

**THE UNIVERSITY OF WESTERN ONTARIO  
DEPARTMENT OF CIVIL AND  
ENVIRONMENTAL ENGINEERING**

**Water Resources Research Report**

**Use of Quantitative Resilience in Managing Urban  
Infrastructure Response to Natural Hazards: A  
Web-Based Decision Support Tool – ResilSIMt**

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**USE OF QUANTITATIVE RESILIENCE IN MANAGING URBAN  
INFRASTRUCTURE RESPONSE TO NATURAL HAZARDS  
A WEB-BASED DECISION SUPPORT TOOL – ResilSIMt**



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**October, 2018**

## **Executive Summary**

Damages to urban infrastructure systems, as a result of various natural hazards, have escalated in recent years. The observed trend is expected to increase in the future as the impacts of population growth, rapid urbanization and climate change persist and worsen. To alleviate the damages associated with these impacts, it is recommended to integrate disaster management methods into planning, design and operational policies under all levels of government. Work presented in this report proposes the use of quantitative resilience criterion (dynamic in time and space) to plan for disturbing effects of, assess damage to, and implement the response of urban infrastructure systems to, natural hazards. The implementation of the resilience criterion has been done in the form of the web-based decision support system (ResilSIMt) that operates in near real-time. The decision support system is designed to assist decision makers in selecting the best options for integrating adaptive capacity into their communities to protect against the negative impacts of natural (and/or non-natural) hazards. The tool is built as a generic framework allowing its application to various locations. This document presents (i) the system user's manual; and (ii) illustration of possible system uses in the form of pre-loaded scenarios, developed for the City of Toronto, Ontario, Canada.

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# 1 Introduction

Natural hazards have caused an increasing amount of damage to urban systems in the recent years. The observed trend is expected to increase in the future as the impacts of population growth, rapid urbanization, and climate change persist. Natural disasters have become more frequent and damaging to physical and socioeconomic environments Irwin et al. (2016). In the last decade, approximately \$4 trillion of direct economic damages is attributed to natural disasters globally, and this does not account for the loss of life and cultural assets that are difficult to evaluate (World Bank, 2015; IPCC, 2012). Furthermore, in the last two decades, the estimated annual economic losses caused by natural disasters have increased from \$50 billion to \$180 billion. Most of these losses are associated with extreme weather events such as floods, droughts, landslides, cyclones, extreme temperature and others (World Bank, 2015). According to WHO (2017), in 2015 alone, 346 significant disasters were linked to natural hazards, and an estimated 22,500 fatalities and over \$66 billion in economic damages.

The rising number of natural disasters that have occurred in recent years are linked to three key factors including climate change, rapid and sometimes poorly planned land use change (especially massive urbanization) and population growth. Climate change is increasing the frequency and intensity of extreme weather-related events. The average global temperature is projected to rise significantly, disrupting the balance of the climate system and hydrological cycle, causing unprecedented extreme meteorological events that will overwhelm critical infrastructure capacity, Irwin et al. (2016).

Integrating disaster management methods into planning, design and operational policies may aid or mitigate the damages induced by hazardous events. With the ResilSIMt tool, we propose the use of the quantitative resilience to assess (i) the response of an urban system to the hazardous events; and (ii) the impact of different adaptation measures.

Traditional risk management is defined as the combination of three elements: 1) probability of an extreme event; 2) exposure of infrastructure or human elements; and 3) susceptibility of people, property, infrastructure, to damage caused by an extreme event (Irwin et al. 2016; World Bank, 2015). There has been a shift from the traditional risk-based approach to resilience-based disaster management (Simonovic, 2016; Simonovic and Peck, 2013).

Decision support systems (DSS) are used to provide meaningful inputs for improved decision making in complex domains. The DSS tool created by Irwin et al. (2016) named ResilSIM, to the best

knowledge of the authors, was one of the first tools to use resilience as a measure of the urban system's ability to function in the event of a hazard as well as recover from the damages.

The objective of the work documented in this report is to present the evolution of the ResilSIM tool and introduce the new version, ResilSIMt. The ResilSIMt is developed in the form of the web-based and mobile friendly DSS. It is designed to assist decision makers in analyzing different adaptation measures in order to mitigate the negative impacts of a hazard. The tool is developed for general application with user input data capabilities combined with the open source OpenStreetMap GIS database. Five illustrative applications for the City of Toronto, Ontario, Canada are presented in Section 3. The pre-loaded projects are available to all users of the tool and can be duplicated and used as base scenarios for new user-created projects.

The remainder of the document is organized as follows. First, the resilience definition, research objectives, and the methodological background are presented in Section 1. A detailed description of the ResilSIMt tool follows in Section 2. The illustrative projects to demonstrate and showcase the use of the tool are presented in Section 3. Finally, Section 4 presents some concluding remarks.

## 1.1 Resilience Definition

The IPCC defines resilience, in the context of disaster management, as *“the ability of a system and its component parts to anticipate, absorb, accommodate or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration or improvement of its essential basic structures and functions”* (IPCC, 2012). The definition of risk is the susceptibility of the system and its components to damage caused by hazards scenarios. The traditional risk is a static metric that does not change over time. Resilience is a dynamic metric that is capable of presenting system performance over the duration of a disaster event.

According to Simonovic (2016), Bruneau et al. (2003), Chang and Shinozuka (2004), and Cutter et al. (2008) a resilient system may be achieved by choosing a sufficient set of adaptation measures. Recently, Simonovic (2016), introduced the dynamic resilience metric using a simulation model integrated with GIS processing, similar to the procedure adopted by Irwin et al. (2016). In Simonovic and Arunkumar (2016), a comparison of static and dynamic resilience applied to multipurpose reservoir operation is presented. Their results show that the dynamic resilience is a powerful tool for selecting proactive and reactive adaptive response to hazard events that could not



be achieved using the traditional risk-based approach. The dynamic resilience concept is expanded by Kong and Simonovic (2017) using network theory and applied to the City of Toronto infrastructure as a case study. These concepts are incorporated into the current version of the ResilSIMt for the quantification of the dynamic resilience metric.

## 1.2 Objectives of ResilSIMt tool

The ResilSIMt is a web-based tool that allows (i) user representation of the physical and socioeconomic urban system; and (ii) assessment of its resilience to natural or human made disasters. It can assist decision makers in selecting appropriate adaptation measures that will maximize urban system resilience to a hazardous event.

The tool can function with a variety of datasets that describe key urban infrastructure systems, critical facilities (such as hospitals, schools, ambulance, fire and police stations), land use characteristics and social infrastructure. It is paramount that geographic information is associated with the data. Network data format are allowed, and specialized algorithms are employed to calculate the resilience metric for network infrastructure systems. The system relies on publicly available infrastructure, social, buildings, and other data. However, private data can be incorporated into the tool database by the user for the resilience calculation, as well.

The ResilSIM v2 can simulate one or more hazardous scenarios, defined by the users through the user interface and GIS tool to map the hazard event in the region and compute an initial value of the urban system's resilience. The tool offers the user the possibility of creating a list of proactive and reactive measures that affect adaptive capacity and that can be applied to improve the system performance and increase resilience. The user can select an adaptation option to be implemented interactively and observe how community resilience responds. After the selection of adaptation measures, the resilience is re-calculated and compared to its initial value. In this way, various measures can be compared effectively using resilience as a comparison criterion.

The tool enables users to quickly make decisions that can reduce the physical, social and economic consequences of various hazards. The consequences to be considered include damages to the built and natural environments (roads, housing, buildings, urban systems) as well as the danger and disruption posed to human welfare.

### 1.3 Methodological Background

The ResilSIMt is build as a generic decision support system that can calculate resilience using a variety of datasets that describe key urban infrastructures, critical facilities, land use characteristics and social infrastructure. The tool mainly utilizes two types of data inputs: (i) network data, with a formal structure containing nodes connected by links or edges, and for which, specialized algorithms are employed to calculate the resilience; and (ii) other GIS data layers containing information about urban infrastructure, social data, buildings, critical facilities and others. For the network layers, each component element must have its own physical capacity (usually represented as cost of a link for the mathematical representation).

The physical capacity measurement consists of the infrastructure's structural integrity or a unit related to its functionality. Dependencies can be in either intra-dependent form (a node or edge within a network depends on another node or edge within the same network type), or interdependent form (a node or edge within a network depends on another node or edge from a different network type). GIS data layers have flexibility to incorporate other data types, such as point, line and polygon shapes.

The ResilSIMt dataflow and case analysis can be summarized in a few steps, as follows:

1. Description of Infrastructure System: population of the decision support system data base with the network data, infrastructure data in form of GIS layers, social information and any other information or data the user judges relevant;
2. Hazards Input: definition of the hazard scenarios, input of the affected areas and regions and the magnitude in time and space;
3. Impact Assessment: the impact on the urban infrastructure (networks and data layers) caused by the hazard;
4. Adaptation Measures: identification of adaptation measures for each layer and hazard;
5. Assessment of System Performance and Resilience: assessment of the resilience and the impacts of adaptation measures.

Hazards are characterized by their damage area and magnitudes. They are inputs from the user. The tool allows the user to change the hazard affected area and severity over time to describe the progression of hazard. The impact assessment step then uses damage functions to estimate the reduction in capacity for various system elements.

User input adaptation measures can then be specified to demonstrate how system component behaviors shift with their implementation. These can be classified as pre-disaster measures, that change

the disaster impact relationship for the system component, or post disaster measures, that speed up system element recovery. The ResilSIMt tool integrates physical, social and economic impacts of disaster events and adaptation measures implemented to an urban system into a single measure known as resilience,  $R$ . The procedure for computing the resilience metric is adapted from Irwin et al. (2016), Simonovic and Peck (2013), Kong and Simonovic (2017) and Peck and Simonovic (2013).

The overall system resilience calculation for each time step is illustrated in the flowchart presented in Figure 1. The physical performance of individual networks and layers is aggregated to form a single network/layer system performance and resilience. Once this process is repeated for all infrastructure, it is aggregated further to calculate the overall system resilience.

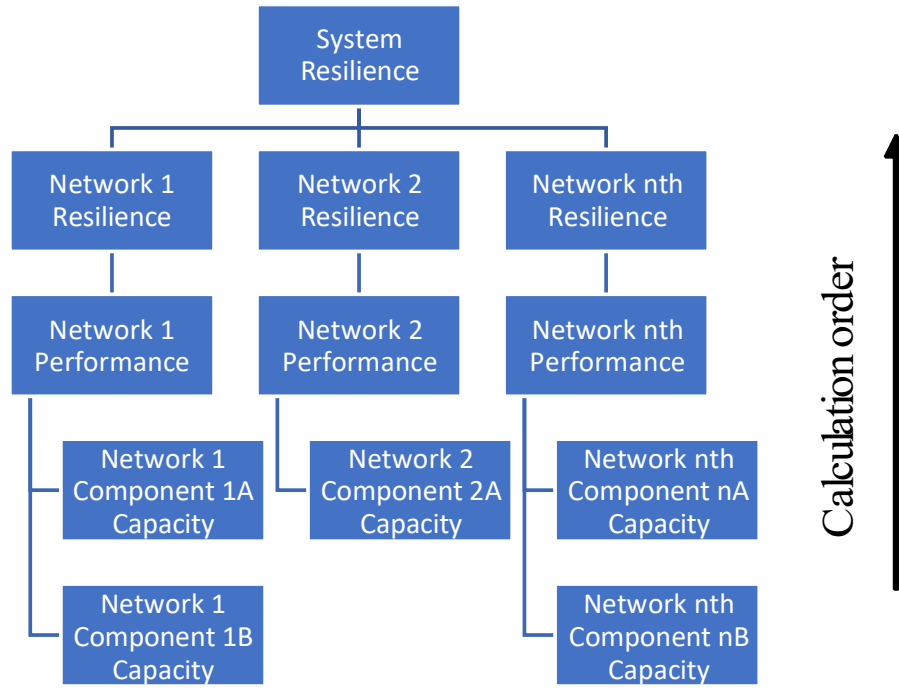


Figure 1. Resilience calculation order and flowchart of the ResilSIMt

An example of typical system performance curve (black line) is presented in Figure 2. The shaded area under the curve represents the loss of system performance caused by the hazard over time. The x-axis represents time, where  $t_0$  and  $t_1$  represent the time at the beginning and end of the disaster event respectively. The system performance drops once the disaster begins at  $t_0$  and recovers over time.

The area above the system performance curve represents the loss in system performance over time ( $\rho^i$ ). The area spans from the initial time of disturbance to the time at the end of system recovery and is calculated as:

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

where  $P_0^i$  is the initial system performance level,  $i$  the impact,  $P^i(t, s)$  represents measure of system performance for each time step  $t$  and location in space  $s$ , and  $t_r$  the end of the recovery process.

The resilience of each system component,  $r^i(t, s)$ , represented by the area below the system performance curve in Figure 2 is calculated using:

$$r^i(t) = 1 - \left( \frac{\rho^i(t)}{P_0^i \times (t - t_0)} \right) \quad (2)$$

The resilience of each system component can be combined into the final, system resilience using:

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

where  $M$  is the number of impacts.

Figure 3 illustrates one representation of the four components of resilience graphically. The resilience components include robustness, redundancy, resourcefulness and rapidity. Based on the mathematical representations of the four resilience components from Simonovic and Arunkumar (2016), the tool can estimate a value for them from the generated resilience curve(s).

The application of the methodology is demonstrated using OpenStreetMap (OSM, 2018) data and other publicly available data for the City of Toronto. Two theoretical hazard scenarios are created to showcase the use of the tool and the calculation of the system performance and resilience.

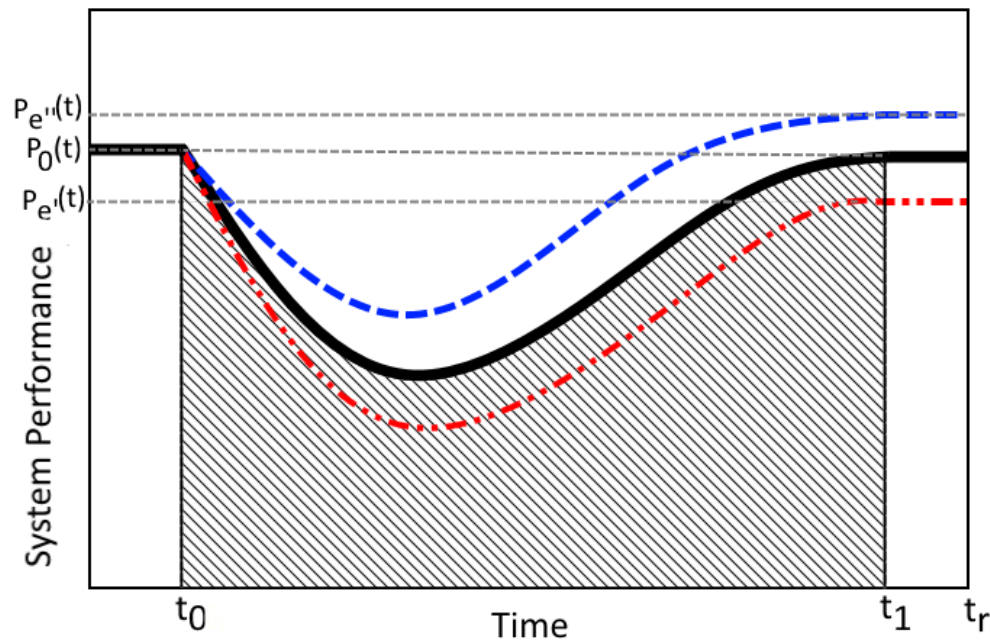


Figure 2. System performance to a disturbance (partial recovery, recovery to pre-hazard system performance, and improving system performance) (adapted from Simonovic and Arunkumar, 2016)

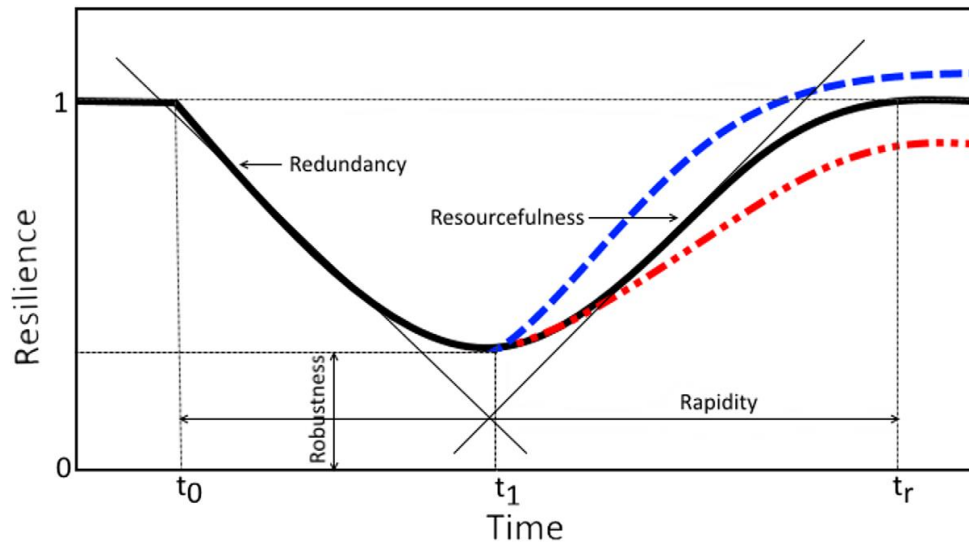


Figure 3. System performance to a disturbance (partial recovery, recovery to pre-hazard system performance, and improving system performance) (adapted from Simonovic and Arunkumar, 2016)

## 1.4 Decision Support System

The ResilSIMt tool is implemented as a generalized decision support system (DSS) that calculates the system performance and resilience to one or more extreme events that disrupt urban systems. The following section describes major components of the tool: (i) the user interface; (ii) the database; and (iii) the mathematical module.

The procedure for calculating the resilience within the ResilSIMt tool can be described in following steps: 1) selection of the analysis (city, or urban center); 2) organization of the data for input into the tool: layers and networks representing urban system such as buildings, critical facilities, energy, and others, as well as social data; 3) input of the hazard scenarios and damage functions; 4) definition and input of the adaptation measures; 5) simulation of the hazardous event and computation of the resilience metric.

## 2 Description of the ResilSIMt Tool

This section presents the user's manual for the ResilSIMt tool. The main features of the tool are described and illustrated in the following sections. The analyses of several different scenarios are possible with the tool and this is accomplished by creating projects. Projects hold the information about infrastructure layers, hazard scenario inputs, damage outputs and adaptation measures. Detailed description of how to input and create projects, is presented in section 2.3. The tool's database is also provided with pre-loaded projects accessible to all users with an account. The preloaded projects are presented and briefly discusses in section 3.

### 2.1 System Architecture of the ResilSIMt Tool

The interactions between software components are summarized in Figure 4. These interactions can be divided into three main steps, including the user interface (UI), the application server and the database. Beginning with the UI, the user provides input data and requests for resilience values from the system. This request is then submitted to the server where it is processed. Data input is then added to the database. Open data is also retrieved from the database and goes to the server.

The server applies the algorithms developed in the methodology coupled with the available data to calculate resilience values, which are then fed back to the UI to be presented to the user.

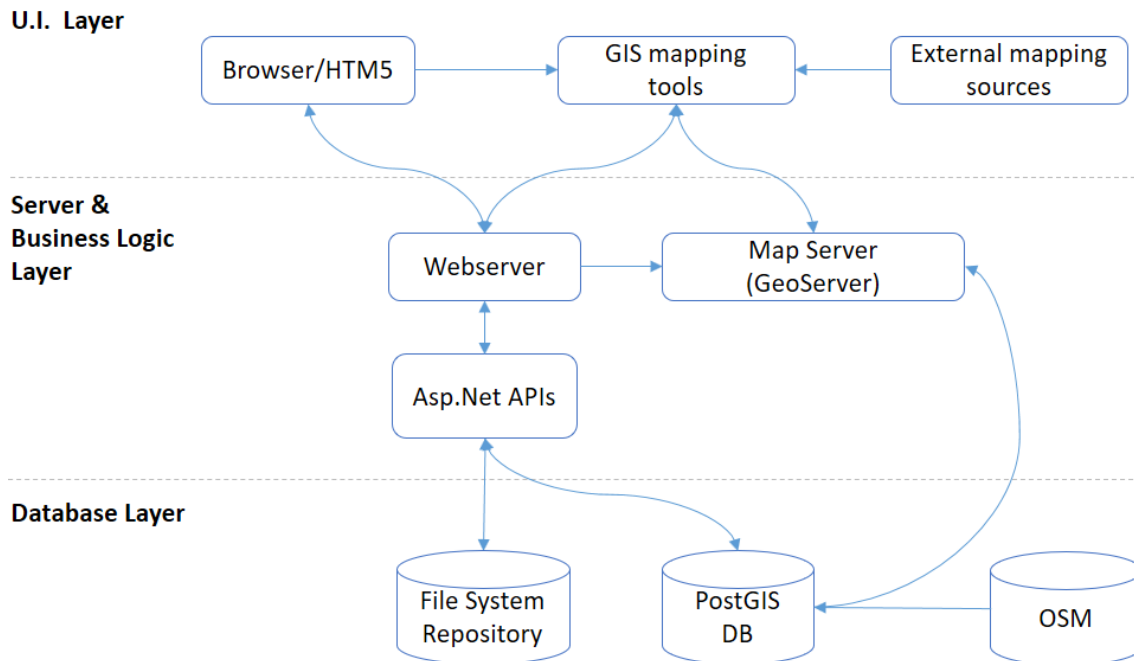


Figure 4. System architecture of the ResilSIMt tool

Within each of these main steps, there are multiple activities to perform the overall task. For the ResilSIMt tool, HTML5 acts as the browser, displaying the information and results. Specifically, HTML5 is a combination of hypertext markup language (HTML) and cascading style sheet (CSS) that allow the design and placement of text on the screen for the user to see. This is also how the user can input adjustments to the extent of adaptation measures. GIS mapping tools are employed to enhance the visualization process by providing a spatial infrastructure and hazards locations. The GIS mapping tools use Java Scripts to help the local processing. In the context of inputting or editing infrastructure networks, this component controls their spatial placement. In the context of hazard input, the GIS mapping tools enable the user to draw polygon areas that represent where the hazards strike. External mapping services are used to provide various maps, to give the user a sense of how the infrastructure placement relates to geographical surroundings. Additional geographic layers, such as property boundaries, geo-political boundaries, municipalities, etc., can be selected.

The database is primarily made of the PostgreSQL software with a PostGIS extension. The database allows for the storage of inputs and results. Open Street Maps (OSM) are one of the primary

data sources made available by the tool. OSM contains various network and layer data such as road networks and locations of various critical facilities.

The communication process between the UI and the database is where most of the computation and processing occurs and consists of the Asp.Net which acts as the storage of the code representing the methodology described earlier. Specifically, it uses C# programming language. The webserver is the component that enables executing the stored code over the internet. In contrast, the Map Server enables the processing of geospatial imaging, such as zooming into and out of a mapped area. For example, whenever zooming in or out of the map image takes place, it is actually accessing different rectangular tiles at various resolutions and details. Some of these details are simplified and kept hidden from the user.

## 2.2 User Account

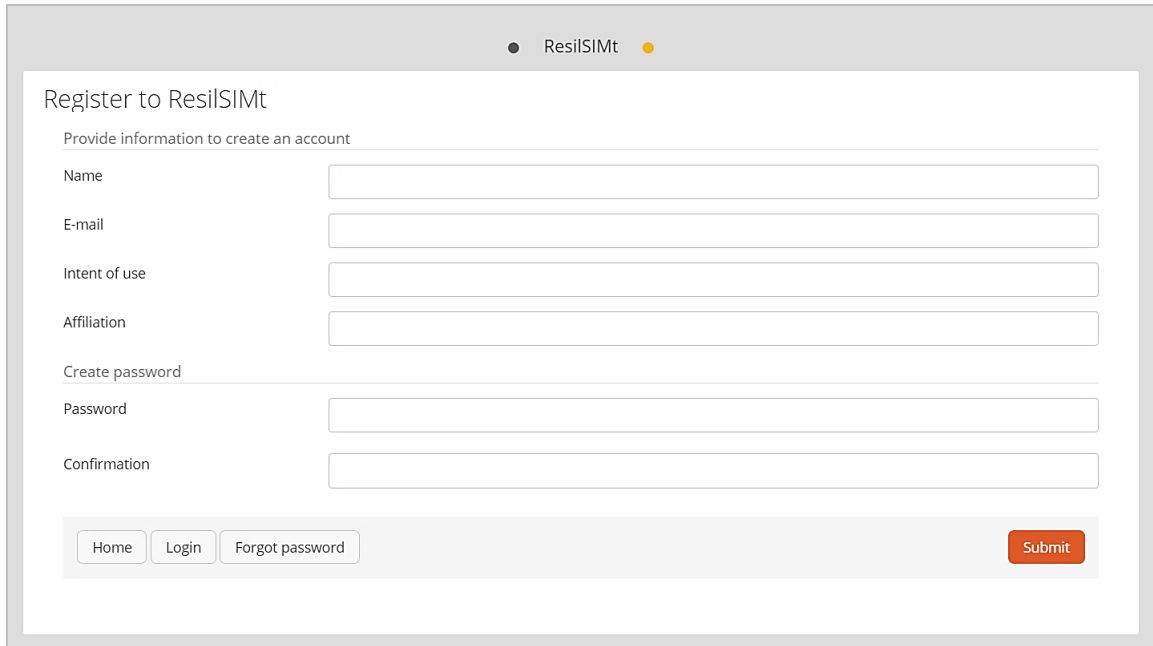
The user must create an account before accessing the ResilSIMt tool functionalities. The account is necessary to allow users to customize the projects, input new data layers, create and provide hazard scenarios, define the damage output, include adaptation measures and visualize and export the system performance and resilience output from the tool, as well as create copies of the pre-loaded projects and create duplicates of existing projects.

### 2.2.1 Creating an account

The following information is required from the user to create an account (Figure 5): Name, Email address, Intent of use, Affiliation, and Password. The password is required to be at least 4 characters long and simple passwords are allowed.

After completing and submitting the form, an email will be sent to the user with the activation code and an activation link as shown in Figure 6. By clicking on the link provided, the user will activate the account. If, for some reason, the link does not work, the user can provide an activation code when they first access the tool (Figure 7).





The screenshot shows a web browser window with a single tab titled "ResilSIMt". The page is titled "Register to ResilSIMt" and contains a form for creating a new account. The form is divided into two sections: "Provide information to create an account" and "Create password". The first section includes input fields for Name, E-mail, Intent of use, and Affiliation. The second section includes input fields for Password and Confirmation. At the bottom of the form, there are three buttons: "Home", "Login", and "Forgot password", and a red "Submit" button.

ResilSIMt

### Register to ResilSIMt

Provide information to create an account

Name

E-mail

Intent of use

Affiliation

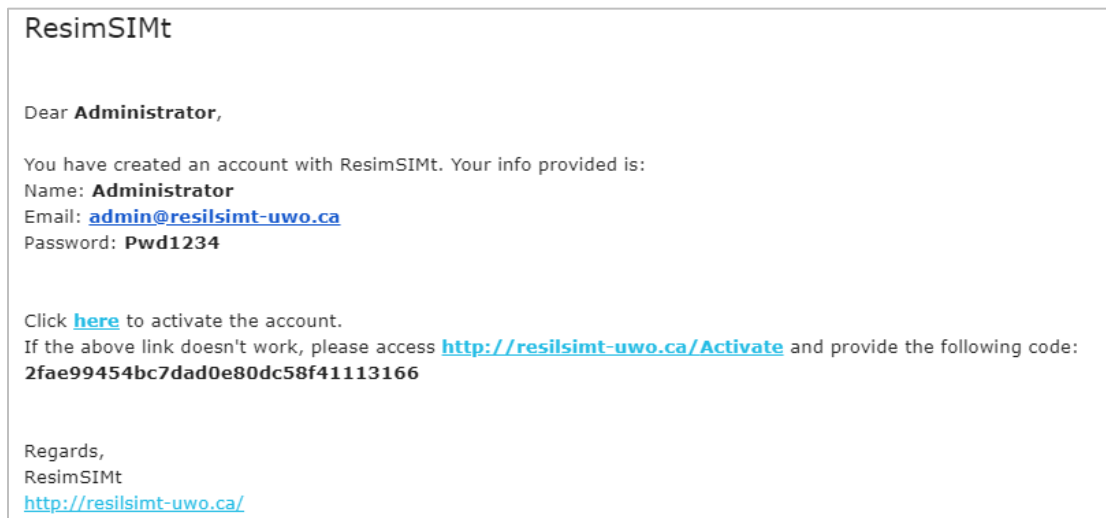
Create password

Password

Confirmation

[Home](#) [Login](#) [Forgot password](#) [Submit](#)

Figure 5. Screenshot of the user account creation page of the ResilSIMt tool



The screenshot shows an email from ResimSIMt. The email is addressed to "Administrator" and contains information about a newly created account. It includes the user's name, email address, and password. It also provides a link to activate the account and a code to use if the link doesn't work. The email ends with a signature from ResimSIMt and a link to the website.

ResimSIMt

Dear **Administrator**,

You have created an account with ResimSIMt. Your info provided is:

Name: **Administrator**

Email: [admin@resilsimt-uwo.ca](mailto:admin@resilsimt-uwo.ca)

Password: **Pwd1234**

Click [here](#) to activate the account.

If the above link doesn't work, please access <http://resilsimt-uwo.ca/Activate> and provide the following code:  
**2fae99454bc7dad0e80dc58f41113166**

Regards,  
ResimSIMt  
<http://resilsimt-uwo.ca/>

Figure 6. Account activation email from the ResilSIMt tool

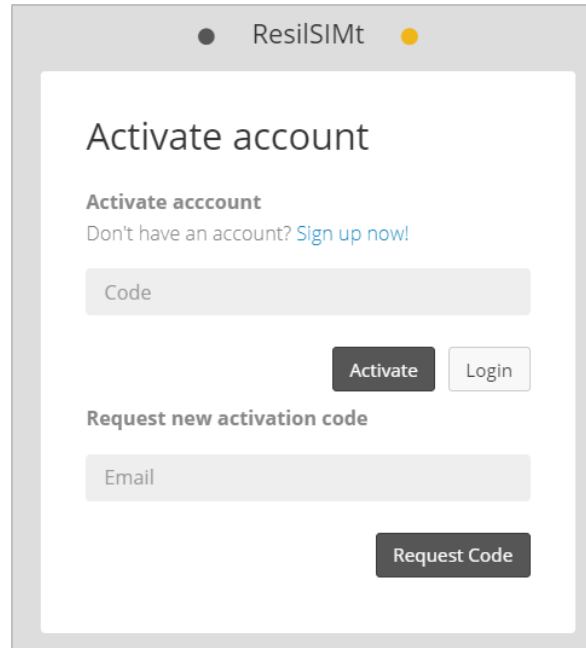
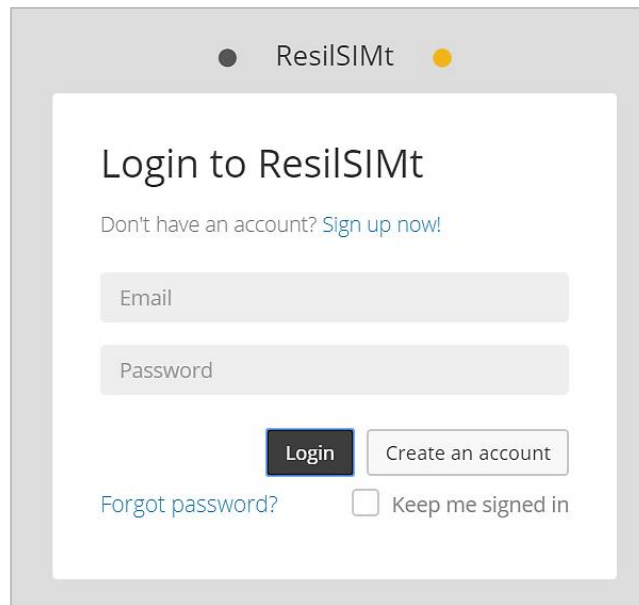
The image shows a web browser window with the title 'ResilSIMt'. The main heading is 'Activate account'. Below it, there is a sub-heading 'Activate account' and a link 'Don't have an account? Sign up now!'. There is a text input field labeled 'Code'. To the right of this field are two buttons: 'Activate' (dark grey) and 'Login' (light grey). Below these is another section titled 'Request new activation code' with a text input field labeled 'Email'. To the right of this field is a dark grey button labeled 'Request Code'.

Figure 7. Account activation page of the ResilSIMt tool

### 2.2.2 Login and password recovery

After the account is created and activated, following the activation email, the user is able to login using the email and provided password. The login page is shown in Figure 8 and if successful a message will be presented (Figure 9) and the tool will redirect to the main screen. The user can create a new password using the 'Forgot password' option on the login screen (Figure 8).

On the recovery password screen, Figure 10, the user can provide the email address used to create the account. A new random password will be generated and provided to the user by email as illustrated in Figure 11.



The image shows a web browser window with the title 'ResilSIMt'. The main content area is a white box with a light gray border. At the top, it says 'Login to ResilSIMt'. Below that, it says 'Don't have an account? [Sign up now!](#)'. There are two input fields: 'Email' and 'Password'. Below the 'Password' field, there is a dark blue 'Login' button and a light gray 'Create an account' button. At the bottom, there is a link 'Forgot password?' and a checkbox labeled 'Keep me signed in'.

Figure 8. Login page of the ResilSIMt tool

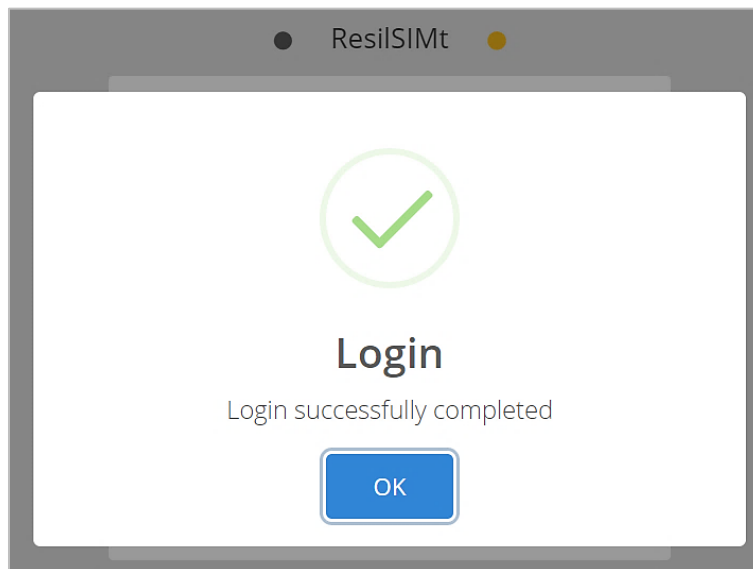


Figure 9. Successful login into the ResilSIMt tool

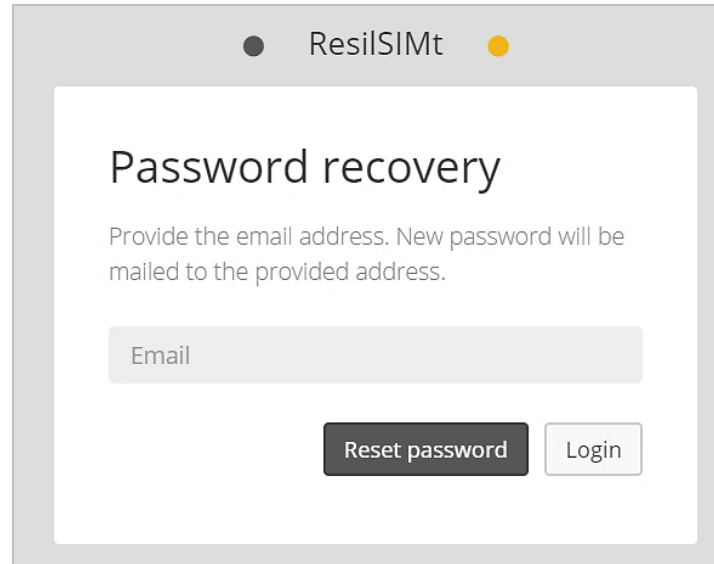


Figure 10. Password recovery option in the ResilSIMt tool

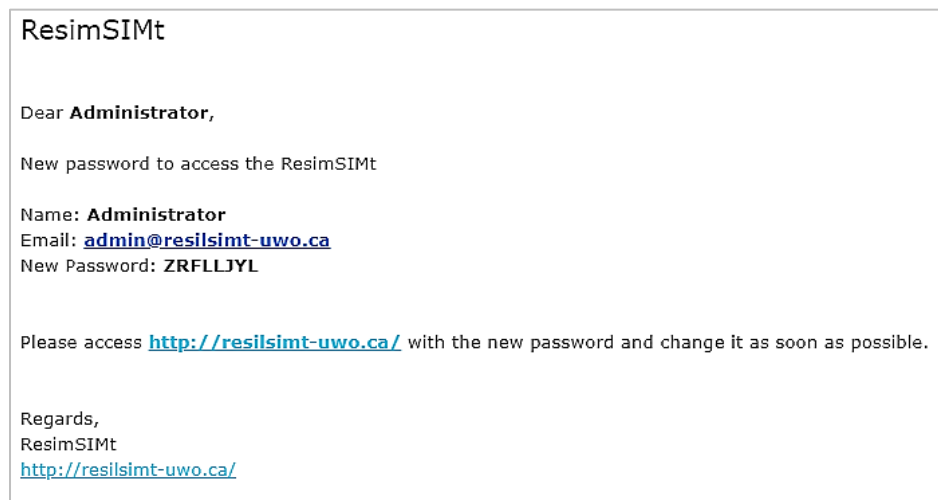


Figure 11. New password email from ResilSIMt tool

## 2.3 Managing Projects

The use ResilSIMt starts with the creation of projects. A project holds the following data: networks and layers; hazard scenarios for the analysis of the system performance and resilience of urban infrastructures and components; and possible adaptation measures for responding to the disturbance caused by hazards. Structuring the ResilSIMt tool use in projects allows a high level of generalization and experimentation with a large combination of different disturbance and response scenarios. There are public and private projects. The public projects are accessible to all users that

register with the ResilSIMt tool, however, in read-only mode. Users can view and explore these projects and experiment with the different adaptation measures without modifying the data inputs. Section 3 describes the pre-loaded public projects available in the tool's database.

The second type, private projects, are associated with a user account. These projects are only visible to the user that creates them. The user is also able to create copies of projects, included a pre-loaded public project, which then can be modified or expanded. It's worth reminding that a copy of a public project becomes private to the user that is creating the duplicate.

The lists of projects in the ResilSIMt database is presented in Figure 12. The list briefly shows details of each project, such as description, location, the owner (the user that created the project), if it is public, and the date created. The options in the last column are:

- Open: will open the project and redirect to the home screen of the tool.
- Edit: allows editing details such as description and location (only available to the owner of the project - Figure 13)
- Copy: creates a duplicate of the project
- Delete: excludes a project and all data associated with it from the database (only available to the owner of the project)

Projects				
Select a project from the list. You can also duplicate or create a new project				
DESCRIPTION	LOCATION	OWNER	CREATED ON	
Example 1 - Toronto flooding event Aug 7, 2018	Downtown Totonno	Administrator	09-08-2018	Open Edit Copy Delete
Example 2 - Illustration of flood impact on transportation and buildings	Toronto	Administrator	13-08-2018	Open Edit Copy Delete
Example 3 - Illustration of wind impact on buildings and critical infrastructure	Toronto	Administrator	13-08-2018	Open Edit Copy Delete
Example 4 - Illustration of impacts of multi-hazards on buildings and roads	Toronto	Administrator	13-08-2018	Open Edit Copy Delete
Example 5 - Illustration of cascading impacts on electricity supply and transportation	Toronto	Administrator	13-08-2018	Open Edit Copy Delete
Copy of: Example 5 - Illustration of cascading impacts on electricity supply and transportation	Toronto	Administrator	11-09-2018	Open Edit Copy Delete
Create new				

Figure 12. List of projects in the ResilSIMt tool

Project: ×

Details of the project

Name:

Description:

Location:

Longitude:

Latitude:

Figure 13. Editing details of a project in the ResilSIMt tool

New projects can be created using the ‘Create new’ option from the project list (Figure 12). This option will present a tree step process to the user: 1) Details: project title and description (Figure 14); 2) Location: location, usually a city name and the coordinates of the location (Figure 15); 3) Create: final step to confirm and create the project. After the project is created it will be added to the user’s projects list (Figure 16). The project can then be opened, and the data provided as described in the following sections.

Create a project

Follow the steps to create a project

1. Details

2. Location

3. Create

---

Project title

Project title can contain any letters or numbers

Description

Please provide a description

◀ Previous

Next ▶

Figure 14. New project creation screen – project title and description

Create a project

Follow the steps to create a project

1. Details

2. Location

3. Create

---

Name of the City/Location:

Please provide the name of the city or location

Longitude

Please provide the Longitude

Latitude

Please provide the Latitude

◀ Previous

Next ▶

Figure 15. New project - location and coordinates

Create a project

Follow the steps to create a project

1. Details 2. Location 3. Create

Project will be created.

You will be directed to the list after the project is created. You can open the new project to provide the data, hazards, adaptation options and calculate the Resilience.

Previous Finish ✓

Figure 16. New project – final step

## 2.4 Main Screen

The user interface, as presented in Figure 17, has the following components: (i) GIS mapping component used to present geographic data and assist user's input; (ii) data input functionalities that allow users to select a set of adaptation measures; and (iii) results visualization - functionalities for the presentation of the system performance as interactive graphs, and tables to export the data extracted from the database.

The GIS interface is used in the resilience calculation screen to aid the user selecting a region of the city for the resilience calculation. Additionally, it is used to present all the geographic layers used in the tool's database. The adaptation measures controls are built as simple sliders where the user can select from a range between a minimum and maximum value defined for each measure.



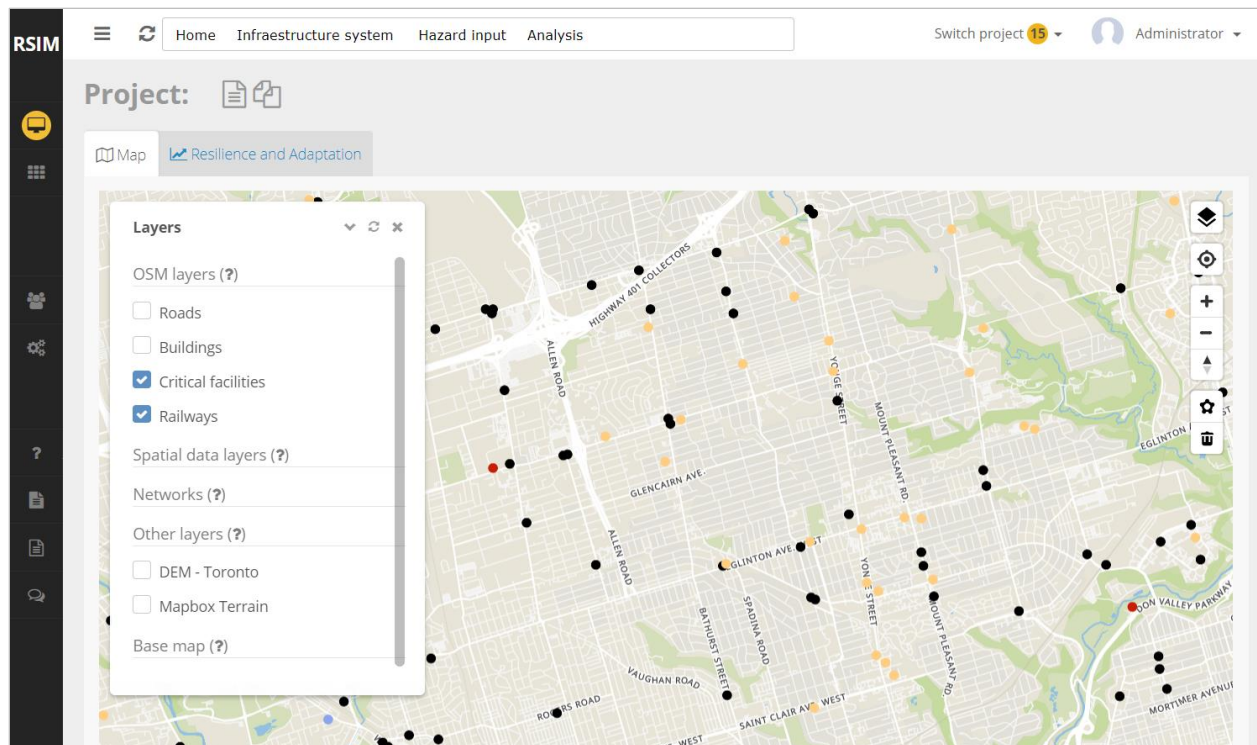


Figure 17. The ResilSIMt tool main screen

On the top left to the home screen the user name is displayed, the number of projects associated with the logged-in user, and an option to quickly switch the project (Figure 18).

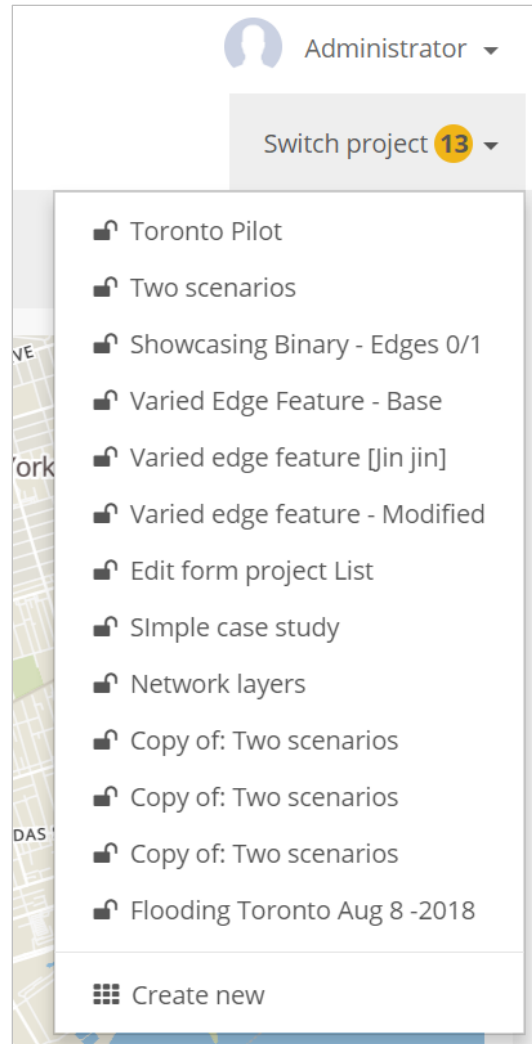


Figure 18. Name of the user and list of projects

## 2.5 GIS Tool in the ResilSIMt

The ResilSIMt tool uses a JavaScript based GIS tool to display the layers and networks as maps. The tool used is the Mapbox GL JS ® (Mapbox, 2018). The GIS tool options can be accessed using the left toolbar on the main screen (Figure 17 and Figure 19). The listed options are described as:

- ◆ Show/hide the layer menu (Figure 20)
- ⊙ Show the users current location
- + Zoom-in a level
- Zoom out a level

- ▲ 3D visualization and modification of the tilt angle of the map
- ☆ Drawing tool for selecting polygons on the map (used for the definition of the hazard areas)
- 🗑 Delete tool for erasing polygons from the map (used for the definition of the hazard areas)



Figure 19. GIS tool options off the ResilSIMt tool

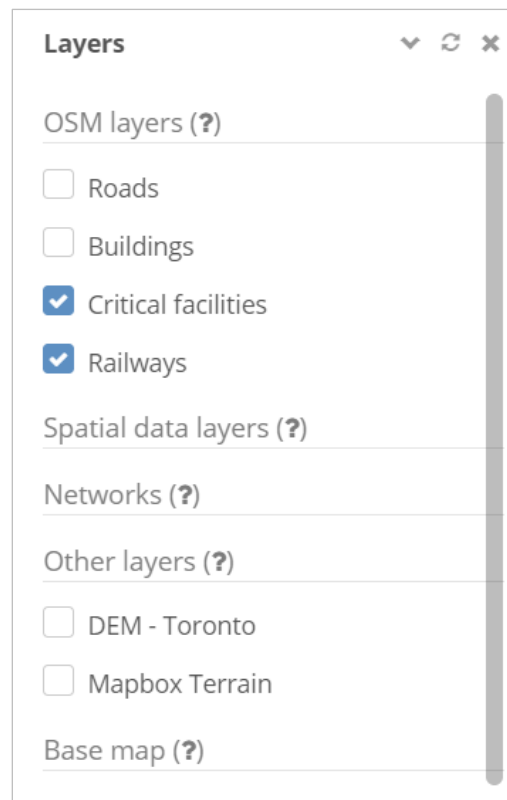


Figure 20. Layer menu for the GIS tool

## 2.6 Base Maps

The tool provides three options of background maps that are presented in Figure 21. The background maps used by the tool, follow the free and open source styles, OpenMapTiles (2018). The options are: 1) *Basic*: simple map presentation with fewer details on the element labels and smooth colors. Ideal for displaying many data layers and networks; 2) *3D*: similar map to the *Basic* style, however, with 3D presentation of buildings; and 3) *OSM Bright*: a base map that presents the detailed OpenStreetMap data with emphasis on major roads. By switching the background map, the tool will reload the home page and the current project.

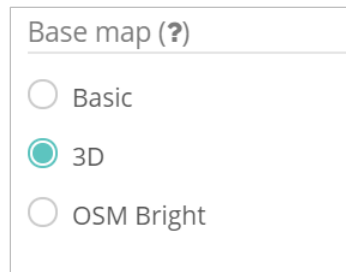


Figure 21. Base maps available in the ResilSIMt tool

## 2.7 Top Menu Options development

The home screen top menu of the tool includes the following options:

- *Infrastructure system*
  - *Existing*
    - *Networks*: List of user-added networks. Management and editing of existing infrastructure networks.
    - *Spatial data*: Management of user-provided GIS data layers
  - *Existing expansion*: Expansion of an existing network by adding new nodes
  - *New development*: Introduction of the road network for a new development
- *Hazard input*: Management of the hazard scenarios and impact output functions.
- *Analysis*:
  - *Adaptation measures*: Management of adaptation measures.
  - *Resilience*: Resilience calculation

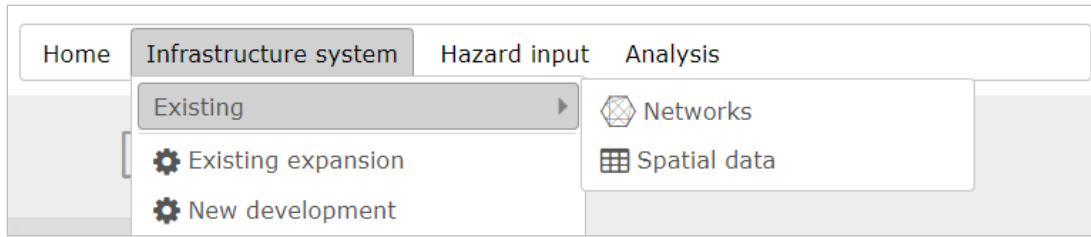


Figure 22. Top menu option of the tool

## 2.8 Data Input

The ResilSIMt tool allow the input of supplementary data (to the pre-loaded and ready to use OpenStreetMap layers) that represent urban systems in the GIS or network format.

### 2.8.1 Preloaded OpenStreetMap layers

The tool's database is pre-loaded with some of the most relevant layers imported from the OpenStreetMap (OSM) dataset. The OSM contains various network and layer data such as road networks and locations of various critical facilities (Figure 23).

All projects within the tool have the OSM layers available for analysis and the damage output can be defined for each of the layers based on the hazard inputs. At this stage of the development, the OSM layers in the ResilSIMt tool cover the GTA (Grater Toronto Area).

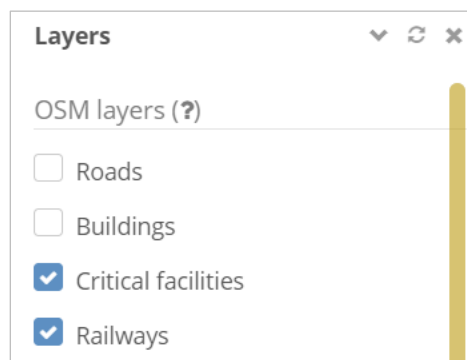


Figure 23. List of OpenStreetMap (OSM) layers available for the analyses

## 2.8.2 Network layers

The network layers can be added to the user's projects as needed and desired. The added networks will appear on the layer menu for display by the map tool (Figure 24).

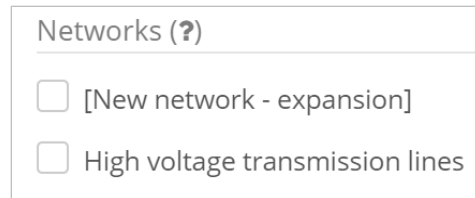


Figure 24. User provided network layers of the ResilSIMt tool

Network layers can be managed from the tool using the '*Networks*' option from the top menu of the home screen. A list of networks added by the user for a given project is presented in Figure 25. There is an option to 'Edit' and 'Remove' an existing network, and add a new network using the 'Add new network' button on the screen.

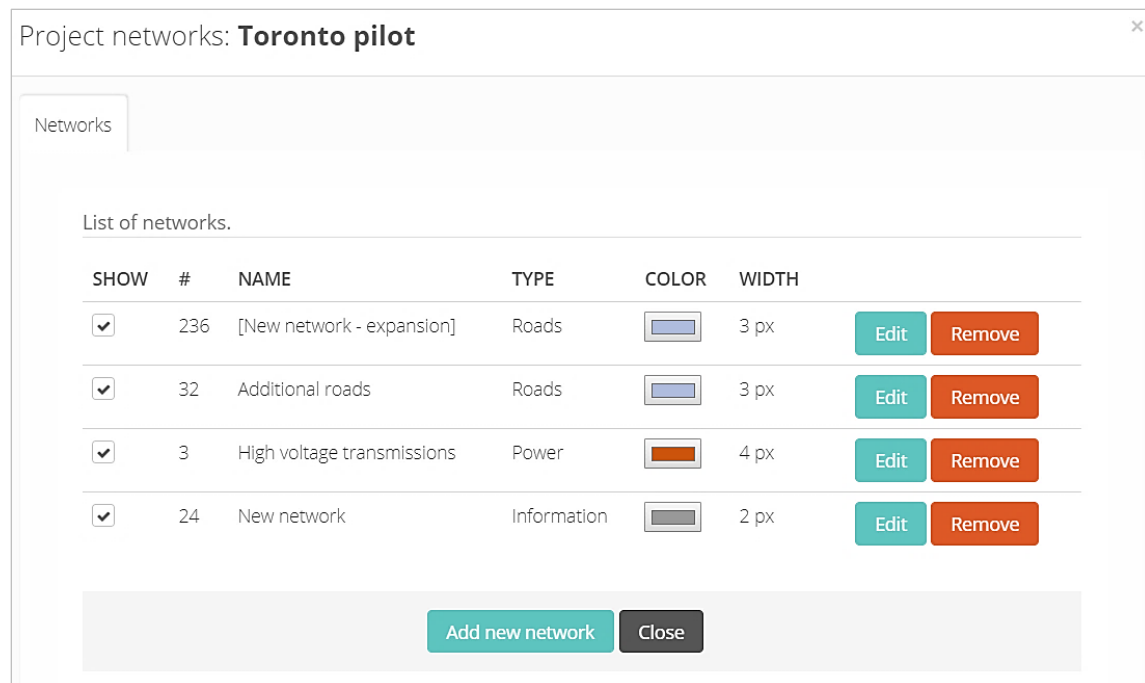


Figure 25. List of networks added to a project

The 'Edit' or 'Add new network' options will open a new ResilSIMt screen as presented in Figure 26. First, some basic information for the new network will have to be provided: name, color

and line width (used to plot the network on the map), the type of the network and a description that is optional (Figure 26). After the network is created the user can provide a set of files representing the elements of the network: 1) *Nodes*: CSV-formatted file with the list of network nodes, with a code (ID) and the GIS coordinates; 2) *Edges*: CSV file with the list of edges or links for the networks containing the ID of the link, the initial and ending node for each of the links and, if available, the cost/capacity of the link; 3) *Geometry file*: an optional GeoJSON-formatted file (see Appendix A for more details) that incorporates the GIS geometry of the edges connecting the nodes, for more realistic map representation of the network. GeoJSON files can be create using free software such as QGIS. (Quantum GIS).

The screenshot shows a web interface titled "Project networks: Toronto pilot". It has two tabs: "Networks" (active) and "Edit network". Under "Network information", there are fields for "Network name" (filled with "High voltage transmissions"), "Color (for the map)" (a color picker showing orange), "Width (for the map)" (a numeric input set to 4), "Select network type" (a dropdown menu showing "Power"), and "Description" (filled with "High voltage transmissions lines"). Below these are "Update network" and "Cancel" buttons. The "Network files" section has the instruction "Provide the files for the nodes and edges." and four file selection fields: "Nodes input file (CSV format)", "Edges input file (CSV format)", "Service areas for nodes (optional - GeoJSON format)", and "Edges geometry file (optional - GeoJSON format)". Each field has a "Select file" button. At the bottom is an "Upload" button with an upward arrow icon.

Figure 26. Providing data for newly added network

### 2.8.3 Spatial data layers

Spatial data layers are GIS enabled files that can represent all non-network layer data. GIS data layers can be presented using point, line and/or polygon shapes. For example, critical facilities can be presented as points or polygons. Figure 27 presents the list of layers added to a given project. Once the layer is uploaded it can be displayed on the map and will be listed in the layer menu of the GIS tool.

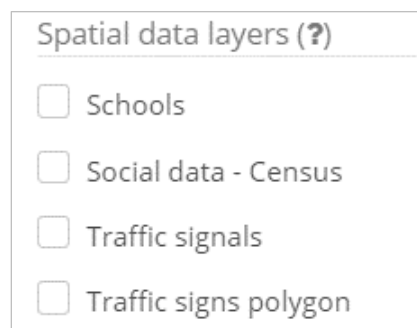


Figure 27. List of project spatial data layers added by the user

The 'Layers' option on the top menu is used to manage the spatial project non-network data. The first screen presented will show the list of layers of the project (Figure 28). The listed layers can be modified using 'Edit' option or removed with the 'Remove' option. In addition, the color used to plot the data on the map can be modified too. The button 'Add new layer' will allow user to add and upload a new layer's data with assistance of a new screen, as shown in Figure 29. The following information is required to add a new layer: name of the layer, color, type of geometry (point, line or polygon) and data type (critical facilities, buildings, social data). Once the layer is created, the data file, using a GeoJSON format can be provided (Figure 30). In case of social data, the user should define what field from the uploaded GeoJSON file will contain vulnerable and total population (Figure 30).



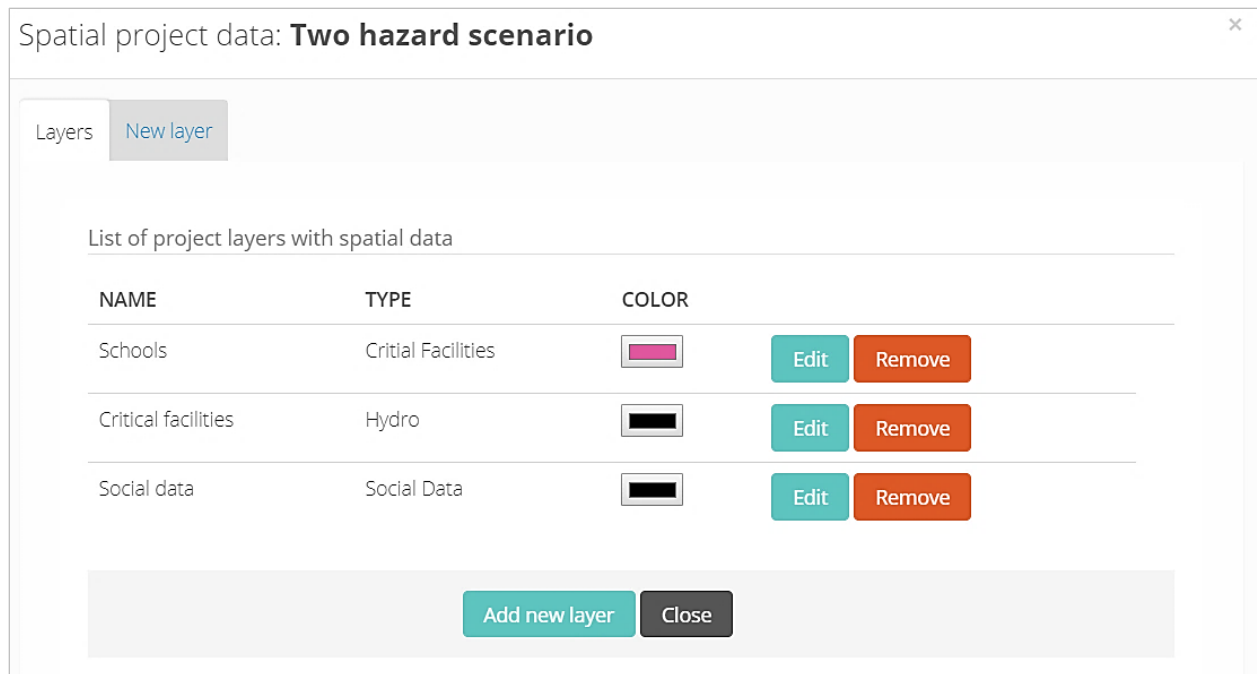


Figure 28. Managing the list of data layers added by the user

Spatial project data: **Two hazard scenario**

**Layers** New layer

Layer information

Layer name:

Color:

Line/point width:

Layer geometry type:

Layer data type:

Description:

[Add layer](#) [Cancel](#)

Figure 29. Adding a new general data layer

The ResilSIMt also requires the definition of ‘categories’ depending on the type of the data layer. For social data, two categories that should be defined by the user are: (i) vulnerable population and (ii) total population (Figure 30). The list of options for both categories will be filled out by the tool based on the input file data fields. In the GeoJSON file, each of the geographic features

(representing a physical region) contains information associate to each of them. The census data files usually are organized in aggregation units (census tracts or dissemination areas), and each of these regions has information about the population.

Spatial project data: **Two hazard scenario**

Layers Edit layer Data file/categories

Layer data file

Provide the GeoJSON file for the layer.

GeoJSON file:  Select file Upload

Social data

GeoJSON social data file should include records with Census/NHS area (i.e. dissemination area) and indication of vulnerable and total population.

Vulnerable population:

Total population:

Save

Cancel

Figure 30. Population fields of the social data layer

#### 2.8.4 Urban expansion

The tool allows users to develop new infrastructure systems (for the new developments – urban expansion) from scratch using a pre-loaded algorithm. The algorithm is adapted from Wickramasuriya et al. (2011) and divides a parcel of land into lots and roads to create a subdivision. Currently, only the roads are captured through the algorithm within this tool. When the new development option is selected, the screen shown in Figure 31 pops up. The first two parameters refer to the network and layer management. They determine where the new roads are placed. The next three parameters refer to dimensions of lots and streets in meters. When the “Draw on map” button is selected, the user can draw a polygon to outline the boundaries of the new development. When data input completion, selection of “Create and save” results in a new network.

Figure 31. New development

### 2.8.5 Network expansion

The tool comes with an infrastructure network expansion algorithm based on methodology developed by Fu et al. (2017). The main purpose of this option is to allow for modifications, maintenance, and improvements of existing infrastructure networks. Note that this expansion algorithm is only applicable to networks, not the spatial data layers. The algorithm adds additional nodes and edges to an existing network by applying the inputs shown in Figure 32. For the first menu item, select the infrastructure network to expand. Next, decide on the number of nodes to add. Afterwards, draw the area of expansion with the “Draw on map” option, as shown in Figure 33. The Fu et al. (2016) algorithm places the node based on the demand for infrastructure, which is correlated to population information, and a gamma factor. The social layer data contains the population information. A higher positive gamma value means that population density is correlated to the infrastructure while a negative gamma value means it is inversely proportional. The input parameters as in Figure 32, are described by Fu et al. (2016) and affected how civil infrastructure could expand in a network format. Gamma is a regulated parameter that determines how some infrastructure network nodes appear in relationship to population demand. For example, a higher positive gamma value suggests that an infrastructure node is likely to appear in relatively densely populated areas. Conversely,

a negative gamma value indicates that the infrastructure node is more suited to remote areas. An example of an infrastructure type that has a negative gamma could be water dams where they are typically situated further from a populated area. alpha and beta are scaling parameters that affect the cost and efficiency of a new network edge respectively. Alpha has a range of decimal values from zero to one, excluding the value of zero itself. A smaller alpha value increases the probability that a closer geographical edge is established. Beta has a range of decimal values ranging from zero to one. A zero Beta value signifies there is no relationship between the attachment of an edge to a well-connected infrastructure node. Conversely, a Beta value closer to one signifies that a greater importance is placed in connecting to an existing node with many connections.

Network expansion

Provide values for the required parameters.

Select the network:

[New network - expansion]

Select the social data layer:

Social data - Census

Number of nodes:

2

Alpha:

0.03700

Beta:

0.00000

Gamma:

0.54000

Draw expansion area on the map

Create new node(s)

Close

Figure 32. Network expansion

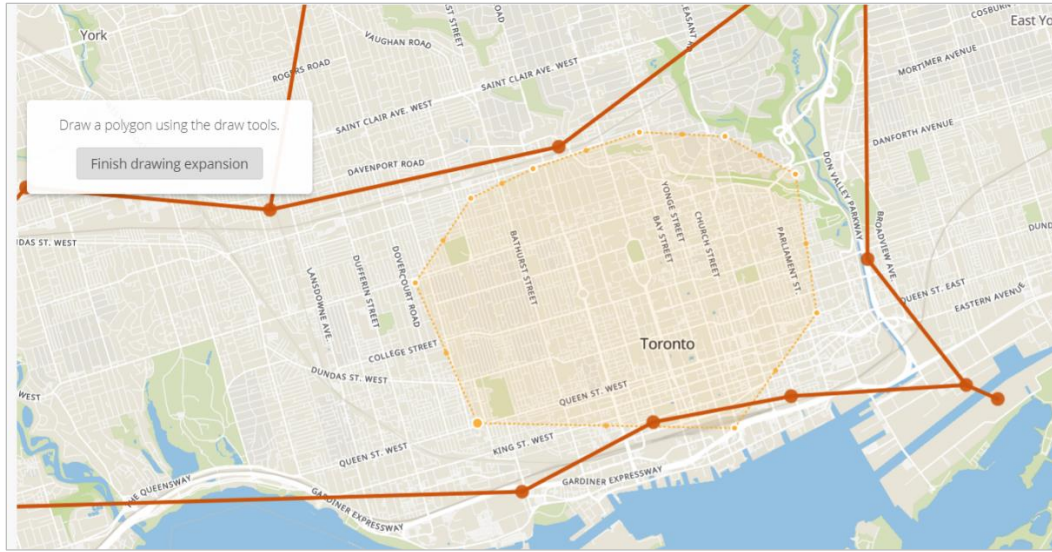


Figure 33: The network expansion – selection the region

New edges are probabilistically formed between the new and existing node(s) based on the cost (edge capacity) and efficiency factors, as represented by alpha and beta respectively. Efficiency is represented by the degrees of existing nodes and costs is based the geographical distance between the set of nodes. Note that alpha and beta values must be between 0 and 1. Furthermore, alpha values cannot be 0. Additional explanation of the parameters and algorithm can be found in Fu et al. (2016). Figure 34 shows the end result of the network expansion algorithm.

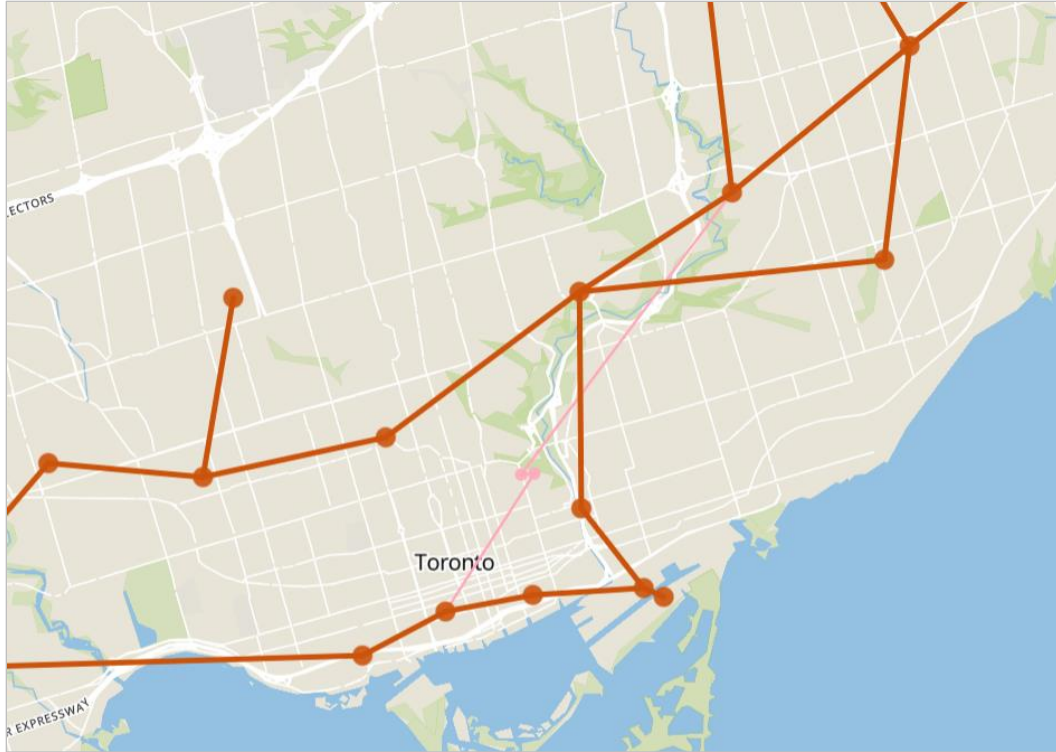


Figure 34. The network expansion – preview of the expansion

## 2.9 Hazard Scenarios

The hazard scenarios are managed from the user interface selecting the ‘Hazard scenarios’ option from the top menu. A list of hazards created by the user, is present as shown in Figure 35 with some basic information, such as hazard type, description and starting time, ending time and duration. Hazards can be added using the ‘Add new hazard scenarios’ button and existing hazards can be modified using the ‘Edit’ option and deleted using the ‘Remove’ option.

When adding or editing a hazard scenario, a screen with the details will be shown (Figure 36). For the hazard description the following information is required: hazard type, description, and starting and ending time steps. Additionally, the affected areas need to be defined by the user by either drawing the polygons on the map using the ‘Draw polygon’ or importing polygons from external GeoJSON files using the ‘Import polygons’ options. The polygons drawn on the map can be seen for example in Figure 37. Multiple areas can be selected for the same hazard. Figure 36 also shows the ‘Impact’ tab that is used for the input of the impact of the projects as presented in detail on section 2.9.1.

Hazard scenarios: **Toronto pilot**

Hazard scenarios
Impact

List of hazard scenarios:

TYPE	DESCRIPTION	START	PEAK	END		
Flooding	Heavy rainstorm	10	14	40	Edit	Delete
Wind	Wind storm	1	25	11	Edit	Delete
Flooding	Polygon area flooding	5	10	20	Edit	Delete
Flooding	Varied edge flood	3	10	20	Edit	Delete

Add new hazard scenario
Close

Figure 35. Managing the hazard scenario in the ResilSIMt tool.

Hazard scenarios: **Toronto pilot**

Hazard scenarios
Edit scenario
Impact

Hazard scenario, duration and affected area

Select the hazard type: Wind

Description: Wind storm

Starting time: 1

Ending time: 11

Time unit: Hours

Areas and magnitudes: Draw polygons Edit magnitudes

Polygons geometry file (GeoJSON format): Select file Import polygons

AREA (KM <sup>2</sup> )	ID
444.5246	8f90003e2813fbc7104bd08a94d815ff
468.7465	b0b1e9e11afb78b5c35d162b34ba6007

Save hazard scenario
Cancel

Figure 36. Adding or modifying a hazard scenario.



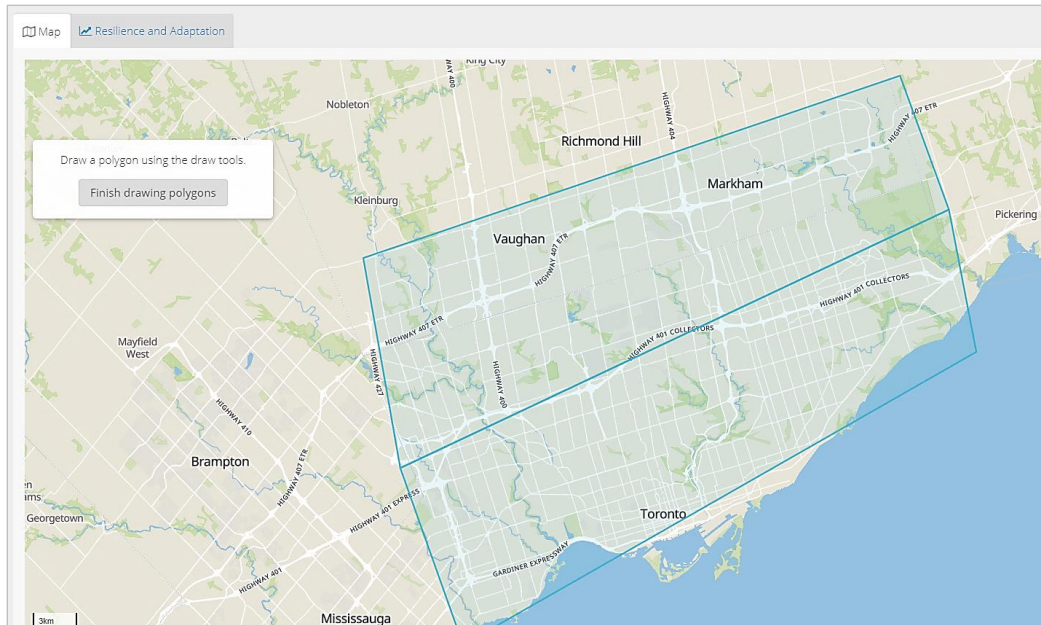


Figure 37. Hazard scenario – definition of the impacted areas.

After defining the impacted areas on the map, the tool requires the hazard characterization for each of the defined areas. By selecting the region, a table will be displayed to input the hazard value for each time step (Figure 38). The input units should be selected according the type of hazard. The example in Figure 38 shows the windstorm hazard, and the input units are km/h.

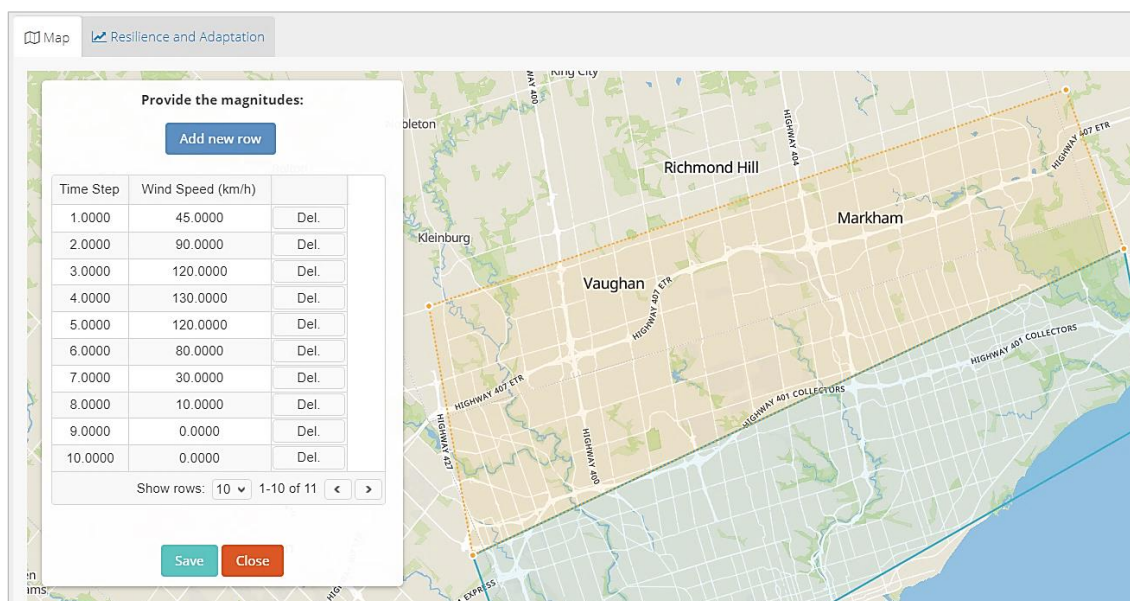


Figure 38. Hazard scenario – input of the hazard data over time.



### 2.9.1 Impact definition

The ResilSIMt tool is flexible regarding the input and impact assessment (definition of impact) for each of the created hazards. For each hazard, a set of impacts can be defined for each of the layers in the project (Figure 39). The user is able to manage the impacts by adding, editing, delete and defining the interdependencies between different infrastructure types. The independencies are displayed as a causal tree, as shown in Figure 39.

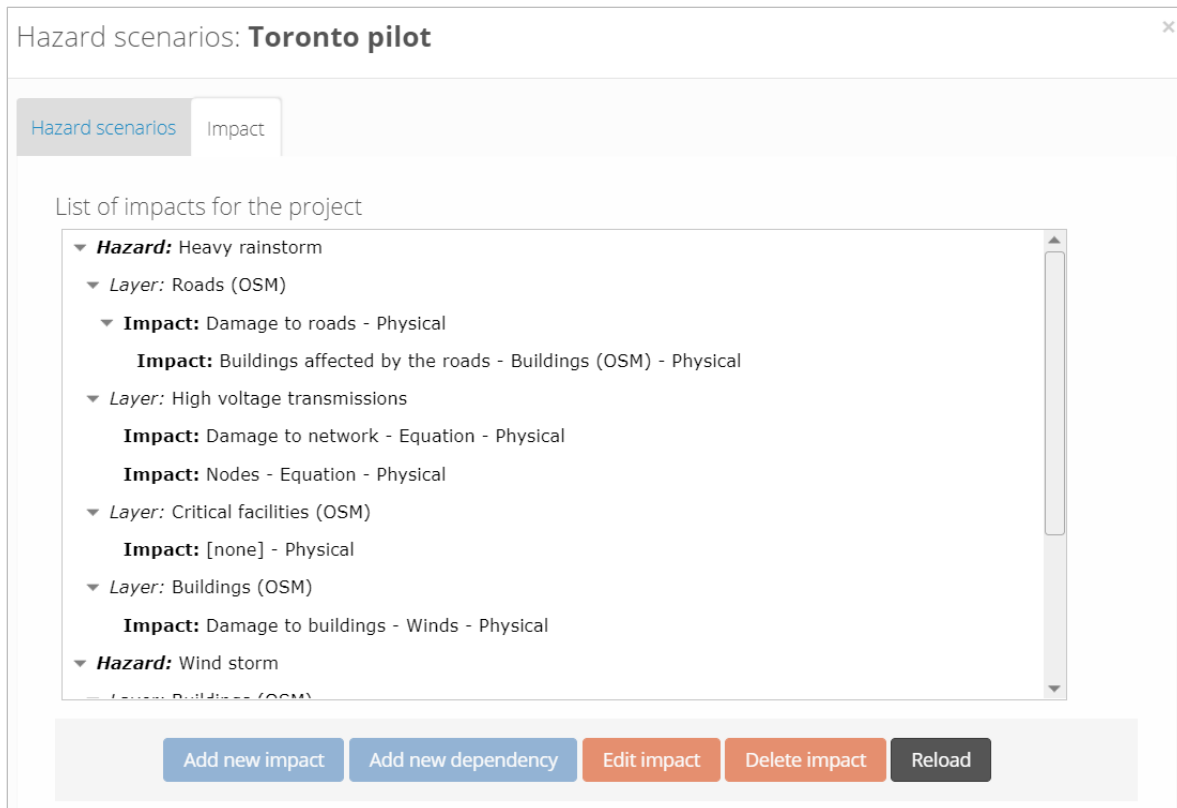


Figure 39. Damage input for the various hazards scenarios created by the user.

Each impact requires detailed definition (Figure 40): the infrastructure (layer) affected; description (should reflect the impact as accurately as possible); the type of damage (physical or functional); indication is the physical damage permanent; and the damage units. The damage units depend on the selected layer (infrastructure).

The impacts can be provided as: 1) damage tables (Figure 40); 2) damage equations (Figure 41); and 3) fragility curves (Figure 42).

Hazard scenarios: **Toronto pilot**

Hazard scenarios
Edit scenario
Impact
Edit impact

Impact for hazard: **Heavy rainstorm**

Description:
Buildings affected by the roads

Select the layer:
OSM: Buildings (OSM)

Impact type:
Physical
Functional
☐ Physical damage is permanent

Damage units:
Damage (\$/m2)
Type of damage:
Loss in system performance

Base system performance:
100.00

Damage curves (table)
Damage functions (equation)
Fragility curves

Add new row

Water depth (m)	Damage (\$/m2)	
0.00	0.00	Rem.
100.00	10.00	Rem.

Go to page: 1 Show rows: 10 1-2 of 2

Save damage functions
Cancel
Delete impact

Figure 40. Definition of the infrastructure damage impact caused by hazards.

Damage curves (table)
Damage functions (equation)
Fragility curves

Write the equation:
10 \* [d]

Equation validity (limit on [d]):
Min. value [d]: 0.00
Max. value [d]: 50.00

When writing the equation use [d] to denote the damage variable. The damage should be compatible with the selected unit.

Figure 41. Equation damage impact

Damage curves (table)

Damage functions (equation)

Fragility curves

☒ Probability
☐ Damage

Add new row

Water depth (m)	DS 1	DS 2	DS 3	DS 4	
0.00	0.00	0.00	0.00	0.00	Remove

Go to page: 
Show rows: 
1-1 of 1

DS (i): is damage state –  $i = 1, \dots, 4$ . DS values are between 0 and 1 from the cumulative probability.

Figure 42. Fragility curves damage impact.

## 2.10 Adaptation Measures

Increase in adaptive capacity of an urban system reduces the loss of system performance over the duration of the hazard and shortens the recovery time. As a result, the system resilience is improved. The ResilSIMt allows adaptation measures to be freely defined by the user (Figure 43 and Figure 44) for each of the data layers and networks pre-loaded in the database or provided by the user. The adaptation measures will improve the overall performance of an urban system when subject to hazards and the user will be able to evaluate their efficiency. The list Figure 43 includes the range of adaptation allowed for each measure ('Min' and 'Max' columns) as well as the layer where the adaptation is being applied. Options on this screen are 'Add new adaptation measure' to add new adaptation measures and 'Edit' to modality and 'Delete' to remove.

Additional forms of adaptation can occur by adjusting the impact relationship(s) shown in section 2.9.1. Note that these alternative forms of adaptation require a base scenario to have been simulated and exported beforehand in order to perform the comparison. One may want to show the impact of hardening infrastructure to a hazard event. For example, an underground electrical infrastructure pump may originally be vulnerable to flood damage. So, a submersible pump may be considered as an adaptation option, as it can continue to perform even when the pump is submerged in water. Introduction of hardening measures can be done by adjusting the original impact relationship that flooding had on electrical pumps.

Another form of adaption can be implemented by moving the location(s) of the original infrastructure. For example, one scenario where this may be applicable is during the planning phase of housing development. One alternative may be to locate a housing complex in a flood prone area. Another alternative could be to locate the housing complex outside of a flood prone area. Although the tool does not incorporate other relevant criteria such as cost or aesthetics, it can show that resilience to flooding would be higher if the housing complex is located outside of the flood prone area.

Adaptation measures: **Toronto pilot**

Adaptation measures

List of measure(s)

MEASURE	TYPE	MIN	MAX	LAYER		
Maintenance of drainage infrastructure	Proactive	0.00	100.00	Roads (OSM)	Edit	Delete
Invest in resilience building projects	Proactive	0.00	100.00	Buildings (OSM)	Edit	Delete
Efficient payment of claims	Reactive	0.00	100.00	Buildings (OSM)	Edit	Delete
Temporary dyking	Reactive	0.00	20.00	Roads (OSM)	Edit	Delete
Improving evacuation	Proactive	0.00	80.00	Critical facilities (OSM)	Edit	Delete
Increase the number of adjusters	Reactive	0.00	100.00	Buildings (OSM)	Edit	Delete
Transformers protected	Proactive	0.00	100.00	Toronto Hydro	Edit	Delete
Surface drainage	Proactive	0.00	100.00	Roads (OSM)	Edit	Delete
Reinforcement of the towers	Proactive	0.00	100.00	High voltage transmissions	Edit	Delete

Add new adaptation measure
Close

Figure 43. Managing the adaptation measures for a given project.

Figure 44 presents the screen to add adaptation measures to the project. The measures added will be available for the analysis of the system performance and resilience, and the input of information is required: measure type, the infrastructure affected (layer), name, description and the possible range (minimum and maximum values of adaptation). Figure 45 shows how are the adaptation measures

presented to the user, in the form of sliders, that can be adjusted or modified the desired levels to produce different outcomes. In the ResilSIMt tool the system performance before application of the adaptation measures (pre-adaptation) will always be presented in orange colour in the output graphs, and in blue for the system performance and resilience after the application of the adaptation measures (post-adaptation).

The screenshot shows a dialog box titled 'Add adaptation measure' with two tabs: 'Adaptation measures' (selected) and 'Edit measure'. The main area contains the following fields and controls:

- Measure type:** A dropdown menu with 'Reactive' selected.
- Select the layer:** A dropdown menu with 'Layer: Roads (OSM)' selected.
- Recovery starting time:** A slider control with a value of 10 displayed in a blue box. The slider range is from 0 to 40, with 40 also displayed in a grey box.
- Measure:** A text input field containing 'Temporary dyking'.
- Measure description:** A text input field containing 'Lot level and buildings/homes protection'.
- Minimum value:** A text input field with '0' and up/down arrow buttons.
- Maximum value:** A text input field with '20' and up/down arrow buttons.

At the bottom of the dialog are two buttons: 'Update' (in a blue box) and 'Close' (in a grey box).

Figure 44. Adding an adaptation measure to the ResilSIMt tool

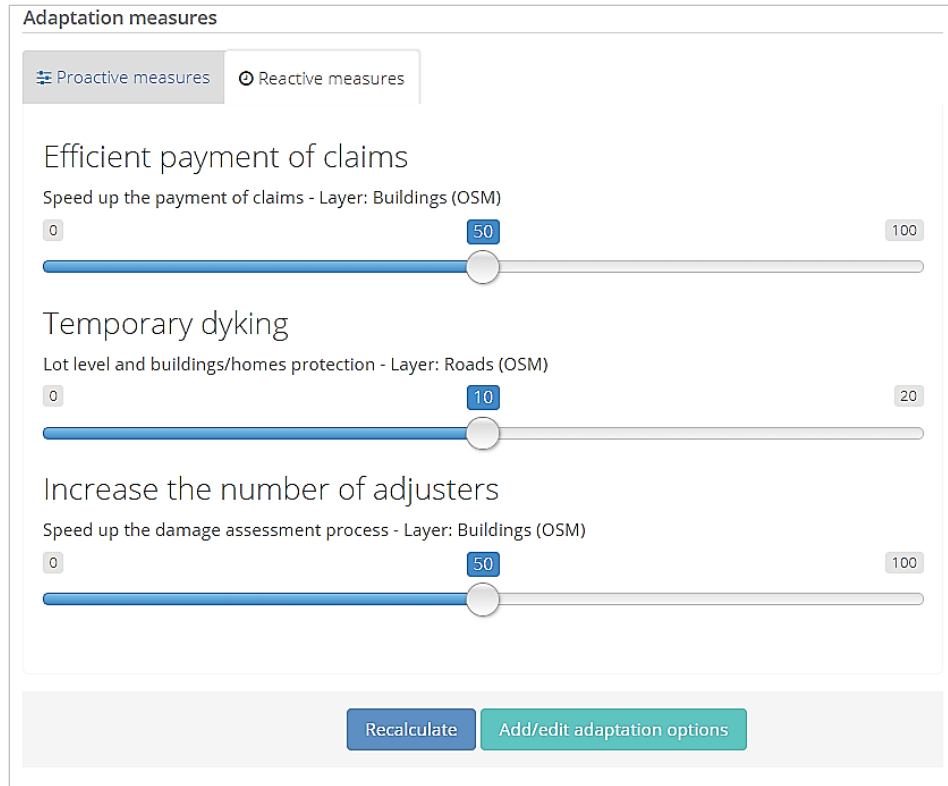


Figure 45. Selecting the level of adaptation

## 2.11 System Performance and Resilience Simulation

The user's inputs for the hazard scenarios limit the geographic extension of the resilience calculation by the tool. Examples of typical system performance graphs are presented in Figure 46 and Figure 47. The first is showing the impact (system performance) of a wind storm on the building layer over time. The second one shows the impact of the same hypothetical windstorm on the school layer. The graphs in both figures (Figure 46 and Figure 47) are presenting a loss of performance and then a recovery to the full pre-hazard performance.

The system performance and resilience graphs are shown with two lines: one presenting the pre-adaptation, in orange color, performance and resilience of the infrastructure system with original configuration; a second line, in blue color, representing the system performance and resilience after the application of selected adaptation measures. The user can hide or show the lines from the plots by clicking on the name in the legend below the graph. A zoom option is also available by dragging out a rectangle in the chart with the mouse pointer. A "Reset zoom" option reverts the initial zoom

level. By hovering the mouse pointer over dots, the user can view the time steps and the value of the system performance and resilience.

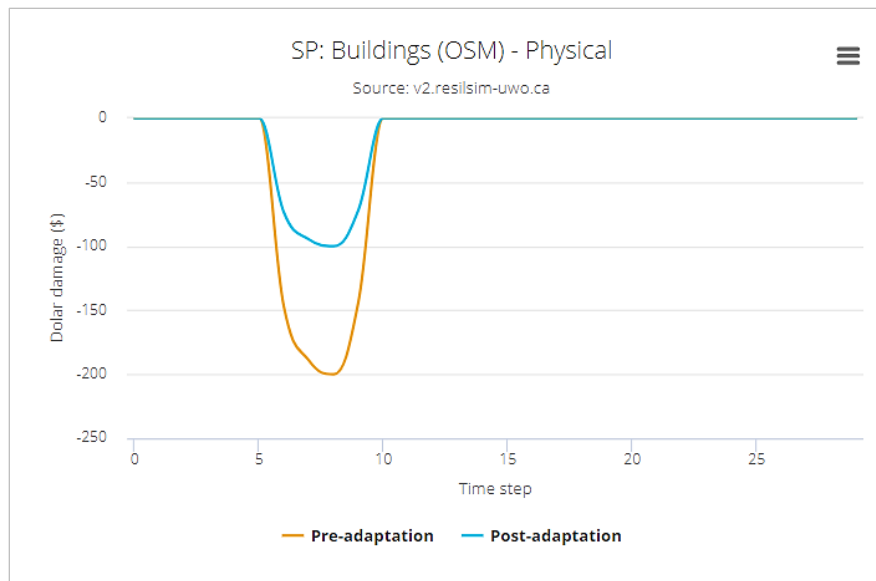


Figure 46. Example of a system physical performance graph for the buildings layer

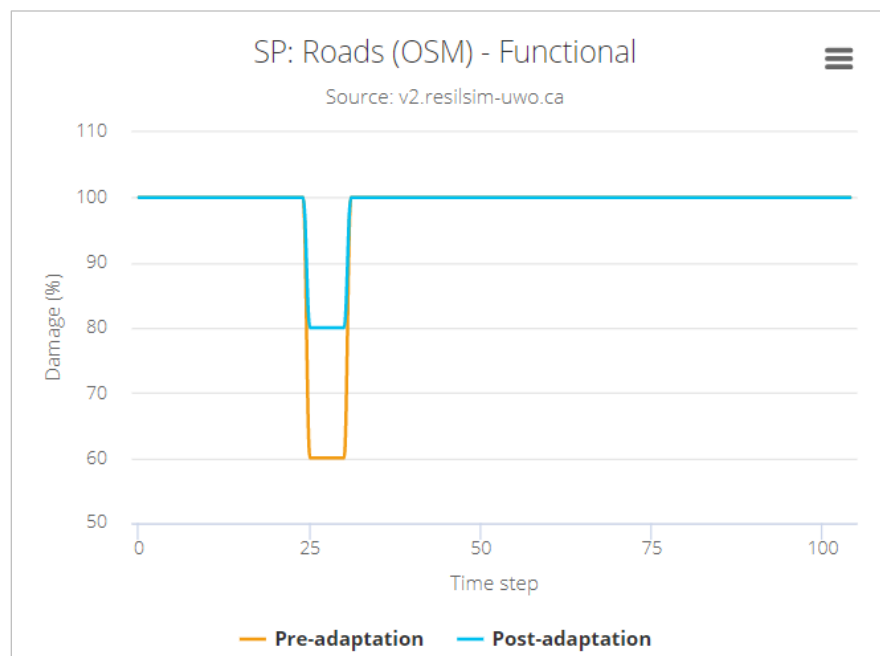


Figure 47. Example of system functional performance graph for the roads layer

The correspondent resilience graphs, for the system performance presented in Figure 46 and Figure 47 are shown in Figure 48 and Figure 49, respectively.

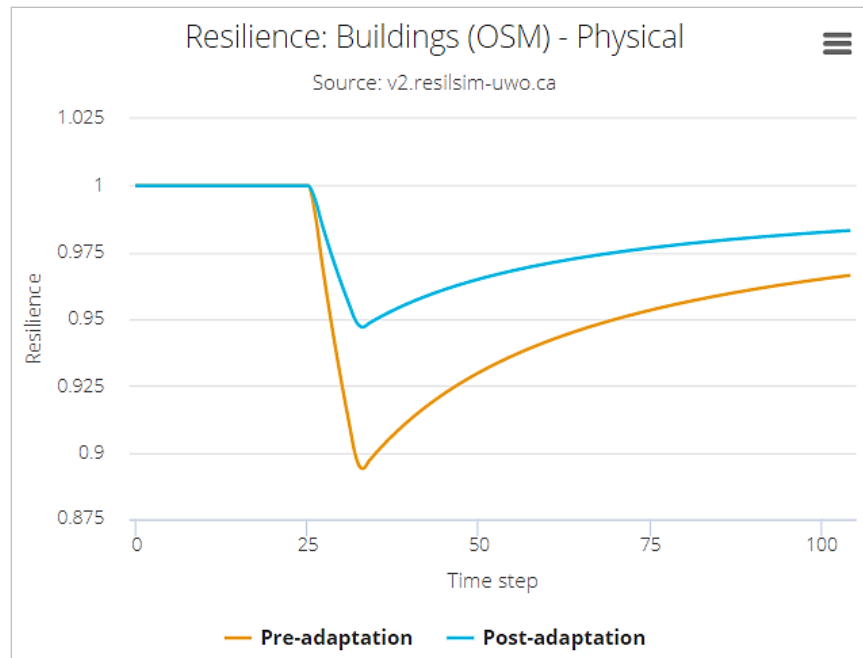


Figure 48. Example of a physical resilience graph for the buildings layer

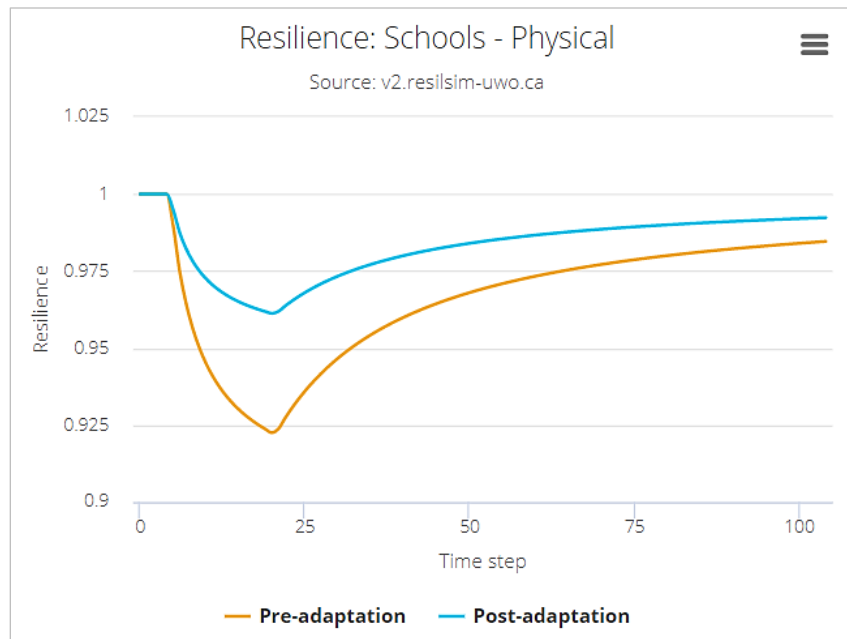


Figure 49. Example of a physical resilience graph for the schools layer

After selection of the hazard scenarios and damage functions, the tool calculates the impacts (system performance) and the combined resilience value (Figure 50) using the methodology presented in Section 1.3. The value of the robustness (Figure 50) is presented under the resilience graph.



Robustness is the minimum value of resilience the system experiences during the hazard event. This metric is presented for the pre and post-adaptation scenarios with the occurrence time. Higher values of robustness are desirable and indicate a more resilient system.

The choice of pro-active or reactive adaptation measures defined by the user for each infrastructure layer and disaster scenario will impact the resilience calculated by the tool. The selection of the adaptation measures is controlled by a set of sliders with upper and lower limits defined by the input scenarios in Figure 43 and shown at the right hand side of Figure 51. The user can quickly evaluate the impact of changing the adaptation measures on infrastructure system's resilience. Based on the system response, the measure which improves resilience the most can be easily identified.

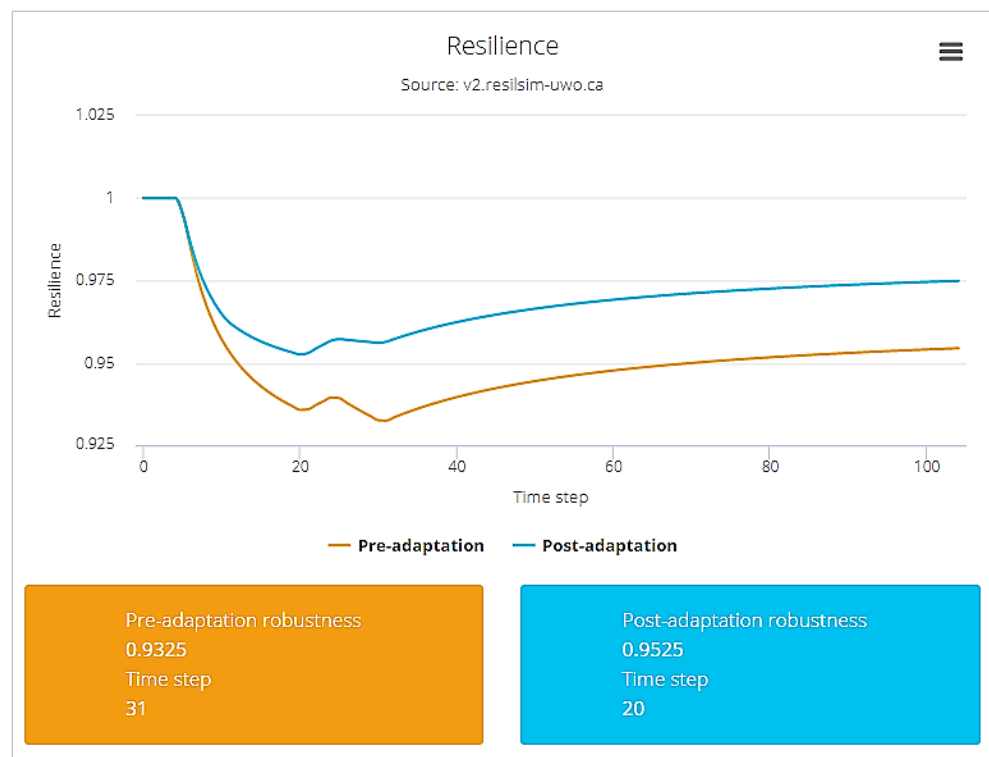


Figure 50. Final resilience graph combining the resilience for all layers and hazards, physical and functional system performance

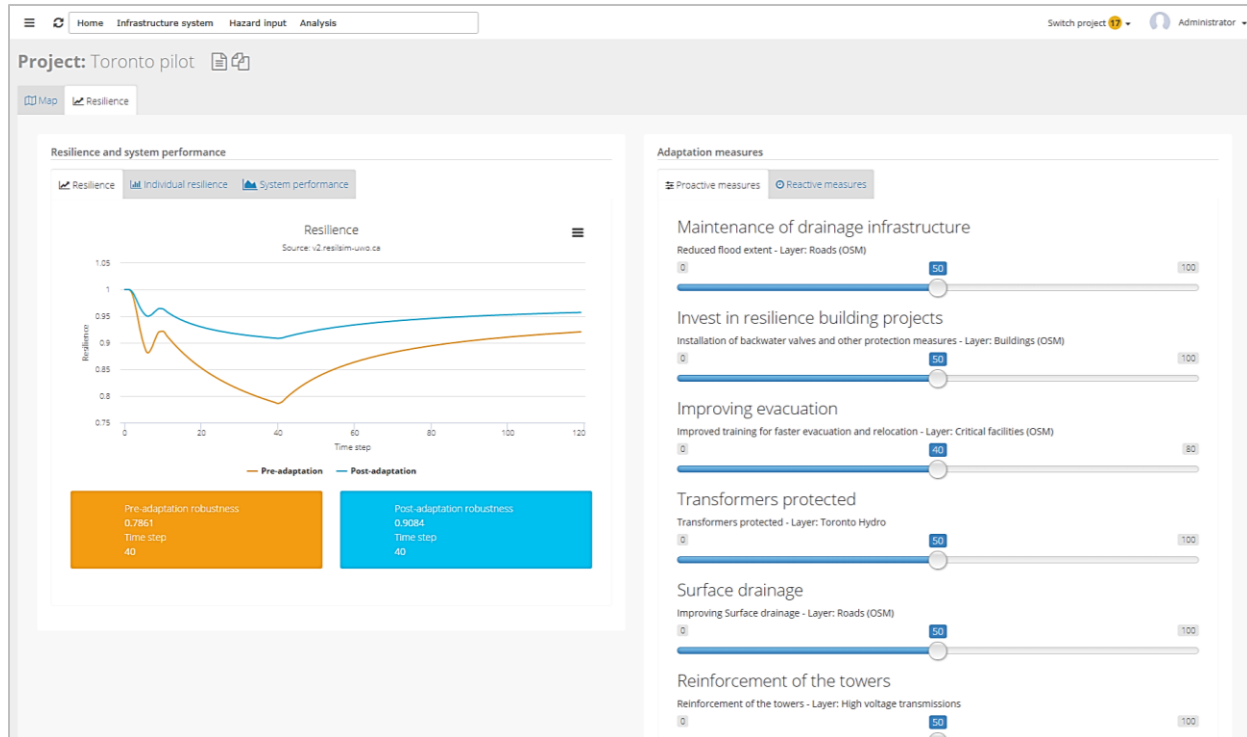



Figure 51. Pro-active adaptation measures applied to the system and response of the resilience. The orange line shows the system resilience without adaptation and the blue line with pro-active and reactive adaptation measures.

## 2.12 Exporting Data

The data used to build the graphs can be exported to external files and figure formats. A button on the top left of the plot () allows user to print and export/download the graph to an image file or Excel format (Figure 52). The 'View data table' option shows a table with the data as presented by Table 1.

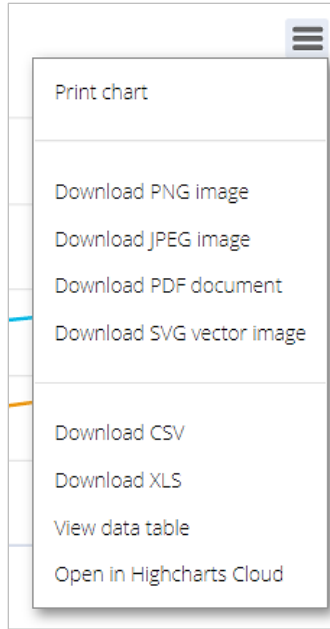


Figure 52. Option to export the data from the graphs in the ResilSIMt

Table 1. Data presented in a table format (same data presented on the graph)

Time step	Pre-adaptation	Post-adaptation
0	1	1
1	1	1
2	1	1
3	1	1
4	1	1
5	0.99	0.995
6	0.975	0.9875
7	0.96429	0.98214
8	0.95625	0.97813
9	0.95	0.975
10	0.945	0.9725

### 3 Example Projects

Five pre-loaded example projects are available in the ResilSIMt's database using the City of Toronto data. They illustrate tool's functionalities and can be used as a starting point in development of projects by the new users of the system. Example projects offer insight into the data input, hazard

definitions, impacts and adaptation measures. These projects can be further modified by creating copies, as discussed in Sections 2.3 and 2.4. The pre-loaded projects are listed in Table 2 and Figure 53. They are described in the following sections with a brief presentation of the hazard (magnitude and affected region), and choice of adaptation measures that will affect the system performance and resilience.

Table 2. List of example projects included in the tool's database

Example	Project name	Hazard type(s)	Description
1	Toronto flooding event Aug 7, 2018	Flooding	Flooding event that affected the city of Toronto on Aug 7, 2018, downtown core and some transportation routes
2	Illustration of flood impact on transportation and buildings	Flooding	Hypothetical flooding affecting roads (transportation) and buildings
3	Illustration of wind impact on buildings and critical infrastructure	Windstorm	Hypothetical windstorm affecting buildings and critical infrastructure
4	Illustration of impacts of multi-hazards on buildings and roads	Flooding and windstorm	Hypothetical multi-hazard windstorm and flooding event affecting roads and buildings
5	Illustration of cascading impacts on electricity supply and transportation	Windstorm	Hypothetical windstorm to showcase the infrastructure interdependencies

## Projects

Select a project from the list. You can also duplicate or create a new project

DESCRIPTION	LOCATION	OWNER	CREATED ON
Example 1 - Toronto flooding event Aug 7, 2018	Downtown Totonro	Administrator	09-08-2018
Example 2 - Illustration of flood impact on transportation and buildings	Toronto	Administrator	13-08-2018
Example 3 - Illustration of wind impact on buildings and critical infrastructure	Toronto	Administrator	13-08-2018
Example 4 - Illustration of impacts of multi-hazards on buildings and roads	Toronto	Administrator	13-08-2018
Example 5 - Illustration of cascading impacts on electricity supply and transportation	Toronto	Administrator	13-08-2018
Copy of: Example 5 - Illustration of cascading impacts on electricity supply and transportation	Toronto	Administrator	11-09-2018

Create new

Figure 53. Pre-loaded illustrative projects for the ResilSIMt tool

### 3.1 Example 1 - Toronto flooding event Aug 7, 2018

This example project seeks to reproduce and describe the real flooding event that affected downtown region of the City of Toronto, Canada, late night on Aug 7, 2018. The flooding was mostly caused by insufficient capacity of the drainage system to move a high volume of rainfall in a short period of time. Observations at rainfall gauges indicate that more than 60 mm of rain fell over the period of 2 hours. The flooding affected the roads and some underpasses were completely inundated, interrupting the flow of traffic. Many office buildings and private homes have reported basement and parking flooding due to overflow and backwater flooding.

Using the social media report, and news and videos published by the major media outlets the flooded areas were estimated as presented in Figure 54. The blue circles indicate underpasses that were inundated and not usable during the event due to the high water depth. The rest of the polygons identify regions affected by the flood. In those areas roads were still usable, and vehicles could transit, although at reduced speed. Buildings and homes in these areas also experienced basement and parking flooding.

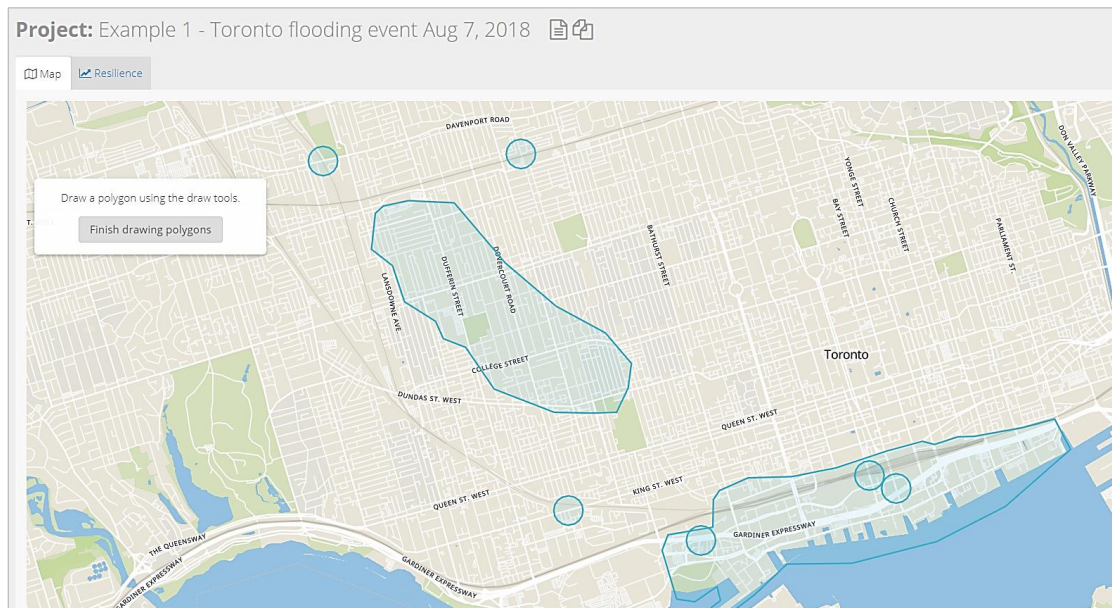


Figure 54. Estimated affected areas by the flood event of Aug 7, 2018 in the city of Toronto, Canada. Blue circles indicate flooded underpasses

The impact of Aug 7, 2018 flooding on the transportation layer (roads) in the City of Toronto is estimated as a percentage loss of functional performance. Locations indicated by the smaller blue

circles in Figure 54 lost 100% of their function during the period of heavy rain, meaning the traffic was completely interrupted for some time (Figure 55).

Hazard scenarios: **Example 1 - Toronto flooding event Aug 7, 2018**

**Hazard scenarios** | **Impact** | Edit impact

Impact for hazard: **Flooded area**

Description:

Select the layer:

Impact type: ☐ ☒ Permanent functional damage:

Damage units:  Type of damage:

Base system performance:

Damage curves (table) | **Damage functions (equation)** | Fragility curves

Water depth (m)	Damage (%)	
0.00	0.00	<input type="text" value="Rem."/>
0.10	10.00	<input type="text" value="Rem."/>
0.20	20.00	<input type="text" value="Rem."/>
0.50	50.00	<input type="text" value="Rem."/>
1.00	95.00	<input type="text" value="Rem."/>
1.50	100.00	<input type="text" value="Rem."/>
2.00	100.00	<input type="text" value="Rem."/>

Go to page:  Show rows:  1-7 of 7

Figure 55. Damage output to the transportation layer (roads) from the flood event of Aug 7, 2018 in the City of Toronto, measured in percentage of functional loss.

As result of the flooding (hazard) and its impact (Figure 55) the system performance is calculated and shown in Figure 57. The system performance shows high impact of the rainfall event on the affected regions, which is in line with the video records from the day of the event in the City of Toronto. News video reports from the day of flooding were showing some cars moving through the deep water with difficulties and some underpasses completely blocked.

For this example project, two proactive adaptation measures were selected (Figure 56) to improve the system performance and resilience in response to the flooding: (i) 'Improvements to the

drainage system' that would improve the drainage of the surface water and reduce de flooding; and (ii) 'Backwater valves' which consist of installation of backwater valves to prevent basement flooding. The resilience graph corresponding to the system performance in Figure 57 is presented in Figure 58. The orange line is presenting the resilience without adaptation and the blue line with some level of adaptation. By modifying the adaptation measures, presented in Figure 56, the user can evaluate the efficiency of various measures using resilience as the criterion for comparison.

The screenshot shows a web-based interface titled "Adaptation measures". It has two tabs: "Proactive measures" and "Reactive measures", with "Reactive measures" being the active tab. Below the tabs, there are two sections. The first section is titled "Improvements to the drainage system" and has a subtitle "Improvements to the drainage system - Layer: Roads (OSM)". It features a horizontal slider with a blue bar and a white knob, with numerical markers at 0, 50, and 100. The knob is positioned at 50. The second section is titled "Backwater valves" and has a subtitle "Installation of backwater valves - Layer: Buildings (OSM)". It also features a horizontal slider with a blue bar and a white knob, with numerical markers at 0, 50, and 100. The knob is positioned at 50. At the bottom of the interface, there are two buttons: a blue "Recalculate" button and a green "Add/edit adaptation options" button.

Figure 56. Adaptation measures to improve the system performance and resiliencies for the flooding event of Aug 7, 2018 in the City of Toronto.

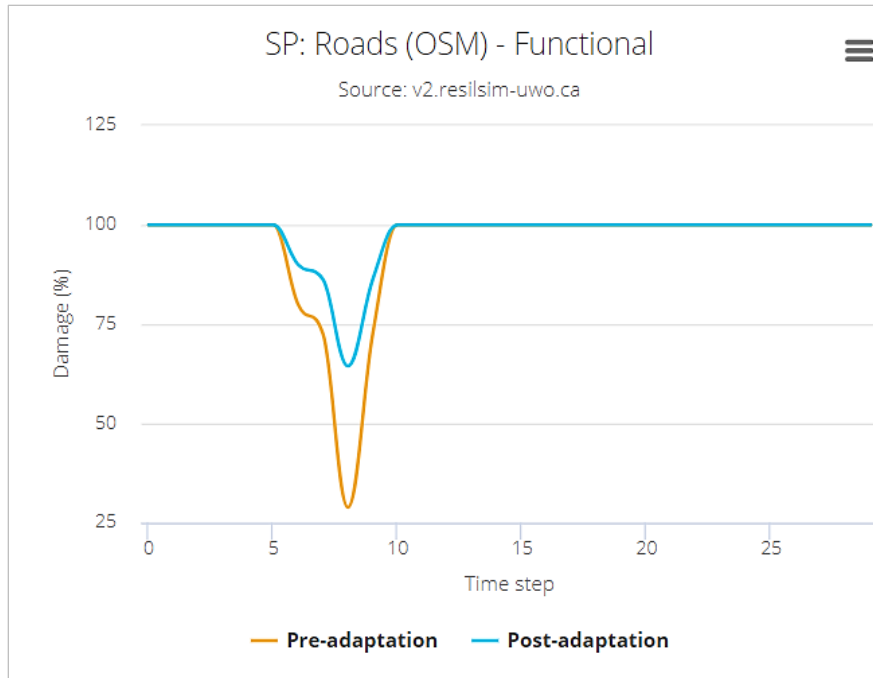


Figure 57. System performance of the roads layer service level decrease in % - Aug 7, 2018 event, the City of Toronto, Canada. Orange and blue lines represent the system performance without and with adaptation, respectively.

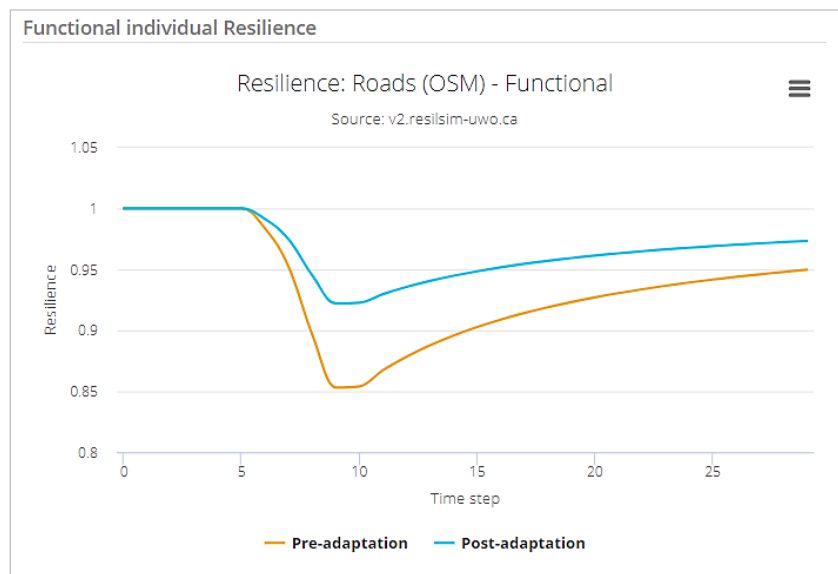


Figure 58. Resilience of the transportation system (roads) - Aug 7, 2018 event, the City of Toronto, Canada.

For the damage caused by the flooding event to buildings in the affected areas, a stage damage curve was used for the assessment of the impact. The curve was adapted from the Natural Resources Canada Canadian Guidelines and Database of Flood Vulnerability Functions document (NRC, 2017).



The damage curve is presented in Table 3 and refers to monetary damage by  $\text{m}^2$ . The resulting damage in graphical form is presented as system performance in Figure 59.

Table 3. Damage curve used for Example 1 (adapted form NRC, 2017).

Water level (m)	Damage (\$/m <sup>2</sup> )
0	0
0.1	670
0.3	833
0.6	1,115
0.9	1,306
1.2	1,404
1.5	1,446

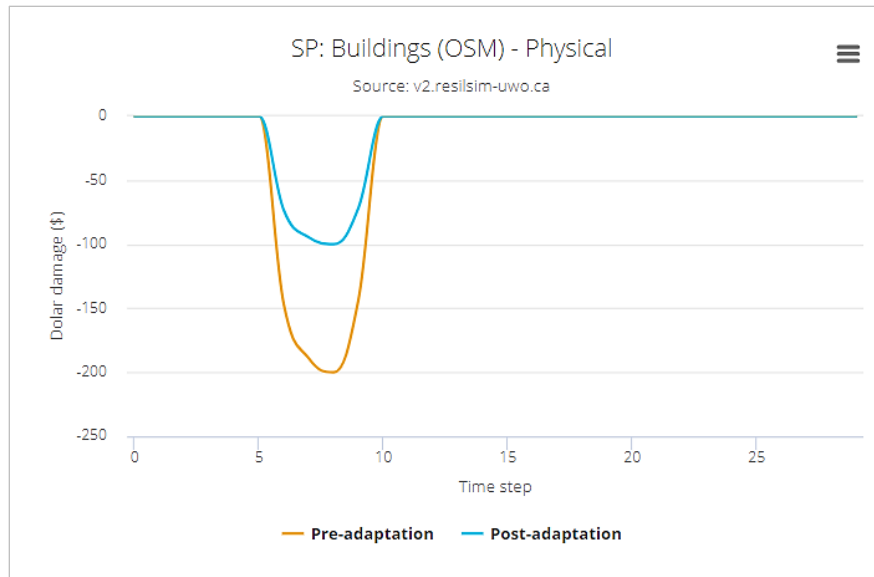


Figure 59. System performance (material losses) due to basement and parking flooding - caused by the Aug 7, 2018 event, in the City of Toronto, Canada. Orange and blue lines represent the system performance without and with adaptation, respectively.

The resilience calculated for each impact (roads and buildings) as presented in Figure 60 is then combined into a total infrastructure resilience. The graph in Figure 61 presents the combined/total resilience for this example that describes the response of roads and buildings infrastructure to the functional damage caused by the flooding event.

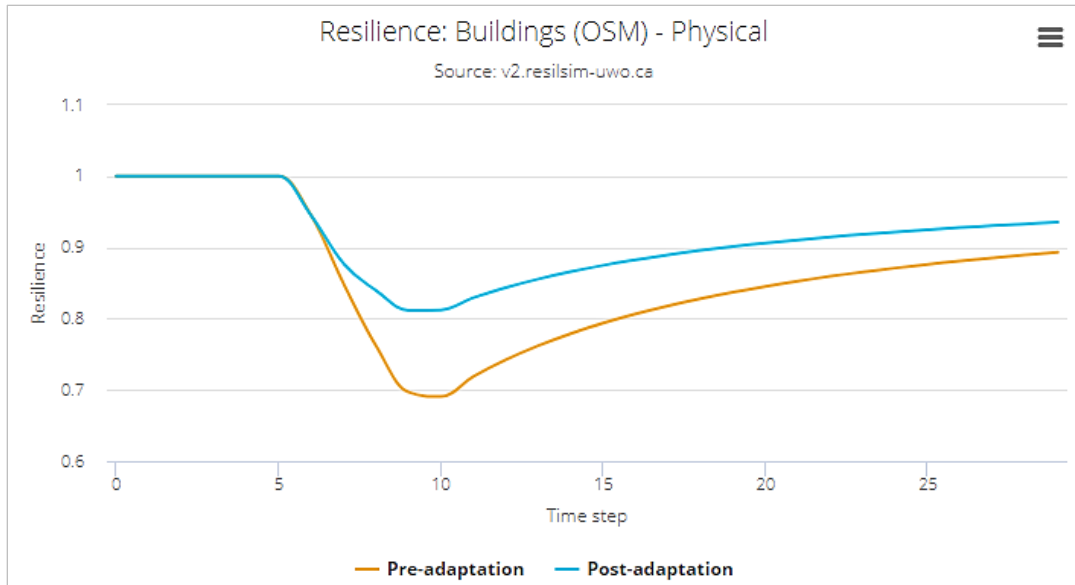


Figure 60. Resilience of the buildings - Aug 7, 2018 event, the City of Toronto, Canada.

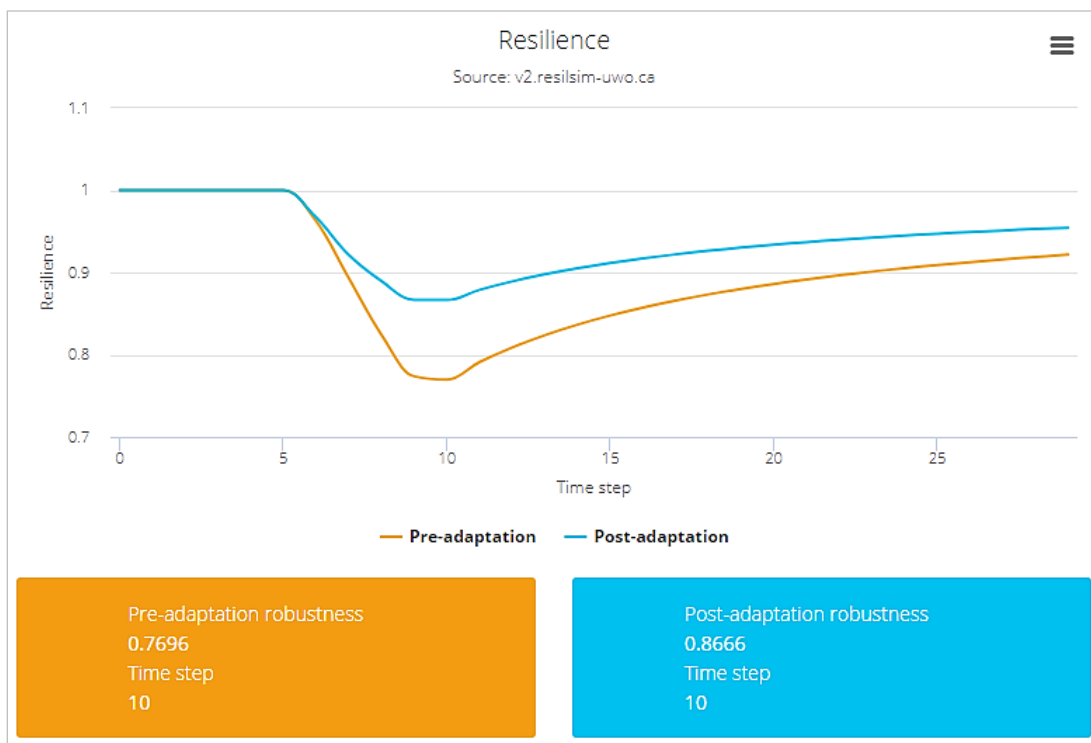


Figure 61. Combined resilience of the system. The orange line presents the resilience of the system at current state and the blue line with the adaptation measures in place.

### 3.2 Example 2 - Illustration of flood and wind impacts on new development and an expanded network

In this example, a flooding event affecting transportation infrastructure (roads) of a newly created development using the algorithm presented in section 2.8.4, and a windstorm affecting the high transmission network lines with and expansions (nodes added by the algorithm shown in section 2.8.5).

The impact of flooding on the roads is measured by a percentage of functional loss, and no permanent or physical damage is assumed. The new development is also present in the same figure with the lines representing roads and the dots the intersections, both in dark red colour. The road design is theoretical and is automatically created by the algorithm presented in section 2.8.4. The flooding and windstorm events are shown in Figure 62. The duration of events is estimated to be approximately 10 hours for both the flooding and the windstorm, however, starting at different time steps.

Hazard scenarios

Impact

List of hazard scenarios:

TYPE	DESCRIPTION	START	PEAK	END		
Wind	Strong wind gusts	25	10	35	Edit	Delete
Flooding	Flooding event	10	10	20	Edit	Delete

Add new hazard scenario

Close

Figure 62. Hypothetical flood event affecting the City of Toronto

The area flooded region is shown in Figure 63, and it is affecting part of the newly created development. The magnitude and duration of the event are presented in Table 4.



Figure 63. Area affected by the flooding

Table 4. Magnitude and duration of the flooding event

Time Step	Water depth (m)
10.0000	0.0000
11.0000	0.1000
12.0000	0.2000
13.0000	0.5000
14.0000	0.8000
15.0000	1.2000
16.0000	0.7000
17.0000	0.5000
18.0000	0.2000
19.0000	0.0000

Figure 64 presents the area affected by the hypothetical windstorm, with the dark red lines indicating the existing infrastructure and the purple lines denoting the expanded network using the algorithm shown in section 2.8.5. The magnitude and duration of the windstorm are presented in Table 5.

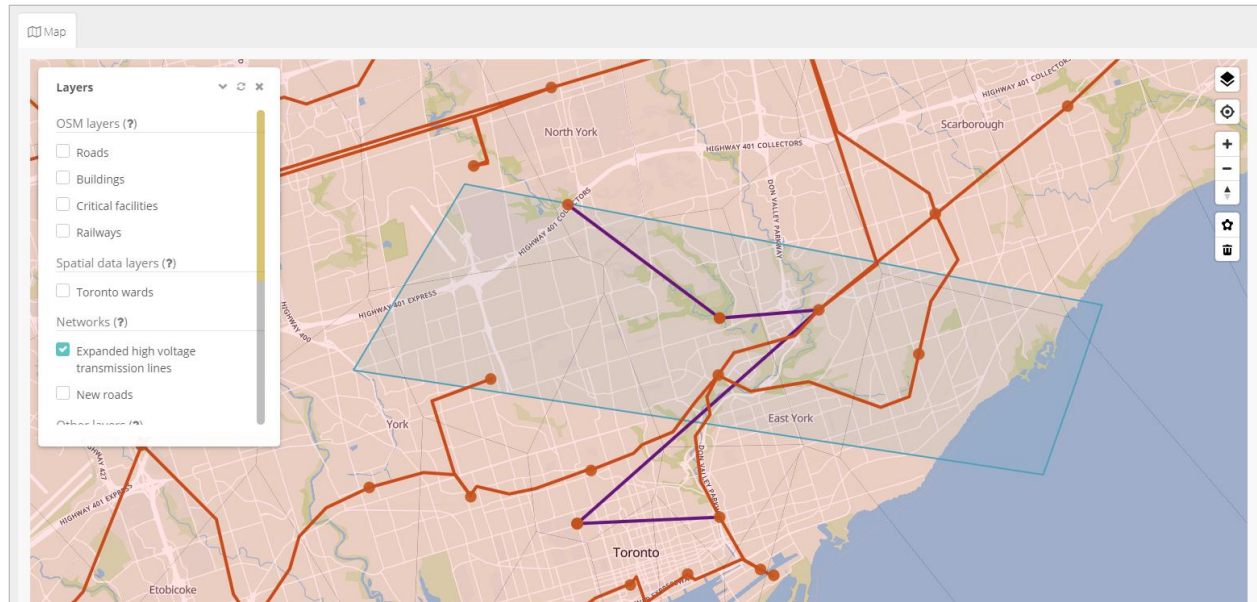


Figure 64. The area affected by the wind storm. The dark red lines indicate existing infrastructure and the purple lines represents the expanded network.

Table 5. Magnitude and duration of the windstorm

Time Step	Wind Speed (km/h)
25.0000	0.0000
26.0000	5.0000
27.0000	9.0000
28.0000	20.0000
29.0000	70.0000
30.0000	100.0000
31.0000	111.0000
32.0000	85.0000
33.0000	50.0000

The impacts of the flood and wind hazard events shown in Figure 63 and Figure 64 are assessed as listed in Figure 65. For the high voltage transmission lines impact is defined for the windstorm hazards and for the new roads (new development) the impact is defined for the flooding event. The damage is calculated for the new roads layer and the expanded and existing high voltage layer. For the roads layer, the functional damage is defined to illustrate the use of the tool. In both cases, the damage is measured in percentage (%) loss of performance on the scale between 0 and 100.

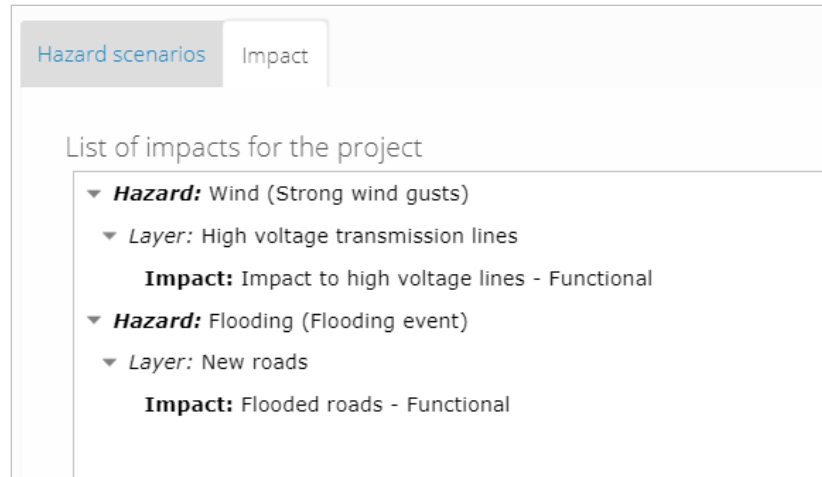


Figure 65. List of flood impacts

Figure 66 presents the loss of functional performance of the new roads layer (measured in %) over time. It can be noted that the system performance experiences a decline, which in practical terms means, that the roads capacity is dramatically reduced for traffic during this time. Once the water recedes and the roads return to full service, the functional damage becomes 0, meaning that there is no permanent damage to roads due to the flooding. This behaviour is well captured by the system performance graph (Figure 66) and converted into resilience graph (Figure 67).

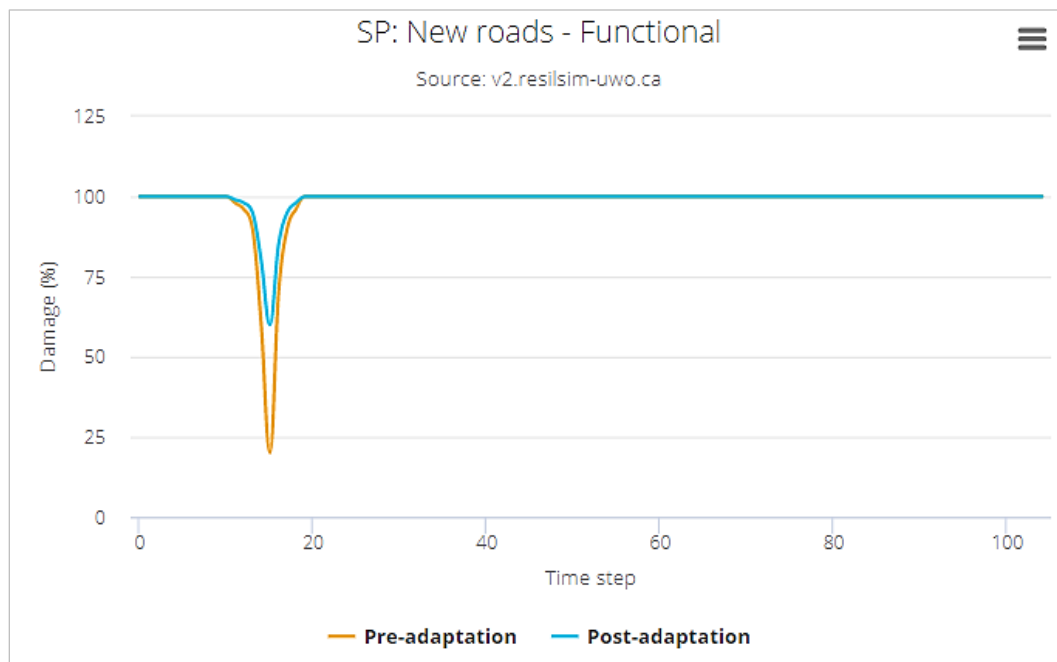


Figure 66. System performance over time of the new roads layer. Pre-adaptation (orange line) and post-adaptation (blue line)

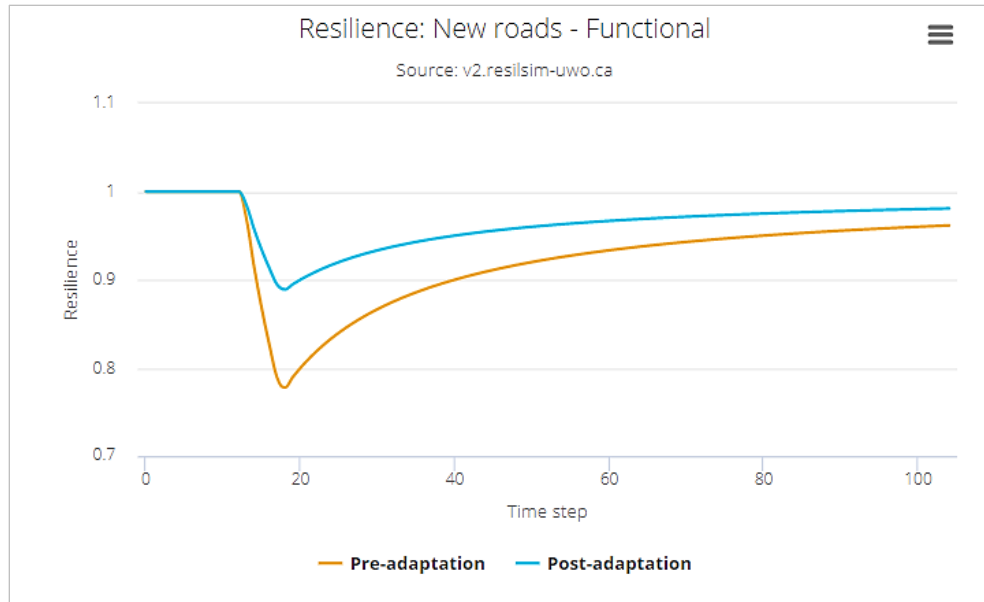


Figure 67. Resilience of the new roads layer. Pre-adaptation (orange line) and post-adaptation (blue line)

Similarly, Figure 68 shows the system performance resulting from the damage to the expanded high voltage transmission lines. In this case, we can notice that the performance for this infrastructure declines on a later time step due to the different time frame defined for the event affecting the system. The blue line is showing the system performance after applying the adaptation options that are reducing the impact. In this case, the damage defined is not permanent, allowing the system to recover when the hazard is over. The resilience for this layer is shown in Figure 69 and the combined resilience for the two infrastructures in the analysis are shown in Figure 70.

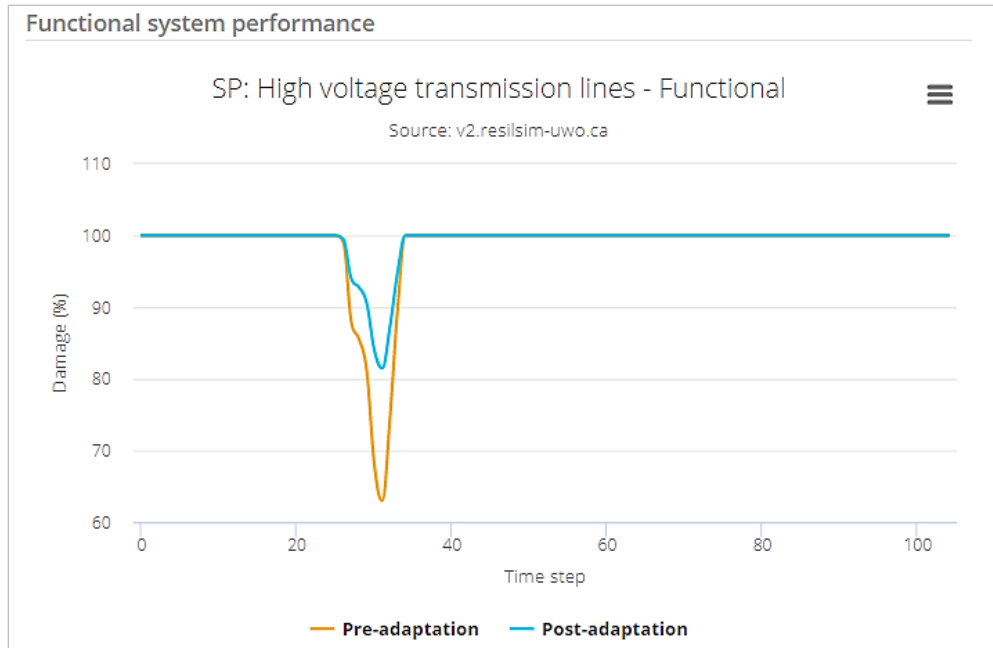


Figure 68. System performance over time of the high transmission lines network. Pre-adaptation (orange line) and post-adaptation (blue line)

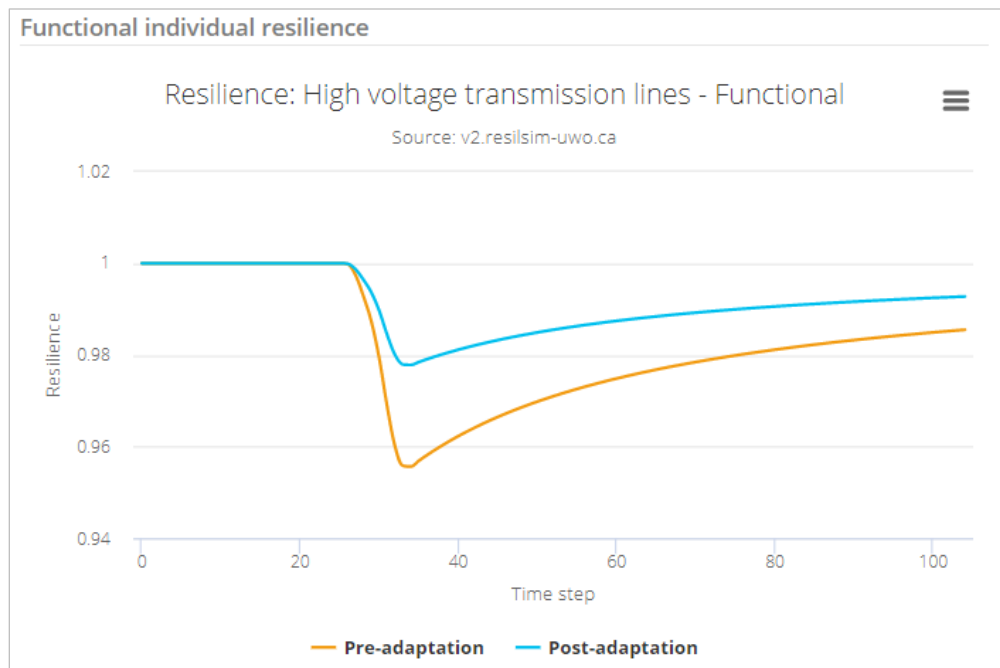


Figure 69. Resilience of the high voltage expanded layer. Pre-adaptation (orange line) and post-adaptation (blue line)



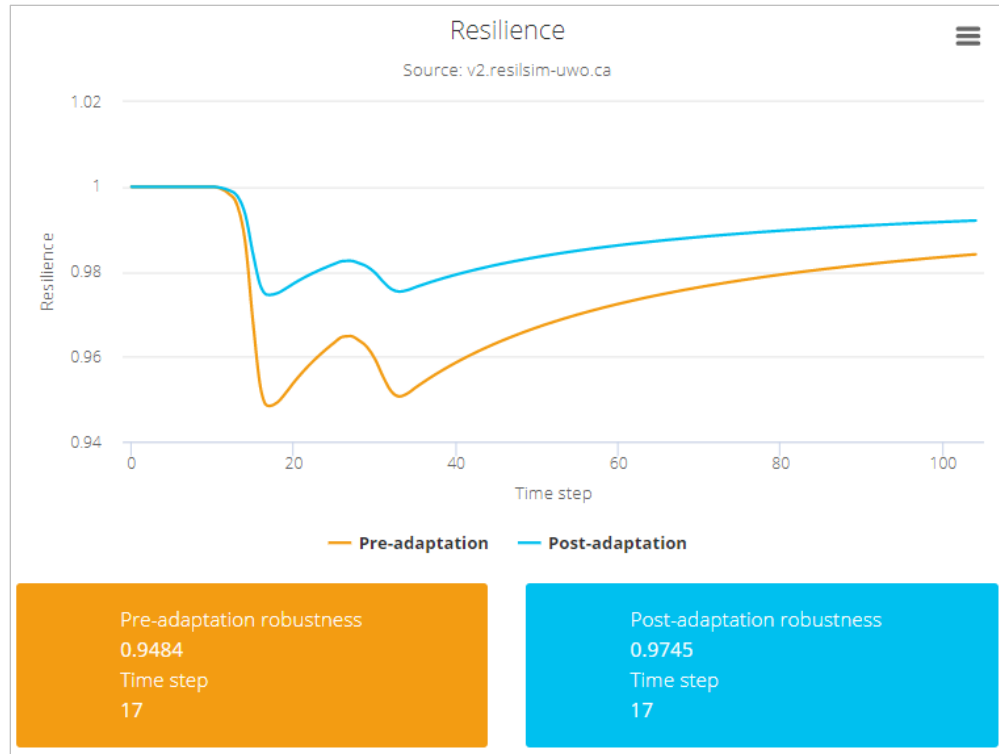


Figure 70. Final system resilience to the flood hazard. Final resilience combines all individual resilience (all layers, physical and functional). Orange line presents the pre-adaptation and the blue line, the post-adaptation conditions.

Two adaptation measures are defined for the example project and applied to the new roads and the expanded high voltage transmission lines layers (Figure 71). The magnitude of the adaptation measure shapes the post-adaptation resilience over time (blue line in Figure 70) and the difference between the orange and blue lines. Other combinations of adaptation measures values will result in different level of post-adaption resilience.

Adaptation measures

☒ Proactive measures ☐ Reactive measures

Improving drainage system

Improving drainage system - Layer: New roads

0 50 100

Increasing redundancy of the network

Increasing redundancy of the network - Layer: Expanded high voltage transmission lines

0 50 100

Recalculate Add/edit adaptation measures

Figure 71. Adaptation measures for the presented hazard scenario.

### 3.3 Example 3 - Illustration of wind impact on buildings and critical infrastructure

In this example, a hypothetical windstorm (Figure 72) is affecting the building layer and the system performance is measured by physical damage (in percentage) as well as functional system performance loss. For the critical infrastructure layer, a stage damage curve is used to measure functional damage. The magnitude of the hazard over time is presented in Table 6 and the region affected by the windstorm is shown in Figure 73.

Hazard scenario, duration and affected area

Select the hazard type: Wind

Description: Strong wind gusts

Starting time: 25

Ending time: 35

Time unit: Hours

Areas and magnitudes: Draw polygons Edit magnitudes

Figure 72. An illustrative windstorm scenario

Table 6. Wind speed magnitudes over time for the windstorm hazard

Time Step	Wind Speed (km/h)	
25.0000	0.0000	Del.
26.0000	50.0000	Del.
27.0000	60.0000	Del.
28.0000	70.0000	Del.
29.0000	85.0000	Del.
30.0000	110.0000	Del.
31.0000	80.0000	Del.
32.0000	50.0000	Del.
33.0000	40.0000	Del.
34.0000	30.0000	Del.
Show rows: 10 ▾ 1-10 of 11 <		

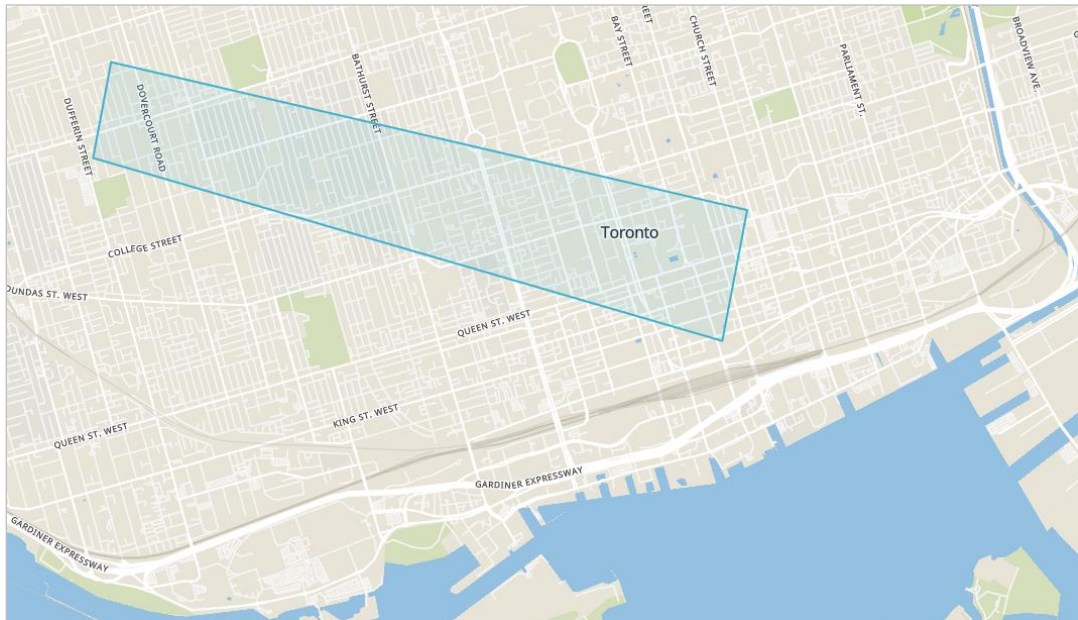


Figure 73. Hypothetical wind band representing the affected region

For this project one impact is defined affecting the buildings layer as in Figure 74.

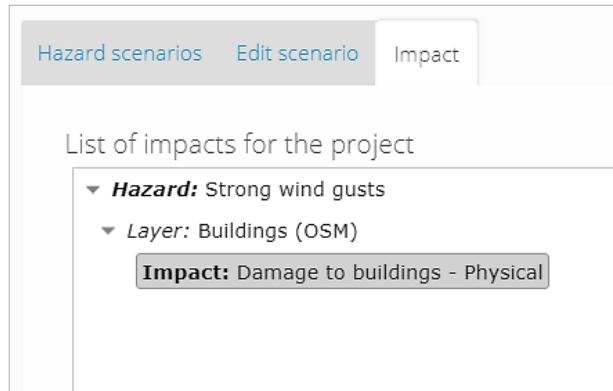


Figure 74. Damage to building layer infrastructure due to windstorm hazard

The system performance resulting from the impact to buildings is shown in Figure 75. The blue line is showing the system performance after applying adaptation option that is reducing the impact. In this case, the damage defined is not permanent, allowing the system to recover when the hazard is over. The resilience is shown in Figure 76.

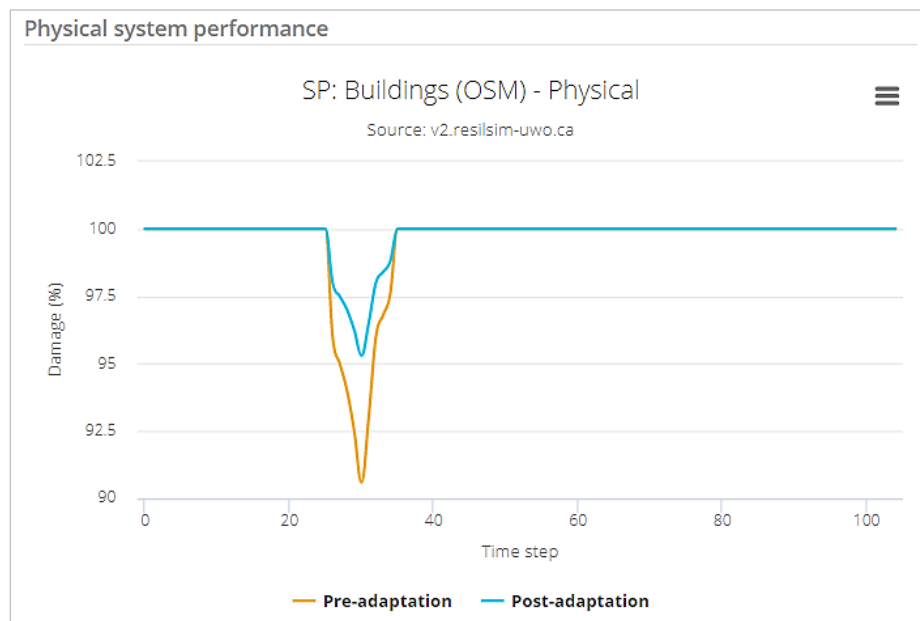


Figure 75. System performance of the building layer infrastructure due to windstorm hazard

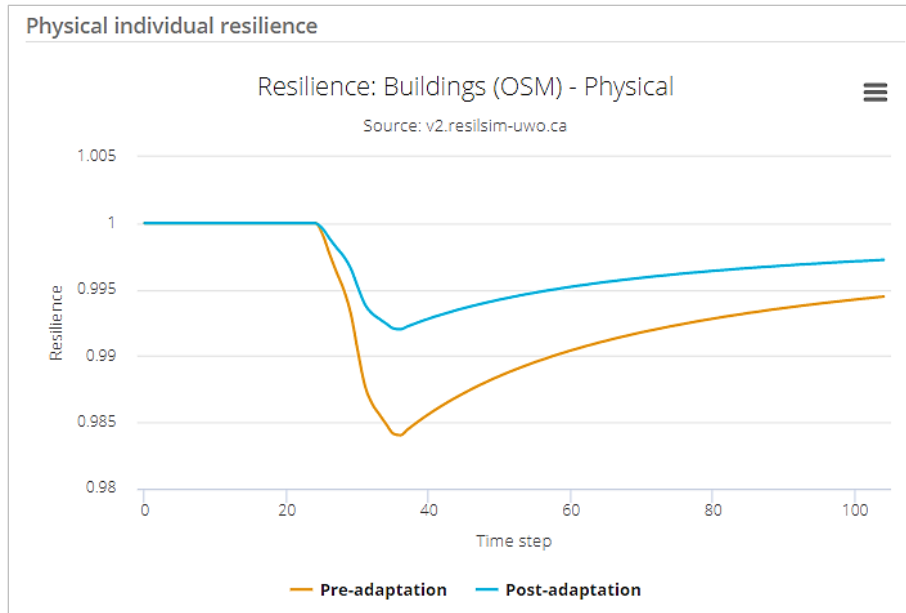


Figure 76. Resilience of the buildings layer in response to the damage due to windstorm hazard

One adaptation measure is defined for the example project and applied to the buildings infrastructure layer (Figure 77). The magnitude of the adaptation measure shapes the post-adaptation resilience over time (blue line in Figure 76) and the difference between the orange and blue lines. Other combinations of adaptation measure values will result in different level of post-adaption resilience.

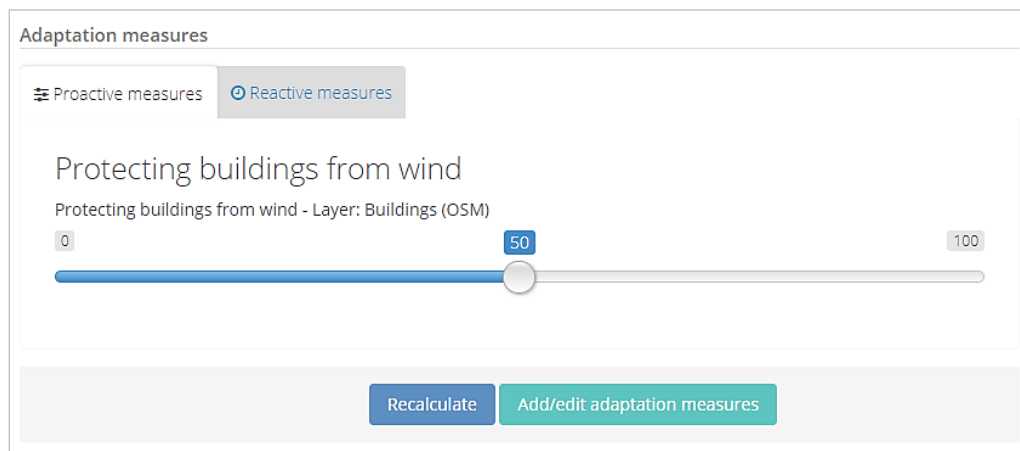


Figure 77. Adaptation measures for the presented hazard scenario.

### 3.4 Example 4 - Illustration of impacts of multiple-hazards on buildings and roads

In this example, the impacts of two hazards, occurring at the same time, and their effects on urban infrastructure such as transportation, buildings, and critical infrastructure (Figure 78) are presented.

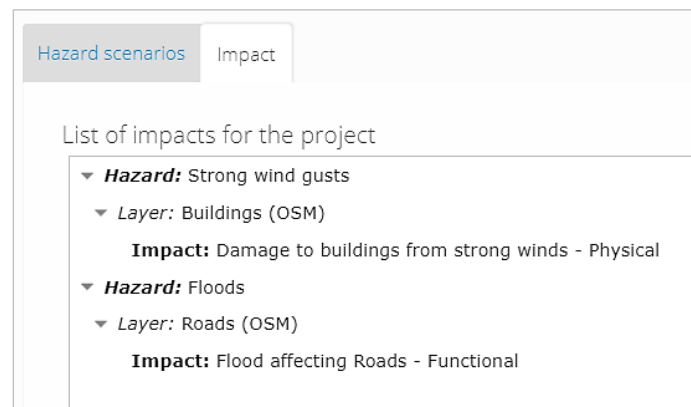


Figure 78. Impacts to buildings and roads caused by windstorm and flooding hazards

The impact of flooding to the roads is shown in Figure 79, defined as a functional disturbance. The performance/availability of roads is affected during the flood event and returns to the previous level after the water recedes. The resilience graph is shown in Figure 80.

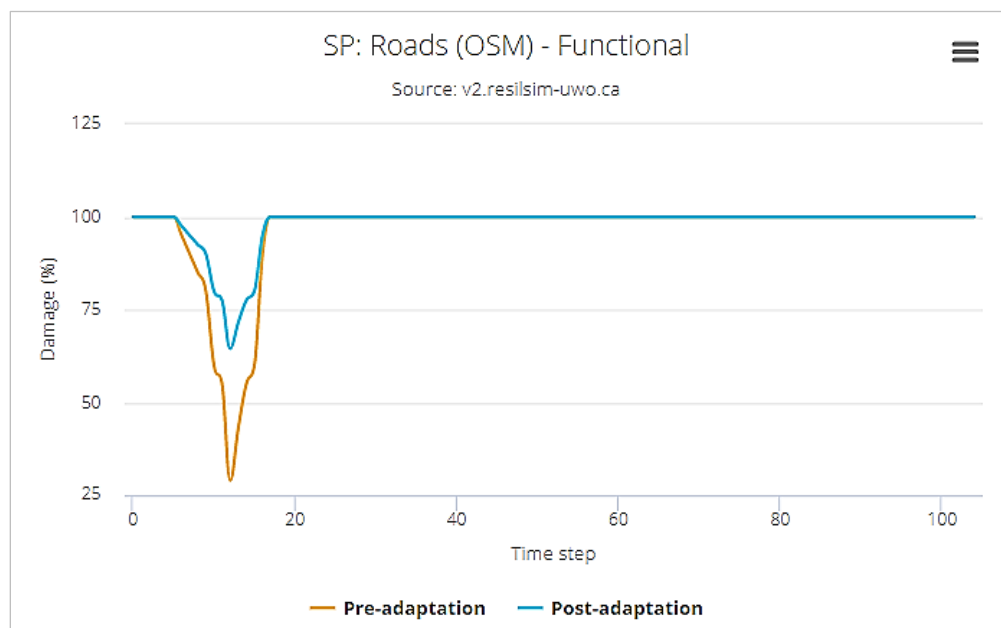


Figure 79. System performance, functional damage to roads due to flooding

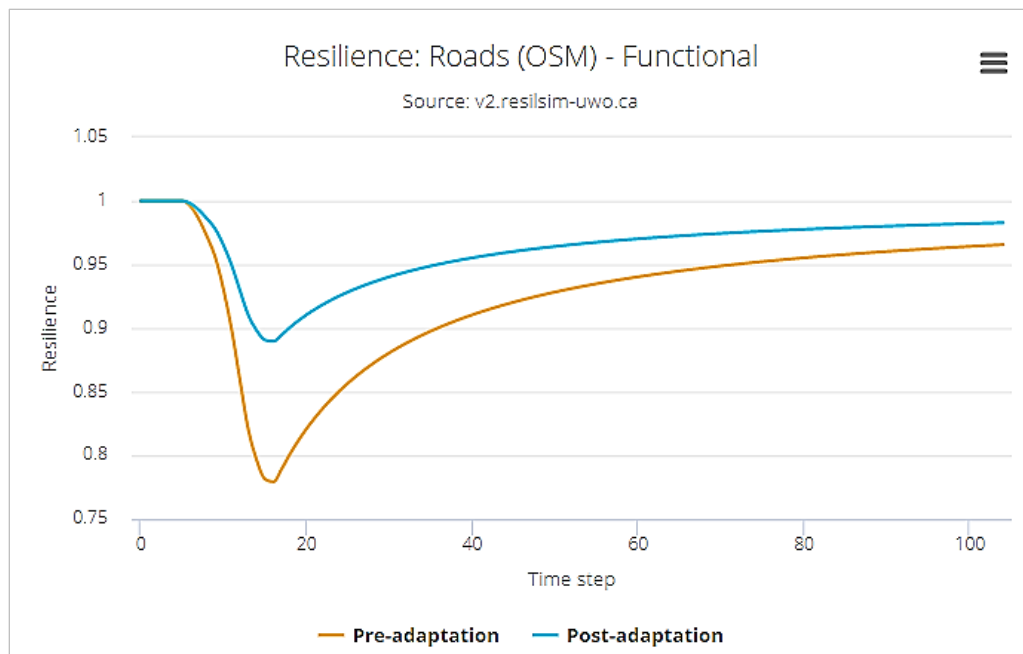


Figure 80. Resilience to functional damage to roads due to flooding

Figure 81 presents the impact/system performance of windstorm on the buildings layer. The damage is assessed based on the wind speed and the flat line after the hazard ends indicates that the damage is permanent. The resilience graph in response to this scenario is presented in Figure 83. Due to the permanent physical damage (Figure 83) the resilience of the buildings will not fully recover unless higher levels of adaptation are applied. Once more, on both graphs the pre and post-adaptation resilience are presented in orange and blue, respectively.

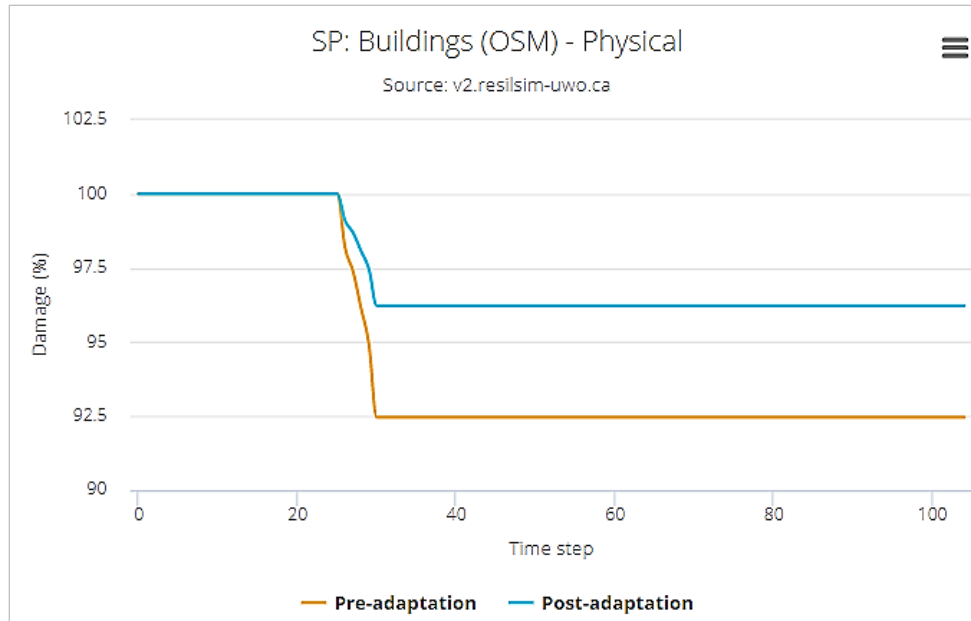


Figure 81. System performance, physical damage to buildings due to wind and flooding

Impact for hazard: **Strong wind gusts**

Description:

Select the layer:

Impact type: ☒ Physical ☐ Functional ☐ Physical damage is permanent

Damage units:  Type of damage:

Base system performance:

Damage curves (table) [Damage functions \(equation\)](#) [Fragility curves](#)

[Add new row](#)

Wind Speed (km/h)	Damage (%)	
0.00	0.00	<input type="text" value="Rem."/>
50.00	4.00	<input type="text" value="Rem."/>
80.00	7.00	<input type="text" value="Rem."/>
100.00	9.00	<input type="text" value="Rem."/>
150.00	11.00	<input type="text" value="Rem."/>

Go to page:  Show rows:  1-5 of 5

Figure 82. Definition of the permanent physical damage



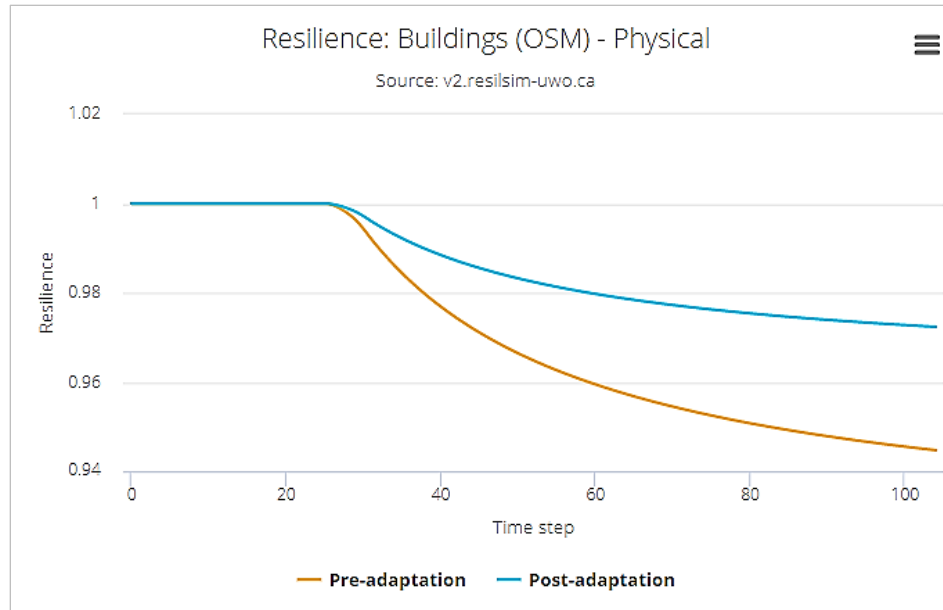


Figure 83. Resilience of the buildings layer

The combined resilience, taking into account the infrastructure affected by the hazards, is shown in Figure 84. In this example, it is visible that the roads performance is affected at the higher magnitude and therefore it is affecting the resilience at earlier time steps more significantly.

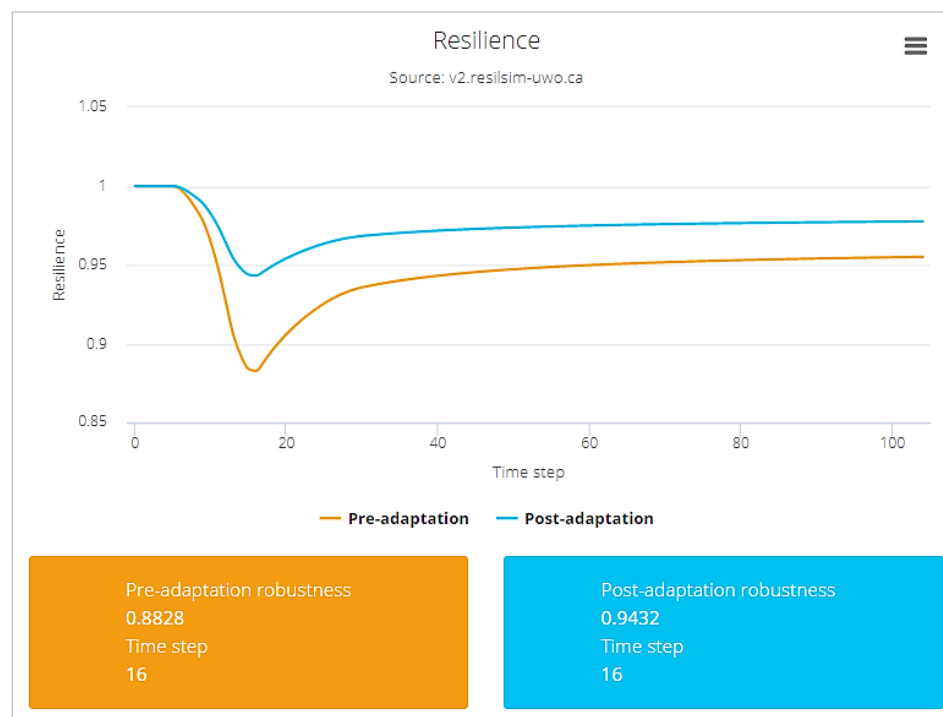


Figure 84. Final and combined resilience for the current project

For this example, the adaptation measures are implemented for the buildings and roads (Figure 85). The impact on the post-adaptation system performance and resilience is noticeable. If the adaptation magnitude is increased the system performance and the resilience respond accordingly, as can be seen in Figure 86.

The screenshot displays a web-based interface titled "Adaptation measures". At the top, there are two tabs: "Proactive measures" and "Reactive measures", with the latter being selected. Below the tabs, there are two main sections, each with a title and a slider control. The first section is titled "Protecting windows and doors" and has a subtitle "Protecting windows and doors before the storm - Layer: Buildings (OSM)". Its slider ranges from 0 to 100, with a blue bar indicating the current value is 50. The second section is titled "Improving drainage system" and has a subtitle "Clean of stormwater drains - Layer: Roads (OSM)". Its slider also ranges from 0 to 100, with a blue bar indicating the current value is 50. At the bottom of the interface, there are two buttons: "Recalculate" and "Add/edit adaptation measures".

Figure 85. Adaptation measures for the roads and buildings layers

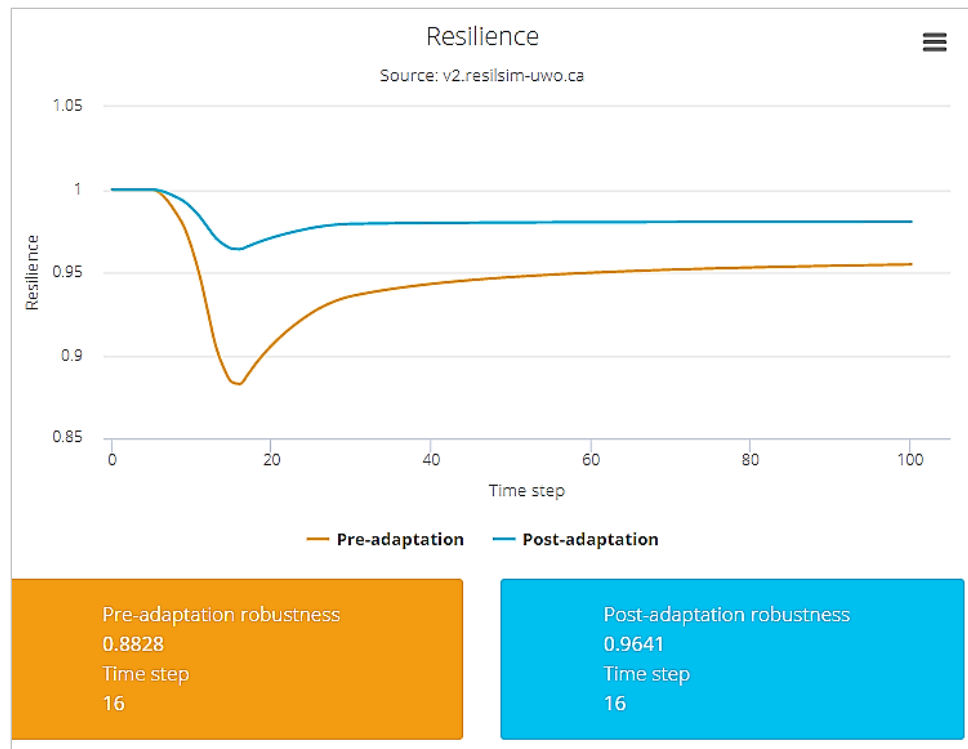


Figure 86. Updated resilience graph after applying a different set of adaptation measures

### 3.5 Example 5 - Illustration of cascading impacts on electricity supply and transportation

In this example, the wind hazard affects the high voltage transmission lines (network layer) causing power outages, and cascading failures occur affecting the interconnected infrastructure such as traffic signals that affect the transportation system by reducing the average traffic speed on the roads. The high voltage transmission lines are represented by the orange dots and lines in Figure 87. The dots represent transformers and it is assumed that each transformer is supplying one region of the city delineated by the Thyssen polygons. This simplified assumption was necessary to illustrate the use of the tool and lack of precise information about the regions the transformers supply. The dark blue dots in Figure 87 represent the traffic signals in the City of Toronto and are obtained from the open data portal of the City of Toronto (<https://www.toronto.ca/city-government/data-research-maps/open-data>) with precise coordinates. The area affected by the strong wind gusts is shown in Figure 87 and represented by the light blue polygon.

The input of the cascading failures is shown in Figure 88, where the impacts are presented in tree formats for easy identification of the dependencies between the infrastructure.



Figure 87. Hypothetical wind bands representing the hazard (represented by the light blue polygon) causing damage to the high voltage distribution (lines in dark red color).

Hazard scenarios: **Example 5 - Illustration of cascading impacts on electricity supply and transportation**

Hazard scenarios
Impact
Edit impact

List of impacts for the project

- ▼ **Hazard:** Strong wind gusts
  - ▼ **Layer:** Roads (OSM)

Impact: Functional damage to roads - Reduced speed - Functional
  - Layer:** Buildings (OSM)
  - ▼ **Layer:** High voltage transmission lines
    - ▼ **Impact:** Damage to high voltage lines. Cascade to transportation - Functional
      - Impact:** Cascade failure from high transmission lines to buildings - Power outage - Buildings (OSM) - Fun
    - ▼ **Impact:** Damage to traffic signals - Traffic signals - Functional
      - Impact:** Traffic signals failures affecting transportation - Speed reduction - Roads (OSM) - Functional
  - Layer:** Traffic signals

Figure 88. Impact to the high voltage transmission lines (in the background) and its cascading effect to other infrastructure layers

In the case of cascading impacts, the impacts of the hazard on the initial infrastructure, or the uppermost layer in Figure 88, are assessed first and then the infrastructure that depends on it. In this hypothetical example, the impact on ‘High voltage transmission lines’ infrastructure is calculated then, the ‘Traffic signals’, and finally the “Roads”. The ResilSIMt tool allows high flexibility in defining the damage due to each hazard as well as the cascading impacts.

Figure 89 presents the list of adaptation measures applied to this example: (i) increase of the redundancy for the transmission lines aiming at the higher availability of the power to the generators and consequently to the regions they supply; and (ii) installation of backup power sources on traffic signals, allowing them to function when the main power source is lost.

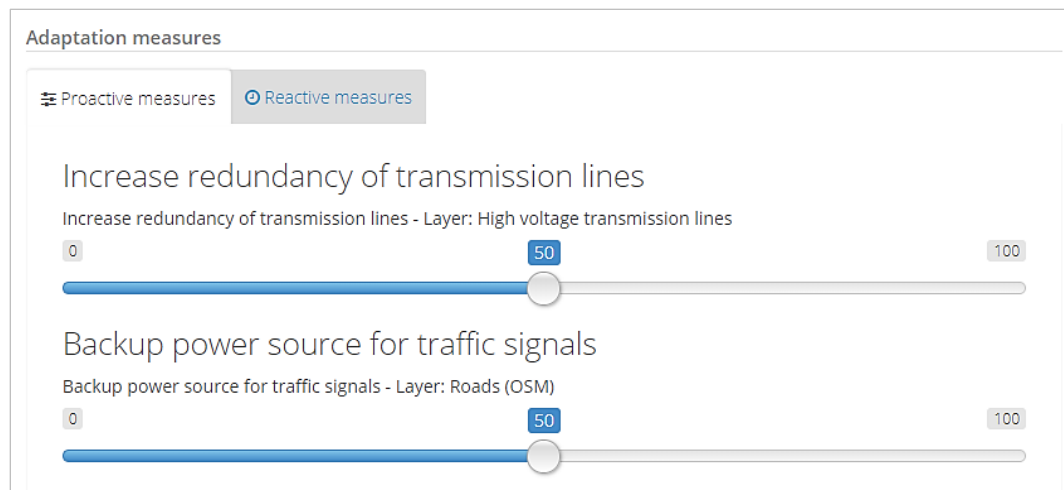


Figure 89. Adaption options for the project.

The graph in Figure 91 shows the impact on traffic signals caused by the failure of the transmission lines to provide the power. For this example, the traffic signals supplied are assumed to fail due to failure of the transformer that supplies the signals (signals that are in the Thiessen polygon of the transformer). This assumption can be easily modified in the tool.

Similarly, the impact on roads layer (traffic movement) is set to depend on the availability of traffic signals (Figure 88) and the resulting system performance graph is in Figure 91. The impact is less pronounced on the performance on roads (traffic movement). The assumption made here is that even without the power and available signals the traffic will continue to flow, with lower efficiency.

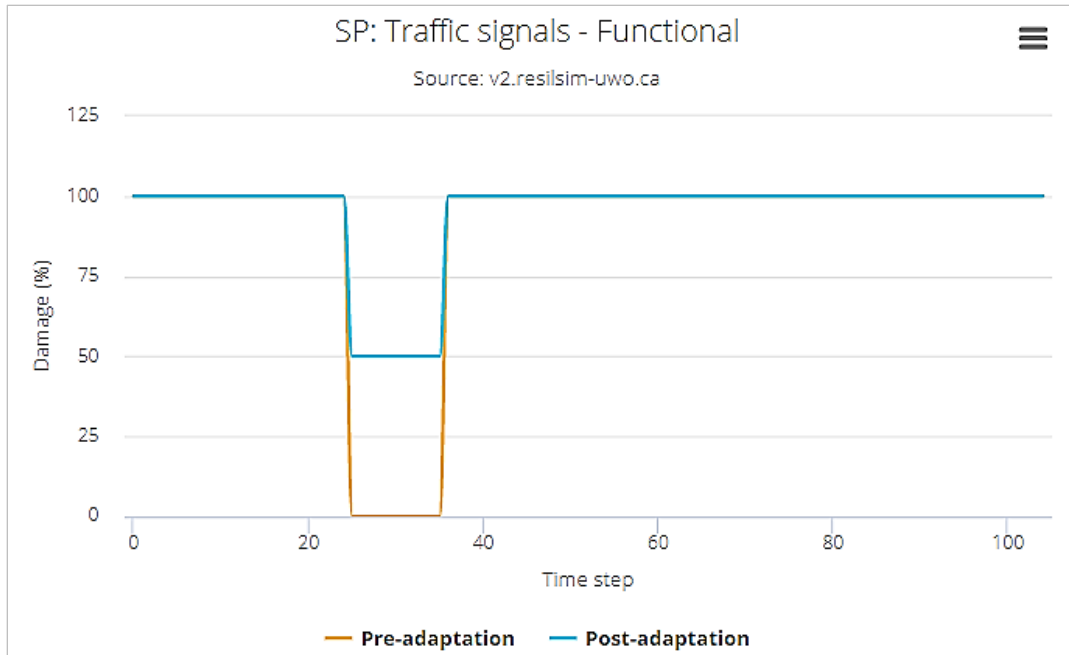


Figure 90. System performance of the traffic signals affected by the high transmission lines power outage

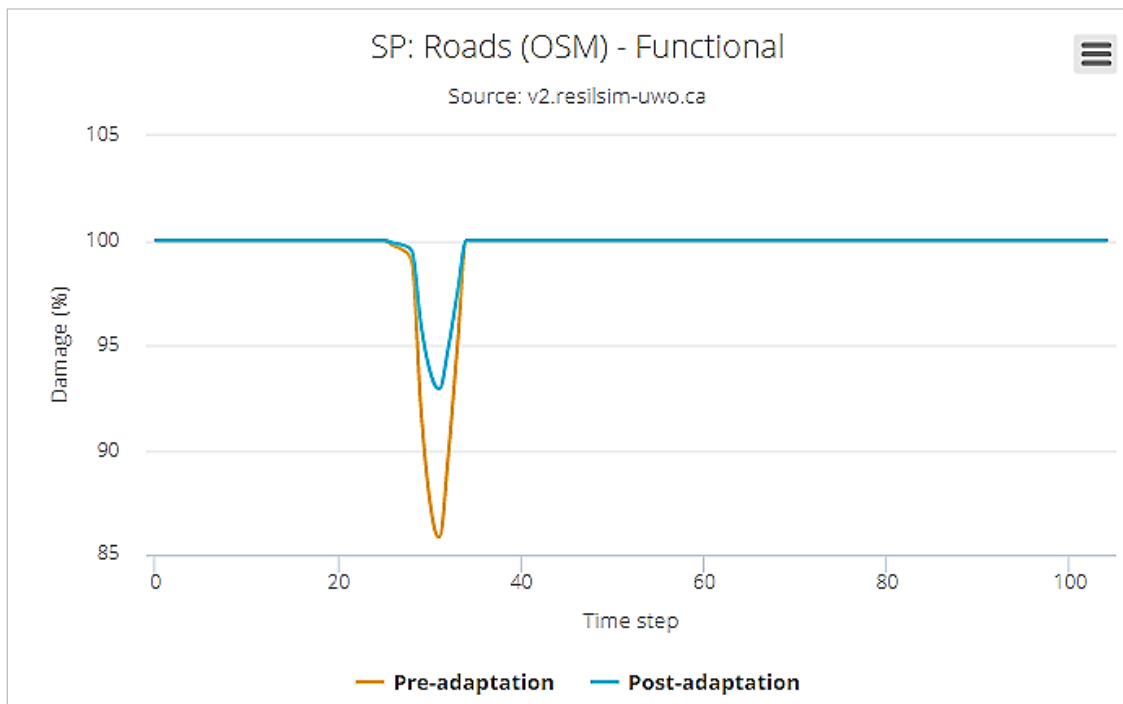


Figure 91. System performance of the road layers affected by the failure of the traffic signals due to the high transmission lines power outage

For this example, the resulting resilience graph is presented in Figure 92 due the hazard impacting the high voltage transmissions lines which then affect to other infrastructure such as buildings, roads and traffic signals. The traffic signals then have a cascading effect on the functional performance of roads, affecting its average speed of vehicles using the affected roads.



Figure 92. Resilience for the project with several interdependencies.

## 4 Conclusions

This document presents the decision support tool ResilSIMt, that is able to estimate the resilience of an urban system exposed to the impacts of various types of hazards, such as floods, hurricanes, fire, and others. The tool uses an open source GIS dataset as the starting point for the analyses. The user, however, is provided with options to incorporate additional data in form of GIS layers and networks to describe the physical and socioeconomic components of the urban system under consideration. Using spatial programming techniques, the resilience of the system subject to hazard is computed based on the system adaptive capacity that can be modified by the introduction of various adaptation measures (before and/or after the hazardous event).

The ResilSIMt calculates an initial value of urban system resilience as the basis for comparison. The user can experiment with different proactive and reactive adaptation measures and compare their impact using the system resilience as a comparison criterion.

The tool is tested with data for the City of Toronto, Canada. However, its generic nature allows its easy application to any other urban center. Hazard scenarios and adaptation measures are user defined inputs allowing various combinations of disaster and recovery strategies to be evaluated. The tool is in a public domain and can be accessed at: <http://resilsimt.uwo.ca>. Five illustrative examples (presented in this report) are available for users to experiment with the tool.

Resilience is an innovative disaster management measure that can assist decision makers in selecting and prioritizing actions for upgrading urban systems with high exposure to extreme events.

## 5 Acknowledgements

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## Appendix A: Creating GeoJSON files for input to the ResilSIM v2

The ResilSIM v2 tool relies heavily on the data input in the GeoJSON format. The GeoJSON format is a modern and widely used file format for geographic information. The traditional vector formats such as shape-files, can easily be converted to the GeoJSON format using a free GIS software, Quantum GIS (QGIS). The latest version of QGIS can be downloaded from <https://www.qgis.org/>, and the version for several operating systems are available (Figure 93). After the selection the operational system, the version of the QGIS can be selected. For modern computers, the 64-bit version will most likely be the choice. Once the installer file is downloaded, QGIS can be installed for use.

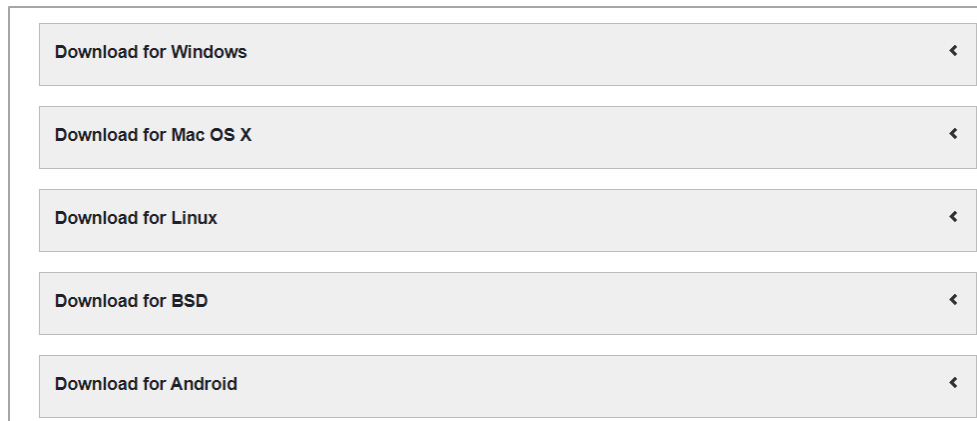


Figure 93. QGIS operating system options

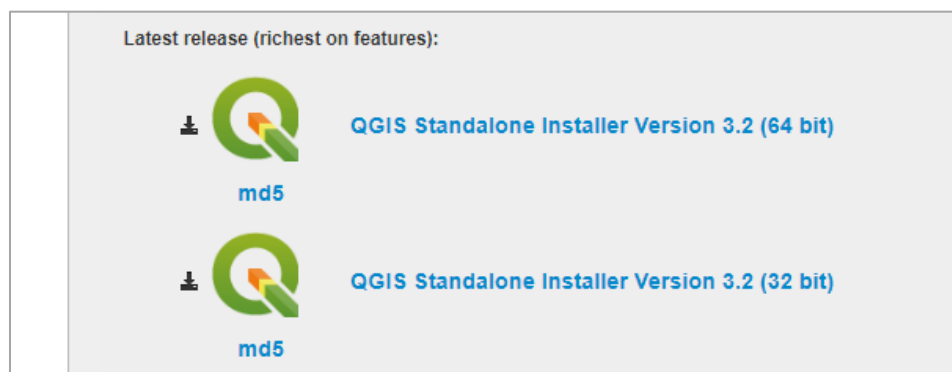


Figure 94. QGIS version options (32 or 64 bits)

After installing and starting QGIS to load vector files such as shape-file format (SHP), the Layer -> Add Layer -> Add Vector Layer option from the main QGIS menu should be used as

presented in Figure 95. An option to select a folder on the computer, where the file is located, will be presented. After loading the file, the data will be display in QGIS as in Figure 96. The loaded file will be listed on the bottom left window in QGIS (Layers).

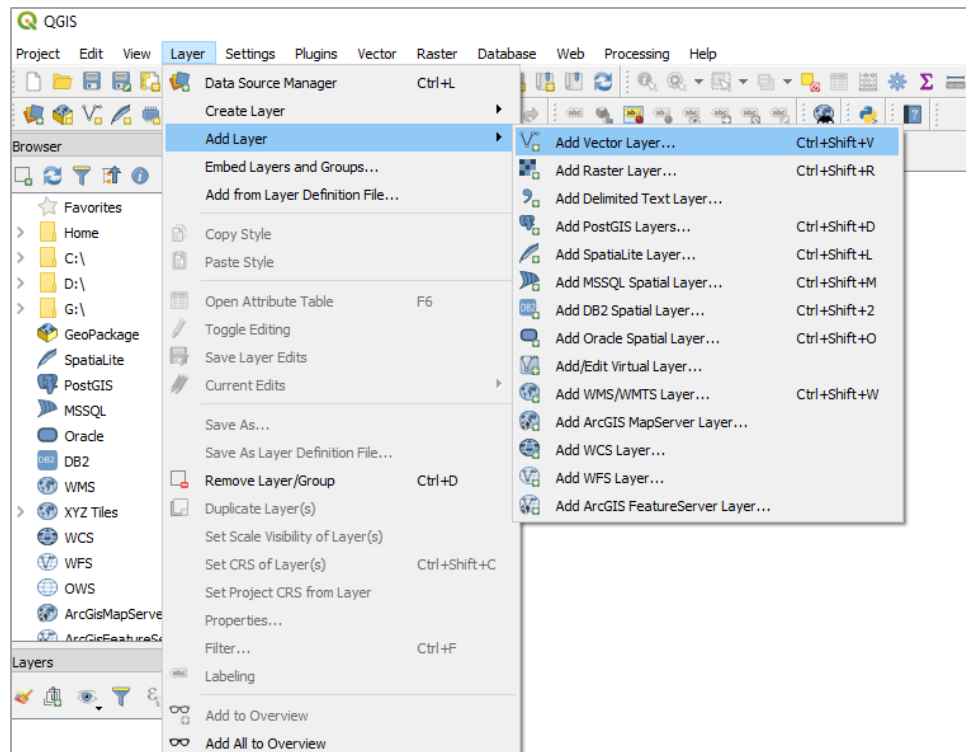


Figure 95. Loading a shape file format file

Once the file is loaded, it can be converted to the GeoJSON with the option ‘Save Vector Layer As’ by right clicking over the name of the added layer. A screen as in Figure 97 will be presented with the options to export the file. For the ResilSIM, the GeoJSON format should be selected and the projection (CRS) needs to be ESPG:4326 or simply WGS 84. Other coordinate systems are not compatible with the ResilSIM v2. The exported GeoJSON file can then be used or imported in the ResilSIM v2 as described in section 2.8 – Data Input.

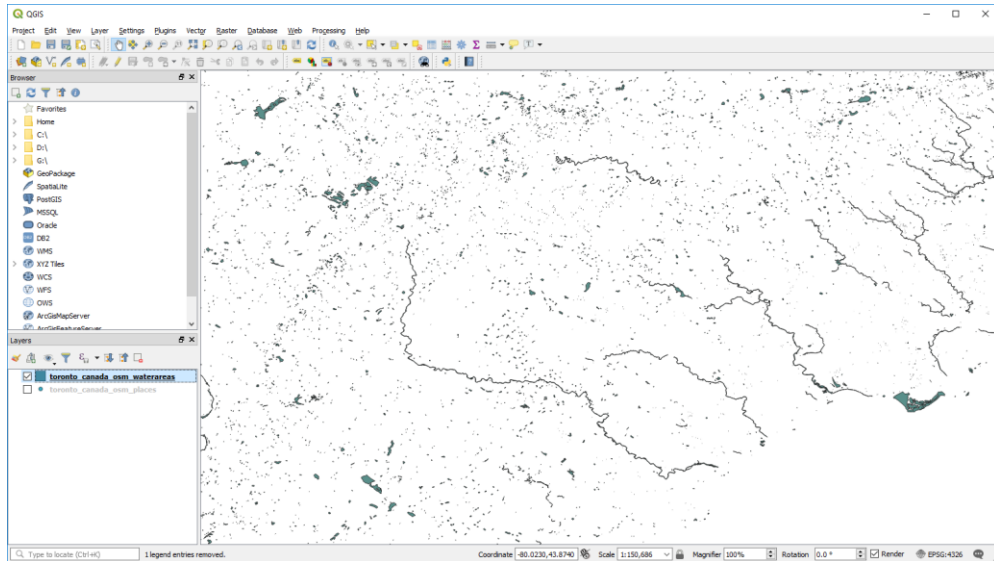


Figure 96. Vector file data displayed on QGIS

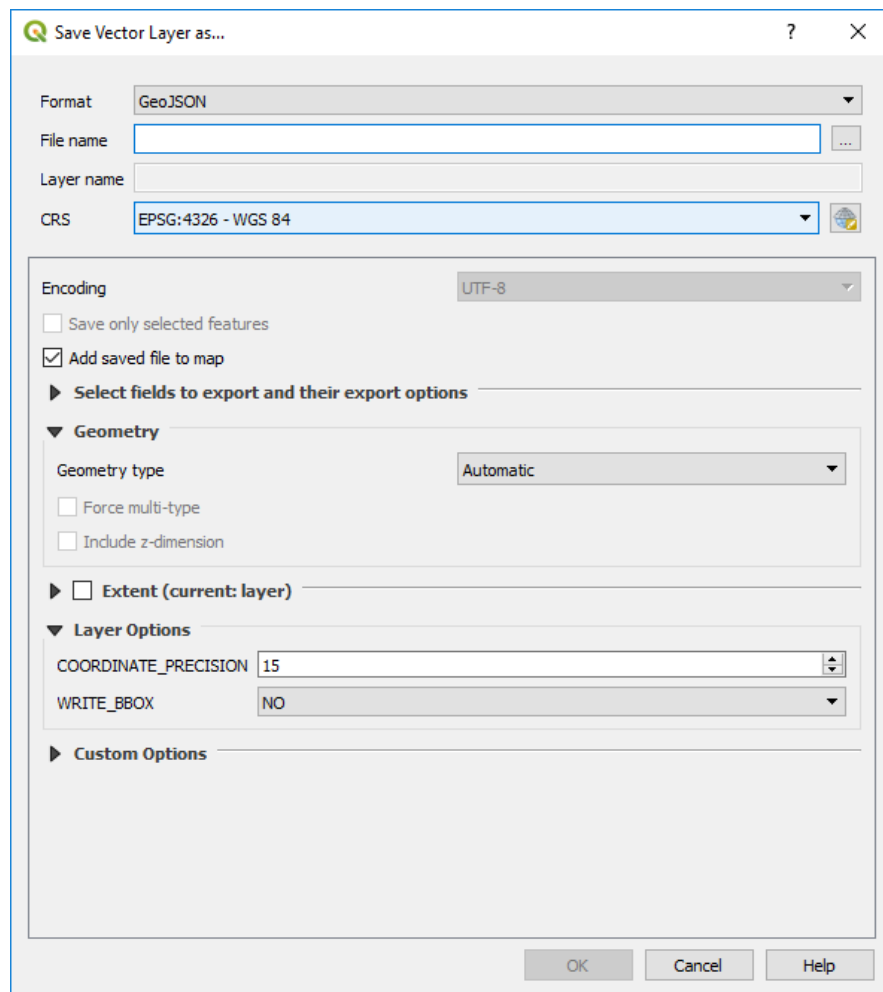
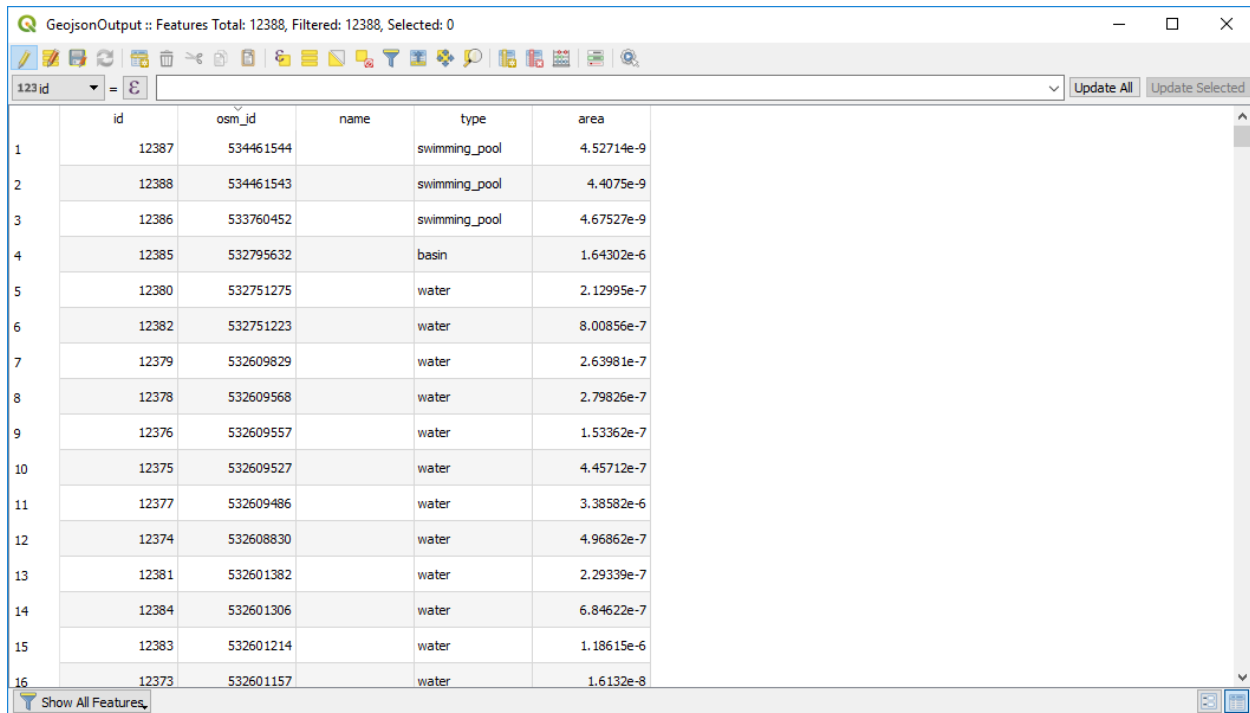


Figure 97. Converting to GeoJSON format

After creating the file to GeoJSON, QGIS allows editing the fields and updating data on the file. This is done by right click on the name of the file on the bottom left window (Figure 96) and selecting the ‘Open Attribute Table’ option. A new window (Figure 98) will be displayed with the features (object or polygons on the GIS file). On this screen the top menu allows editing (removing, adding, updating existing fields) in the GeoJSON file. These options are useful for changing of names, adding and removing data is necessary or desired.



	id	osm_id	name	type	area	
1	12387	534461544		swimming_pool	4.52714e-9	
2	12388	534461543		swimming_pool	4.4075e-9	
3	12386	533760452		swimming_pool	4.67527e-9	
4	12385	532795632		basin	1.64302e-6	
5	12380	532751275		water	2.12995e-7	
6	12382	532751223		water	8.00856e-7	
7	12379	532609829		water	2.63981e-7	
8	12378	532609568		water	2.79826e-7	
9	12376	532609557		water	1.53362e-7	
10	12375	532609527		water	4.45712e-7	
11	12377	532609486		water	3.38582e-6	
12	12374	532608830		water	4.96862e-7	
13	12381	532601382		water	2.29339e-7	
14	12384	532601306		water	6.84622e-7	
15	12383	532601214		water	1.18615e-6	
16	12373	532601157		water	1.6132e-8	

Figure 98. Adding or removing columns on the GeoJSON file

**Appendix B: A. Schardong, S.P. Simonovic, and H. Tong (2018) “Use of Quantitative Resilience in Managing Urban Infrastructure Response to Natural Hazards”, in print, International Journal of Safety and Security Engineering, 8(5):1–13.**

## USE OF QUANTITATIVE RESILIENCE IN MANAGING URBAN INFRASTRUCTURE RESPONSE TO NATURAL HAZARDS

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### ABSTRACT

Damages to urban systems as a result of various natural hazards have escalated in recent years. The observed trend is expected to increase in the future as the impacts of population growth, rapid urbanization and climate change persist. To alleviate the damages associated with these impacts, it is recommended to integrate disaster management methods into planning, design and operational policies under all levels of government. This manuscript proposes the use of quantitative resilience concept (dynamic in time and space) to assess the response of an urban system to natural hazards. The implementation of the concept has been done in the form of the web-based decision support system that operates in near real-time. It is designed to assist decision makers in selecting the best options for integrating adaptive capacity into their communities to protect against the negative impacts of hazards. The tool is developed for application in Toronto, Ontario, Canada.

*Keywords: adaptation, decision support, disaster management, hydro-meteorological, online tool, Resilience, urban systems*

### 1 INTRODUCTION

Natural hazards have caused an increasing amount of damage to urban systems in the recent years. The observed trend is expected to increase in the future as the impacts of population growth, rapid urbanization, and climate change persist. Natural disasters have become more frequent and damaging to physical and socioeconomic environments in recent years and decades [1]. In the last decade approximately \$4 trillion of direct economic damages have been attributed to natural disasters globally. This does not account for the loss of life and cultural assets that are difficult to evaluate [2, 3]. Furthermore, in last two decades the estimated annual economic losses caused by natural disasters have increased from \$50 billion to \$180 billion. Most of these losses are associated with extreme weather events such as floods, droughts, landslides, cyclones, extreme temperature and others [2]. According to [4], in 2015 alone, 346 significant disasters were linked to natural hazards, and an estimated 22,500 fatalities and over \$66 billion economic damages were lost.

The rising number of natural disasters that have occurred in recent years may be linked to three key factors including climate change, rapid and sometimes poorly planned land use change and population growth, especially mass urbanization. Climate change is believed to increase the frequency and intensity of extreme precipitation events. The average global temperature is projected to rise significantly, disrupting the balance of the climate system and hydrological cycle, causing unprecedented extreme meteorological events that will overwhelm critical infrastructure capacity as current design [1].

Integrating disaster management methods into planning, design and operational policies may aid or mitigate the damages induced by hazard events. In this manuscript, we propose the use of the quantitative resilience concept to assess the response of an urban system to hazardous event and how this changes as a result of varying adaptation measures.

Traditional risk management is defined as the combination of three elements: (1) probability of an extreme event; (2) exposure of infrastructure or human elements; and (3) susceptibility



of people, property, infrastructure, to damage caused by an extreme event [1,2]. There has been a shift from the traditional risk-based approach to resilience-based disaster management [5, 6].

Decision support systems (DSS) are used to provide meaningful inputs for improved decision making in complex domains. The DSS tool created by [1] named ResilSIM, to the best knowledge of the authors, was one of the first tools to use resilience as a measure of the urban system's ability to function in the event of a hazard as well as recover from the damages.

The objective of this manuscript is to present the evolution of the ResilSIM tool and introduce the updated version, ResilSIM v2. The implementation has been done in the form of the web-based and mobile friendly DSS. It is designed to assist decision makers in experimenting with different adaptation in order to mitigate the negative impacts of a hazard. The tool is developed for general application with user input data capabilities combined with the open source OpenStreetMap GIS database. One potential application for the Toronto, Ontario, Canada is presented.

The remainder of the manuscript is organized as follows: the method including the resilience definition, research objectives and methodological background are presented in section 2; a case study of the ResilSIM v2 tool in Toronto, Ontario is demonstrated in section 3; and finally, recommendations for future work are provided in section 4.

## 2 METHODOLOGY

In this section: (i) the resilience measure is defined; (ii) the objectives of ResilSIM v2 are identified; (iii) the methodological background is outlined; and (iv) the decision support tool features are described.

### 2.1 Resilience Definition

The IPCC defines resilience, in the context of disaster management, as “the ability of a system and its component parts to anticipate, absorb, accommodate or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration or improvement of its essential basic structures and functions” [3]. The definition of risk is the susceptibility of the system and its components to damage caused by hazards scenarios. Traditional risk is a static metric that does not change overtime. Resilience is a dynamic metric that is capable of presenting system performance over the duration of a disaster event.

According to [5], [7], [8], and [9] a resilient system may be achieved by choosing a sufficient set of adaptation measures. Recently, [5], introduced the dynamic resilience metric using simulation model integrated with GIS processing, similar to the procedure adopted by [1]. In [10], a comparison of static and dynamic resilience applied to multipurpose reservoir operation is presented. Their results show that the dynamic resilience is a powerful tool for selecting proactive and reactive adaptive response to hazard events that could not be achieved using the traditional risk based approach. The dynamic resilience concept is expanded by [11] using network theory and applied to the city of Toronto infrastructure as a case study. These concepts are incorporated into the current version of the ResilSIM v2 for the quantification of the dynamic resilience metric.

### 2.2 Objectives of ResilSIM v2 tool

The ResilSIM v2 is a web-based tool that allows (i) user input for representing physical and socioeconomic urban systems and (ii) assessment of its resilience to natural or human made

disasters. It can assist decision makers in selecting appropriate adaptation options that will maximize urban system resilience to a hazardous event.

The tool can function with a variety of datasets that describe key urban infrastructures, critical facilities (such as hospitals, schools, ambulance, fire and police stations), land use characteristics and social infrastructure. It is paramount that geographic information is associated with the data. Network data format are allowed, and specialized algorithms are employed to calculate the resilience metric. Infrastructure, social data, buildings, is mostly publicly available. However, private data can be incorporated into the tool database by the user for the resilience calculation as well.

The ResiSIM v2 can simulate one or more hazard scenarios, defined by the users through the user interface and GIS tool to project the hazard event for the region and compute an initial value of the urban system's resilience to the disturbance. The tool offers the user the possibility of creating a list of proactive and reactive measures of adaptive capacity that will be applied to improve the system performance and resilience. The user can select an adaptation option to be implemented virtually and observe how community resilience is affected. After the adaptation options are defined, the resilience is re-computed and compared to its initial value, serving as a basis for comparison for potential upgrades to the system.

The tool enables users to quickly make decisions that can reduce the physical, social and economic consequences associated with the hazards. These include damages to the built and natural environments (roads, housing, buildings, urban systems) as well as the danger and disruption posed to human welfare.

### 2.3 Methodological Background

The ResilSIM v2 is build as a generalized system allowing the calculation of Resilience metrics using a variety of datasets that describe key urban infrastructures, critical facilities, land use characteristics and social infrastructure. The tool mainly utilizes two types of data inputs: i) network data format, with a formal structure containing nodes connected by links or edges, and for which, specialized algorithms are employed to calculate the resilience metric; ii) other GIS data layers containing information about urban infrastructure, social data, buildings, critical facilities and others. For the network layers, each element component may have or its own physical capacity (usually represented as cost on a link for the mathematical representation).

The physical capacity measurement consists of the infrastructure's structural integrity or a unit related to its functionality. This is also the step related to the input of dependencies between network components. Dependencies can be classified as intra-dependent, a node or edge within a network dependent on another node or edge within the same network type, or interdependent, a node or edge within a network dependent on another node or edge from a different network type. GIS data layers have flexibility to incorporate other data types, such as point, line and polygon shapes.

The ResilSIM v2 dataflow and case analysis can be summarized in a few steps, as follows:

1. Description of Infrastructure System: on step the data is provided, i.e., network data, infrastructure data in form of GIS layers, social information and any other information or data the user judges relevant;
2. Hazards Input: definition of the hazard scenarios and input of the affected areas and regions and the magnitude on time and space;

3. Impact Assessment: the impact on the urban infrastructure (networks and data layers) caused by the hazards.
4. Adaptation Options: adaptation options are defined for each layer and hazards and will impact (improve) the resilience metric;
5. Assessment of System Performance and Resilience: Assessment of the Resilience and the impacts of the adaptation options.

Hazards are characterized by their damage area and magnitudes. They are inputs from the user. The tool allows the user to change the hazard affected area and severity over time to demonstrate the progression of the hazard. The impact assessment step then uses damage functions to estimate the reduction in capacity for the various system elements.

User input adaptation options can then be specified to demonstrate how system component behaviors shift if they are implemented. These can be classified as pre-disaster measures that change the disaster impact relationship for the component or post disaster measures that speed up system element recovery. The ResilSIM v2 tool integrates physical, social and economic impacts of disaster events and adaptation options implemented to an urban system into a single measure known as resilience,  $R$ . The procedure for computing the resilience metric is adapted from [1], [6], [11] and [12].

The overall system resilience calculation for each time step is illustrated on the flowchart presented in Fig. 1. The physical performance of individual networks and layers is aggregated to form a single network/layer system performance and resilience. Once this process is repeated for all infrastructure, it is aggregated further to calculate the overall system resilience.

An example of typical system performance curve (black line) is presented in Fig. 2. The shaded area under the curve represents the loss of system performance caused by the hazard over time. The x-axis represents time, where  $t_0$  and  $t_f$  represent the time at the beginning and end of the disaster event respectively. The system performance drops once the disaster begins at  $t_0$  and recovers over time.

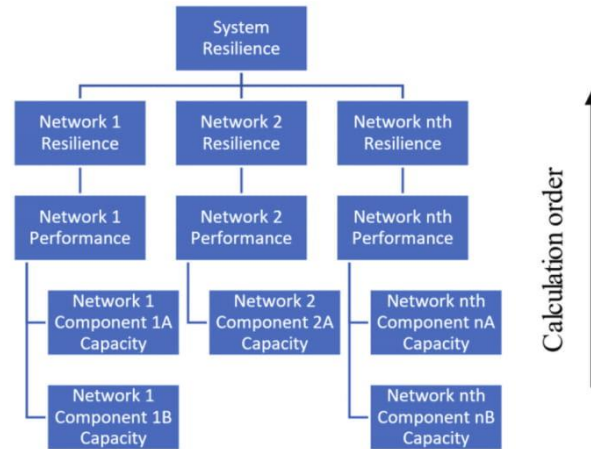


Figure 1: Resilience calculation order and flowchart of the ResilSIM v2



The area above the system performance curve represents the loss in system performance over time ( $\rho^i$ ). The area spans from the initial time of disturbance to the time at the end of system recovery and is calculated as:

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

where  $P_0^i$  is the initial system performance level,  $i$  the hazard,  $P^i(t, s)$  represents measure of system performance for each time step  $t$  and location in space  $s$ , and  $t_r$  the end of the recovery process.

The resilience of each system component,  $r^i(t, s)$ , represented by the area below the system performance curve in Fig. 2 is calculated using:

$$r^i(t) = 1 - \left( \frac{\rho^i(t)}{P_0^i \times (t - t_0)} \right) \quad (2)$$

The resilience of each system component can be combined into the final, system resilience using:

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

where  $M$  is the number of hazards.

Figure 3 illustrates one representation of the four components of resilience graphically. The resilience components include robustness, redundancy, resourcefulness and rapidity. Based on the mathematical representations of the four resilience components from [10], the tool can estimate a value for them with the resilience curve(s) generated.

The application of the methodology is demonstrated using OpenStreetMap (OSM) data and other publicly available data for the city of Toronto. Two theoretical hazard scenarios are created to showcase the use of the tool and the calculation of the system performance and resilience.

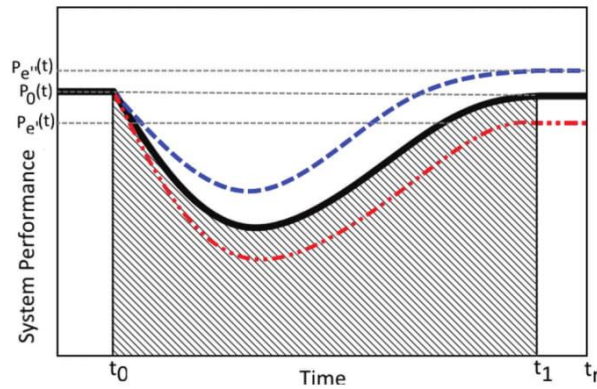


Figure 2: System performance to a disturbance (partial recovery, recovery to pre-hazard system performance, and strengthening of system performance) (adapted from [10])

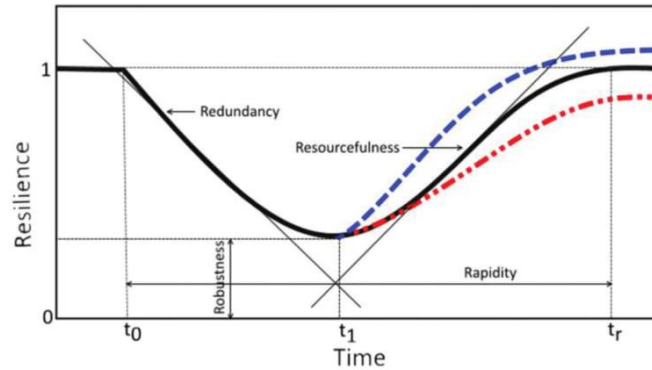


Figure 3: System performance to a disturbance (partial recovery, recovery to pre-hazard system performance, and strengthening of system performance) (adapted from [10])

#### 2.4 Decision Support System Description

The ResilSIM v2 tool is implemented as a generalized decision support system (DSS) that calculates the system performance and resilience to one or more extreme events that disrupt urban systems. The following section describes the major components of the tool: (i) user interface; (ii) database and (iii) mathematical module.

The procedure for calculating the resilience within the ResilSIM v2 tool can be described in following steps: (1) selection of the analysis (city, or urban center); (2) organization of the data for input into the tool: layer and networks representing urban system such as buildings, critical facilities, energy, and others, as well as social data; (3) input of the hazard scenarios and damage functions; (4) definition and input of the adaptation measures; (5) simulation of the hazardous event and the computation of the resilience metric.

##### 2.4.1 User Interface

The user interface, as presented in Fig. 4, has the following components: (i) GIS mapping component used to present geographic data and assist user's input; (ii) data input functionalities that allow users to select a set of adaptation measures; and (iii) results visualization - functionalities for the presentation of the system performance as interactive graphs, and tables to export the data extracted from the database.

The GIS interface is used in the resilience calculation screen to aid the user selecting a region of the city for the resilience calculation. Additionally, it is used to present all the geographic layers used in the tool's database. The adaptation measures controls are built as simple sliders where the user can select from a range between a minimum and maximum value defined for each measure.

##### *Data: OSM, Layers, Networks*

The tool has several pre-loaded layers that are imported from the OpenStreetMap (OSM) dataset [13]. The OSM is open-sourced dataset and is available with high level of details, especially for larger urban centers. The user can use this set to start the analysis without providing additional data. Some of the layers included are: roads, buildings, land use, critical facilities and railways. Other layers with geographical information can be provided, as well as social data and network-based layers.

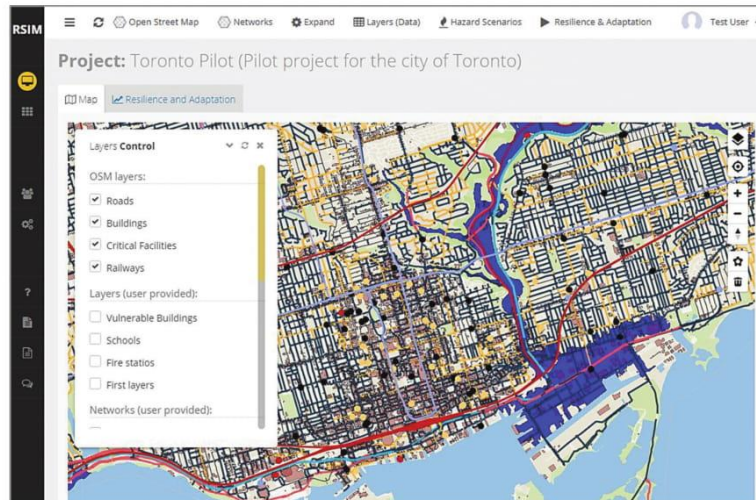


Figure 4: The ResilSIM v2 tool user interface

#### *Hazard Scenarios*

Several different types of disaster scenarios are supported by the ResilSIM v2: flooding, hurricanes (strong winds), fire and extreme temperature. The hazard scenarios are defined by the user using the GIS interface and both location or extent of the disaster and its duration have to be provided, as well as the magnitude of the event for each time step.

#### *Adaptation Measures*

Following similar concepts as the previous version, ResilSIM v2 classifies the options in two categories: (i) Reactive adaptation measures that are implemented during the disaster event; and (ii) Proactive adaptation measures that are implemented in advance of the disaster event.

Proactive adaptation measures intend to reduce the loss in system performance (over the duration of the disturbance) and improve resilience. On the other hand, reactive adaptation options, improve the rapidity of the recovery of system performance to a normal level of function, also enhancing the value of resilience. Evidently, the urban system performance returns to a normal level of function faster after the real-time adaptation options have been introduced.

#### 2.4.2 Database

The database system stores the OpenStreetMap dataset, DEM data and several other geographic data, such as land use layers, engineering data, provided by the users and the tool's configuration parameters. The database management system (DBMS) used is the latest version of PostgreSQL with the PostGIS extension.

#### 2.4.3 Mathematical module

The ResilSIM v2 incorporates a mathematical module that provides support for computation of system performance and resilience metrics, based on the methodology presented. This module also incorporates the codes and logic to extract and process the data from the database.

### 3 CASE STUDY

The tool is capable of estimating community resilience for a variety of natural or human disasters. The tool is demonstrated for application in the city of Toronto, Ontario that is vulnerable to climate change caused flooding. This section provides a brief description of the data used, the hazard scenarios and damage functions created and demonstration of the use of adaptation options; and (iii) demonstration of model output for this specific case study.

#### 3.1 Hazard Scenario and Impact assessment

The ResilSIM v2 tool allow the input of supplementary data (to the ready to use Open-StreetMap layers) that represent urban systems in the GIS or network format. Similarly, several hazards can be defined and will be used for the calculation of the resilience. The hazards are created by providing the duration, the affected areas (using the GIS API) and the magnitudes of the hazard over the duration of the event (Fig. 5).

The ResilSIM v2 tool is also flexible regarding the input and impact assessment for each of the hazards created. The impacts can be provided as: (1) damage tables; (2) damage equations and (3) fragility curves (Figs 5 and 6).

#### 3.2 Data and parameters of the simulation

For the simulation presented, a few layers from the Open Street map dataset were selected: roads, buildings and critical facilities (schools, police stations and fire stations). Additional geographical enabled data, provided by the City of Toronto and Toronto Hydro was used: digital elevation model for the city of Toronto, power supply network provided by Toronto Hydro (transformers and supplied areas), as well as additional critical facilities (schools, hospitals, fire stations and police stations). Two hazards were defined as one flooding and windstorm event, affecting the downtown area of the city of Toronto, Canada as presented in Fig. 9 (red polygons), and the hypothetical test case hazards were defined with a duration of approximately 24 hours.

Hazard scenarios for: **Toronto Pilot**

Hazard scenarios Edit Scenario **Damage**

Hazard scenario, duration and affected area

Select a disaster type: Flooding

Start time: 10

Ending time: 21

Select a Unit: Hours

Areas and magnitudes: Draw and modify polygons Edit magnitudes

AREA (KM <sup>2</sup> )	ID
0.3206	deb6486a21372668193621aa38adde26
0.2098	460c8046cbf1146e68bd788e79b550d2

Save hazard scenario Cancel

Figure 5: Characteristics of a hazard scenario in the ResilSIM v2 tool.



Hazard scenarios for: **Toronto Pilot**

Disaster Scenarios Edit Scenario **Damage**

Provide the damage curves (tables) or functions (equations) for physical and/or functional damage.

Select the layer: OSM: Roads (OSM) Category: All

☒ Edges ☐ Nodes

Damage output unit: Percentage (%)

Damage Curves (tables) Damage Functions (equations) **Fragility Curves**

☐ Physical ☒ Functional

Write your equation:

0.0009 \* Pow (d\*\*1000, 2) - 0.5529\*(d\*\*1000) + 86.9448

When writing the equation use  $d$  to denote the damage variable (Flood depth). The output should be compatible with the selected output unit.

Save damage functions

Figure 6: Damage input for the various hazards scenarios created by the user.

### 3.3 Adaptation Options

Increase in adaptive capacity of an urban system reduces the loss of system performance over the duration of the hazard and the recovery time, and as a result, the system resilience is improved. The ResilSIM v2 allows adaptation options to be freely defined (Figs 7 and 8) for each of the data layers and networks pre-loaded in the database or provided by the user. The adaptation options will improve the overall performance of an urban system when subject to hazards and the user will be able to evaluate their efficiency.

Adaptation options for:

Adaptation options Edit measure

#	MEASURE	TYPE	MIN	MAX	LAYER
2	Maintenance of drainage infrastructure	Proactive	0	100	Roads (OSM)
3	Invest in resilience building projects	Proactive	0	100	Buildings (OSM)
4	Efficient payment of claims	Reactive	0	100	Buildings (OSM)
8	Temporary dyking measures	Reactive	0	100	Roads (OSM)
10	Improving evacuation	Proactive	0	80	Critical Facilities (OSM)
15	Increase the number of adjusters	Reactive	0	100	Buildings (OSM)

Add new adaptation option Close

Figure 7: Adaptation options defined by the user in the ResilSIM v2 user interface.



Figure 8: Characteristics of the adaptation options in the ResilSIM v2.

### 3.4 System Performance and Resilience simulation

The user's inputs for the hazard scenarios limit the geographic extension of the resilience calculation in the tool. Figure 9 shows the combined disaster regions (light red shaded areas) from different scenarios for a hypothetical case study. These regions will then be used by the tool's mathematical models to calculate the loss of system performance over time and ultimately the combined system resilience.

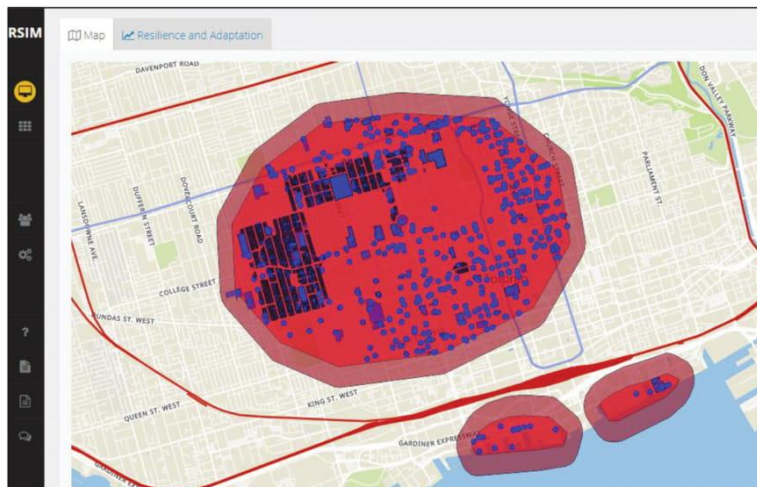


Figure 9: Geographic extension of the area defined by the hazards from the user's inputs.

After defining the hazard scenarios and damage functions, the tool calculates the system performance measures and the combined resilience metric using the methodology presented (Fig. 10).

The pro-active or reactive adaptation measures defined by the user for each layer and disaster scenario will impact the resilience calculated by the tool. The selection of the adaptation measures is controlled by a set of sliders with upper and lower limits, as defined in the input scenarios (right hand side of Figs 10 and 11). The user can quickly evaluate the impact of changing the values of the adaptation options on the system's resilience and, based on the response, identify measure/s with high efficiency in improving resilience in response to the hazard scenario.

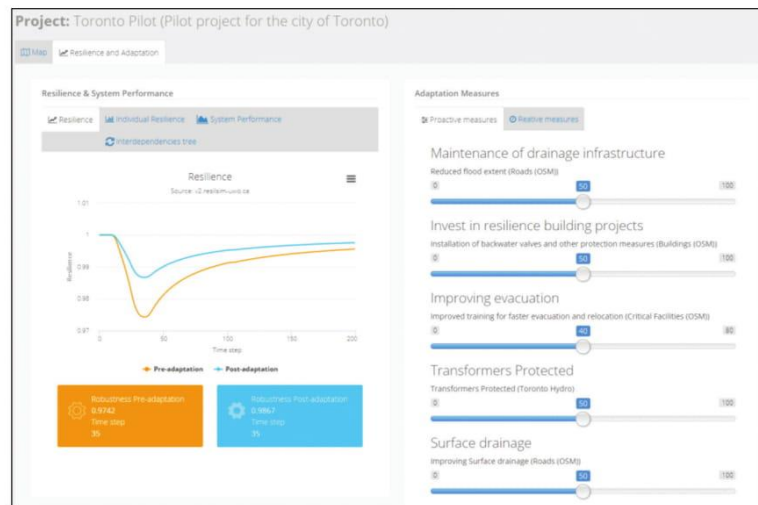


Figure 10: Pro-active adaptation measures applied to the system and response of the resilience.

The orange line shows the system resilience without adaptation and the blue line with pro-active and reactive adaptation measures.

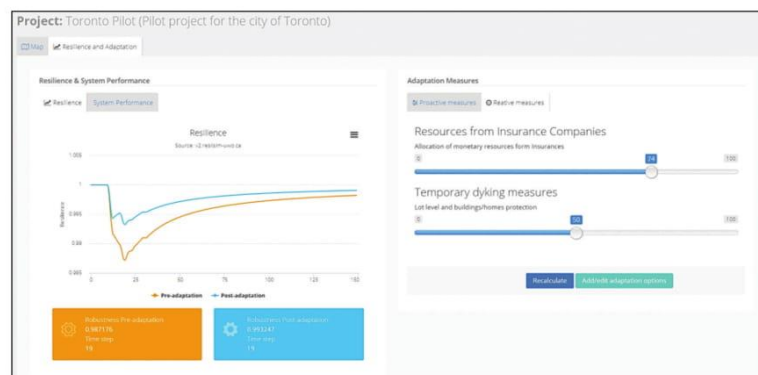


Figure 11: Reactive adaptation measures applied to the system and response of the Resilience metric. The orange line shows the system resilience without adaptation and the blue line with pro-active and reactive adaptation measures.

#### 4 CONCLUSION

This manuscript presents a decision support tool, ResilSIM v2, that is able to estimate the resilience of an urban system exposed to the impacts of various types of hazards, such as floods, hurricanes, fire, and others. The tool uses an open source GIS dataset as starting point for the analysis. The user, however, has the ability to incorporate additional data in form of GIS layers and networks to represent the physical and socioeconomic components of the urban system. Using spatial programming techniques, the resilience metric is computed as an amalgamation of system performance measures with respect to various impacts of the hazard scenarios.

The ResilSIM v2 calculates an initial value of resilience as basis for comparison. The user can subsequently add and experiment with different proactive and reactive adaptation measures and compare their impact on the system resilience.

The tool is tested with data for the city of Toronto, Canada, however, its generalized nature allows it to be applied to any urban center. Hazard scenarios and adaptation measures are user defined inputs allowing a various combinations of disaster and recovery strategies to be evaluated.

Resilience is an innovative disaster management measure that can assist decision makers in selecting and prioritizing actions for upgrading urban systems with high exposure to extreme events.

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