Vulnerability of infrastructure to sea level rise: a combined outranking and system-dynamics approach

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ABSTRACT: In order to develop an adaptation plan for sea level rise (SLR), coastal councils often conduct hazard line studies to investigate present and expected future risks on coastal stretches (e.g., beaches) that harbour various types of infrastructures (e.g., roads, sewerage system, water supply system, electricity, telecom etc). Interdependencies of infrastructure components and systems are frequent with disruption of services in one, likely to cascade through the infrastructure network and produce a compound effect on users. To help decision-makers at a local council in prioritising management actions, we developed an analytical vulnerability assessment tool called EVA-INFRA (Environmental Vulnerability Assessment for infrastructures) which starts from the IPCC framework of vulnerability and considers the biophysical impacts of the hazard as well as a measure of its social and institutional dimensions. In this paper, we describe the incorporation of a system dynamics model inside EVA-INFRA that can quantify the cascading effects of disruption of any infrastructure component, leading to a more precise assessment of vulnerability.

1 INTRODUCTION

It has been estimated that global mean sea level may rise between 0.18m and 0.59m by 2100 (Meehl et al., 2007) with recent studies predicting even higher levels (e.g., 0.5m to 1.4m by 2100 according to Rahmstorf (2007). Of the 63 most populated cities of the world (with 5 million or more inhabitants in 2011), 72 per cent are located on or near the coast (United Nations, 2012). SLR may accelerate the erosion of coastal margins, threatening surrounding land, property and infrastructures. Rising seas may also lead to an increase in coastal flooding, either by providing a higher base and therefore increasing the height of storm surges, or by acting as a higher seaward barrier restricting the escape of flood waters caused by excessive runoff (Walsh et al., 2004). Therefore, many coastal councils around the world have included climate change adaptation as part of long term infrastructure and environmental planning.

Coastal Local Government Areas (LGA) in Australia usually harbour a set of infrastructures that provide vital social and engineering services to population centres. Infrastructure consists of the connected engineered systems that deliver basic urban services such as transportation, energy, telecommunication, water, solid and liquid waste disposal (Jacob et al., 2000; Rinaldi, 2004). Often individual components in these systems are highly interdependent and disruption of services to one component can impact other components and propagate the whole system. This phenomenon is well known in the literature as infrastructure interdependency (Rinaldi, 2004; Rinaldi et al., 2001; Min et al., 2007). On the other hand, the life spans of some of these infrastructures are long enough for SLR and associated erosion processes to affect them (Walsh et al., 2004). Therefore, the development of adaptation actions for infrastructures are crucial.

Assessing vulnerability of infrastructures to SLR helps in identifying populations most at risk and optimising resource allocation for adaptation (Füssel and Klein, 2006). While the SLR vulnerability literature is rich with multi dimensional focus (Ozyurt and Ergin, 2009, Viehhauser et al., 2006, Abuodha, 2010, Clark et al., 1998, Harvey and Woodroffe, 2008, Yoo et al., 2011, Kelly and Adger, 2000), studies on vulnerability to SLR of infrastructure systems and their users appear to have given very little consideration to social and institutional dimensions of risk, especially at local-government level. Jacob et al. (2000) conducted a study assessing vulnerability to SLR of infrastructures around the Metropolitan East Coast of the United States by focusing on possible economic losses. Sahin and Mohamed (2009) conducted a spatiotemporal analysis of SLR vulnerability of the infrastructure on the Gold coast, Australia. But neither studies took into account infrastructure interdependency or social dimensions of risk. Interdependency, on the other hand, is foregrounded in studies conducted from a national security perspective though typically at regional and national, rather than local, scales (Pederson et al., 2006, Min et al., 2007).

Processes generating vulnerability of a community of users of an infrastructure service can be predominantly geophysical (e.g., proximity of an infrastructure component to the coast; loss of structural foundation to erosion), socio-economic (e.g., high level of dependence of users on the service provided; inability of users to replace the disrupted service) or institutional (e.g., lack of resources for repairing damaged infrastructure). Hence, attempting to build an overall measure of vulnerability out of these disparate components can be challenging (Tonmoy and El-Zein, 2013). For example, to what extent does a low degree of geophysical risk (ie low probability of damage to infrastructure) compensate for poor institutional capacity and so on. This is the well known problem of compensation (Munda and Nardo, 2009). Furthermore, vulnerability assessment must inevitably be conducted on the basis of both scientific evidence and stakeholder consultation, including a multiplicity of value- and expert judgements. It is therefore important that any assessment framework be capable of incorporating the relative imprecision and normative nature of some variables present in the exercise while maintaining a consistent and robust scientific process.

In a previous set of papers, we proposed a new indicator-based vulnerability assessment framework called SEVA (the Sydney Environmental Vulnerability Assessment framework) that allows for partial compensation and non-linear relationships between indicator and vulnerability (El-Zein and Tonmoy, 2013a; Tonmoy and El-Zein, 2012; El-Zein and Tonmoy 2013b). It is based on an outranking procedure borrowed from decision-making which generates ranking of vulnerabilities of socio-ecological systems (SESs) based on pair-wise comparisons that reflect both the objective and normative nature of indicators representing vulnerability and can therefore accommodate partial compensation and non-linearities. The framework was used as a basis for developing a local-scale model of vulnerability of users of coastal infrastructure to SLR at eight beaches in Shoalhaven, south of Sydney (Tonmoy et al., 2012). The model, called EVA-INFRA, considers three dimensions of risk (exposure, sensitivity and adaptive capacity) and incorporates measures of institutional capacity as well as the social importance of a service provided by the infrastructure. However, infrastructure components are assessed without considering interdependency.

In this paper, we describe the development of a systems dynamics (SD) model of interactions between infrastructure components and its incorporation in EVA-INFRA. We call the new model EVA-INFRA-SD. System dynamics, first introduced by Forrester (1961), is a powerful computer-based technique for the simulation of a complex system over time. In the remainder of the paper, we describe EVA-INFRA-SD.

2 VULNERABILITY FRAMEWORK AND EVA-INFRA-SD

We start from the widely used definition of vulnerability provided by the Intergovernmental Panel on Climate Change (IPCC) which states that vulnerability is a function of three dimensions of the system's relationship to the hazard in question: its *exposure* to the hazard, its *sensitivity* to the impacts of that hazard as well as its ability to cope with, or adapt to, those impacts, known as its *adaptive capacity* (IPCC, 2001, Adger, 2006). We used this definition in the context of infrastructure vulnerability and developed EVA-INFRA, a conceptual model of the vulnerability to SLR of users of infrastructure present at Shoalhaven beaches, shown in Table 1. A set of indicators were then identified for each dimension (table 2, 3 and 4). Although we only considered the five categories of infrastructure components relevant to Shoalhaven (and shown in the tables), it is possible to expand this model by including others such as telecommunication.

Table 1: EVA-INFRA: How vulnerable is the public infrastructure network and its users to sea level rise (SLR) and coastal processes associated with it, namely beach erosion and inundation (collectively called SLRAP)

Information Type	**Description**
Socio-Ecological System (SES)	The beach defined as the area between the shoreline and the main road running alongside it
Valued attribute of concern (VA)	All public infrastructures and the well-being of their users
Climatic stress	SLRAP (sea-level rise as predicted for 2050 + design storm with same magnitude as 1974 NSW storm)
Time	Present-day vulnerability to SLRAP
Exposure of infrastructure to hazard	Extent to which public infrastructure systems are exposed to SLRAP
Sensitivity of infrastructure to the impacts of hazard	1. Extent to which the well-being of the community of users of the public infrastructure is likely to suffer as a result of disruption to service; 2. Extent to which, and speed with which, relevant public authorities are able to repair damaged infrastructure components and restore disrupted services to users or offer substitute services
Adaptive capacity of users	Extent to which, and speed with which, users are able to substitute, or do without, disrupted services, without help from government institutions

EVA-INFRA indicators of exposure (Table 2) are replacement costs of damage to infrastructures inflicted by an event in a do-nothing scenario. These can be estimated by hazard studies that downscale sea-level rise generated as output of climate models and combine them with local coastal, geomorphologic and hydrodynamic models, in order to develop hazard lines and identify long-term coastal erosion, as well as possible flooding during a storm event.

Table 2: EVA-INFRA-SD Indicators of Exposure

Public infrastructures and services	Code	$ value of Affected	Variable Type	Unit	D_a
Sewerage	I1	pumping stations			
	I2	rising main			
	I3	gravity main			
Water supply	I4	supply main			
Power Supply	I5	Substation	C	$	+
Roads	I6	Roads			
Public buildings and other infrastructures	I7	other affected infrastructure (e.g., car park)			

a :Dir= Direction: ↑ (↓) indicates that vulnerability increases (decreases) with increasing indicator. C= Continuous variable

The sensitivity dimension of EVA-INFRA is represented by the number of households affected by service disruption as well as the capacity of authorities to replace or restore the service (table 3). Sensitivity of roads and public buildings is represented by variables R1 and R2, estimated through expert-judgement. On the other hand, our system dynamics model, which we will describe in the next section, allows us to develop a single sensitivity indicator which reflects the interdependent and dynamic nature of the infrastructure components of sewerage, water supply and power supply. The indicator in question, H_{max}, is the maximum number of households affected by disruption of a single service (to be derived below). It measures the collective service performance of the above components when under stress, as well as the capacity of the public authority to maintain the service (consistently with our definition of sensitivity in Table 1).

Finally, the adaptive capacity of users is captured by expert- and stakeholder-judgement about the degree to which the disrupted service is critical, ie the extent to which it serves a vital function (e.g., water supply is more vital than a car park at a beach). The indicators are shown in Table 4.

Clearly, the indicators for exposure are outcomes of mechanistic modelling (climate projection and hazard line studies combined with financial estimates of replacement costs) based on deductive arguments. SD allows us to introduce mechanistic modelling to the sensitivity dimension as well (as far as water, wastewater and power are concerned), rather than rely on rough expert judgement. Figure 1 shows the overall architecture of the framework. Once all indicators have been evaluated (including H_{max}) and assembled in a vulnerability matrix (SESs x indicators), the SEVA outranking approach is applied to rank different SESs according to their vulnerabilities to sea level rise. The ranking can be

Table 3: EVA-INFRA-SD indicators of sensitivity

Public infrastructures and services	Code	Nodes	Indicators	Variable type	Unit	D_a
Sewerage	I8	Pumping stations				+
		Rising main		D	H/T	+
		Gravity main	H_{max}			+
Water supply	I9	Supply main		D	H/T	+
Power Supply	I10	Substation		D	H/T	+
Roads	I11	Roads(direct impact)	R1	O	NA	+
	I12	Roads (indirect impact)	R2	O	NA	
Public buildings and other infrastructures	I13	Other affected infrastructure	R1	O	NA	+

D_a: Direction: + (-) indicates that vulnerability increases (decreases) with increasing indicator. D: discrete variable H: Number of households; H/T: Number of household served per unit time; O: Ordinal; Hmax: maximum number of household affected by disruption of service per unit time-output of EVA-INFRA-SD; R1: No of households affected by the service disruption of the infra; R2: Impact to passing traffic; NA: Not applicable

Table 4: EVA-NFRA-SD indicators of adaptive capacity

Public infrastructures and services	Code	How critical is the affected infrastructure?	Type of variable	Unit	D^a
Sewerage	I14	pumping stations			-
	I15	rising main			-
	I16	gravity main			-
Water supply	I17	supply main			-
Power supply	I18	Substation	O	NA	
Roads	I19	roads			-
Public buildings and other infrastructures	I20	other infrastructures (e.g., car park)			-

D^a: Direction: + (-) indicates that vulnerability increases (decreases) with increasing indicator. O: Ordinal variable; NA: Not applicable conducted for each dimension separately or by clustering all indicators in one matrix.

1. Problem Definition

a. Define the SESs that need to be compared (e.g., beach, coastal developments)
b. Define possible disaster scenarios and their magnitudes (e.g., SLR for 2050)
c. Define infrastructure system components that are at threat for a given scenario (e.g., power, water supply, roads, waste etc)
d. Define point of assessment in terms of time (e.g., present or some specific time in the future)

↓

2. Conduct a coastal hazard study for a given scenario of SLR

↓

3. Superimpose hazard lines on infrastructure network layout to identify infrastructure under threat

↓

4. Model dependency of infrastructure nodes using systems dynamics

↓

5. Model Exposure, Sensitivity and Adaptive capacity using EVA-INFRA indicators

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6. Vulnerability Matrix

↓

7. Use SEVA outranking approach for aggregation

Determine thresholds from stakeholders

↓

8. Vulnerability Rankings

Figure 1: Overall architecture of the framework for assessing SLR vulnerability of infrastructure systems

3 DEVELOPMENT OF SYSTEM DYNAMICS MODEL FOR EVA-INFRA-SD

3.1 *Objectives*

EVA-INFRA-SD is developed with an objective of measuring system performance (e.g., performance of water supply system, wastewater transport etc) during a possible disaster scenario (e.g., increased coastal flooding due to SLR). Performance of an infrastructure system is dynamic, ie it can change over time. SD concepts are used to attain two objectives:

a) identify the effects of the failure of one infrastructure component as they propagate through the system(s) and
b) measure performance over time.

The first objective can be achieved by modelling different nodes of a given infrastructure systems and identifying their linkages and dependencies (see Figure 2). The second objective can be achieved by using system dynamics concepts of stock and flow. In

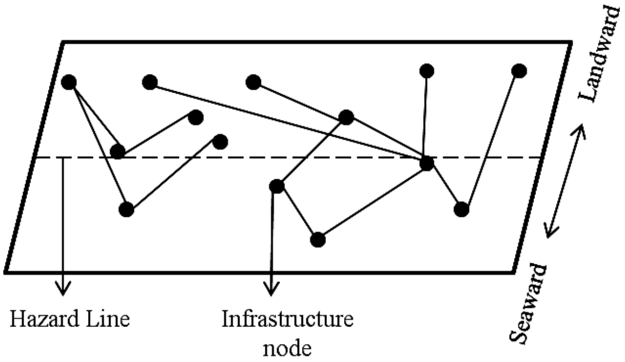


Figure 2: Schematic representation of infrastructure interdependency concept in the context of SLR

the following sections, we define urban infrastructure systems and their dependencies at a local scale

3.2 *Infrastructure interdependency at a local scale*

3.2.1 *Urban infrastructure systems*

Each of the services studied here (sewerage, water and energy supply) rely on multiple infrastructure components (e.g., water main, rising main, pipe network) to function. Following convention, we refer to these individual components as *"infrastructure nodes"*, a set of connected nodes providing a service as *"infrastructure system"* (e.g., water supply infrastructure system), and multiple systems (e.g., water supply, power supply, transportation etc) as *"infrastructure network"* (Rinaldi et al., 2001, Pederson et al., 2006).

3.2.2 *Dependency and interdependency of infrastructure*

An infrastructure node is said to be *dependent*, if its serviceability (ie ability to fulfil its function) depends on that of another infrastructure node within the same infrastructure system. As an example, the serviceability of downstream water main is dependent on its neighbouring upstream water main. On the other hand, if such a dependency exists between two nodes from different infrastructure system (e.g., power supply from one specific station influencing the serviceability of a connected water pump), it is called *interdependency* (Figure 3).

3.2.3 *Local scale*

Local scale refers to the geographical extent of the analysis and in this research it is considered to be as the lowest level of administrative boundary within an urban context (e.g, council, county). In this paper, we use the Australian term Local Government Area (LGA).

3.3 *Classification of dependencies and interdependencies*

Four types of infrastructure interdependencies have been identified by Rinaldi et al. (2001): physical (output of one node is an input to another), cyber (infrastructures are connected via information links), geographic (possibility of disruption due to proximity of location), and logical (dependent on factors related to human decisions and actions). It is possible to incorporate all four concepts but, in this paper, we have considered only physical interdependency because data for the other three types are not available in the context of Shoalhaven.

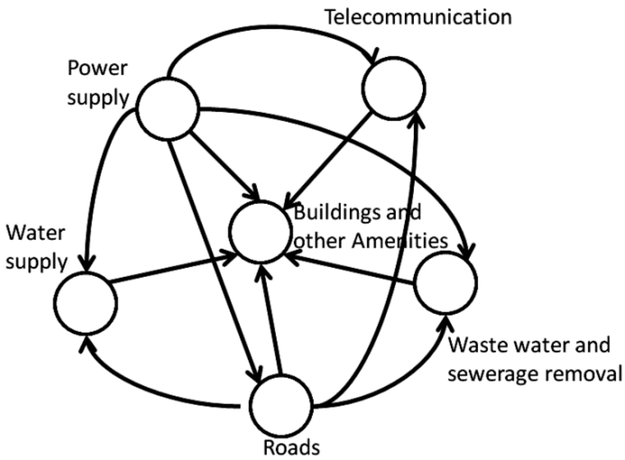


Figure 3: Infrastructure interdependency

4 MODELLING INTERDEPENDENCY USING SYSTEM DYNAMICS

System Dynamics have been used widely to model dynamic behaviour of a complex system through the simulation of complex feedback systems. Stocks (the accumulation of resources in a system), flows (the rates of change that alter those resources), controls (variable that control the flow) and feedback are the central concepts in this methodology. Min et al. (2007) argued that SD simulations can offer insight into important causes and effects that may result in a better understanding of the dynamic and evolutionary behaviour of a system.

4.1 *Conceptual model*

Modelling and conceptualization of urban infrastructure systems using SD concepts are conducted through two diagrams: (i) causal-loop diagrams; and (ii) stock-and-flow diagrams. Figure 3 is a causal loop diagram demonstrating the concept of higher levels of interdependency (among systems). Stock and flow diagrams are developed in the following sections to model dependency between nodes both within and across systems.

4.2 *Causal loop diagram*

Figure 3 shows a diagram of interdependencies which, though not universal, is typical coastal infrastructure systems. Hence, the entire urban infrastructure delivers its service to buildings. Physical interdependency (output of one infrastructure influencing the service of the other) is evident in all the links from power supply. On the other hand, roads often house components of other infrastructure (e.g., water and wastewater pipes, power cables) and therefore the latter are geographically dependent on roads. Two sources of complexity are evident here. The first is obviously the need to clearly articulate dependencies and interdependencies in order to simulate the overall performance of the system. The second is to do with the fact that the performance of each system is measured by incommensurable variables which are therefore hard to compare. As an example, the serviceability measure of a water supply system is typically the number of households it serves at a certain point in time. On the other hand, such a measure of performance is not useful for road networks. This is because traffic generated by a road is composed of both direct use (local residential access) and indirect use (non-residential traffic). Therefore, comparing performance measures of systems often becomes a problem of incommensurability. As mentioned earlier, the SEVA framework and its outranking approach allow us to deal with this problem. The performance of each infrastructure system under stress is measured separately for all the SESs and used as indicators of EVA-INFRA-SD followed by SEVA outranking procedure to generate vulnerability rankings of SESs (Figure 1).

4.3 *Stock and flow diagram*

We use STELLA, an SD simulation tool for building the conceptual framework of the stock and flow diagram. Here the basic unit of analysis is the number of households served, although total number of population can also be used. The service provider of the infrastructure (e.g., water supply authority) can usually supply this data.

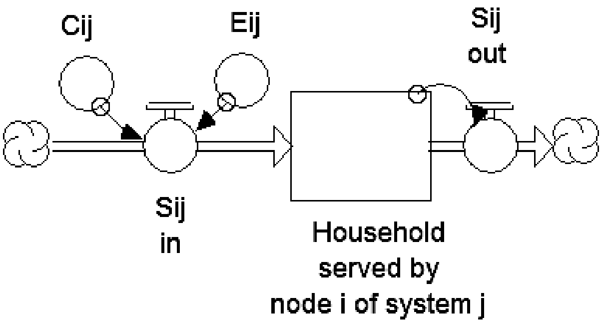
4.3.1 *Problem definition*

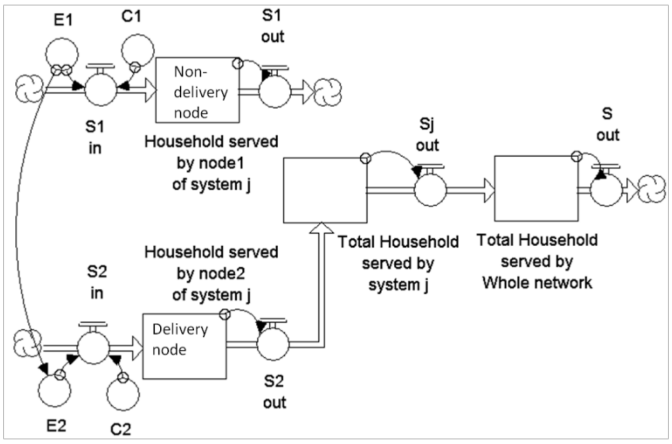
Fluctuation of service can be measured by comparing between No Stress (NS) scenario (e.g., baseline of no disruption) and Under Stress (US) scenario (e.g., when the system loses one or more of its nodes). The maximum difference in population served between these scenarios over a period of time for a given SES will be calculated and used as variable H_{max} representing sensitivity (step 5 of figure 1). We make the following assumptions in the model.

a) under a no-stress scenario the number of household served per unit of time for the whole system is constant (hence, ignoring routine technical difficulties that might cause fluctuation in this number).
b) the adaptive capacity of the council is reflected by the time it takes to respond to an event causing service failure.

Figure 4: SD model for a single node i of system j

Figure 5: Interdependency of EVA-SD





4.3.2 *Model: general equation to measure system performance*

In the following section we will describe the development of a general equation to measure an infrastructure node's performance at any given time.

If m infrastructure systems (e.g., water supply, power supply, wastewater transport etc) are physically interdependent and have comparable measures of performance (e.g., number of households served), then we aim to measure such performance over a period of time using an SD concept.

We consider the number of households served by a specific infrastructure node as a flow that accumulates in a stock (for each infrastructure node i). Rate of this flow is the number of households served per unit of time. The flow is regulated by two control variables applied to each node: capacity and efficiency (Figure 4). Capacity refers to the number of households node i is designed to serve and efficiency is the degree to which the node is able to deliver its service at design capacity. Capacity of a node is often constant as the infrastructure is designed to serve a specific unit (e.g., gallons of water supply, KW of power supply etc) with an objective to serve a specific number of household. Efficiency, on the other hand, is not and may be affected by the stress under consideration. Therefore, the serviceability of a node is time-dependent and can be described by:

$$S_{ij}(t) = C_{ij} * E_{ij}(t) \qquad (1)$$

where S_{ij} is the serviceability of node i of system j ie the number of households served at a given point in time; C_{ij} is the design capacity of node i of system j; E_{ij} is the efficiency of node i in system j defined as degree to which the node is able to deliver its service at design capacity ($0 \le E_{ij} \le 1$, where $E_{ij} = 0$ for complete failure and $E_{ij} = 1$ for full function).

If any physical dependency between nodes is present, we distinguish between node efficiency as determined by its own physical integrity ($E_{ij}(t)$) and node overall efficiency as determined by its own physical integrity AND the efficiencies of its mother nodes ($\bar{E}_{ij}(t)$) (see Figure 5). Hence:

$$\bar{E}_{ij}(t) = E_{ij} \prod_{k=1\ (k\neq i)}^{N_n} \{[\bar{E}_{kj}(t) - 1]D_{ki} + 1\} \qquad (2)$$

where N_n is the total number of nodes in the entire network; D_{ki} is the degree of dependence of node i on node k ($0 \le D_{ki} \le 1$; D_{ki}=0: no dependence; D_{ki}=1: complete dependence). Note that the term inside multiplication operator of equation 2 is 1 if D_{ki}=0 (no dependence) and $E_{kj}(t)$ if D_{ki}=1 (complete dependence).

Clearly, node overall efficiency must be used in equation (1) rather than node efficiency. Therefore, the general equation for serviceability of any node i of a system j at any point in time t, taking dependencies into account is as follows:

$$S_{ij}(t) = C_{ij} E_{ij} \prod_{k=1\ (k\neq i)}^{N_n} \{[\bar{E}_{kj}(t) - 1]D_{ki} + 1\} \qquad (3)$$

Equation (3) may conceivably be nested (ie two nodes are directly or indirectly mutually dependent) in which an iterative scheme would be needed to evaluate $S_{ij}(t)$.

Now, all the nodes of a system do not deliver service to households while some of the nodes do. As an example, distribution main of a water supply system that carries water from its point of production (e.g., treatment plant) does not deliver its service to households directly, while the one near to households does. We call nodes that deliver service directly to household as delivery or system boundary nodes $(S_{ij})_d$. As our objective is to measure system performance in terms of number of households that the system serves, overall system serviceability is the summation of the serviceability of all the delivery nodes:

$$S_j(t) = \sum_{i=1}^{n_d} (S_{ij}(t))_d \qquad (4)$$

where n_d is the number of delivery nodes in a system. Finally, serviceability of the whole infrastructure network can be measured by:

$$S(t) = \sum_{i=1}^{m} S_j(t) \quad (5)$$

(m, defined earlier, is the number of systems in the network).

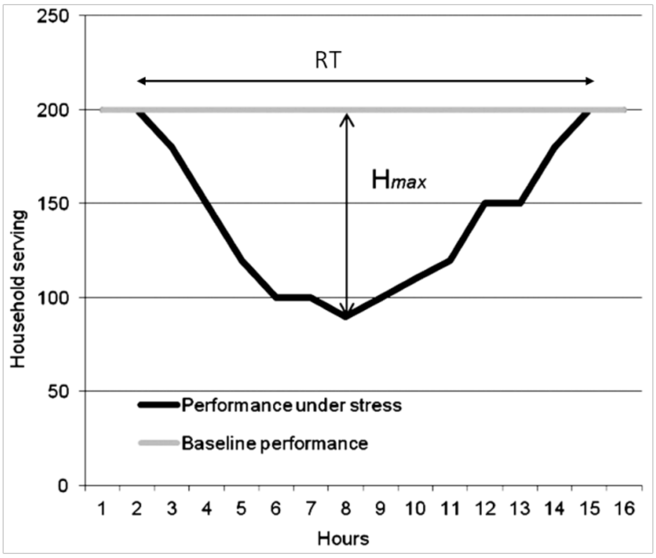
4.3.3 *Measuring system performance under stress (US)*

Using equation 1 to 5 it is now possible to measure serviceability of an infrastructure system (e.g., number of household it serves) at any given time. As per our model assumption, at its full efficiency, serviceability of any node is constant over a period of time at NS (S_{NS}). Let's assume that a storm event affect the infrastructure network of an SES under consideration (e.g., a highly populated beach of an LGA). The fluctuation in serviceability is given by:

$$H(t) = S_{NS} - S(t) \quad (6)$$

It is now possible to measure the sensitivity of the infrastructure network of the SES as H_{max}, the maximum equivalent number of households experiencing single-service interruption in the period RT, between the beginning of the event and the point in time at which all services have been restored to full baseline capacity (see Figure 6). This is measured for all the SESs under consideration and used as an sensitivity indicator of EVA-INFRA-SD to complete the vulnerability matrix (step 6 of figure 1).

Figure 6: Illustrative example of System Dynamics model output



5 CONCLUSION

We presented an infrastructure vulnerability assessment framework in the context of disaster scenario of increased coastal flooding due to SLR that can be used at a local scale. The framework combines an outranking approach that can incorporate partial compensation and non-linearity with a system dynamics model simulating dependencies of infrastructure components and systems. We used the SD model to measure system performance under stress and incorporated the measure as an indicator of sensitivity in the outranking framework. Currently, we are applying this framework to the study of infrastructure vulnerability of a local council in Australia (Shoalhaven City Council) and analysis outcomes will be reported in a separate paper.

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7 REFERENCES:

Abuodha, P. a. O. W., C. D. 2010. Assessing vulnerability to sea-level rise using a coastal sensitivity index: A case study from southeast australia. *Journal of Coastal Conservation,* 14**,** 189-205.

Adger, W. N. 2006. Vulnerability. *Global Environmental Change,* 16**,** 268-281.

Clark, G., Moser, S., Ratick, S., Dow, K., Meyer, W., Emani, S., Jin, W., Kasperson, J., Kasperson, R. & Schwarz, H. 1998. Assessing the vulnerability of coastal communities to extreme storms: The case of revere, ma., USA. *Mitigation and Adaptation Strategies for Global Change,* 3**,** 59-82.

El-Zein, A. & Tonmoy, F. N. 2013a. Incorporating uncertainty and incommensurability in climate change vulnerability assessments: An outranking approach. *Risk Analysis (Under review).*

El-Zein, A. & Tonmoy, F. N. 2013b. Nonlinearity, fuzziness and incommensurability in assessments of vulnerability to climate change: A new framework *Environmental Modeling & Software (Under Review).*

Forrester, J. W. 1961. *Industrial dynamics*, Wiley.

Füssel, H.-M. & Klein, R. 2006. Climate change vulnerability assessments: An evolution of conceptual thinking. *Climatic Change,* 75**,** 301-329.

Harvey, N. & Woodroffe, C. 2008. Australian approaches to coastal vulnerability assessment. *Sustainability Science,* 3**,** 67-87.

IPCC, J. J. M., O.F Canziani, N.A. Leary, D.J. Dokken, K.S. White (Eds.) 2001. Climate change 2001: Impacts, adaptation and vulnerability. Contribution of working group ii to the fourth assessment report of the intergovernmental panel on climate change, cambridge university press, cambridge, uk.

Jacob, K. H., Edelblum, N. & Arnold, J. 2000. Risk increase to infrastructure due to sea level rise. *Climate Change and a Global City: An Assessment of the Metropolitan East Coast Region***,** 17-30.

Kelly, P. M. & Adger, W. N. 2000. Theory and practice in assessing vulnerability to climate change andfacilitating adaptation. *Climatic Change,* 47**,** 325-352.

Meehl, G. A., Stocker, T. F., Collins, W. D., Friedlingstein, P., Gaye, A. T., Gregory, J. M., Kitoh, A., Knutti, R., Murphy, J. M. & Noda, A. 2007. Global climate projections. *Climate change***,** 747-845.

Min, H.-S. J., Beyeler, W., Brown, T., Son, Y. J. & Jones, A. T. 2007. Toward modeling and simulation of critical national infrastructure interdependencies. *IIE Transactions,* 39**,** 57-71.

Munda, G. & Nardo, M. 2009. Noncompensatory/nonlinear composite indicators for ranking countries: A defensible setting. *Applied Economics,* 41**,** 1513-1523.

Ozyurt, G. & Ergin, A. 2009. Application of sea level rise vulnerability assessment model to selected coastal areas of turkey. *Journal of Coastal Research***,** 248-251.

Pederson, P., Dudenhoeffer, D., Hartley, S. & Permann, M. 2006. Critical infrastructure interdependency modeling: A survey of us and international research. *Idaho National Laboratory***,** 1-20.

Rahmstorf, S. 2007. A semi-empirical approach to projecting future sea-level rise. *Science,* 315**,** 368-370.

Rinaldi, S. M. Modeling and simulating critical infrastructures and their interdependencies. System sciences, 2004. Proceedings of the 37th annual Hawaii international conference on, 2004. IEEE, 8 pp.

Rinaldi, S. M., Peerenboom, J. P. & Kelly, T. K. 2001. Identifying, understanding, and analyzing critical infrastructure interdependencies. *Control Systems, IEEE,* 21**,** 11-25.

Sahin, O. & Mohamed, S. Decision dilemmas for adaptation to sea level rise: How to, when to? Industrial Engineering and Engineering Management, 2009. IEEM 2009. IEEE International Conference on, 2009. IEEE, 1622-1626.

Tonmoy, F. N. & El-Zein, A. Climate change vulnerability assessment by outranking methods: Heat stress in sydney *In:* SORIAL, G. & HONG, J., eds. Environmental Science and Technology, 2012 2012 Houston, USA American Science Press, 272-279.

Tonmoy, F. N., El-Zein, A., Ghetti, I. & Massie, R. Vulnerability to sea level rise of 8 beaches in shoalhaven: A new multi-dimensional assessment methodology. 21st NSW Coastal Conference, NSW Coastal Management-Coming of Age? November, 2012, Kiama, Australia., 2012.

United Nations, D. O. E. a. S. A., Population Division: 2012. World urbanization prospects, the 2011 revision: Highlights. New York.

Viehhauser, M., Larsson, K. & Stålnacke, J. 2006. Impacts of future climate change and sea level rise in the stockholm region: Part ii - gis analysis of future flooding risks at regional and municipal scales.

Walsh, K., Betts, H., Church, J., Pittock, A., Mcinnes, K., Jackett, D. & Mcdougall, T. 2004. Using sea level rise projections for urban planning in australia. *Journal of Coastal Research***,** 586-598.

Yoo, G., Hwang, J. H. & Choongik, C. 2011. *Development and application of a methodology for vulnerability assessment of climate change in coastal cities,* Kidlington, ROYAUME-UNI, Elsevier.