Canada, will be presented.

**Current advances in modelling**

Sea level rise and storm surge models are advancing rapidly, continuously improving in detail, accuracy and precision, and are being consulted for policy regarding storm surge preparation and adaptation (NOAA, 2013). Concurrently, easy-to-use tools, such as COAST, for policy-makers and community stakeholders continue to be improved and incorporated into planning policy (Merrill, Kirshen, Sowers, Keeley, & Cunningham, 2013). However, the models lack a systems perspective. Both the current technical and participatory models still do not incorporate dynamic feedback loops, which limits them to static analysis and fails to incorporate the interconnections between the different components of a region. Coastal regions are complex, interconnected systems whose individual components cannot be fully understood in isolation. Accurately predicting storm surge severity and capturing initial economic impact are important, but a full understanding of the regional system as a whole, both spatially and temporally, is necessary to understand and prepare holistic responses to storm surge activity.

Spatial system dynamics combines the temporal strengths of system dynamics, itself developed to produce explanations of complex dynamic systems in large-scale problems, with GIS’s spatial strengths. Ahmad and Simonovic (2004) first presented this approach to address then-current limitations of dynamic spatial modelling. They chose to run the system dynamics and GIS models in parallel. Introducing spatial dimensions into the dynamic model was limited by the inability to represent them explicitly, and translating the dynamic model equations to run in GIS lacked interactive power, as iterative, changing feedback loops were not possible in the simulation.

Studies using system dynamics and GIS together have largely focused on water modelling and management (Winz, Brierley, & Trowsdale, 2008). In 2012, an evaluation
of system dynamics simulation tools for modelling water processes recognized 12 easy-to-use integrated applications, although only the spatial system dynamics methodology was capable of accounting for spatial variability (Mirchi, Madani, Watkins, & Ahmad, 2012). Designed as an easy-to-understand method, the spatial system dynamics approach has had little application in other fields outside water resource management. This paper aims to bridge this gap by outlining its applicability and practicality to the wider audience of coastal vulnerability and regional studies, where spatial system dynamics could have direct policy and procedural implications concerning storm prediction, preparedness and damage reporting.

Spatial system dynamics model

The methodology of the modelling technique presented in this paper may have technical discipline-specific elements, but the overarching concepts guiding the methodology are quite simple. This model bridges a significant gap in the systems and spatial modelling research literature: ‘Traditional modelling approaches focus on either temporal or spatial variation, but not both […] patterns in time and space need to be examined together’ (Ahmad & Simonovic, 2004, p. 331).

Figure 1 provides a simple overview of the modelling system process where the region is defined by four component inputs (environmental, economic, social and cultural). A simulation introduces a storm surge, defined by limited historical data, to the system and outputs monetary storm damage values based on immediate impacts. The storm damage is component-specific, detailing the environmental, economic, social and cultural damages based on historical storm data.
and cultural damage separately. These direct damage values then act as inputs into the system dynamics model, which ascertains the indirect damage incurred. The looped system dynamics feedback process, as depicted in Figure 2, can be run several times dependent on the temporal scale. The specific assumptions and definitions of the feedback loops are not within the scope of this paper, however it is important to note that their complexity is variable as even crass systems models can provide additional insight regarding the indirect effects of storm surges.

This technique provides the basis for a powerful tool for decision-makers and citizens of coastal communities to assist in storm response planning preparedness, and adaptation to the changing coastal climate. By highlighting environmental, economic, social and cultural vulnerabilities, this technique delivers a more thorough and holistic account of potential storm damage. Furthermore, by including the iterative interactions amongst components along a temporal scale rather than a one-time initial impact analysis, a greater understanding of the medium and long-term impacts can be gained. By providing an inherently complex tool with a simplified, visual user interface, not only are easily understood results produced for users outside the discipline, but also the tool boasts simple adjustable elements so that decision-makers and other stakeholders can toggle between scenarios to grasp a better understanding of the system impacts. This interaction of components and ease of use can ultimately assist decision-makers to make informed decisions regarding preparation for future impacts and, as a result, adaptation to best prevent or reduce impacts.

The importance of this tool lies in its interdisciplinary and multidisciplinary systems approach. Challenges associated with coastal emergency preparedness are vast and intricate; strategies and solutions stemming from only one perspective (i.e. economic) are short-sighted and have the potential to misguide. In order to connect appropriately, and effectively, the many facets required to discover problem formulation and resolution, a holistic viewpoint must be taken. Understandably, many decision-makers and community stakeholders will not have the necessary background skills to engage in such a process, which is why a tool such as the one presented in this research is necessary to bridge such scientific-institutional gaps.

Figure 2
Charlottetown, Prince Edward Island, Canada – a vulnerable coastal region

Charlottetown is the capital city of the province of Prince Edward Island, situated on Canada’s Atlantic coast. With a population of 64,487, Charlottetown makes up 46% of the provincial population (Statistics Canada, 2012). Charlottetown is positioned at the convergence of three rivers, forming Charlottetown Harbour on the south shore of the island, which in turn opens onto Northumberland Strait (Figure 3). Population and infrastructure density is highest in the southern, coastal region of the city where the bulk of public administration and retail trade, Charlottetown’s biggest industries, as well as most of the city’s 500 historic properties are located.

For the past 50 years, the Charlottetown metropolitan region has been heavily affected by storm surges and empirical evidence shows that there has been an increase in frequency and severity of the storms (Department of Fisheries and Oceans Canada, 2010). For example, in January 2000, a storm struck the Charlottetown coastal region with record water levels of 4.23 m above chart datum (Natural Resources Canada, 2009). The storm surge severely damaged many public and private properties: the wharves in Charlottetown harbour, a power-generating station, a lighthouse and numerous gas stations. The total monetary damage of the storm surge was estimated at C$20 million (Natural Resources Canada, 2009).

Due to its location and infrastructure, and population densities in the coastal region, the Charlottetown metropolitan region needs a variety of dynamic response plans. Available non-storm spatial data (economic and cultural landmarks and social demographics)
were organized using ArcGIS mapping software, while the anticipated storm scenarios were modelled using narrative and empirical data from 13 historical storms. Through a baseline comparison analysis, an ‘assets at risk’ determination of monetary values was achieved totalling the value of all ‘at risk’ assets included in the expected damage area. This approach is adopted to determine community vulnerability and to avoid reliance on insurance claim reports (often underestimated) and media damage reports (often overestimated).

The ‘assets at risk’ results represent the full valuations of exposed assets as estimated by Milloy and MacDonald (2002); however, it is recognized that when estimating damage, the length of storm has a great deal of importance as it determines closure lengths, lack of work lengths and event postponements. As such, when adjusting the estimated values of the assets at risk to estimated damage values, length of storm surge impacts must be considered, as the damage increases as semi-immediate (indirect) storm impacts extend. Therefore, the system dynamics model is used to integrate the temporal element. From this model, monetary damage is captured as either ‘direct’ or ‘indirect’. The resulting estimations are not meant to be predictions or collectively exhaustive measures, but are merely presented to illustrate the process linking impacts to overall damage.

Multiple trials were conducted for each storm scenario. Figure 4 shows the visual output from the model – depicting three storm surge scenarios in Charlottetown’s downtown core and various key economic points. For the sake of brevity, only the average results of the most severe storm are presented. The expected total damage calculated for the most severe storm scenario is C$29.6 million, with approximately C$22 million resulting from direct damage and the remaining C$7.6 million from indirect damage. Generally, the environmental and economic impacts make up the majority
(approximately 92%) of the overall total estimated damage, whereas the cultural and social components make up the remaining 8%. These results provide a comprehensive storm damage estimation system that is expected to be used to identify Charlottetown’s storm vulnerability and to instigate discussion of strategies for (1) adapting to pending damage from more frequent storms; and (2) how best to report storm damage so that future policy planning can be more informed as to where damage is done. Moreover, this model recognizes the need for planning and preparedness even if data are not readily available, as many communities facing detrimental climate change impacts are in less developed countries and have limited or no access to quality data.

Conclusion

This study used an interdisciplinary approach, spatial system dynamics, to examine the impact that storm surges have on vulnerable coastal regions. It was shown that by using historical data as a guide, simulations and models can estimate the changes, damage and impacts that storms will have on a region as a whole and on the environmental, economic, social and cultural components that define the regional system.

The damage incurred by a severe storm surge to a coastal region clearly goes beyond an aggregate monetary amount that simply addresses the immediate economic impacts. Without the knowledge of how and where storm damage occurs, coastal regions will continue to be ill-prepared for severe storm damage. Spatial system dynamics considers both spatial and temporal aspects of a complex regional system and provides robust duration and component-specific results to understand better storm surges and their resultant damage. Although the methodology has yet to be used to its full capacity, the concept of coupling system dynamics and GIS to produce a dynamic map can potentially be applied to a plethora of situations beyond storm surge modelling. This work takes a significant step in an emerging field, and the model process of this study is designed to be helpful for planners and decision-makers. Enhanced system storm damage reporting and vulnerability identification have considerable implications for policy regarding climate change preparedness, adaptation and mitigation.

Note

1. Chart datum is a consistent base water level from which all other measurements are taken.

References

Ahmad, S., & Simonovic, S. P. (2004). Spatial system dynamics : new approach for simulation of water resources systems. *Journal of Computing in Civil Engineering, 18*(4), 331–340.

Barnett, J., & Campbell, J. (2010). *Climate change and small island states: Power, knowledge, and the South Pacific*. London: Earthscan.

Department of Fisheries and Oceans Canada (2010). Tides, currents, and water levels: Data archive: Station data. Retrieved August 29, 2010, from http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/twl-mne/inventory-inventaire/index-eng.htm

Hartt, M. D. (2011). *Geographic information systems and system dynamics – Modelling the impacts of storm damage on coastal communities*. Ottawa: University of Ottawa.

Jongman, B., Kreibich, H., Apel, H., Barredo, J. I., Bates, P. D., Feyen, L., & Ward, P. J. (2012). Comparative flood damage model assessment: towards a European approach. *Natural Hazards and Earth System Science, 12*(12), 3733–3752. doi:10.5194/nhess-12-3733-2012

Lane, D. E., & Watson, P. (2011). *Managing adaptation to environmental change in coastal communities: Canada and the Caribbean*. C-Change Working Paper Series, No. 4. Ottawa.
Lemmen, D. S., Warren, F. J., Lacroix, J., & Bush, E. (2008). *From impacts to adaptation: Canada in a changing climate 2007*. Ottawa: Government of Canada.

Merrill, S. B., Kirshen, P., Sowers, D., Keeley, C., & Cunningham, P. (2013). Demonstrating the utility of a new 3D benefit: cost tool for adaptation to sea level rise and storm surge. Paper presented at the 2013 Fourth International Conference on Computing for Geospatial Research and Application, 96–100. doi:10.1109/COMGEO.2013.16

Merz, B., Kreibich, H., Schwarze, R., & Thieken, A. (2010). Review article: Assessment of economic flood damage. *Natural Hazards and Earth System Science, 10*(8), 1697–1724. doi:10.5194/nhess-10-1697-2010

Milloy, M., & MacDonald, K. (2002). Evaluating the socio-economic impacts. In D. Forbes & R. Shaw (Eds.), *Coastal impacts of climate change and sea-level rise on Prince Edward Island*. Geological Survey of Canada, Open File 4261, Supporting Document 10. Dartmouth, NS.

Mimura, N., Nurse, L., McLean, R. F., Agard, J., Briguglio, L., Lefale, P., Payet, R., & Sem, G. (2007). Small islands. In M. L. Parry, O. F. Canziani, J. P. Palutiko, P. J. van der Linden, & C. E. Hanson (Eds.), *Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 687–716). Cambridge: Cambridge University Press.

Mirchi, A., Madani, K., Watkins, D., & Ahmad, S. (2012). Synthesis of system dynamics tools for holistic conceptualization of water resources problems. *Water Resources Management, 26*(9), 2421–2442. doi:10.1007/s11269-012-0024-2

Natural Resources Canada (2009). Storm surges. Retrieved September 16, 2009, from http://atlas.nrcan.gc.ca/site/english/maps/environment/naturalhazards/storm_surge/1

NOAA (2013). *Storm surge overview*. National Hurricane Center. Retrieved April 9, 2014, from http://www.nhc.noaa.gov/surge/

Statistics Canada (2012). *Focus on geography, 2011 Census* (Statistics Canada Catalogue No. 98–310-XWF2011004, Analytical Products(2011). Census). Ottawa: Statistics Canada.

Tita, G. (2014). *Coping with inherent vulnerabilities and building resilience in small islands: Socioeconomic and governance perspectives*. Centre de recherche sur les milieux insulaires et maritimes (CERMIM), affiliated with Université du Québec à Rimouski, Îles-de-la-Madeleine, QC.

Winz, I., Brierley, G., & Trowsdale, S. (2008). The use of system dynamics simulation in water resources management. *Water Resources Management, 23*(7), 1301–1323. doi:10.1007/s11269-008-9328-7