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**Simulation of Dynamic Resilience:  
A Railway Case Study**

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## Executive Summary

This report presents the application of generic framework for implementation of dynamic resilience in modeling complex system behavior as a consequence of natural disasters. The report represents the final outcome of the project “*Simple Proxies for Risk Analysis and Natural Hazard Estimation*” supported by MITACS and Property and Casualty Insurance Compensation Corporation. It documents an application of the dynamic resilience simulation to the analysis of railways exposed to flooding. The proposed resilience framework quantifies the dynamic behavior of the system which can be used (i) for the comparison of various alternate strategies for system performance improvement and (ii) support of decision making processes. The objectives of the study are to (i) apply dynamic resilience simulation based on the system dynamics modeling approach to railways system behavior under flooding conditions; and (ii) use dynamic resilience framework to compare various strategies, and performance of different railway companies under disaster conditions.

The methodology developed in this research and reported here can be implemented by various industries/companies/organizations: (i) to quantify and compare different hazard response strategies; and/or (ii) to compare the performance of different industries/companies/organizations under similar hazard conditions (for example, comparison of the performance of the two railway companies under similar flood conditions). The generic framework for spatial dynamic resilience can be implemented either (i) for the calculation of spatial and temporal resilience under various hazard response strategies; or (ii) for the comparison of resilience of different companies/industries/organizations under same hazard conditions; or (iii) for the combination of

previous two. The framework uses ArcGIS/MATLAB spatial tool for spatial analysis and VENSIM system dynamics simulation for temporal resilience calculation.

The remainder of the report is organized as follows. Section 1 introduces the background of the research work. In Section 2, the concept of spatial dynamic resilience measure is outlined. Following this, the application of the spatial dynamic resilience using system dynamics modeling is presented in Section 3. The illustration of the resilience framework is brought out using a case example on railways subject to flood hazard is presented in Section 4. Finally, Section 5 outlines the summary and conclusions of the present study and the scope for future research work. Appendix A provides description of generic framework and steps involved in building dynamic resilience model. The details of C# programming code for linking dynamic models, and MATLAB programming code to produce dynamic resilience map are provided in Appendix B and C, respectively. List of previous reports published in this series is provided in Appendix D.

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## **1.0 Introduction**

Increasing number of catastrophic disaster events across the world due to natural hazards (floods, droughts, hurricanes, and tornadoes) has led to loss of thousands of human lives and shattered the global economic growth. The current scientific consensus is that this could be due to the effects of climate change. According to the Intergovernmental Panel for Climate Change fifth assessment report (IPCC, 2013) the climate characteristics and patterns are changing in time and space. Further it is reported that the increase in the concentration of greenhouse gases would lead to more catastrophic events in the near future with varying degree of exposures. Therefore, there is a need to (a) increase our understanding of mechanisms causing natural disasters; (b) investigate various options for mitigation of their impacts; and (c) develop various adaptation options in order to minimize their future impacts. Natural disaster management is embedded in the study of complex systems (natural and constructed) that are vulnerable to multiple failures.

Recent research focus of many disaster management studies has been related to the concept of resilience – measure that integrates vulnerability and adaptive capacity of a complex system (Park et al., 2013). Resilience of complex systems is linking their behavior to system structure through feedback (in time and space). The concept of resilience has been adopted in various fields such as ecology, economics, risk management, and others (Holling, 1973; Arthur, 1999; Folke et al. 2002; Starr et al. 2003; Fiksel 2006; Park et al, 2013). Recently this concept is been adopted to quantify the impacts of climate change on urban environments (Chang et al., 2013; Simonovic and Peck, 2013).

Past disaster management work focused on management, planning, resource allocation, structural/non-structural issues, risk, rehabilitation, sustainability and system resilience (Simonovic, 2011). Recently, the research focus is shifted to addressing the gaps between the resource allocation, sustainability and resilience. This report presents the work in progress that is focused on the development of a generic spatial dynamic resilience simulation modeling tool to assist in natural disasters management. The research presented in this report is a collaborative effort between the Western University and Property and Casualty Insurance Compensation Corporation (PACICC). The main objective of the presented research is to develop an innovative concept of resilience and investigate its implementation in natural disasters management as a replacement for a traditional risk management.

Simonovic and Peck (2013) proposed a framework to quantify spatial dynamic resilience through system dynamics simulation to assess the impacts of climate change on coastal megacities. Peck and Simonovic (2013) presented the design and implementation of generic system dynamics simulation model (GSDSM) for use in coastal city resilience quantification and assessment. In their work, they show the implementation of the dynamic resilience (which is addressing temporal change in resilience measure) but not the spatial dynamic resilience. Srivastav and Simonovic (2014) developed a generic framework which integrates the spatial and the dynamic characteristics of resilience to assess the physical, economic, social, health and organizational impacts of sudden hazard event. The framework is flexible and can be used for creating dynamic resilience maps for a wide variety of impacts. Recently, Peck et al (2014) developed the coupling program tool to link spatial and temporal resilience using GIS and VENSIM system dynamics

simulation software. This report builds on the works of Srivastav and Simonovic, 2014 which provides a simplified framework to integrate spatial and dynamic characteristics of resilience.

The impacts of hazardous event are characterized by: (i) the location - where it has occurred (space); and (ii) the timing - when it has occurred (time). Same impacts may have different effects in different domains. For example, floods in cities have wide spread spatial effects on the overall city performance (here the spatial scale plays a major role). However, the same flood may have a different impact for different industry/company/organization and their performance (here individual systems resources and management strategies play a major role – sub-domain problem). This report builds on the work of Srivastav and Simonovic, 2014 and extends the generic framework for dynamic resilience to develop a model for sub-domain systems such as industries/companies/organizations wherein the systems’ resources and management strategies are used to improve resilience of the system. Hereafter, industries/companies/organizations are called *companies*, unless stated otherwise.

This report divides the dynamic resilience problems faced by companies into two types.

Type 1: A single company under the impact of natural hazard, referred as **intra-system dynamic resilience (IaSDR) problem**.

- The possible solution to such a problem can be found through the development of multiple strategies that provide for a wide range of system performances and use of dynamic resilience for their comparison.

Type 2: Multiple companies under the impact of natural hazard, referred as **inter-system dynamic resilience (IeSDR) problem**.

- The possible solution to this type of problem can be obtained by testing and comparing the performance of different companies in response to the disturbance using dynamic resilience.

The implementation of dynamic resilience integrates system dynamics simulation and the spatial mapping tools. We have adopted VENSIM system dynamics simulation software (Ventana Systems, 1995) for system dynamics modeling. In the following section we present a detail explanation of resilience and the calculation of spatial dynamic resilience.

## **2.0 Resilience**

According to the United Nations (UNISDR, 2012) report it is expected that there will be significant increase of world's urban population and the majority of economic capital will be concentrated in cities which are very often situated in disaster prone areas (Ayyub, 2013; UNISDR, 2012). It is also reported that in 2011 alone there were 29,782 deaths and a loss of USD \$366 billion due to natural disasters (UNISDR, 2012). It is expected that these numbers will increase with future increase in frequency and magnitude of natural hazards due to climate change.

In recent years the concept of system resilience is adopted to study the impacts of natural hazards, to reduce their impacts and provide more efficient response strategies. In the past, most of the disaster management systems were focused on the minimization of the risk of failure. Two definitions of risk can be located in the literature: (a) hazard based risk definition; and (b) impact based definition (Simonovic, 2012). According to the first definition the risk is defined as the chance of a particular event occurring. According to the second one, the risk is a combination of the chance of a particular event and the impact that the event would cause if it occurred. The main characteristic of these definitions is a static view of disaster risk – no change of risk with time.

The concept of resilience is much broader. It describes the ability of a complex system to respond and recover from a disaster. The resilience concept also includes those system characteristics that allow system to absorb impacts and cope with a disaster, during the emergency phase as well as during the recovery phase. The concept includes adaptive processes

that facilitate the ability of the system to re-organize, change, and learn in response to a threat (Simonovic and Peck, 2013). There are many definitions of resilience (taken from Simonovic and Peck, 2013), from general:

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

to ecology-based:

- (v) The ability of a system to withstand stresses of ‘environmental loading’;

to hazard-based:

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

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

often viewed as static. It is important to understand the difference between concept of risk management and resilience. They both offer different perspectives for handling impacts. Table 1 gives one potential comparison between the risk and resilience (after Park et al., 2013).

Table 1: Comparison of concepts of resilience and risk (Park et al., 2013)

	<b>Risk Management</b>	<b>Resilience</b>
<b>Design principles</b>	minimize risk of failures	Adaptation to changing conditions without permanent loss of function
<b>Design objectives</b>	Minimization of probability of failure	Minimization of consequences of failure
<b>Design strategies</b>	Armoring, strengthening, oversizing, resistance, redundancy, isolation	Diversity, adaptability, cohesion, flexibility, renewability, regrowth, innovation, transformation
<b>Relation to sustainability</b>	Security, longevity	Recovery, renewal, innovation
<b>Mechanisms of coordinating response</b>	Centralized, hierarchical decision structures coordinate efforts according to response plans	Decentralized, autonomous agents respond to local conditions
<b>Modes of analysis</b>	Quantitative (probability-based) and semi-quantitative (scenario-based) analysis	Possible consequence analysis of involving scenarios with unidentified causes

Any physical and non-physical system when subjected to external shock such as natural hazard (for example flood or earthquake), has a limited capacity to resist, absorb and recover from this shock depending upon the shock intensity, system vulnerability and adaptive capacity. The external shocks are usually termed as impacts. Depending upon the type, intensity and the duration of the impacts the performance of the system is affected and can be represented as loss of system performance.

The capacity to handle the shocks or impacts is termed as adaptive capacity of the system. The adaptive capacity (AC) of the system is an integrated behavior of the various components of the system that varies with time and space. It can be measured using four performance indicators: robustness, redundancy, resourcefulness and rapidity (four R's) first introduced by Bruneau et al. (2003, 2007). These performance indicators are defined as

- (i) Robustness ( $R_1$ ): ability of a system to resist external shocks without suffering any damages
- (ii) Redundancy ( $R_2$ ): the readiness of the system in which it resists external shocks beyond its natural capacity
- (iii) Resourcefulness ( $R_3$ ): the ability of the system to disseminate the resources during external shocks
- (iv) Rapidity ( $R_4$ ): the ability of the system to recover (in terms of time) from damages caused by external shocks

The adaptive capacity of a system is a function of both, time and space. It is mathematically expressed as a function of four R's as:

$$AC(t, s) = f(R_j(t, s)) \quad j = 1, 2, 3, 4 \quad (1)$$

where  $AC$  is the adaptive capacity of the system;  $f()$  is the mathematical function combining the effects of four  $R$ 's;  $j$  is the index for each of the  $R$ ;  $t$  represents the time period;  $s$  represents the spatial location.

In the following sections we present (i) mathematical framework for the computation of dynamic resilience based on the concepts of performance loss and adaptive capacity and (ii) the implementation of the framework to the solution of Type 1 and Type 2 problems.

### 3.0 Mathematical framework for dynamic resilience

The computational definition presented here is taken from Simonovic and Peck (2013). A typical system performance under shock and recovery is presented in Figure 1. Before the shock or impact, the system performance level is denoted by  $P_o^i(t,s)$ . The system experiences a shock and change of performance between time  $t_o$ , which denotes the beginning of the disaster event, and time  $t_1$ , which indicates the end of the event. The system performance change continues beyond time  $t_1$ , till  $t_r$  the time when system fully recovers from the shock. It is evident from Figure 2 that ending system performance level may (i) be the same as the initial level (solid line) (ii) not reach the initial performance level (dashed line); or (iii) reach the performance level exceeding the initial level (dotted line).

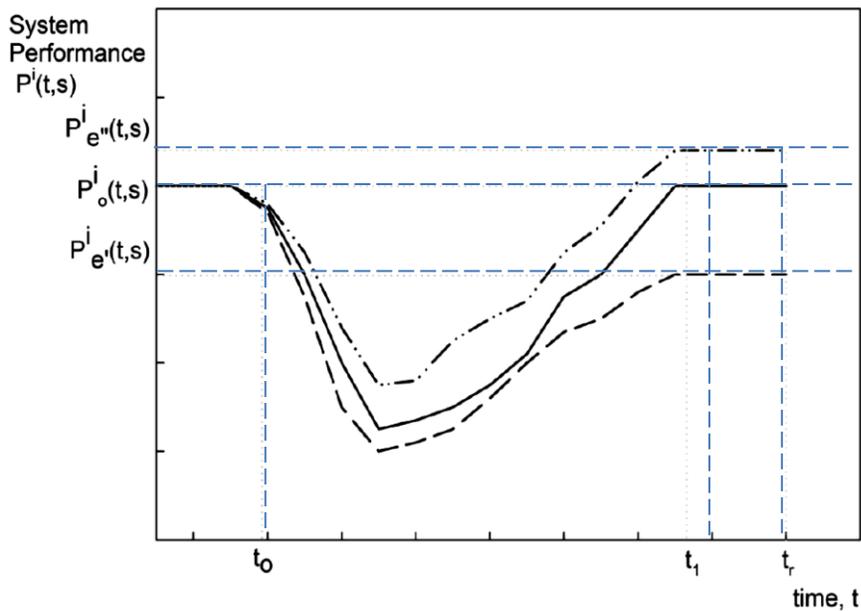


Figure 1: Performance of a system when subject to a shock (after Simonovic and Peck, 2013)

Mathematically the measure of change (loss) in system performance for impacts 'i' can be represented using the area under the system performance curve between the start of the impact ( $t_o$ ) and the recovery time period ( $t_r$ ):

$$\rho^i(t, s) = \int_{t_o}^{t_r} [P_o^i - P^i(t, s)] dt \quad \text{where } t \in [t_o, t_r] \quad (2)$$

where the resilience  $\rho^i$  measures the level of system performance for impact 'i' in time ( $t$ ) and at a particular location in space ( $s$ ) (Simonovic and Peck, 2013);  $P^i$  denotes the performance of the system for impact 'i' at any given time ( $t$ ) and a particular location ( $s$ );  $P_o^i$  represents initial state of the system for impact 'i'.

The system resilience at any time ( $t$ ) is calculated from the change in system performance for impacts 'i' as follows

$$r^i(t, s) = 1 - \left[ \frac{\rho^i(t, s)}{P_o^i \times (t - t_o)} \right] \quad (3)$$

where  $r^i$  now takes value between 0 and 1 (0 denoting no resilience and 1 maximum resilience).

The three possible outcomes of system performance illustrated in the resilience space are shown in Fig 3. A shock to the system may create various impacts. The same computational principles can be used for each impact and the overall system resilience ( $R$ ) can be obtained by their integration using

$$R(t, s) = \left( \prod_{i=1}^M r^i(t, s) \right)^{\frac{1}{M}} \quad (4)$$

where  $M$  is the total number of impacts.

It is important to note that the use of  $s$  in this mathematical derivation as the notation of spatial location can be easily expanded and/or replaced to better describe other possible problem

domains: for example space of decision options; space of companies; space of affected regions; and similar. Two case studies in Chapter 5 are illustrating this point very well.

Figures 3 and 4 illustrate the process of resilience calculation when a systems performance is subject to a shock and recovery. As it can be observed from Figure 2, the shaded area between  $t_0$  and  $t_1$  shows the cumulative loss/gain of system performance after the system has been subject to a shock. The time of recovery  $t_r$  indicates the moment when the the physical characteristics of the disturbed system return to pre-disturbance state (for example, in the case of flood river water level returns to pre flood level; in the case of damaged highway the time when the highway opens for tarffic after the disaster); and similar). The three possible outcomes of system performance illustrated in the resilience space are shown in Figure 3. It is to be noted that the system resilience will vary in time and space. In the next section we present a detail computational framework for the implementation of spatial dynamic resilience calculation under various impacts and its use in the development of dynamic spatial maps that can assist in better understanding of systems behavior under shock.

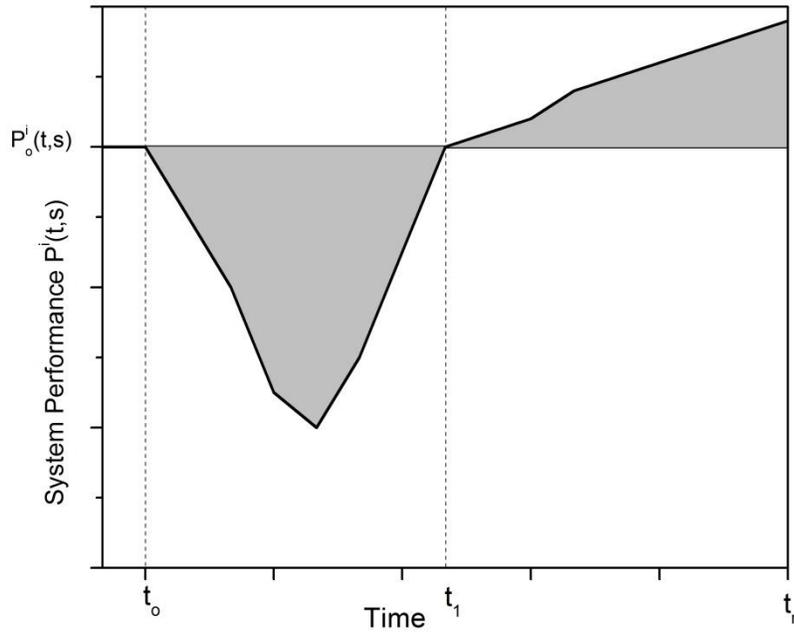


Figure 2: Variation of system performance after a shock

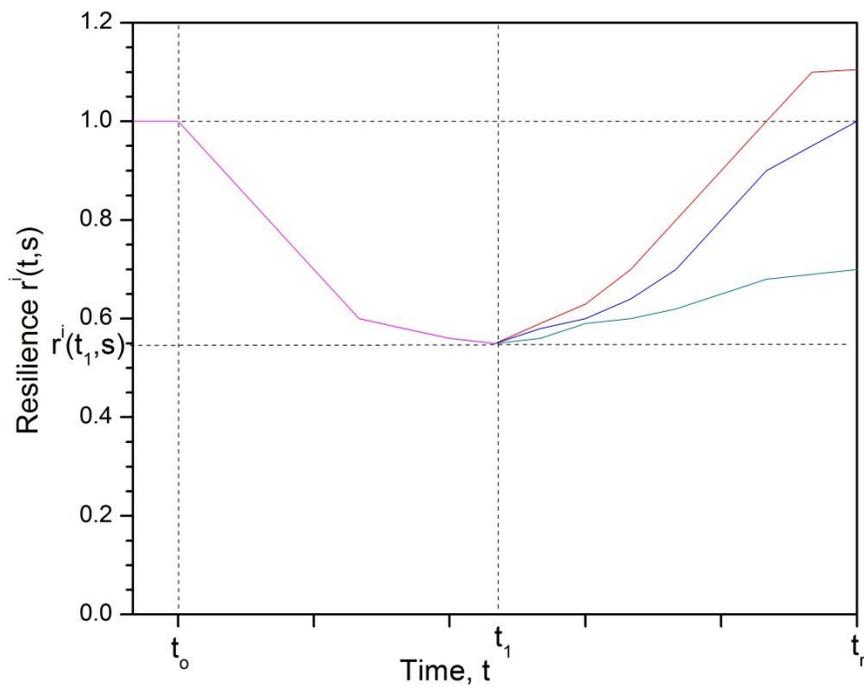


Fig. 3: Variation of system resilience after a shock

## **4.0 Dynamic resilience computation for companies**

In this section, we present a generic computational framework for the development of dynamic resilience maps for companies. The dynamic resilience of companies is computed for two problem types, IaSDR and IeSCR. The generic implementation framework for both problems consists of three main components: (i) system dynamics simulation model; (ii) C# integration modules; and (iii) mapping modules developed using MATLAB/GIS. The details of these components are presented in Appendix A.

### **4.1 Intra-system dynamic resilience simulation (IaSDR) model**

Ability to handle shocks from, or impacts of, natural hazards can be used as a measure of the performance of a company. The IaSDR model architecture is presented in Figure 4. The model is divided into three components: (i) system dynamics simulation model; (ii) spatial mapping tool; and (iii) model results (resilience of the system). The performance of the system depends on the ability of the system to recover from the shock (temporal) and location of the impact (spatial). In this model, the response or a set of adaptation strategies (referred only as strategies further in the text) to be compared for a given shock is selected by the user (Figure 4). The strategies are composed of variations in adaptive capacity (4R's i.e., Robustness, Redundancy, Resourcefulness and Rapidity). The company can adopt any strategy and find out the corresponding performance by using the resilience value calculated from performance loss and adaptation capacity. Each strategy would result in one graph showing dynamic resilience value for each pixel in space. All values together will present a dynamic resilience map corresponding to the change of system resilience as a consequence of a particular strategy. The use of these information can be determined by the decision maker and later in this Section a few ideas are

provided for potential adoption. The mapping tool links the system dynamics simulation model to spatial mapping software such as GIS. The output of the model is the resilience of the company and can be used to compare different strategies.

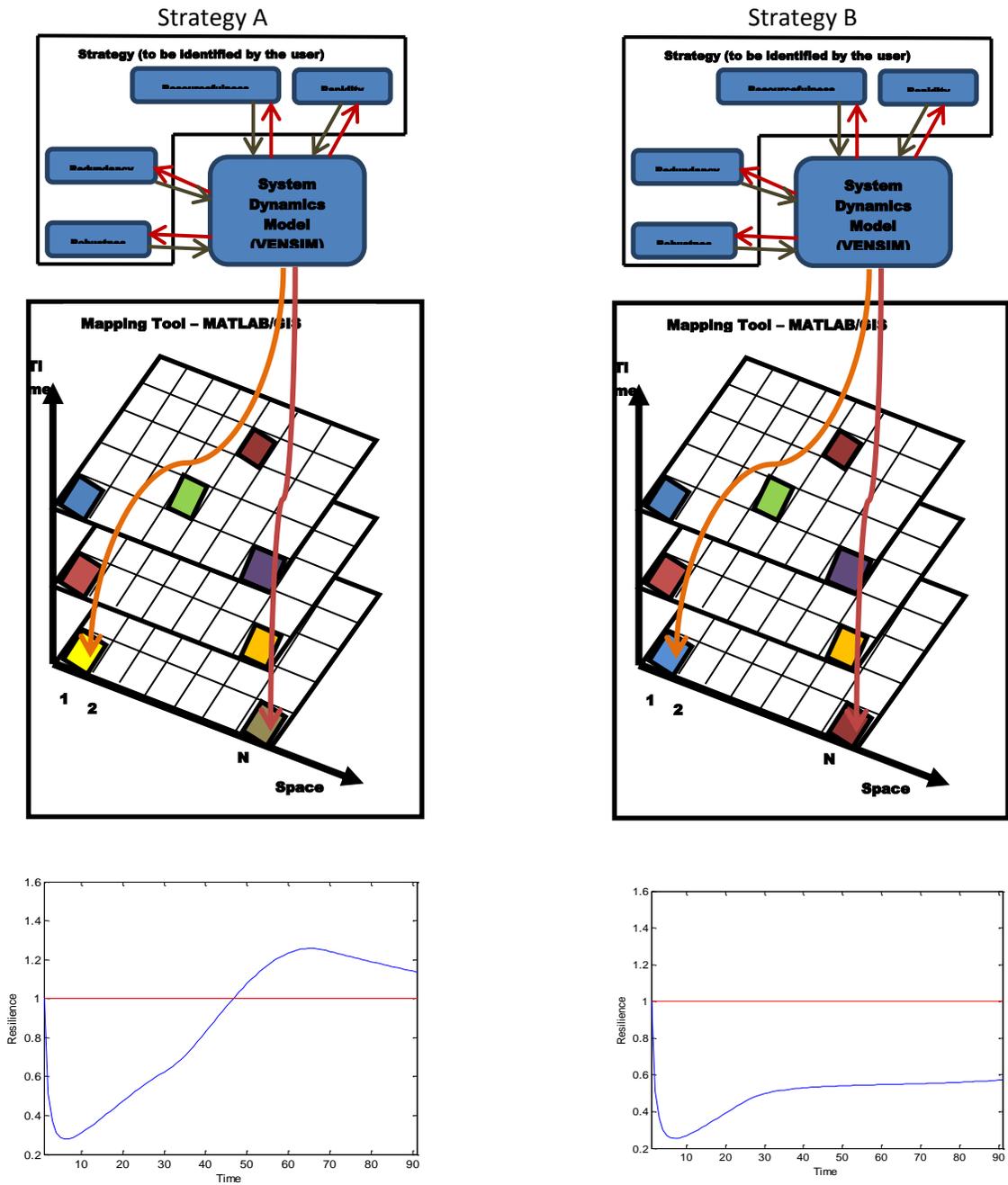


Figure 4: Intra-system dynamic resilience model for mapping spatial dynamic resilience. Comparison of two strategies (A and B) for a company based on the dynamic resilience

The following steps are involved in the implementation of generic dynamic spatial resilience framework using IaSDR model:

1. Identify all impacts associated with the system disturbance.
2. Generate number of alternate strategies (to be obtained from the decision maker or user).  
These strategies are represented as 4R's.
3. Build a system dynamics model to simulate system performance.
4. For each of the strategies in Step 2, simulate the system dynamics model in space.
5. For each strategy calculate the resilience of the company using Equations (1) to (4).
6. Rank/select the adaptation strategy for the company based on the dynamic resilience of the system. The possible selection criteria are discussed in Section 4.3

The dynamic spatial resilience offers various information to the decision maker. The use of the information can reflect the decision maker's preferences. One possible choice is to select a strategy based on the speed of performance recovery. Another choice can be based on the highest level of resilience achieved at  $t_r$ , and so on. Section 4.3 offers further discussion of selection criteria.

#### **4.2 Inter-system dynamic resilience simulation (IeSDR) model**

In real world, many companies function together and provide services in the same space. These companies will respond differently when subject to the same natural hazard shock (such as flood, storm, hurricane, etc.). The performance of the various companies can be compared using the proposed concept of dynamic spatial resilience, IeSDR model. The architecture of IeSDR model is presented in Figure 5. The IeSDR model is similar to IaSDR except that each of these models represents a company unlike in the later where each of the system dynamics models would

represent the strategy adopted by a single company. In this problem, depending on the company location in space and strategy adopted, the system would exhibit varying levels of dynamic resilience. In Figure 5, we consider two companies X and Y, which adopt different strategies when subjected to the same shock.

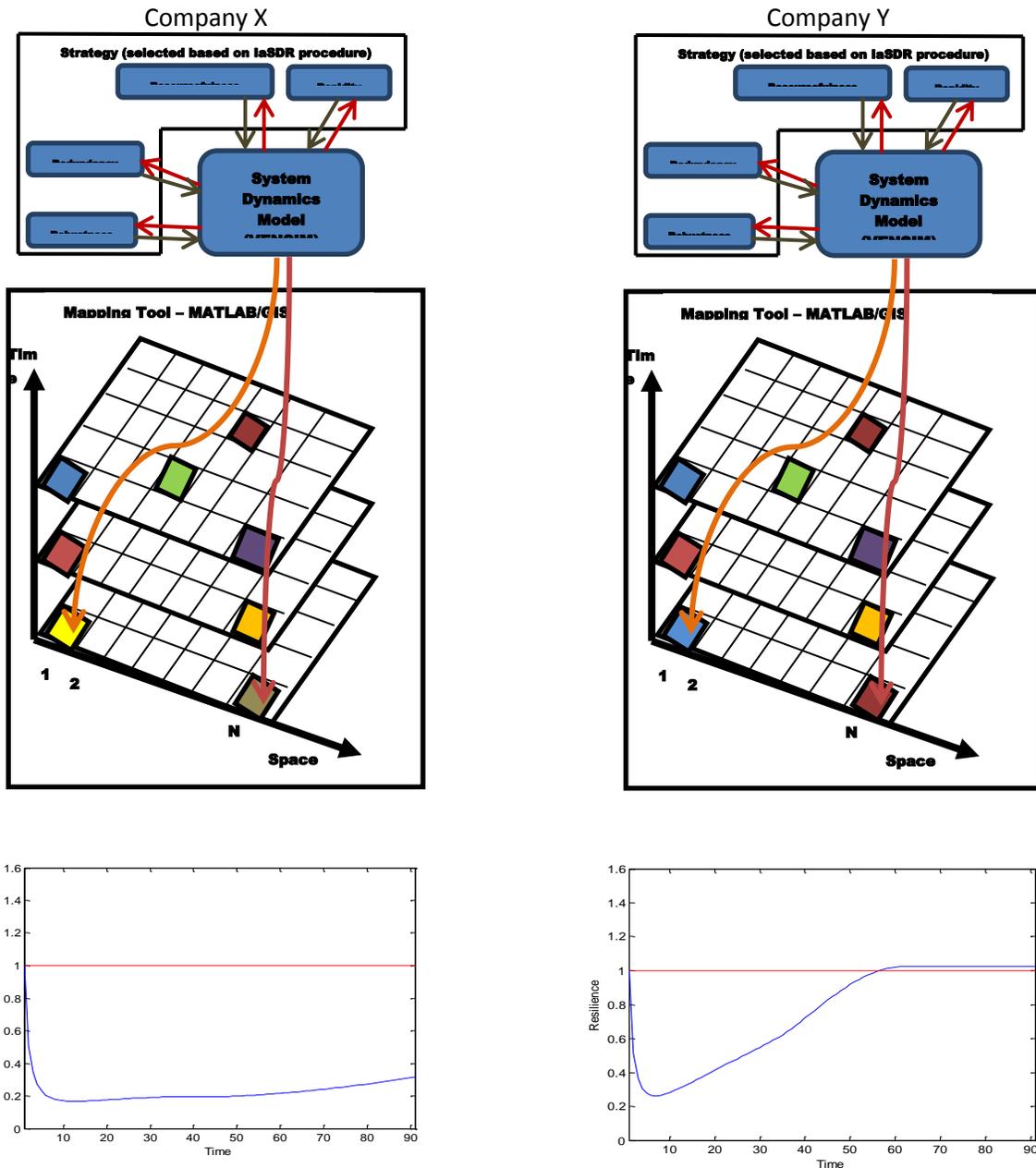


Figure 5: Inter-system dynamic resilience model for mapping spatial dynamic resilience. Comparison of two companies (X and Y) based on the dynamic system resilience.

The following steps are involved in the implementation of generic dynamic spatial resilience framework using IeSDR model:

1. Identify all impacts associated with the system disturbance for each of the companies.
2. Generate a strategy for each of the companies (to be obtained from the respective company decision maker). The strategies for the individual companies can be selected based on the IaSDR modelling procedure through the selection of values for 4Rs.
3. For each company, build a system dynamics model to simulate system performance.
4. Simulate the system dynamic model in space for each of the companies using the strategies defined in Step 2.
5. Calculate the resilience for each of the companies using Equations (1) to (4).
6. Rank/select the best performing company based on the dynamic resilience of the system.

The possible selection criteria are discussed in Section 4.3

### **4.3 Decision criteria**

The use of dynamic spatial resilience for the comparison of various strategies using IaSDR, and companies using IeSDR, offers a plenty of insight in the system performance in response to the disaster impact/s and the response strategy selected. All the information can be used at the same time to make the choice of the ‘best solution’, or various criteria for the selection of the ‘best solution’ can be derived from the available information based on the preferences of the decision maker. In this report, four criteria have been derived to illustrate to decision making context based on the dynamic spatial resilience illustrated in Figure 6.

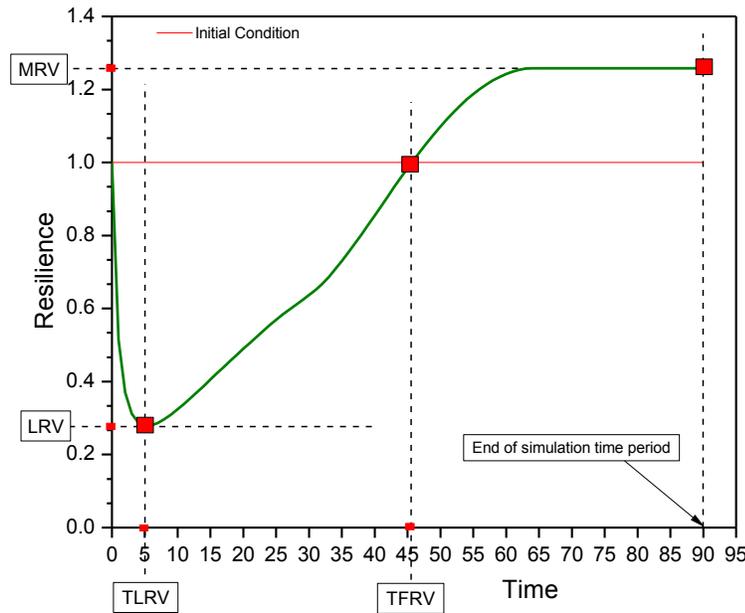


Figure 6: Decision making selection criteria based on the dynamic spatial resilience framework

The selected criteria are:

- (i) The maximum resilience value (MRV): the level of system performance achieved when the physical characteristics of the disturbed system return to pre-disturbance state (end of simulation period). According to this criterion the higher value of MRV is preferred.
- (ii) Time to fastest recovery of system performance (TFRV): the time required by the system under the impact of a disaster to reach the resilience value of one. According to this criterion the shortest time TFRV is preferred.
- (iii) Lowest resilience value (LRV): the maximum loss of system performance due to the disturbance over the simulation period. According to this criterion the higher value of LRV is preferred indicating the smaller loss of system performance.

Time to lowest resilience value (TLRV): the time at which the system reaches the lowest resilience value (LRV). There are different ways how can this criterion used in the decision making process: (1) select the lowest TLRV which shocks the system fast and hard but offer longer time for recovery (mobilization of resources, assistance to population; etc); and (2) select the highest TLRV which shocks the system in a much more controlled way and leaves much shorter time for recovery.

#### **4.3.1 Implementation of decision criteria to IaSDR problem**

For illustrative purposes, in Figure 4, the system performance is evaluated for two strategies (A and B) and the resulting dynamic resilience for each of them is presented. The potential implementation of four decision criteri in selection of the preferred strategy is discussed below:

1. MRV: The strategy which results in highest system performance (i.e., greater overall resilience value) when compared to others is considered to be the best. In Figure 4, the strategy A results in higher value of resilience then strategy B. In this case, the choice of strategy A over strategy B is justified according to MRV criterion.
2. TFRV: The strategy which results in shortest system recovery (i.e., the shortest time in which the resilience value reaches one, Figure 6) will be preferred according to this criterion. Figure 4 shows again that the strategy A results in dominating system performance when compared to the strategy B. In case of strategy B the system is unable to recover from the shock (as the value of resilience remains below one over the simulation time period).
3. LRV: In this case the strategy which results in lower loss of system performance will be considered preferred. Figure 4, shows that according to this criterion the minimum

resilience value for strategy B is lower than the value of strategy A, and therefore strategy B will be a preferred choice according to this criterion.

4. TLRV: The strategy which results in minimum resilience value faster is considered as a preferred one. In Figure 4, strategy B is dominating strategy A according to this criterion too. It is important to note that the implementation of this criterion depends on the decision maker and particular decision problem at hand. It is possible that larger TLRV may be preferable if the circumstances are calling for let us say more time for mobilization of rescue equipment or financial resources.

#### **4.3.2 Implementation of decision criteria to IeSDR problem**

In Figure 5, an illustrative example is considered, where the performance of two companies, X and Y, in response to the same disturbance is compared. The selection of the best performing company according to the proposed criteria derived from dynamic spatial resilience is company based on the system performance is discussed for the four selection criteria as follows.

1. MRV: In Figure 5, the systems performance of Company Y reaches the higher value of resilience than Company X. Further, the strategy adopted by Company X will never result in pre-disturbance company performance. .
2. TFRV: The performance of Company Y is superior to Company X as the former is able to recover faster from the shock (Figure 5).
3. LRV: In Figure 5, the minimum resilience value for Company X is lower than the LRV of Company Y. In this case, the performance of Company Y is preferred to Company X.
4. TLRV: The performance of the company which reaches minimum resilience value faster is considered to be preferred. In Figure 5, Company Y shows more preferable performance than Company X.

## 5.0 Case study –railway under flooding

In order to effectively demonstrate the utility of dynamic spatial resilience framework for the implementation with IaSDR and IeSDR problems, a hypothetical example has been created for analyses of railway companies' resilience when subjected to flooding conditions. Extreme weather events such as floods have major implications on railways. The potential damage to railway infrastructure results service disruption for both public and commercial sectors. The major impacts due to flooding lead to scouring and flooding of bridges, inundation of tracks, embankment scouring, culvert washout and failure of equipment. In order to deal with flooding the rail companies usually insure losses due to the inundation of tracks, damages to rail infrastructure and interruption of business. Figure 7 shows a structure of the simplified theoretical dynamic simulation model for a company. The system dynamics simulation model consists of different variables that affect the resilience of the system. The key variables that define the performance of the company are the 4R's, i.e., robustness, rapidity, resourcefulness and redundancy. Every performance measure indicators are used in the quantification of impacts and adaptive capacity 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 impacts or adaptive capacity standards. This is how are 4R's quantified in this example. In Figure 7, certain variables such as climate change, exposure, vulnerability and influence from external factors are ill defined. These variables are intended to be "placeholders" for further model expansion. For more details on how to develop system dynamics models the readers are directed to Simonovic (2011) and Peck and Simonovic (2013).



illustration of the framework two example cases are presented, one corresponding to the generic problem IaSDR and other corresponding to IeSDR. First example illustrates selection of the best adaptation strategy and the second offerc comparison of two railway companies operating under the same disturbace (flood).

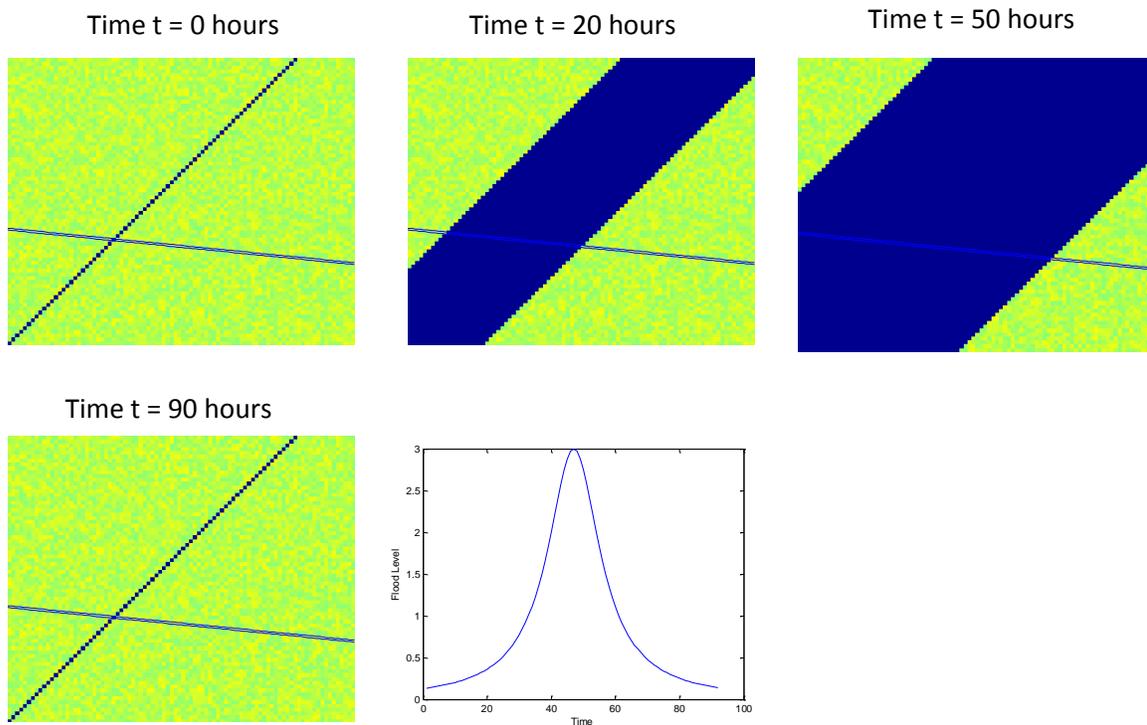


Figure 8: Flood inundation map with flood levels. The light blue parallel lines indicate railway tracks and dark blue shaded area indicates extent of flood inundation.

### 5.1 Railway case study - IaSDR problem

The adaptive capacity represents one of the main inputs that allows the use of spatial dynamic resilience simulation for comparison of various adaptation options. In this report we propose the use of four key variables: robustness (R1), rapidity (R2), resourcefulness (R3) and redundancy (R4) as the way of describing the adaptive capacity. Theoretical framework presented here can easily accept any other form of quantitative description of adaptive capacity. The 4R's should fully describe the adaptation strategy implemented with the system that defines its performance

under the disturbance (flood). The mathematical form of adopted 4R's (they can be very simple, from number of hospital beds to very complex economic functions of business disruption due to disturbance, for example) can be very different and it will directly affect the system performance under changing conditions.

A simplified (arbitrarily selected) time dependent functions for the 4R's used in this illustrative example are shown in Figure 9. In this example the 4R's represent: (i) the ability to maintain services and railway tracks and equipment - robustness function; (ii) multiple response units and alternative transport arrangements - redundancy function; (iii) arrangements for reimbursement or insurance - resourcefulness function; and (iv) procurement of new equipment to return to normal operations - rapidity function. The functions can take any form, however for illustration, these are assumed linear as shown in Figure 9. The change of these functions with time is the consequence of interdependence of disturbance impacts. The schematic presentation of the implementation of dynamic resilience framework to IaSDR problem is in Figure 4.

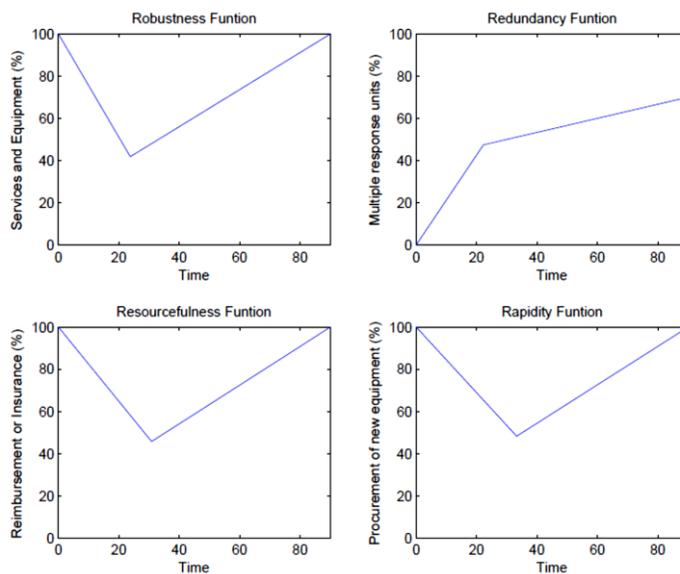


Figure 9: A typical example of four R's functions at a given location

In this example, the spatial resolution of the study area is assumed 90×90 spatial units for illustrative purpose only. In the event of flooding the railway tracks (a) could get inundated, and/or (b) damaged. Under these conditions, the functionality of the railway is affected and this in-turn affects the performance of the railway company. The dynamic resilience framework provides an effective tool for analyzing the performance of the railway system under the disturbance – flood. The strategies developed to represent adaptive capacity of the system can be widely simulated and to provide the decision makers with valuable information that can be used for emergency management and mitigation planning. For illustrative purpose 100 alternate strategies are hypothetically generated for a railway company subjected to flood hazard. Figure 9, shows one of the alternate solutions for four R's. As discussed earlier the 4R's can take any functional form depending upon the companies resources, alternate arrangements and procurement of new equipment. In this example, a number of such alternate performance indicators is hypothetically generated to simulate the performance of the railway company.

The maps with temporal and spatial variations of flood inundation and system resilience are shown in Figures 10-12 for the simulation time period  $t = 0, 50$  and  $90$  hours. Each of the figures consists of four panels. The top panel provides the temporal change of dynamic resilience value – multiple lines correspond to multiple adaptation option alternatives (values of 4Rs) which captures the overall performance of the railway system. The second panel (bottom left) in the figures shows a hypothetical flood hydrograph used in this illustrative case study. The third panel (bottom middle) consists of a spatial inundation map with 90×90 spatial units resolution and a railway track crossing the river. The fourth panel (bottom right) illustrates the spatial resilience due to flooding of the tracks. In IaSDR this map shows the change of resilience at one point in

space (intersection of railway tracks and the river). We have selected, for illustrative purposes only, to show the change of resilience value using circles of different diameter. However, this value is the resilience value at one point (intersection point) only.

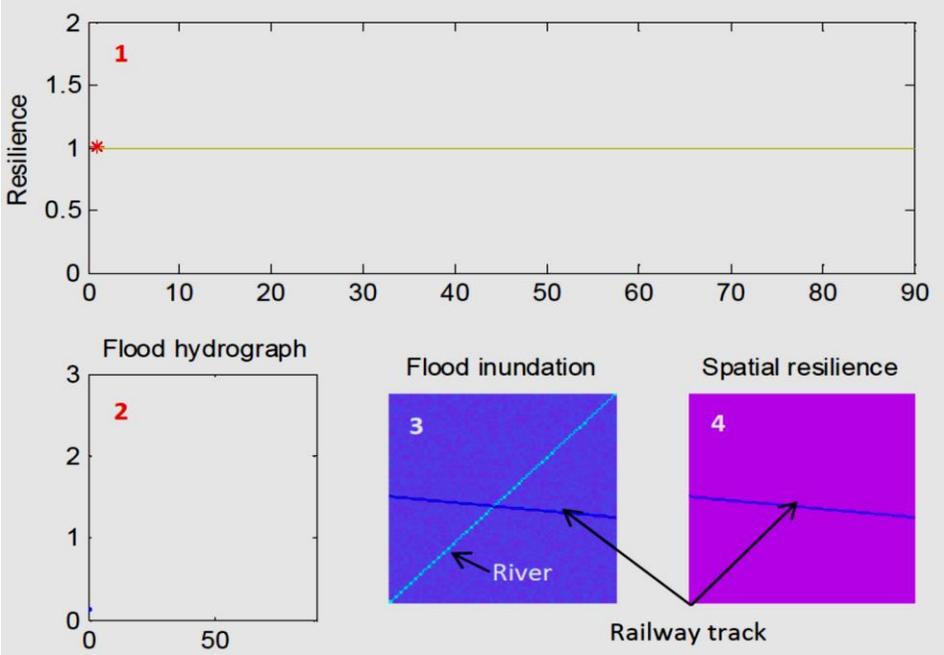


Figure 10: IaSDR problem – Railway company under flood – comparison of adaptation strategies for the initial time period ( $t = 0$ ). The panels represent (i) resilience plot (ii) flood hydrograph; (iii) flood inundation; (iv) spatial resilience.

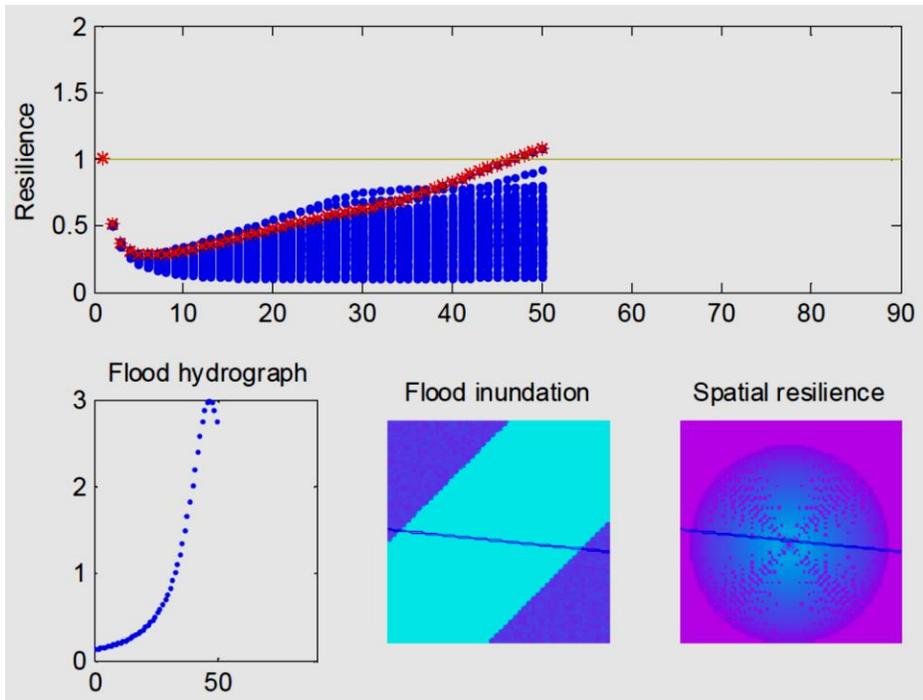


Figure 11: IaSDR model Resilience map at time period ( $t = 50$ ). The spatial resilience is shown for strategy 10 (shown in red asterisk)

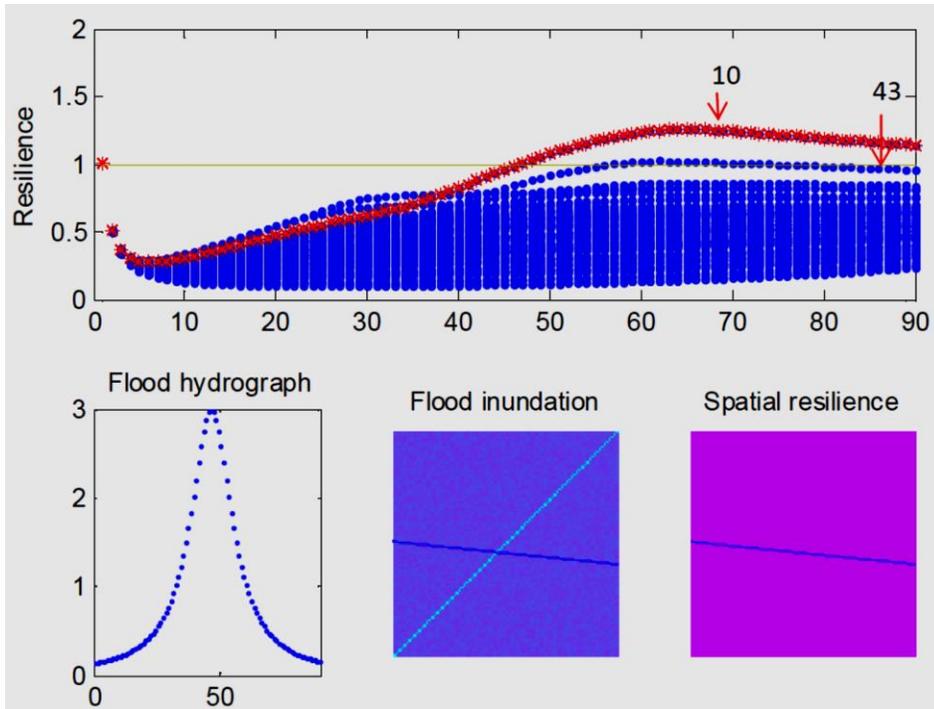


Figure 12: IaSDR model Resilience map at the final time period ( $t = 90$ ). The spatial resilience is shown for strategy 10 (shown in red asterisk)

The dynamic resilience for a railway system is evaluated for 100 alternative adaptation strategies. Once the area is subjected to a flood, the resilience value changes according to the behavior and interactions between the 4R's and system performance. Figure 10 shows the initial conditions (i.e.,  $t = 0$ ) and indicates the beginning of a hypothetical flood event. In Figures 11 and 12 the simulation of the system resilience for 100 strategies at time  $t = 50$  and  $90$  is shown. The flood inundation and the spatial resilience maps are showing the values corresponding to one selected strategy (shown in red in panel 1). The overall system resilience for selected strategies and time intervals is compared in Table 2. It is observed from Figure 12 that only two strategies, No. 10 and 43 were able to recover the system to the initial state, i.e., the resilience index has reached and/or crossed the value of one. Table 3 illustrates the use of four decision criteria for comparison of 100 strategies adopted in this case study. From Table 3 it is observed that:

- (i) MRV: Strategy No. 43 outperforms all other strategies as it has the highest MRV value. The next best strategy is No. 10. All other strategies do not recover the system performance to pre-flood level and have resilience value lower than one.
- (ii) TFRV: Strategy No. 43 outperforms the other strategies as it has the smallest TFRV value. The next best strategy is strategy No. 10 again.
- (iii)LRV: Strategy No. 43 outperforms the other strategies as it is results in the smallest railway performance loss due to flooding. Strategies No. 10, 30 and 26 have the next best performance.
- (iv)TLRV: In case of railways, the companies require more time to recover the system (for example: to repair the flood damaged rail tracks) and hence the shortest time to minimum

resilience value is adopted as preferable for this case study. Strategies No. 10, 43 and 100 outperform the other strategies.

In this example, strategy No. 43 is selected as it was able to show better performance of the railway system when compared to the other strategies. The animated map for the hypothetical example using IaSDR model can be obtained from the project website: ([http://www.eng.uwo.ca/research/iclr/fids/publications/products/relpixel\\_compare\\_strategies.gif](http://www.eng.uwo.ca/research/iclr/fids/publications/products/relpixel_compare_strategies.gif))

Table 2: Railway company case study - Comparison of resilience value under flooding for selected adaptation strategies– IaSDR problem

Time (hrs)	Strategy Number								
	1	10	20	30	43	50	60	80	100
0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
25	0.47	0.49	0.21	0.51	0.57	0.40	0.19	0.11	0.46
50	0.54	0.93	0.31	0.61	1.10	0.61	0.20	0.12	0.80
75	0.56	1.00	0.37	0.64	1.21	0.67	0.26	0.19	0.86
90	0.57	1.00	0.42	0.65	1.21	0.68	0.32	0.25	0.86

Table 3: Railway company case study - Comparison of decision criteria for selected adaptation strategies when a railway system is subjected to flood – IaSDR problem

Criterion	Strategy Number								
	1	10	20	30	43	50	60	80	100
MRV	0.57	1.00	0.42	0.65	1.21	0.68	0.32	0.25	0.86
TFRV	N/A	55	N/A	N/A	48	N/A	N/A	N/A	N/A
LRV	0.25	0.26	0.17	0.26	0.28	0.24	0.17	0.11	0.26
TLRV	6	5	6	6	5	6	8	16	5

(Note – green boxes identify best strategies for different decision criteria)

## 5.2 Railway case study – IaSDR problem

This hypothetical example compares the performance of two railway companies (say P\_ and Q) operating in the same region (not limiting factor in any way) under the flooding conditions. In this example the railway tracks of the two different companies cross a flood prone river as

illustrated in Figures 13 - 15. Although the companies are subjected to similar flooding conditions, the adaptation strategies and response to disturbance can be very different between the companies. Therefore, they may have a very different level of resilience to flooding. The railway companies will recover after the flood differently due to difference in their response (adaptation) strategies. For example, during a flood event, company P has an option to detour the trains using alternate routes and company Q has no such alternates. In this case, company P would be more resilient to flood hazard than the company Q. The dynamic resilience framework is proposed here for use in comparing the performances of different companies.

The map with temporal and spatial variations of flood inundation and resilience value are shown in Figures 13 - 15 for time period  $t = 0, 50$  and  $90$  hours. Each of the figures consists of four panels. The top panel provides the temporal change of dynamic resilience value – the two lines correspond to the overall performance of the companies P and Q respectively. The second panel (bottom left) in the figures shows a hypothetical flood hydrograph used in this illustrative case study. The third panel (bottom middle) consists of a spatial inundation map with  $90 \times 90$  spatial units resolution and a two railway tracks of company P and Q crossing the river. The fourth panel (bottom right) illustrates the spatial resilience due to flooding of the tracks. In IeSDR this map shows the change of resilience at two points in space (intersection of two railway tracks and the river). We have selected, for illustrative purposes only, to show the change of resilience value using circles of different diameter. However, this value is the resilience value at each intersection point for company P and Q respectively. The dynamic resilience in space (locations of intersections of tracks and river) and time is evaluated for both companies. In the event of a flood, the resilience map shows the change of resilience value for each company at the location of intersection of company's tracks and the river. Same as in the case of IaSDR problem, we

have selected, for illustrative purposes only, to show the change of resilience value using circles of different diameter. However, this value is the resilience value at one point (intersection between the railway track and the river) only. Figure 13 shows the initial resilience values for the two railway companies (i.e.,  $t = 0$ ) and indicates the beginning of a hypothetical flood event. In Figures 14 and 15 the simulation of dynamic resilience for both railway companies is illustrated using their respective adaptation strategies for two more time periods, 50 hours and 90 hours.

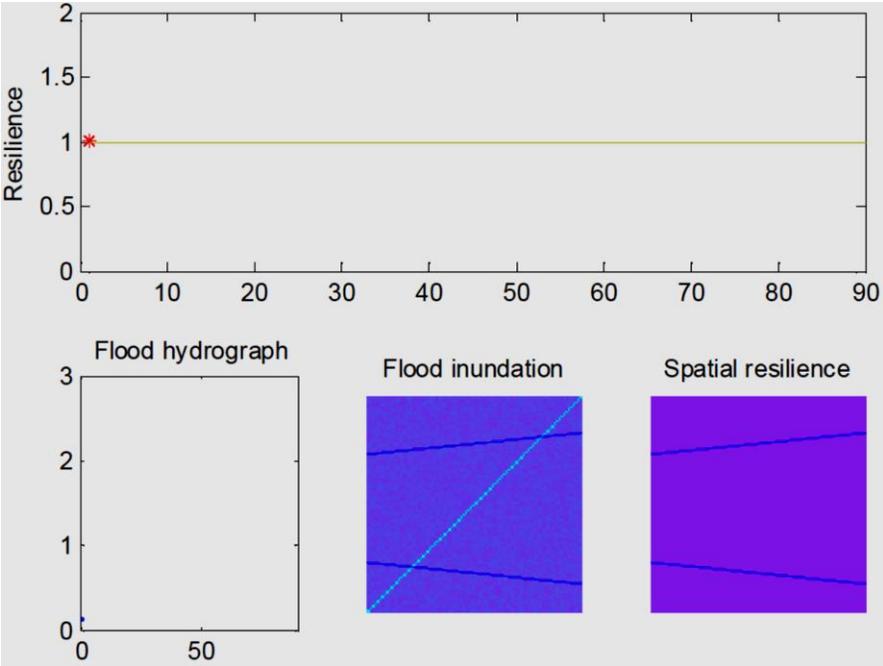


Figure 13: IeSDR model Resilience map at the initial time period ( $t = 0$ ) The panels in the figure illustrate: (i) resilience plot; (ii) flood hydrograph; (iii) flood inundation; (iv) spatial resilience.

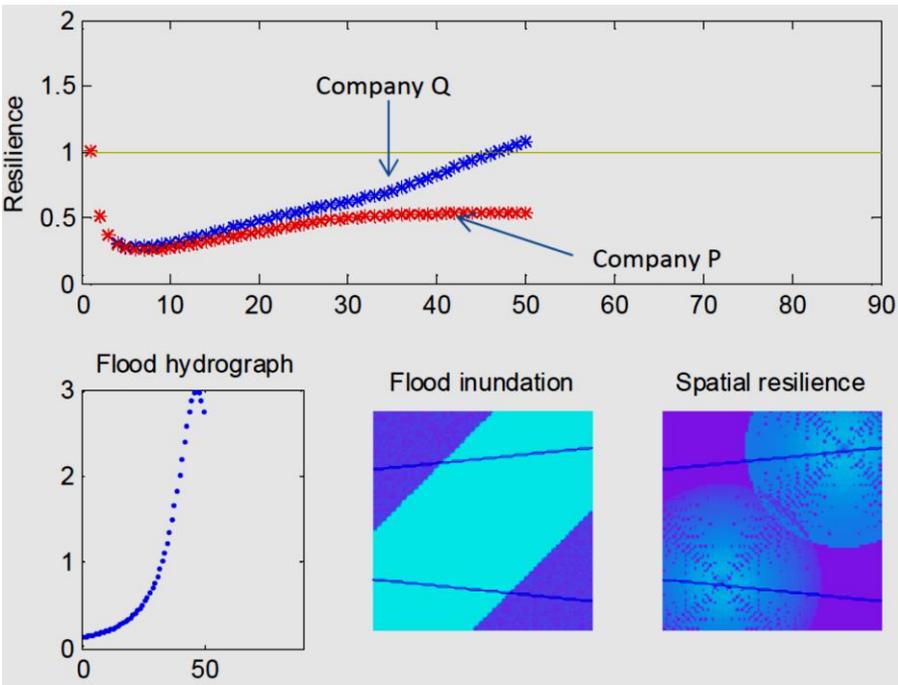


Figure 14: IeSDR model Resilience map at time period (t = 50). Company P is shown in red color and company Q is shown in blue color

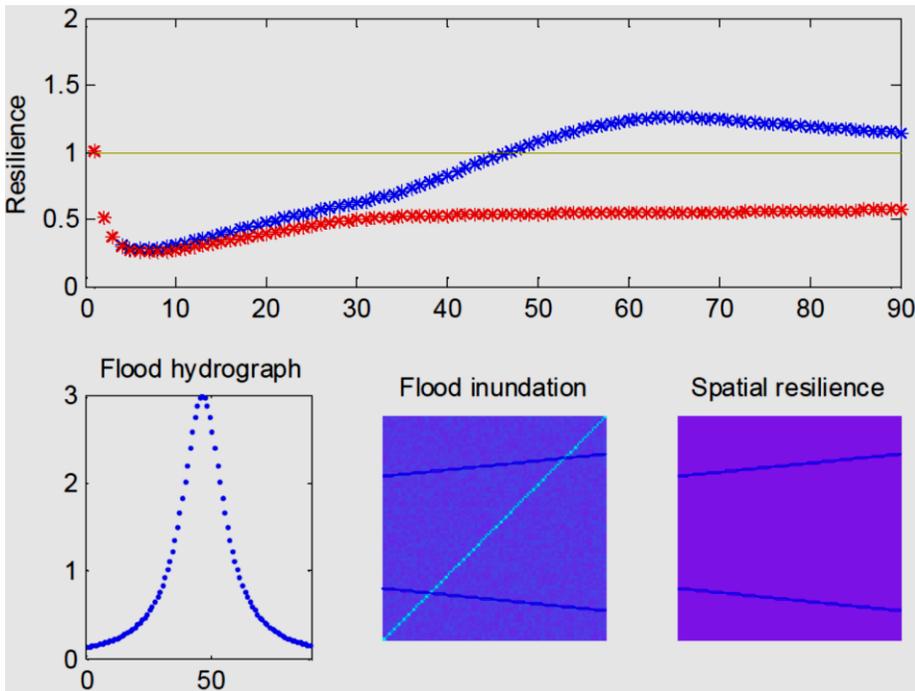


Figure 15: IeSDR model Resilience map at time period (t = 90). Company P is shown in red color and company Q is shown in blue color

The overall system resilience for the two companies and time intervals is compared in Table 4. It is observed from Figure 15 that the only company P is able to recover the system to the initial state, i.e., the resilience index has reached and/or exceeds the value of one. Table 5 illustrates the use of four decision criteria for comparison of two companies P and Q adopted in this case study. From Table 5 it is observed that:

- (i) MRV: Company Q outperforms the other company as it has the highest MRV value. The strategy adopted by company P does not recover the system performance to pre-flood level and have resilience value lower than one.
- (ii) TFRV: Company Q outperforms the other company as it has the smallest TFRV value.
- (iii) LRV: Company Q outperforms the other company as it is results in the smallest railway performance loss due to flooding.
- (iv)TLRV: In case of railways, the companies require more time to recover the system (for example: to repair the flood damaged rail tracks) and hence the shortest time to minimum resilience value is adopted as preferable for this case study. Both the companies show similar performance level in terms of TLRV.

In this example Company Q is selected as it was able to show better performance of the system when compared to company P. The animated map can be obtained from the project website.

[http://www.eng.uwo.ca/research/iclr/fids/publications/products/relpixel\\_compare\\_companies.gif](http://www.eng.uwo.ca/research/iclr/fids/publications/products/relpixel_compare_companies.gif)

)

Table 4: Two railway companies case study - Comparison of resilience value under flooding – IeSDR problem

Time	Company	
	P	Q
0	1.00	1.00
25	0.47	0.57
50	0.54	1.10
75	0.56	1.21
90	0.57	1.21

Table 5: Two railway companies case study - Comparison of decision criteria – IeSDR problem

Criterion	Company	
	P	Q
MRV	0.57	1.21
TFRV	N/A	46
LRV	0.25	0.27
TLRV	5	5

## 6.0 Conclusions

This report presents the application of generic framework for implementation of dynamic resilience in modeling complex system behavior as a consequence of natural disasters. The implementation of the dynamic resilience framework is illustrated for two problems (i) intra-system dynamic resilience (IaSDR) problem which compares different response/adaptation strategies for a given company under the impact of natural hazard and (ii) inter-system dynamic resilience (IeSDR) problem which compares the performance of two companies based on their response/adaptation strategies to similar hazardous conditions. Four decision criteria are identified and used for the assessment of system performance based on the implementation of dynamic resilience framework. The decision criteria are based on i) maximum resilience value; (ii) fastest recovery time; (iii) minimum resilience value; (iv) time to minimum resilience value. The framework is implemented using VENSIM software for system dynamics simulation modeling, C# modules for linking VENSIM with external programs and MATLAB mapping tools for spatial presentation of results.

We illustrate the potential utility of the proposed framework using two hypothetical case studies of the railway companies under flooding conditions. In the first example, the framework is implemented for the comparison of the single railway company performance under various response/adaptation strategies to flooding conditions. In the second example, the performance of two railway companies in response to the same disaster are compared. The modeling framework presented for the railways can be easily extended to the analyses of multiple companies under various natural and non-natural hazards.

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## **Appendix A: Description of the generic dynamic resilience framework components and their implementation (Srivastav and Simonovic, 2014)**

### **A.1 System Dynamics Modeling**

We have adopted VENSIM simulation software (Ventana Systems, 1995) for system dynamics modeling. This software has been used in wide range of applications which include aerospace, engineering, city management, economics, energy, environment, financial services, hospitality, housing, integrated policy, pharmaceuticals and retail surveys. The VENSIM software provides an interface for the development of system structure (input) and presentation of the system dynamic behavior (output). One of the advantages of using VENSIM software is that it provides facility to link with external programs VENSIM also provides the flexibility during the simulation process which allows monitoring the progress at any time during the simulation.

In this study we use the dynamic models to describe each impact used in system resilience calculation. The details on how to develop a system dynamics model are provided in Simonovic (2009) and Peck and Simonovic (2013). In the hypothetical example presented in the following section offers some details of system dynamics modeling. The only drawback of using VENSIM software is that the model structure cannot be altered externally. Therefore, it remains static during the simulation period. The impacts of change in system structure can be examined through multiple simulation runs created with different system structure.

### **A.2 C# Modules**

In building the spatial dynamic resilience map, a link is required between the VENSIM software and the external mapping tool. Further, to describe system resilience we need a different system dynamics model for each impact considered. These models have to be linked externally. In this

study we use C# modules that enable connection between the mapping tool for presenting a spatial variability of resilience and system dynamics models that are presenting temporal variability of resilience. C# programming language is a pure object-oriented language which is very flexible and easy to learn and adopt. The main advantages of C# over the existing other computer languages are (i) it has access to all the .NET Framework class libraries (ii) ease-of-development and (iii) support of distributed system structures. Since the proposed resilience framework is dealing with many system dynamics models and their components, C# is found to be the best choice for their integration. The programming steps and details on linking VENSIM software with C# interface is provided in Appendix B.

### **A.3 Mapping Tool**

Dynamic maps are developed to represent the spatial and temporal change of the resilience. The mapping tools can provide the decision makers a quick overview of the existing conditions in space and their changes over time. In this study we provide a flexible framework to adopt any mapping tool software which can be used to link externally with the VENSIM system dynamics software and C#. MATLAB is used as an external programming language which has a mapping toolbox. There are many other mapping tools which can be adopted instead of MATLAB. One of the popular family of tools for spatial analyses is Geographical Information System (GIS). However, external linking with GIS requires knowledge of PYTHON programming. The computational framework for the development of dynamic maps presented in this report is only one way of doing this task and other computational arrangements are equally feasible.

MATLAB (matrix laboratory) is proprietary software based on fourth-generation programming language. It has an interface with wide variety of programming languages including Fortran, Java and C. It consists of many inbuilt toolboxes and functions used for data computations,

modelling and plotting. MATLAB is used in science and engineering and has been very popular with academia, research institutions and industry.

In this study we use the MATLAB's C# module and mapping toolbox. With the help of mapping toolbox we can create dynamic maps of resilience. The programming steps and details of dynamic resilience mapping are provided in Appendix C.

#### **A.4 Steps Involved in Generic Framework Implementation**

The following steps are involved in the development of dynamic resilience maps by using VENSIM system dynamics software, C# modules and MATLAB mapping tool:

1. Identify all impacts associated with the system disturbance. For example, in Fig.5 five impacts of system disturbance are considered, including economic, health, organizational, physical and social.
2. Build a system dynamics model to capture system performance in the domain of each considered impact.
3. Build a C# VENSIM wrapper module to link the VENSIM dynamic link library (dll) and VENSIM external commands (Appendix B.1)
4. Build a C# main module to run the VENSIM software using the C# VENSIM wrapper module and system dynamics models build in step 2 (Appendix B.2). The main module can include forms or run independently using standalone executable files.
5. Build a MATLAB main file to link the C# main module and mapping toolbox.

The roles of different computational modules are as follows:

1. MATLAB as the main driving tool executes the C# main module.

2. C# main module modifies the resilience sectors (representing considered set of impacts) and sends the information through C# VENSIM wrapper.
3. C# VENSIM wrapper is an external function which can send the information in an appropriate syntax to VENSIM dynamic linked library. The functions in this wrapper are used to run the simulations of the system dynamics models and return the calculated resilience value.
4. C# main module receives the resilience value from the C# VENSIM command wrapper and send it to the MATLAB.
5. MATLAB uses the resilience value for each cell of the spatial grid and presents it with a color code.
6. These color coded values are displayed as a map.

## Appendix B: C# interface – linking VENSIM FILES

In this appendix detail C# coding on (i) how to read the VENSIM commands from the dynamic link library (dll) and (ii) run the dynamics models

### B.1: File to read VENSIM commands

```
using System;
using System.Text;
using System.Runtime.InteropServices;
/// <summary>
/// Summary description for Class1
/// </summary>
///
namespace VensimDLLAPI
{
    public class VensimDLL
    {
        const string strVensimDLL = "vendll32.dll";

        /* information queries for vensim_get_info */
        public enum VensimInfoWanted
        {
```

```

INFO_DLL = 1,          /* returns Minimal, Silent, Full or
Redist */

INFO_VERSION,        /* version info for Vensim */

INFO_USER,           /* user name \0 user company \0 */

INFO_DIRECTORY,     /* the currently active directory */

INFO_MODELNAME,     /* the name of the currently loaded
model (no directory) */

INFO_TOOLSET,       /* the name of the toolset */

INFO_TOOLLIST,      /* the names of the tools in the
loaded toolset */

INFO_GRAPHSET,      /* name of the loaded graph set */

INFO_GRAPHLIST,     /* list of available graphs */

INFO_RUNLIST,       /* the list of loaded runs */

INFO_RUNNAME,       /* the name of the run to be maded
changed with SIMULATE>RUNNAME */

INFO_CINFILES,      /* cin files set with SIMULATE>CHGFILE
*/

INFO_DATAFILES,     /* data file set with SIMULATE>DATA */

INFO_BASED,         /* name of run to base on set with
SIMULATE>BASED */

INFO_OPTMARM,       /* optimization parameter files
SIMULATE>OPTPARM */

```

```

        INFO_PAYOFF,          /* name of payoff control files
SIMULATE>PAYOFF */

        INFO_RESUME,         /* resume satus (0 or 1)
SIMULATE>RESUME */

        INFO_SAVELIST,      /* name of savelist file
SIMULATE>SAVELIST */

        INFO_SESSAVELIST,   /* name of sensitivity save list files
SIMULATE>SENSSAVELIST */

        INFO_SENSITIVITY,   /* name of sensitivity contol file
SIMULATE>SENSITIVITY */

        INFO_BENCHVAR,      /* workbench var name as it would
appear in title bar */

        INFO_VIEWLIST,     /* list of views in the model */
        INFO_TIMEAXIS      /* min\0max\0special */

};

/* return values for vensim_check_status */
public enum VensimStatus
{
    STATUS_IDLE = 0,
    STATUS_SIMULATING,
    STATUS_SIMHANG,
    STATUS_BLOCKACTION,

```

```

        STATUS_MEMLOCK,
        STATUS_INGAME,
        STATUS_NEEDFREE
    };

    /* attribute types for vensim_get_varattrib */
    public enum VensimVarAttrib
    {
        ATTRIB_UNITS = 1,
        ATTRIB_COMMENT,
        ATTRIB_EQUATIONS,
        ATTRIB_CAUSES,
        ATTRIB_USES,
        ATTRIB_INITCAUSES,      /* outputs only initial causes */
        ATTRIB_ACTIVECAUSES,   /* outputs only active causes -
not initial */
        ATTRIB_SUBFAMILY,      /* list the subscript ranges
associated with the variable */
        ATTRIB_SUBALL,         /* lists the expanded subscript
list for the variable */
        ATTRIB_SUBWORK,        /* lists the expanded set of
subscripts that would be used on tool invocation */
        ATTRIB_MIN,
        ATTRIB_MAX,
    }

```

```

ATTRIB_INCREMENT,
ATTRIB_VARTYPE,
ATTRIB_GROUP
};

/* variable types for vensim_get_varnames */
public enum VensimVarNames
{
    VARTYPE_WORKBENCH = -1,
    VARTYPE_ALL,
    VARTYPE_LEVEL,
    VARTYPE_AUXILIARY,
    VARTYPE_DATA,
    VARTYPE_INIITAL,
    VARTYPE_CONSTANT,
    VARTYPE_LOOKUP,
    VARTYPE_GROUP,
    VARTYPE_SUBSCRIPT,
    VARTYPE_CONSTRAINT,
    VARTYPE_TEST_INPUT,
    VARTYPE_TIME_BASE,
    VARTYPE_GAME,
    VARTYPE_SUBSCRIPT_CONSTANT
};

```

```

[DllImport(strVensimDLL)]
public static extern int vensim_be_quiet(int quietflag);

[DllImport(strVensimDLL)]
public static extern VensimStatus vensim_check_status();

[DllImport(strVensimDLL)]
public static extern int vensim_command(string command);

[DllImport(strVensimDLL)]
public static extern int vensim_continue_simulation(int
    number_time_step);

[DllImport(strVensimDLL)]
public static extern int vensim_get_data(string filename, string
varname, string timename, float[] varvals, float[] timevals, int
maxpoints);

[DllImport(strVensimDLL)]
public static extern int vensim_get_dpval(string varname,
    double[] varval);

[DllImport(strVensimDLL)]
public static extern int vensim_get_dpvecvals(int[] vecoff,
    double[] varvals, int veclen);

[DllImport(strVensimDLL)]
public static extern int vensim_get_info(VensimInfoWanted
    infowanted, byte[] buf, int maxbuflen);

[DllImport(strVensimDLL)]

```

```

public static extern int vensim_get_sens_at_time(string
    filename, string varname, string timename, float[] attime,
    float[] vals, int maxpoint);
[DllImport(strVensimDLL)]
public static extern int vensim_get_substring(byte[]
fullstring, int frompos, StringBuilder buf, int maxbuflen);
[DllImport(strVensimDLL)]
public static extern int vensim_get_val(string varname,
    float[] varval);
[DllImport(strVensimDLL)]
public static extern int vensim_get_varattrib(string varname,
VensimVarAttrib attrib, byte[] buf, int maxbuflen);
[DllImport(strVensimDLL)]
public static extern int vensim_get_varnames(StringBuilder
filter, VensimVarNames vartype, byte[] buf, int maxbuflen);
[DllImport(strVensimDLL)]
public static extern int vensim_get_varoff(string varname);
[DllImport(strVensimDLL)]
public static extern int vensim_get_vecvals(int[] vecoff,
    float[] varvals, int nelm);
[DllImport(strVensimDLL)]
public static extern int vensim_set_parent_window(long
    vwidnow, long r1, long r2);

```

```

[DllImport(strVensimDLL)]
public static extern int vensim_show_sketch(int viewnum, int
    wantscroll, int zoompercent, long Vwindow);

[DllImport(strVensimDLL)]
public static extern int vensim_start_simulation(int
    loadfirst, int game, int overwrite);

[DllImport(strVensimDLL)]
public static extern int vensim_tool_command(string Vcommand,
    long Vwindow, int iswip);
    }
}

```

## B.2: C# Program to Run VENSIM Dynamic Model

```

using System;

using System.IO;

namespace ReadVensim
{
    class Vensim
    {
        string strResultString;

        string run_model_name;
    }
}

```

```

bool check_print = false;

public void initven()
{
    string strVensimCommand;
    string path = Directory.GetCurrentDirectory();
    if (check_print == true) Console.WriteLine("Current
Directory is {0}", path);
string strModelPath = "SPS_Ex1.vpm";
    strVensimCommand = String.Concat("SPECIAL>LOADMODEL|",
strModelPath);
    int nResult =
VensimDLL.vensim_command(strVensimCommand);
if (check_print == true) Console.WriteLine("The value of
nResult {0}", nResult);
    if (nResult == 0)
    {
        Console.WriteLine("Error loading model! Aborting.");
        return;
    }

//List of Vensim Variables.
StringBuilder sFilter = new StringBuilder("*");
VensimDLL.VensimVarNames nVarNamesWanted =

```

```

VensimDLL.VensimVarNames.VARTYPE_ALL;

    int nMaxStringLen = VensimDLL.vensim_get_varnames(sFilter,
nVarNamesWanted, null, 0);

    if (check_print == true) Console.WriteLine("The value of
nMaxStringLen = {0}", nMaxStringLen);

    byte[] sBuffer = new byte[nMaxStringLen];

    nResult = VensimDLL.vensim_get_varnames(sFilter,
nVarNamesWanted, sBuffer, nMaxStringLen);

    bool bExitLoop = false;

    int nFromPosition = 0;

    string[] vname = new string[50];

    int num = 0;

    while (bExitLoop == false)
    {

        StringBuilder strVensimVarName = new
        StringBuilder(100);

        nResult = VensimDLL.vensim_get_substring(sBuffer,
nFromPosition, strVensimVarName, 100);

        if (nResult != 0)
        {

            nFromPosition = nFromPosition + nResult;

```

```

        if (check_print == true)
        {
            Console.WriteLine("sBuffer {0}", sBuffer);
            Console.WriteLine("nFromPosition {0}",
                nFromPosition);
            Console.WriteLine("StrVensimVarName = {0}",
                strVensimVarName);
        }
        vname[num] = Convert.ToString(strVensimVarName);
        num++;
    }
    else
    {
        bExitLoop = true;
    }
}
} //END OF OBJECT INITVEN

```

```

public void run_name()
{
    //now set the runname

```

```

    string strVensimCommand =
string.Concat("SIMULATE>RUNNAME|", run_model_name, "|o");
    int nResult = VensimDLL.vensim_command(strVensimCommand);
    if (check_print == true) Console.WriteLine("nResult for
        run name = {0}", nResult);
    if (nResult == 0)
    {
        Console.WriteLine("Error setting runname! Aborting.");
        return;
    }
}
} //END OF RUN NAME

```

```

public void SetInitialPopulation()
{
    VensimDLL.VensimStatus nVensimStatus =
VensimDLL.vensim_check_status();
    string strVensimCommand;
    if (nVensimStatus == VensimDLL.VensimStatus.STATUS_INGAME)
    {
        strVensimCommand =
        string.Concat("SIMULATE>SETVAL|Infection Fraction = ",
            "0.005");
    }
}

```

```

    int nResult =
        VensimDLL.vensim_command(strVensimCommand);
}
else
{
    //set the initial population
    strVensimCommand =
        string.Concat("SIMULATE>SETVAL|initial affected
        population = ", "5000");
    int nResult =
        VensimDLL.vensim_command(strVensimCommand);
    strVensimCommand =
        string.Concat("SIMULATE>SETVAL|adaptive capacity fn",
        lookup);
    nResult = VensimDLL.vensim_command(strVensimCommand);
    strVensimCommand =
        string.Concat("SIMULATE>SETVAL|injured patients
        threshold = ", "2000");
    nResult = VensimDLL.vensim_command(strVensimCommand);
    strVensimCommand =
        string.Concat("SIMULATE>SETVAL|INITIAL TIME = ",
        "0");
    nResult = VensimDLL.vensim_command(strVensimCommand);
}

```

```

strVensimCommand =
    string.Concat("SIMULATE>SETVAL|FINAL TIME = ",
        "90");
nResult = VensimDLL.vensim_command(strVensimCommand);
strVensimCommand = string.Concat("SIMULATE>SETVAL|TIME
    STEP = ", "1");
nResult = VensimDLL.vensim_command(strVensimCommand);
if (check_print == true) Console.WriteLine("I am here
    \n nResult for SetInitialPopulation = {0}", nResult);
if (nResult == 0)
{
    Console.WriteLine("Error setting value!
        Aborting.");
    return;
}
}
} //END OF OBJECT SetInitialPopulation

public void checkstatus()
{
    VensimDLL.vensim_command(""); /* clears memory - comment
out to see needfree status */
    VensimDLL.VensimStatus nStatus =

```

```

        VensimDLL.vensim_check_status();
        strResultString = string.Concat("vensim_check_status
returns ", nStatus);
        Console.WriteLine("I am in Loop Vensim Check Status {0}",
strResultString);
} // END OF OBJECT CHECKSTATUS

public void vensim_quite()
{
    int nResult = VensimDLL.vensim_be_quiet(1);
    strResultString = string.Concat("vensim_be_quiet returns
", nResult);
} // END OF OBJECT vensim_quite

public void vensim_simulate()
{
    SetInitialPopulation();
    float[] varreq = new float[100];
    int[] nVaroffs = new int[3];
    int nResult = VensimDLL.vensim_start_simulation(1, 0, 1);
    strResultString = string.Concat("vensim_start_simulation
returns ", nResult);
    if (check_print == true)
        Console.WriteLine(strResultString);
}

```

```

/* vensim_get_varoff */
nVaroffs[0] = VensimDLL.vensim_get_varoff("H1RES");
nVaroffs[1] = VensimDLL.vensim_get_varoff("Injured Patient
impacts");
nVaroffs[2] = VensimDLL.vensim_get_varoff("time");
float[] varvals = new float[3];
nResult = VensimDLL.vensim_get_vecvals(nVaroffs, varvals)
int count = 0;
varreq[count] = varvals[0];
while (VensimDLL.vensim_continue_simulation(1) != 0)
{
    nResult = VensimDLL.vensim_get_vecvals(nVaroffs,
varvals, 3);
    if (check_print == true)
        Console.WriteLine(strResultString);
    varreq[count] = varvals[0];
    count++;
}
nResult = VensimDLL.vensim_get_vecvals(nVaroffs, varvals)
varreq[count] = varvals[0];
nResult = VensimDLL.vensim_finish_simulation();
strResultString = string.Concat("vensim_finish_simulation

```

```

        returns ", nResult);
} //END OF OBJECT vensim_simulate

public void vensim_run()
{
    initven();
    vensim_quite();
    SetInitialPopulation();

    int[] nVaroffs = new int[3];
    /* vensim_get_varoff */
    nVaroffs[0] = VensimDLL.vensim_get_varoff("Infected
    People");
    nVaroffs[1] = VensimDLL.vensim_get_varoff("Susceptible
    People");
    nVaroffs[2] = VensimDLL.vensim_get_varoff("TIME");
    Console.WriteLine("{0} {1} {2}", nVaroffs[0],
    nVaroffs[1], nVaroffs[2]);
    int nResult = VensimDLL.vensim_command("MENU>GAME");
    nResult =
    VensimDLL.vensim_command("MENU>GAME>GAMEINTERVAL | TIME
    STEP");

```

```

Console.WriteLine("GAME Initialization is Successful if
nResult is one = {0}", nResult);

if (nResult == 0)
{
    Console.WriteLine("Error Simulating! Aborting.");
    return;
}

float[] varvals = new float[3];
nResult = VensimDLL.vensim_get_vecvals(nVaroffs, varvals);
strResultString = string.Concat("At time ", varvals[2], "
Infected People is ", varvals[0], " Susceptible People is
", varvals[1]);
Console.WriteLine(strResultString);
nResult = VensimDLL.vensim_start_simulation(1, 2, 1);
strResultString = string.Concat("vensim_start_simulation
returns ", nResult);
Console.WriteLine(strResultString);
//float[] varvals = new float[3];
nResult = VensimDLL.vensim_get_vecvals(nVaroffs, varvals);
strResultString = string.Concat("At time ", varvals[2], "
Infected People is ", varvals[0], " Susceptible People is
", varvals[1]);
Console.WriteLine(strResultString);

```

```

VensimDLL.vensim_continue_simulation(1);
nResult = VensimDLL.vensim_get_vecvals(nVaroffs, varvals);
strResultString = string.Concat("At time ", varvals[2], "
Infected People is ", varvals[0], " Susceptible People is
", varvals[1]);
Console.WriteLine(strResultString);
//nResult = VensimDLL.vensim_command("MENU>RUN1|o");

string strVensimCommand =
string.Concat("SIMULATE>SETVAL|Infection Fraction = ",
"0.01");//,"x=", "10");
nResult = VensimDLL.vensim_command(strVensimCommand);
Console.WriteLine("nResult for Infection Fraction = {0}",
nResult);
//nResult = VensimDLL.vensim_command("MENU>GAME>GAMEON");
VensimDLL.vensim_continue_simulation(1);
nResult = VensimDLL.vensim_get_vecvals(nVaroffs, varvals,
3);
strResultString = string.Concat("At time ", varvals[2], "
Infected People is ", varvals[0], " Susceptible People is
", varvals[1]);
Console.WriteLine(strResultString);

```

```

        nResult = VensimDLL.vensim_command("MENU>GAME>ENDGAME");
    } //END OF OBJECT vensim_run

public void vensim_data_retrieve(string strVensimParameter)
{
    float[] rVal;
    float[] tVal;

    rVal = new float[500];
    tVal = new float[500];

    run_model_name = "Current.vdf";

    int nResult = VensimDLL.vensim_get_data(run_model_name,
strVensimParameter, "time", rVal, tVal, 500);

    Console.WriteLine("nResult {0}", nResult);

    for (int i = 0; i < nResult; i++)
    {
        strResultString = string.Concat(strVensimParameter, "
: Time = ", tVal[i], ", Value = ", rVal[i]);

        Console.WriteLine(strResultString);
    }
}

```

```
    }  
class Program  
{  
    static void Main(string[] args)  
    {  
        Vensim run = new Vensim();  
        run.initven();  
        run.vensim_simulate();  
    }  
}  
}
```

### **B.3: Output file generated from VENSIM**

	Resilience
Time	Index

1	1.000000
2	0.960176
3	0.920383
4	0.880668
5	0.841081
6	0.801679
7	0.762464
8	0.724115
9	0.688239
10	0.654907
11	0.62412
12	0.595896
13	0.570303
14	0.547396
15	0.527212
16	0.509771
17	0.495088
18	0.483172
19	0.474028
20	0.46766
21	0.464071
22	0.463291
23	0.465453
24	0.470662

25	0.478278
26	0.486585
27	0.495559
28	0.505217
29	0.515586
30	0.526811
31	0.539033
32	0.552344
33	0.566801
34	0.582438
35	0.599279
36	0.617339
37	0.636625
38	0.657143
39	0.678764
40	0.701209
41	0.724288
42	0.747878
43	0.771903
44	0.796316
45	0.821085
46	0.846191
47	0.871591
48	0.896979

49 0.922031  
50 0.946544  
51 0.970391  
52 0.993489  
53 1.015788  
54 1.037255  
55 1.05787  
56 1.07762  
57 1.096481  
58 1.114375  
59 1.131236  
60 1.147022  
61 1.161708  
62 1.175276  
63 1.187716  
64 1.199022  
65 1.209189  
66 1.218214  
67 1.226097  
68 1.232835  
69 1.238429  
70 1.242878  
71 1.246181  
72 1.248348

73 1.249474  
74 1.249674  
75 1.249021  
76 1.247559  
77 1.245319  
78 1.242318  
79 1.238569  
80 1.234078  
81 1.228849  
82 1.222887  
83 1.216192  
84 1.208771  
85 1.200667  
86 1.191928  
87 1.182583  
88 1.172651  
89 1.162143  
90 1.151068  
91 1.139457



## **Appendix C: MATLAB Code for MAPPING**

In this appendix a detail MATLAB code for generating animated spatial maps of resilience index is presented.

```
% MATLAB CODE TO GENERATE SPATIAL MAPS of RESILIENCE INDEX

% AUTHOR: Roshan Srivastav, Slobodon P. Simonovic

% LAB: Facility for Intelligent Decision Support, UW0, CANADA

% Number of Pixels

numpixel = 100;

% SETTING UP THE INPUT FOR THE VENSIM

R1 = xlsread('adaptive_cap_fn.xlsx','R1');
R2 = xlsread('adaptive_cap_fn.xlsx','R2');
R3 = xlsread('adaptive_cap_fn.xlsx','R3');
R4 = xlsread('adaptive_cap_fn.xlsx','R4');

tlim = [20 70];

caplim_R1 = [5000 10000];
caplim_R2 = [5000 10000];
```

```

caplim_R3 = [0.5 1];
caplim_R4 = [0.5 1];

%%

for i = 1:100

    %Create Input FILES

    fid = fopen('Input.txt','wt');

    trand = tlim(1,1) + diff(tlim)*rand(1,1);

    caprand = caplim_R1(1,1) + diff(caplim_R1)*rand(1,1);

    data_text_R1 =

strcat('(',num2str(R1(1,1)),',',num2str(R1(1,2)),')',',', '(' ,num2str(
trand),',',num2str(caprand),')',',',...

        '(' ,num2str(R1(3,1)),',',num2str(R1(3,2)),')')');

    trand = tlim(1,1) + diff(tlim)*rand(1,1);

    caprand = caplim_R2(1,1) + diff(caplim_R2)*rand(1,1);

    data_text_R2 =

strcat('(',num2str(R2(1,1)),',',num2str(R2(1,2)),')',',', '(' ,num2str(
trand),',',num2str(caprand),')',',',...

        '(' ,num2str(R2(3,1)),',',num2str(R2(3,2)),')')');

    trand = tlim(1,1) + diff(tlim)*rand(1,1);

    caprand = caplim_R3(1,1) + diff(caplim_R3)*rand(1,1);

    data_text_R3 =

strcat('(',num2str(R3(1,1)),',',num2str(R3(1,2)),')',',', '(' ,num2str(
trand),',',num2str(caprand),')',',',...

```

```

        '(' , num2str(R3(3,1)), ', ' , num2str(R3(3,2)), ')')');
trand = tlim(1,1) + diff(tlim)*rand(1,1);
caprand = caplim_R4(1,1) + diff(caplim_R4)*rand(1,1);
data_text_R4 =
strcat('(', num2str(R4(1,1)), ', ' , num2str(R4(1,2)), ')', ', ' , '(' , num2str(
trand), ', ' , num2str(caprand), ')', ', ' , ...
        '(' , num2str(R4(3,1)), ', ' , num2str(R4(3,2)), ')')');
fprintf(fid, '%s\n', data_text_R1);
fprintf(fid, '%s\n', data_text_R2);
fprintf(fid, '%s\n', data_text_R3);
fprintf(fid, '%s', data_text_R4);
fclose(fid);
output = [];
% Execute the VENSIM C# FILES
run('Vensim.c#');
rel(:,i) = power(prod(output,2), (1/5));
fprintf('%d\n', i);
end
% Create Dynamic Resilience Index Map
h2 = figure('Renderer', 'zbuffer');
set(gca, 'NextPlot', 'replaceChildren');
num = 10;

```

```

for i = 1: 91
    a = reshape(rel(i,:),10,10);
    subplot(2,1,1), plot(i*ones(1,numpixel),rel(i,:),'.');hold on
    plot(1:90,ones(90))
    axis([0 90 0 2.5]);

    subplot(2,1,2)
    ix = imagesc(a,[0 2.5]);
    alpha(1);
    colormap(jet);
    colorbar
    M(i) = getframe(gcf);
    M(i) = getframe(h2);

end

movie(M)
movie2avi(M,'ResiliencePixel.avi','compression', 'None','fps',1,
'quality',50);

```



## **Appendix D: List of Previous Reports in the Series**

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

In addition to 60 previous reports (No. 01 – No. 60) prior to 2009

Rajesh R. 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.

Hyung-II 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.

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.

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, 62 pages. ISBN: (print) 978-0-7714-2816-6; (online) 978-0-7714-2817-3.

Slobodan P. Simonovic and Angela Peck (2009). [Updated rainfall intensity duration frequency curves for the City of London under the changing climate](#). Water Resources Research Report no. 065, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 64 pages. ISBN: (print) 978-0-7714-2819-7; (online) 978-0-7714-2820-3.

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, 72 pages. ISBN: (print) 978-0-7714-2834-0; (online) 978-0-7714-2835-7.

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.

Hyung-II 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, 103 pages. ISBN: (print) 978-0-7714-2844-9; (online) 978-0-7714-2845-6.

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.

Tarana A. Solaiman and Slobodan P. Simonovic (2011). [Quantifying Uncertainties in the Modelled Estimates of Extreme Precipitation Events at 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.

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