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Assessment of Critical Infrastructure Resilience to Flooding Using a Response Curve Approach

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Abstract: Following a flood the functioning of critical infrastructure (CI), such as power and transportation networks, plays an important role in recovery and the resilience of the city. Previous research investigated resilience indicators, however, there is no method in the literature to quantify the resilience of CI to flooding specifically or to quantify the effect of measures. This new method to quantify CI resilience to flooding proposes an expected annual disruption (EADIS) metric and curve of disruption versus likelihood. The units used for the EADIS metric for disruption are in terms of people affected over time (person × days). Using flood modelling outputs, spatial infrastructure, and population data as inputs, this metric is used to benchmark CI resilience to flooding and test the improvement with resilience enhancing measures. These measures are focused on the resilience aspects robustness, redundancy and flexibility. Relative improvements in resilience were quantified for a case study area in Toronto, Canada and it was found that redundancy, flexibility, and robustness measures resulted in 44, 30, and 48% reductions in EADIS respectively. While there are limitations, results suggest that this method can effectively quantify CI resilience to flooding and quantify relative improvements with resilience enhancing measures for cities.

Keywords: resilience; critical infrastructure; quantification; impact assessment; risk reduction; flood risk

1. Introduction

Disruption and damage to cities due to extreme weather events is on the rise. Because of this, cities are facing increasing shocks and stressors that impact the daily functioning of the city. These extreme weather events can include winter storms, droughts, and floods. Cities have experienced dramatic changes in both the hydrological landscape as well as urban development patterns. This has caused increased damage and disruption as the result of flooding—a trend that is likely to continue in the future. For example global flood damage increased from US $21 billion in 2015 to US $25 billion in 2016 [1]. Studies supported by the OECD have suggested that this could increase to US $52 billion by 2050 with projected socio-economic change alone, not to mention climatic changes [2].

Many policy documents stress the need to increase resilience, and in the interest of working toward this goal several organizations such as the Rockefeller Foundation are working directly with cities to do so. Their "Resilient Cities Framework" developed in partnership with ARUP outlines a methodology to qualitatively evaluate the resilience of cities using 52 indicators. In addition, the program supports cities to hire a Chief Resilience Officer to play a leadership role in this process [3]. While the goal of improving resilience is a clear priority, work on methods and indicators to characterize and quantify resilience is still an evolving field. These methods are needed to evaluate the suitability of proposed solutions and track progress. The resilience of modern cities is dependent on, amongst other factors, the resilience of its critical infrastructure (CI) [4,5]. The interaction between flood hazard and CI resilience is thus an important component of the resilience of cities.

This paper focuses on the question: How can CI Resilience to flooding be quantified and can this be used to evaluate the effectiveness of CI resilience measures? The paper also outlines a method to assess and represent the resilience of the CI of cities and to assess and compare the effect of several types of measures on resilience. The paper illustrates this method through its application to the city of Toronto in Canada.

The paper starts with a brief overview of flood risk analysis, the resilience approach, and their application on CI to explain the gap which the proposed method is aiming to close. Then the method is described and its application to Toronto is discussed. Since the analysis of flood impacts related to CI is always hampered by lack of data and requires input from many stakeholders, the feasible workshop method applying the CIrcle tool was adopted. The use of the CIrcle tool in the present study facilitated the collection of CI network information for a first application of the method. Finally, wider conclusions on the quantification of resilience and resilience measures are provided.

2. Resilience Literature and Application of the Concept

2.1. Flood Risk and Resilience in Literature

Despite the current strong call for improved resilience, many past flood analyses have failed to adopt a resilience approach [6]. In some cases, only the flood hazard is considered and structural flood hazard reduction measures are proposed as solutions. In other cases, a flood risk approach is adopted where vulnerability is also considered, however these studies often focus on a narrow range of solutions and only consider the maximum flood depths for a specific event. Some critical aspects such as recovery, low probability-high impact events, indirect effects, and intangibles may become neglected or undervalued [6]. These are important factors to consider in support of applying a resilience approach to flood analysis.

Resilience refers to the ability of a system to recover from a shock. Resilience science is rooted in the work of Holling [7] and ecological resilience. Ecological resilience is described as the "persistence of relationships within a system" and the degree to which systems absorb disturbances while continuing to persist. Later works have defined engineering resilience as resistance to a particular shock and the speed of return to equilibrium [8]. More broadly, resilience is defined as "the ability to prepare and plan for, absorb, recover from and adapt to adverse events" [9]. A resilient system, community or society has the ability to do this "in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions" [10]. In this paper, we define resilience as the ability to cope with disturbances and flood resilience as the ability to cope with disturbances due to flooding. If the coping capacity is insufficient, measures may be considered to adapt the system to increase its resilience. We thus consider measures which help systems to prepare and plan for, absorb, recover from, and adapt to flood hazard.

Presently, two approaches to resilience metrics can be found in the literature which seeks to quantify aspects of resilient systems. One approach aims to quantify resilience by looking at the response of systems to disturbances while, the second approach assesses the presence of resilient properties that would enable the system to cope with disturbances. For the former systems response approach, several studies have applied a graph model to represent system response such as Bristow and Hay [11]. This model tests the properties of resilient systems, similar to those mentioned in the documents of the City Resilience Framework championed by the Rockefeller Foundation with Arup [3]. Both [4] and Arup [3] mention the resilience characteristics of (1) flexibility, (2) redundancy, and (3) robustness (or hardening) as properties which resilient cities and CI need. According to the report by Arup [3], redundancy refers to "spare capacity purposely created within systems so that they can accommodate disruption" and flexibility is referred to the ability of systems to "change, evolve and adapt to changing circumstances". Bristow and Hay [11] define the concept in a similar way, characterizing redundancy as "duplicating the means by which a need is met" and flexibility as "meeting multiple needs through multiple different components". Arup [3] frames redundancy more broadly, while the definitions from Bristow and Hay [11] are specific to CI networks. These help to characterize different scales of the same resilience properties. Also mentioned are "robust" systems which are referred to as those which can "withstand the impacts of hazard event without significant damage or loss of function" [3]. This corresponds strongly to what is referred to as "hardened" by Bristow and Hay [11] as it is described as measures which reduces direct damage because strength or tolerances to hazards are increased.

As mentioned above, traditional flood risk analyses have focused heavily on both hazard reduction and direct damages. In response the solutions have often been to reduce the hazard with structural measures thereby reducing direct damages. This largely ignores the critical factors that are needed to return urban areas to pre-flood levels of functioning when an area does flood, such as recovery and resilience. Some studies have quantified resilience spatially [12], but do not take into account the configuration of CI networks. In addition, many studies often ignore the contribution of external effects outside the hazard area, interdependencies, and indirect effects [13]. However, some studies have incorporated these effects by including high-level frameworks for analysis [14,15] as well as more detailed hazard and network models [5]. Many of these models, however, are focused on engineered systems and do not take into account social factors antecedent to the hazard or account for the resilience or vulnerability of the natural environment [16]. Methods which can be used to support decisions to make infrastructure more flood resilience are still lacking and there is a need to integrate several areas of research (flood, resilience, and CI network interdependencies) to achieve this.

Modelling or understanding CI network interdependencies and vulnerability to flood is a persistent challenge. Several studies have addressed models for infrastructure interdependencies and resilience from an all-hazards approach [4,11]. Network dependencies can be analyzed in many ways, including methods which adopt an operational resilience approach and look at functional vulnerability [17]. There are also many ways to model interdependencies and the present study generally applies an empirical approach as defined by Ouyang [17]. This approach uses an understanding network vulnerability and interdependency developed from information on past events and expert opinion.

By using a resilience approach to CI and flooding, it is possible to take into account new factors into consideration, such as recovery. While traditional approaches mainly look at the maximum damage (or the impact A in Figure 1) resilience approaches also consider the recovery process (see Figure 1).

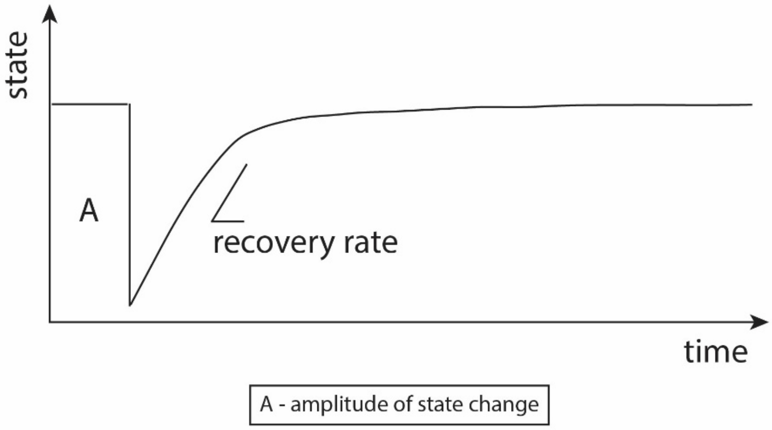

Figure 1. Representations of system response as functions of time following a shock. Adapted from De Bruijn [18].

This recovery rate depends on several different factors related to the vulnerability and the coping capacity of exposes systems. A given system will be able to resist up to a given threshold, however once that threshold is crossed recovery will not be possible. Figure 2 highlights these thresholds and shows how a system will respond to the whole range of potential hazards with different severities.

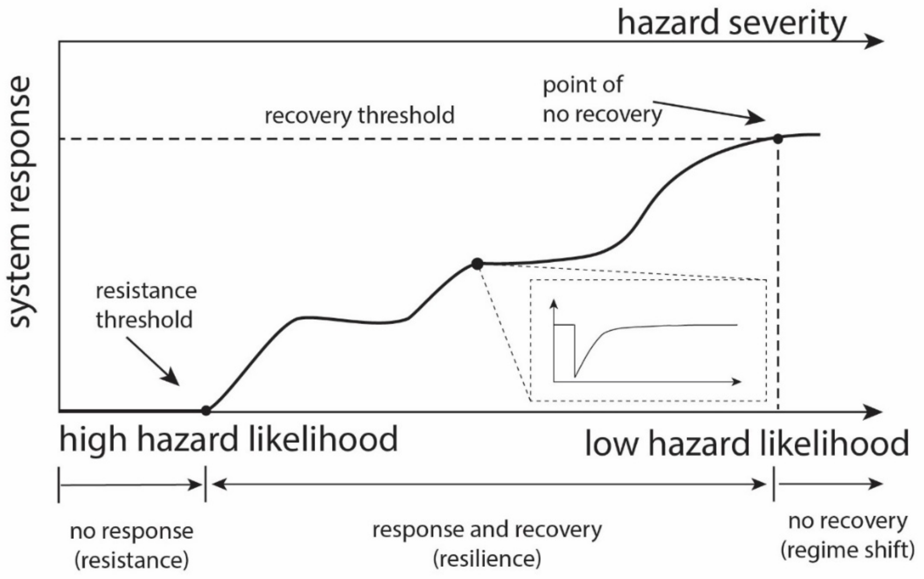

Figure 2. System response as a function of disturbance magnitude. Adapted from Mens et al. [19].

Graphical representations such as these are useful for looking at resilience in two different ways, specifically (1) over the timeline of a disaster or (2) system response for increasing magnitudes of disruption. To be resilient, systems require several characteristics which may partly depend on the hazard they need to be resilient to. Systems may, for example, need to be able to resist the most frequent hazards that they are exposed to or the hazard which causes the greatest damages and disruption. With an all hazards assessment, the most frequent or damaging hazards should be identified. In the case of the case study selected for the present study, flood hazard is the primary concern.

This paper seeks to quantify resilience in terms of disruption for multiple events and for this reason uses graphical representation similar to that of Mens et al. [19]. This is an innovative element of this paper given that graphical representation allows us to assess the effects of flooding at multiple levels of severity. In order to increase system resilience, we look at the second type of framework, which specifies characteristics that resilient systems must have to be able to respond in a resilient way. Those frameworks are thus used to identify measures that are likely to increase resilience. How these measures affect the response is then integrated into the resilience graphs and demonstrates the disruption caused by events with different levels of severity. With a graphical representation, it is possible to show the effect that different measures would have on the system response.

2.2. Resilience Concepts Applied in This Paper

This paper aims to capture the effect of flood-related disturbances within the CI networks on people over time. People are disrupted in different ways during a flood, including direct and indirect impacts. Many components of CI are often affected by flooding, with disruptions of power systems causing the most notable disruptions in many cases. In addition, flooded roads or incapacitated power systems can also have a negative impact on the lives of people. A person's ability to both recover from a flood, as well as be less disrupted by flooding in the first place are both characteristics of resilience. People may be more resilient because they have an alternative route to get home or have access to a backup generator to maintain power supply to their home. It is important to not only understand the system response over time following a disturbance, but also capture the effect of the disturbance on people over that time. This study quantifies this kind of disruption for floods of different probabilities, with a focus on CI non-functioning.

While flood impacts are often quantified in terms of damage and then summarized either graphically or with an expected annual damage (EAD) calculation [20], it is also possible to quantify flood impacts in terms of disruption. This disruption quantification would thus provide a metric for the resilience approach. EAD is calculated by taking the area under the curve for a damage (in monetary terms) over exceedance probability graph as shown in Figure 3. Also shown in Figure 3 is a similar curve with disruption on the *x*-axis instead of damage illustrating the resilience quantification concept.

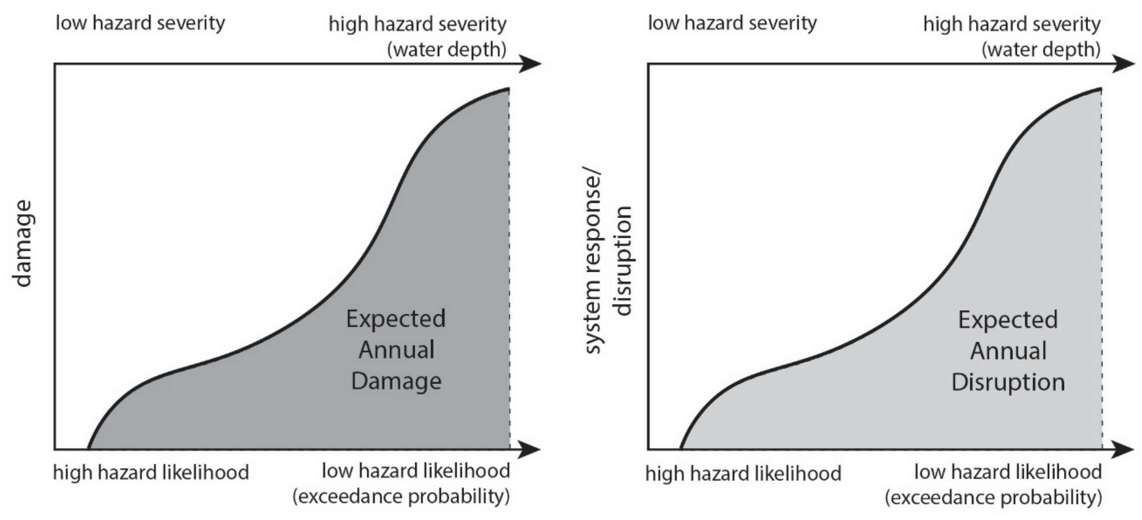

Figure 3. (**Left**) Expected annual damage (adapted from [21]) and (**Right**) expected annual disruption.

Increased resilience of CI to flood is equivalent to a decrease in disruption. Thus, a resilience metric could be calculated using a method adapted from the EAD calculation, which is frequently used for research and professional practice in flood assessment.

It is often difficult to study CI resilience to flooding because of the challenges related to the availability and acquisition of data. In addition, the interdependencies between CI systems are often complex. Another study from [22] also used disruption as a metric for the resilience of CI to natural hazards, however, the assessment in that study was qualitative and based on assessments from expert interviews only. This method did not allow for the calculation of a disruption metric using spatial analysis and hydraulic modeling outputs. Assessing disruption using spatial network data and flood mapping, along with expert and stakeholder information, would could allow for the development of an empirical model of the CI networks and a more quantitative assessment of disruption. To collect information on these interdependencies and start to understand the connections, diverse stakeholders should be involved [23]. The CIrcle tool can be used to do this in a structured way and can address some of the challenges related to acquiring stakeholder input [23,24]. While CI interdependences are complex and detailed information is often private, a combination of high-level input from stakeholders and open data sources can close this gap. Basic mapping of infrastructure is often possible using the open street map (OSM) database and CIrcle helps to collect infrastructure and dependency relationships. This information is needed for an assessment of CI resilience. Partnerships with local authorities can also help in the acquisition of flood modelling results or GIS files of flood maps.

This study also assesses whether the resilience concept can guide the selection of measures. The resilience measures applied in the present study include the resilience aspects of robustness, flexibility, and redundancy which have been mentioned in the previous section. We use them in a way comparable with Arup [3] and Hay and Bristow [11]. We define measures that increase the flexibility, redundancy and robustness properties of CI as increasing the CI resilience to natural hazards and thus also the resilience of the city to natural hazards. These measures increase the resilience of CI systems as they decrease the losses for hazards up to a given level of flood severity. This means that there is a threshold beyond which the loss is not reduced because the event is too severe. The graphs in Figure 4 highlight the changes in severity and disruption relationships with the introduction of CI resilience measures.

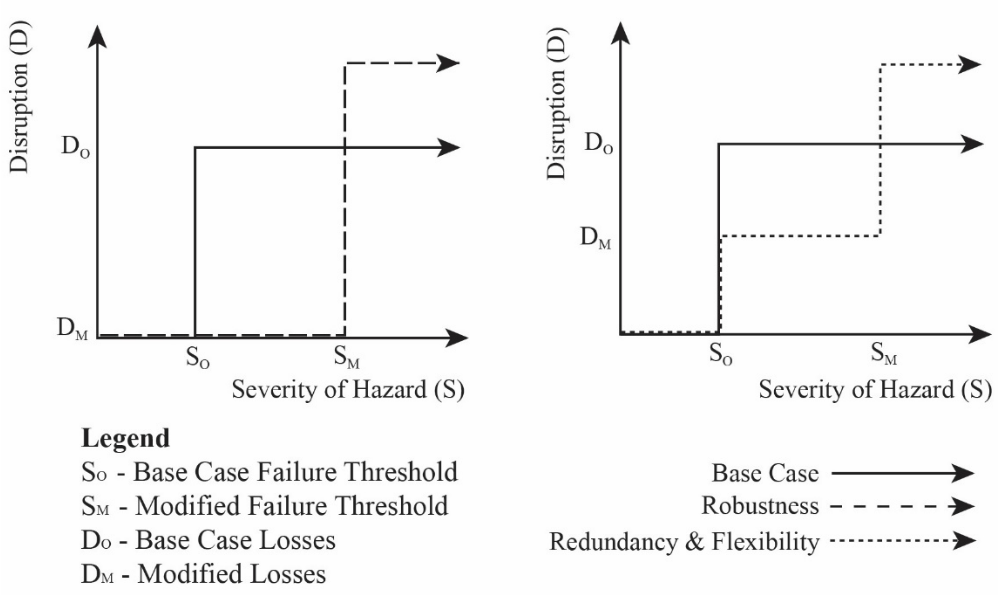

Figure 4. Severity–loss relationship for resilience measures including redundancy, flexibility, and robustness. (Adapted from Bristow and Hay [11]).

The *x*-axis in these Figure 4 graphs is the severity of the hazard (*S*) and the *y*-axis is the disruption (*D*) due a hazard of a given severity. The relationship between severity and disruption is shown for the system with a base case and then for the system with resilience enhancing measures. For the base case there is a system response after the severity threshold S_O up until a disruption level of D_O. With robustness added to the system, disruption is avoided until the new hazard severity of S_M. This disruption is avoided because robustness measures are typically protection measures for a given design threshold, such as putting a wall of a given height around a transmission station.

For redundancy and flexibility measures, the initial resistance remains at S_O, however, the disruption is reduced up until the modified failure threshold S_M. This is because these measures reduce disruption but do not prevent disruption. When redundancy is added to the system, the disruption is reduced because alternative options are available for a given form of CI, such as an alternative power supply or route for transportation. A power distribution network with a loop configuration, for example, is more redundant than a branch configuration. When flexibility is added, there is no change to the network itself, however, the losses and disruption are reduced because the response time is made shorter through, for example, greater availability of spare parts or personnel. The system can be repaired or adapted easily. Identifying specific measures such as those listed above helps to operationalize resilience. Indeed, the properties selected as measures are ones that cities will strive to operationalize [3] and this method proposes a way of doing so.

3. Case Study: Toronto, Canada

The case study used to apply the present method is the Lower Don Transportation Corridor (LDTC) in Toronto, Ontario, Canada. This area is located in the Don River Watershed to the east of downtown Toronto. The city of Toronto covers an area of 630 km^2 and has nine creeks and rivers flowing through it, which all outlet into Lake Ontario, which is one of the great lakes [25]. The Don River watershed has an area of 360 km^2 and stretches for almost 38 km. As shown in in Figure 5 the LDTC includes a small area by comparison to the larger watershed along the final 5 km of the river.

It is however, an important area for the city in terms of flood hazard and disruption. This is because much of the infrastructure that the city depends on, such as a major highway and power infrastructure, is located in this area.

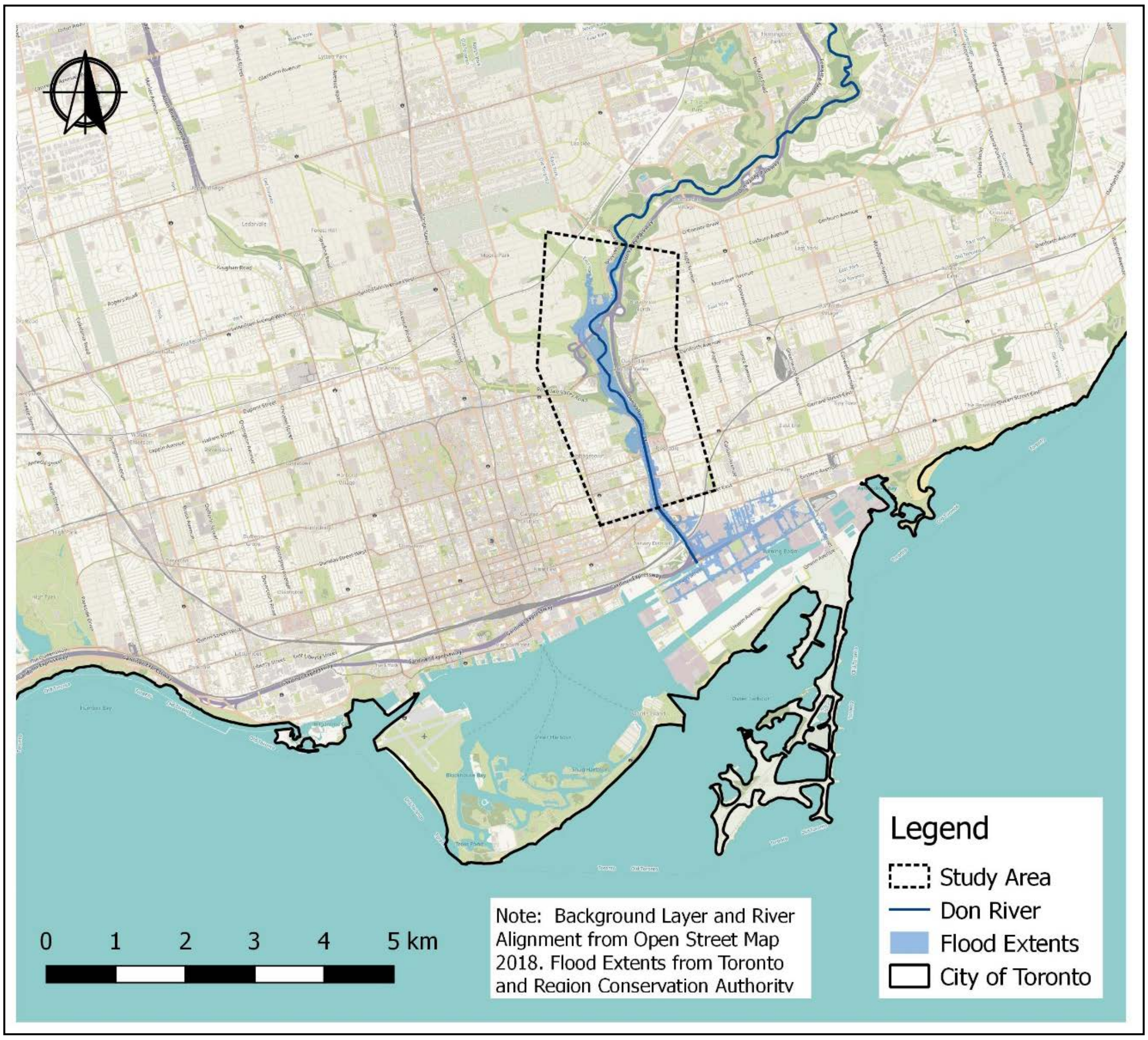

Figure 5. Lower Don Transportation Corridor flood and CI Map.

The city of Toronto has experienced flooding in recent years which has affected CI. This has caused disruption in the form of power outages, traffic delays, and flooded trains. Toronto is also the most populous city in Canada with 2.8 million people and is growing rapidly. The flood issues in this area have been studied and hydraulic models have been developed for watersheds within the city managed by the local conservation authority. In addition, information about impacts from recent and historic flood events is available. The present study was conducted with the support of the Toronto and Region Conservation Authority (TRCA) who are responsible for managing flood risk for the watersheds within the city. This combination of data availability and interest from local authorities enables the application of the proposed participatory method.

This LDTC study area is exposed to flood hazard from the Don River and flooded infrastructure in this area can cause disruption outside the boundaries of this area. As mentioned, several types of linear infrastructure run parallel to the river in this area. Specifically, this includes transportation infrastructure such as a major highway (Don Valley Parkway (DVP)), secondary roads (Bayview Rd.), trails (Lower Don Trail), and a commuter rail track (Go Train). In addition, power lines, telecommunication cables, a gas pipeline, water supply mains, and stormwater infrastructure also follow a similar alignment in this area along the river. The combination of flood exposure and a concentration of CI infrastructure makes it an excellent case study for a method to quantify the resilience of CI to flooding.

4. Method

To quantify the resilience of CI to flooding and test the effectiveness of resilience enhancing measures three main steps and several sub-steps are proposed, as shown in Figure 6.

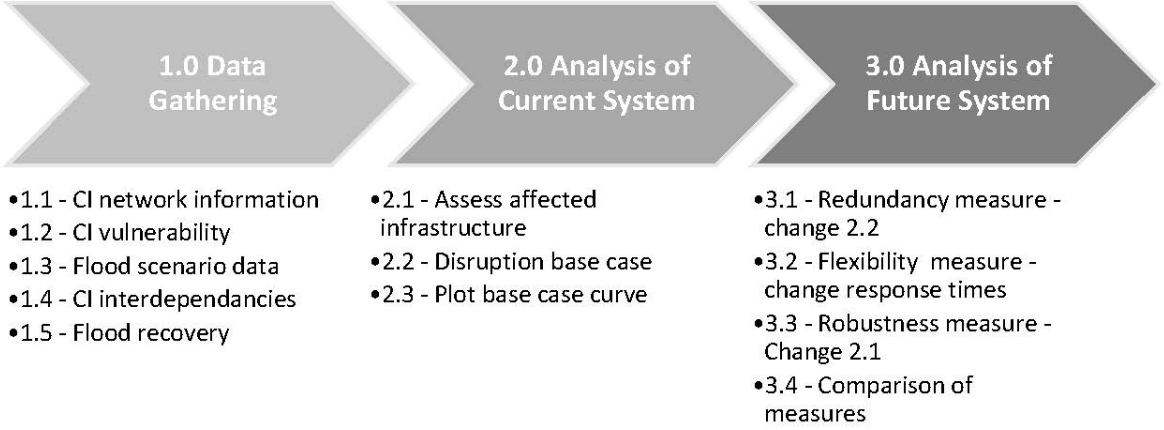

Figure 6. Research method steps and sub-steps.

First data on CI, flooding, and factors influencing recovery need to be collected and analyzed. This is often a challenge given the nature of CI related data and in many jurisdictions, it can be difficult to obtain flood maps and hydraulic modelling outputs. In addition, for some areas, there may be no maps or modelling results available. The present study uses the storyline method as a base, which serves to analyze the whole sequence of events during a flood [26,27]. As described in [23] this method is principally designed to facilitate communication, information exchange and discussions between stakeholders in a workshop setting. It defines three phases for stakeholders to consider including "(1) the rising of the flood threat, (2) the flooding itself, and (3) the recovery from the flooding" [23]. Through discussion on what actions are taken and what effects are observed during each of these phases an understanding of impacts for different water levels can be generated. This helped stakeholders consider their own knowledge and experience related to flood impacts. This helps provides information on interdependencies through the use of the CIrcle tool. The CIrcle tool "supports the development of a mutual understanding in workshop sessions and it visualizes actors' input on different CIs and the interrelations between those CIs" [23]. The method of working with stakeholders to gain an understanding of the system using the CIrcle tool was applied as part of Step 1. This is done to gather interdependency information. For the purposes of this first application, the stakeholder engagement was limited to one group workshop and several individual meetings. CIrcle is a software tool used for collecting expert knowledge on the relations and dependencies of CI elements through simple visualization of this information. In this way, preliminary interdependency information can be collected and validated by the group. With the information produce in this workshop, the effect of flooding on CI elements and then the larger network was evaluated. With this information, the curve and resilience metric are generated for the current system as part of Step 2. Then the relative change in the curve and metric with the addition of resilience enhancing measures was evaluated as part of Step 3.

With this factor of disruption to people graphed for each hazard likelihood, the area under curve can be calculated. This is similar to the way in which expected annual damage is calculated, however, in this case person × days of disruption in person × days or EAD_{IS} is calculated. A system response curve can be used to represent CI resilience graphically and EAD_{IS} is a way of representing resilience quantitatively. In this paper, we characterize resilience quantitatively and look primarily at the disturbance in an area of interest caused by a flood event. This disturbance is quantified by the number of people affected by flooding and the duration of time that they are affected. We present this disruption assessment using a response curve such the one in Figure 3, using the metric of disrupted person × days. Disrupted person × days is a combination of the number of people affected by non-functioning CI and the duration that they are affected for. This combination of applying a disruption metric and building a system response graph serves to close the gap on CI resilience quantification.

4.1. Data Gathering

Gathering data on CI is a challenge, however, open source information from OSM was used as a starting point and additional information was gathered from a workshop with stakeholders facilitated with the use of the CIrcle tool [28]. The overall structure for data gathering and processing follows five sub steps:

1. Gather data gathering for CI networks (Step 1.1).
2. Obtain flood hazard maps (Step 1.2).
3. Combine the CI information and flood information to get insight into the exposure and vulnerability of CI to floods (Step 1.3).
4. Analyze the cascading or indirect effect caused by disruptions of the flood exposed objects identified in Step 1.3 (Step 1.4).
5. Assess recovery time and capacities of the flood-prone CI elements (Step 1.5).

The first two steps provide a basic understanding of what CI is in the study area and what flood hazards they would possibly be exposed to. The CI Network data in is one of the data sets that can often be obtained from the OSM database. Next, information on the vulnerability and exposure of CI should be gathered to determine which CI elements would be exposed to flooding and which elements would be affected by flooding. For example, if the flood extent intersects a power transmission station then elevation of equipment should be known to determine at which level of flooding that equipment could be damaged enough to cause a power outage. After direct impact, information providing an understanding of CI interdependency should be acquired (Step 1.4). This is done so that the total disruption from an outage due to flooding can be determined. It is recommended that local stakeholders are engage at this stage and information is collected using the CIrcle tool as explained in [23]. Often, stakeholders familiar with the system will know what can happen when key equipment gets wet and what the dependencies are. Finally, information regarding recovery from different severities of flooding should be estimated (Step 1.5). This can be done using information on past flood event and typical recovery times. Information collected from stakeholders as well as reports and media from flood events can support this.

4.2. Analysis of Current System

Data on the current CI system and flood hazard should be collected to establish the base case. With the response curve approach, the base case provides a level of disruption for each annual exceedance probability (AEP) to compare improvements with. This base case assessment includes estimated impacts and recovery times for each flood hazard studied. With the necessary data about the current system, the analysis to determine the expected annual disruption can be done in three steps: Assess flood impacts on CI, quantify disruption for the current system in terms of person × days, and combining disruption with event probabilities.

First, it is important to determine what CI will be affected by floods of varying degrees of magnitude (Step 2.1). This means looking at the flood extent for the 1% AEP event and identifying what infrastructure is in the flooded area. This is done in GIS using the outputs of hydraulic models for the river in the study area. The water depths in the study area are extracted from flood inundation map layer at the location of each infrastructure element. This is then repeated for each flood hazard AEP available for the study area. By comparing the water depth at the location of the infrastructure element it is then possible to determine if the water depth in that location exceeds the functioning threshold. The infrastructure is determined to be functioning or non-functioning depending on the height of the water and the height of vulnerable equipment. Knowing what networks would have outages, or what roads would be flooded, the duration of disruption and number of people disrupted should be determined. For power for example, a network would be out if a transmission station is flooded for the duration of the flood, plus the typical time needed to repair a flooded transmission station. The number of people affected can be determined from looking at the number of people serviced by a particular transmission station. This is difficult information to obtain but can often be estimated using census data. Secondly, based on recovery times and the number of people affected, the disruption in the existing system can be determined (Step 2.2) including what is directly affected, network dependencies, and cascading or indirect effects. With the disruption due to flooding calculated for each infrastructure network for each AEP, the base case curve can be plotted. The area under the curve of this base case curve is the EAD_{IS} (Step 2.3).

4.3. Definition of Measures and Analysis of the Future System

After an overview of the current resilience is obtained, measures can be defined to increase resilience. Three types of measures are tested in the present study: measures which increase (1) redundancy, (2) flexibility, or (3) robustness. We assess the effect by comparing the disruption curve and the EAD_{IS} metric with the baseline curve and metric. The change in disruption within a study area with CI resilience measures under the same flooding conditions gives a quantitative indication of the effect of resilience enhancing measures for the study area. In this method, we measure disruption as indicator for the system's response to the disturbance. There are additional factors that would influence system response including economic, social, and other vulnerability indicators. These are not completely covered by this indicator as the aspect of disruption and recovery time measured is dependent on the functioning of infrastructure.

5. Results

5.1. Data Gathering Results

Data on CI networks needed to be gathered to asses vulnerability to flooding and interdependencies. For the LDTC study area data on the CI networks was collected using open data sources and reports. In Canada, federal agencies contribute to the OSM database and therefore for some areas, such as Toronto, this data is quite complete. An example of available power network data with transmission lines and power transmission stations is shown in Figure 7. This includes the power supply network in and around the case study area. In addition to OSM data, other open datasets were used as much as possible, including spatial datasets from the City of Toronto website in addition to publicly available reports and maps from asset owners.

Within the study area there are roads, rail, power and telecommunication infrastructure. Not all types of CI area present within this study area including hospitals, schools, water supply, emergency services buildings or government building for example. For other applications of the assessment method, it would be important to include any other CI if it is in the study area.

This type of network information for CI systems is important to collect as the configuration of the network and the location of vulnerable elements affect the resilience of the system. For example, if a transmission station is in a flood prone area then the larger power distribution system is exposed to flooding, which could potentially affect many people. This contributes to an understanding of CI vulnerability. If the network has few redundancies for example, then the recovery time will be longer, meaning that the overall disruption would be greater and making the system less resilient to flooding. Some of the factors that influence the resilience of infrastructure networks are listed in Table 1.

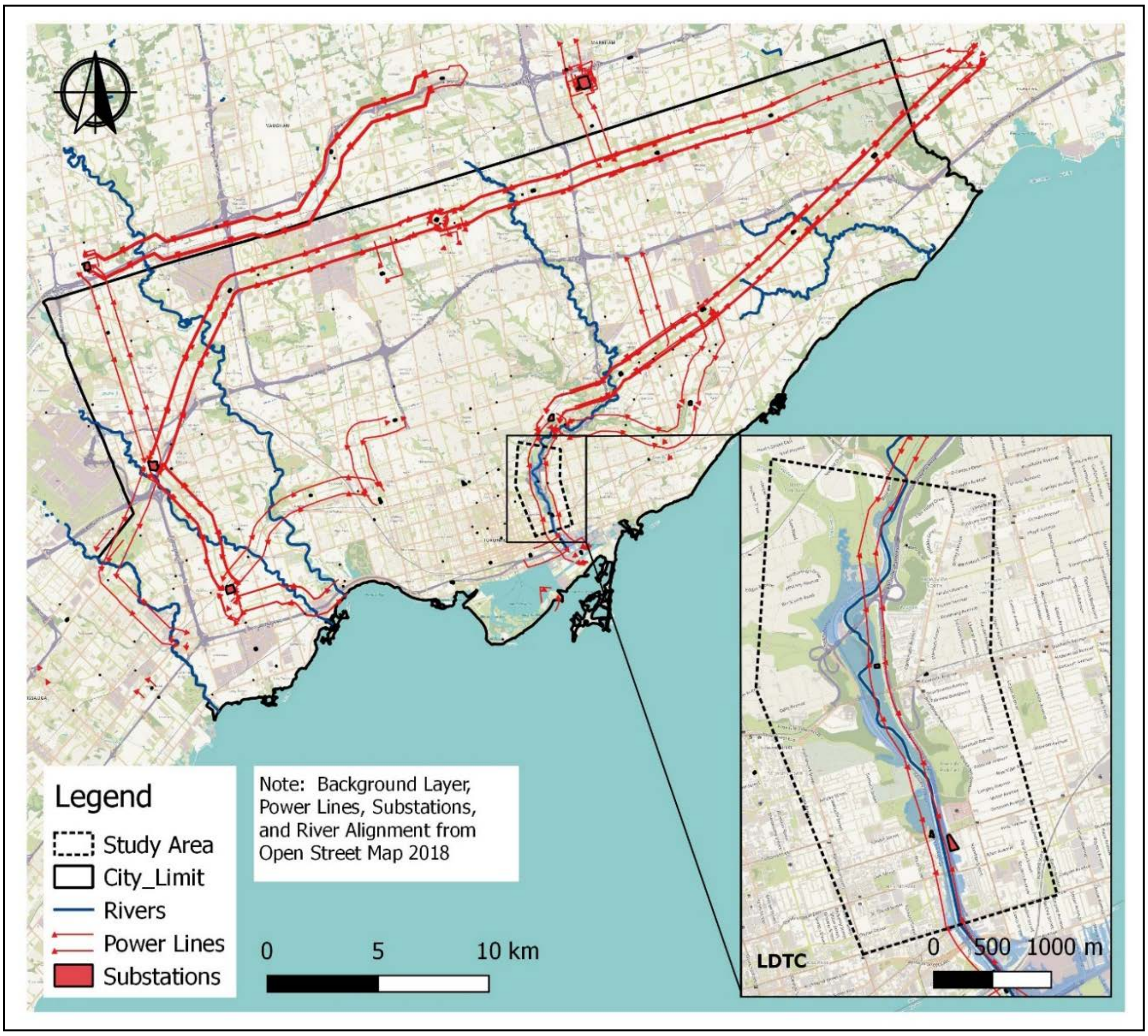

Figure 7. Power transmission in Toronto and LDTC study area from OSM.

Table 1. Resilient network properties.

Resilient Network Properties	Example	Examples for CI
Redundancy	Loop configuration Alternate routes	Loop in power system network Alternate equipment for telecom Alternate roads available Alternate rail tracks can be used Back up equipment available
Flexibility	Alternate modes Reconfiguration possible	Power load can be re-distributed Back-up equipment can be used/installed Vehicles can move to new route
Robustness	Critical components protected	Transmission equipment protected Vulnerable sections of road protected Vulnerable sections of rail protected

The properties of CI networks and how resilient or not resilient they are will affect the level of disruption from a flood hazard. First, the direct effects are assessed for each CI element, meaning that the water depth information was used to determine the functioning of each CI. For the study area, the water depth closure/failure thresholds and cause of closure/failure are listed in Table 2. These thresholds were determined in consultation with stakeholders and are specific to the LDTC study area. For any study area, thresholds should be determined with a combination of stakeholder input, available documentation, and expert knowledge.

Table 2. Example thresholds for functioning/closure of CI elements in LDTC study area (source: stakeholder interviews, workshop, and site visit).

CI Element	Information Source	Water Depth Closure Threshold (m)	Cause of Closure/Failure
Highway	Historic events/local stakeholders	0.15	Cars cannot pass safely
Secondary Road	Historic events/local stakeholders	0.15	Cars cannot pass safely
Commuter Rail	Historic events/local stakeholders	0.1	Trains cannot pass safely
Power Transmission (1) (non-redundant)	Case studies/site observations	0.5	Water damage to equipment
Power Transmission (2) (redundant)	Case studies/site observations	0.5	Water damage to equipment
Power Transmission (3) (redundant)	Case studies/site observations	3	Water damage to equipment

As a result of each of these direct impacts there is disruption to people. This is further amplified by the fact that there are other systems that rely on flooded infrastructure for otherwise normal functioning. This understanding of interdependencies was developed using the CIrcle tool in a workshop conducted with City of Toronto, TRCA staff, and researchers. The interdependencies collected from this exercise are shown in Figure 8.

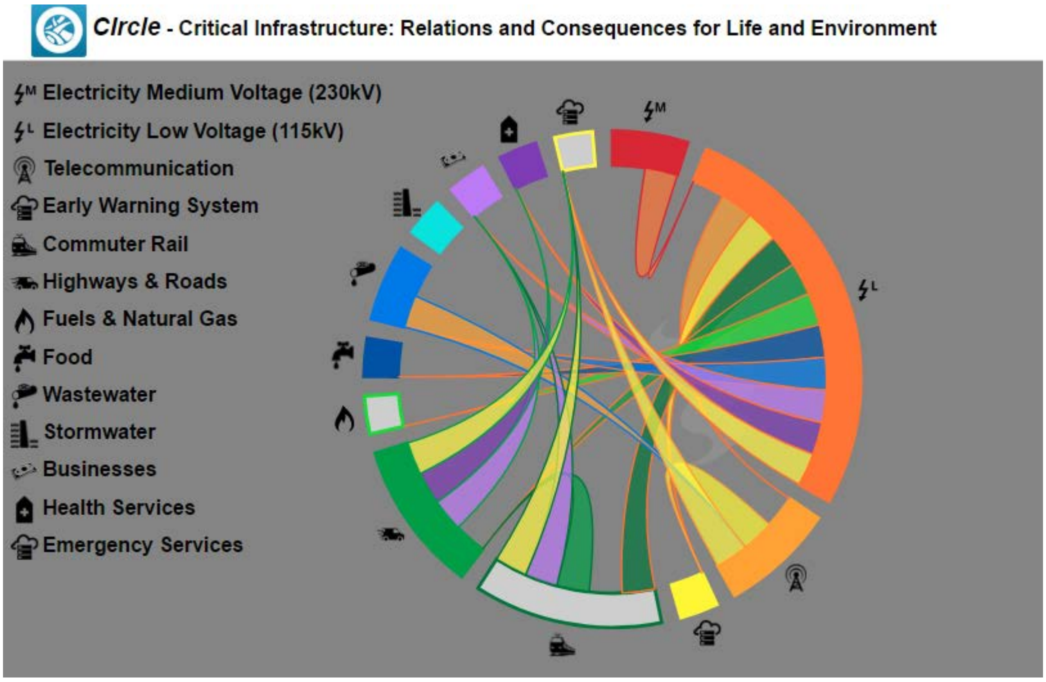

Figure 8. CIrcle tool used to record interdependencies between CI in the study area.

This shows for example that many systems are dependent on the low voltage power network, such as road and rail signaling. This means that if the power is out because of flooding at a transmission station site then there may be additional traffic because signaling lights may be out of order and trains may need to change their operational rules or stop during the power outage. Furthermore, if there is traffic, then emergency services will require additional time to access some areas, which can in particular affect vulnerable populations. An understanding of these interdependencies is needed to quantify disruption due to flooding in the study area and to calculate the $\mathrm{EAD}_{\mathrm{IS}}$ metric. These types of impacts were included in the calculation of disruption due to flooding in the study area and the disruption they cause is calculated in terms of duration and the number of people affected. For example, additional time was added to travel times due to traffic disruption and disruption due to lack of access for emergency services was included. The most significant indirect impacts were chosen for this stud and as a result some dependencies represented in the CIrcle diagram were discussed in the workshop but not assessed.

5.2. Analysis of Current System Results

With the required data and an understanding of the system, the disruption due to flooding in the study area was quantified using disruption in 'person × days' as a unit for the metric (Steps 2.1 to 2.3). These estimates of disruption in terms of person × days are based on several crucial assumptions, choices, and input data. First the delay due to road closures was estimated using traffic study information from the city. It was assumed that the flood event occurred during rush hour (upper limit assumption) but also single occupancy vehicles (lower limit assumption). These assumptions were justified by the facts that this area is heavily used by commuters who are often single occupancy vehicles and one of the critical scenarios is a flood during rush hour. Also, some who are affected by multiple disruptions may suffer more and are therefore be counted multiple times (e.g., persons affected both by transport disruptions and power outages are counted twice).

If the power is non-functioning then the impact is calculated by multiplying the people affected by duration of outage

$$Disruption_{power} = People\ affected\ \times\ Duration\ of\ outage$$

The number of people affected is taken from population data for areas of the city known as wards [29]. If flooding causes a delay, then the disruption is calculated to account for the difference in travel time

$$Disruption_{transport} = People\ affected\ \times\ (Total\ travel\ time - Typical\ travel\ time)$$

For direct impacts in the study area, telecommunications were also affected, and this disruption was calculated in a similar way to disruption to the power network. Otherwise, the impacts from flooding in the study area were indirect. Indirect disruption is calculated using the interdependencies documented with the CIrcle tool. For this study, there were several dependencies identified such as the dependence of telecommunications and traffic signaling on power. It also includes additional traffic delays which may be caused by, for example, the lack of traffic signals due to the lack of power. In addition, the network configuration was taken into account. A power network, for example with a loop configuration, has additional redundancy because supply can be redirected if only one part of the loop is non-functioning. A summary of CI networks, configurations that would cause disruption, and sources of information on disruption used in the study are provided in Table 3.

Within the study area CI networks are increasingly affected as the severity of flooding increases. This means that more severe floods will have higher water depths and will affect an increasingly larger area. As shown in Table 4, as flood severity increases the number of CI systems directly affected and CI systems indirectly affected increases. The indirect effects were identified with input from the CIrcle workshop and add to the total disruption.

Table 3. Factors used to determine disrupted people and disruption duration due to flooding.

Network	Configuration	Source of Information on People Disrupted	Source of Information on Disruption Duration
Power	Branch or loop?	Population data by city ward and power network map	Public incident reports and CIrcle workshop input
Telecommunications	Branch or loop?	Estimated from public reports	Public reports and workshop input
Rail	Alternate routes? Capacity alternate routes?	Weekday train capacity levels	Public reports and interview input
Roads	Alternative routes? Capacity alternate routes?	Traffic study reports	Public reports and CIrcle workshop input

Table 4. Summary of disruption by AEP in LDTC study area with descriptions.

AEP (1/Years)	CI Directly Affected	Additional CI Affected Due to Indirect Effects
0.3% 1% 2%	Rail, secondary road, highway, two power sub-stations	Telecom, traffic signaling, emergency services
4% 10% 20%	Rail, secondary road, highway	
50%	Rail, secondary road	None

As more systems are affected, more people who depend on those systems are affected, and disruption increases. As hazard severity increases, it is not only the number of systems affected that increases but also the duration of disruption. This is because the duration of flooding increases with severity, as does the duration of recovery due to increased damage to systems and thus repair or clean-up time.

The number of disrupted people and disruption duration for each flood hazard level (50% to 0.3% AEP) is calculated and graphed. These values can then be used to calculate the area under the curve to calculate the total EAD_{IS} for the base case. The results are presented in Table 5 showing the disruption for each flood event studied and the final EAD_{IS} of the existing system of 16,388 person × days.

Table 5. Summary of disruption by AEP in LDTC study area.

AEP (1/Years)	Total Direct Impacts Only	Total Disruption w/Indirect Impacts	Annual Disruption
	Impact (Person × Days)	Impact (Person × Days)	Impact (Person × Days/Year)
0.3%	307,409	350,874	1053
1%	305,353	341,741	2424
2%	303,298	332,628	3372
4%	34,792	57,081	3897
10%	4992	20,255	2320
20%	2937	11,187	1572
50%	480	480	1750
	$\mathbf{EAD_{IS}}$		16,388

The disruption with direct impacts is due to power sub stations, roads, and rail lines being flooded. It includes people disrupted due to power outages, lack of transportation, or traffic delays. The disruption with indirect impacts is due to cascading effects like traffic signal non-functioning due to loss of power and additional traffic delays. These effects can also be graphed in a format similar to the disruption and severity graph from [19] as shown in Figure 9. This shows both the disruption with different severities of flood events increasing but also the rate of increase, which relates to the graduality of the response. Graduality determines to what extent increased level of disturbance to a system results in a proportional response. Systems showing low degrees of graduality can show disproportionate response when some threshold is crossed. This sharp increase in disruption can be seen in Figure 9 for events more severe than 10% AEP event after which point some power infrastructure is affected.

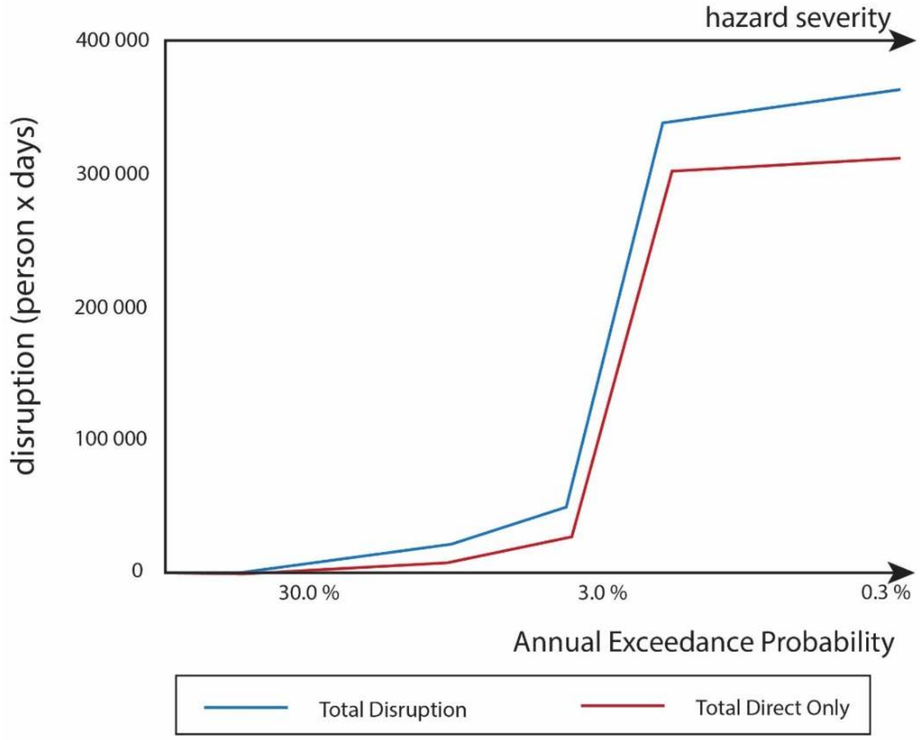

Figure 9. Severity disruption plots for LDTC study area.

5.3. Analysis of Future System Results

Resilience measures and their relative benefit for reducing disruption can be tested once the base case EAD_{IS} has been calculated for comparison. These measures include adding redundancy, flexibility, and robustness (Steps 3.1 to 3.3) to the power transmission system. Power transmission was chosen as the CI for testing resilience measures because it causes some of the highest levels of disruption when not functioning and also the effect from all three types of measures could be estimated. Another study from [30] on CI resilience to flood also focused on the power network due to the high-level of dependency. It should be noted, however, the principles of adding redundancy, flexibility, and robustness could be applied to other CI networks as well.

The redundancy measure to be tested is a change to the power distribution network. The power site in the test area is currently part of a non-redundant section of the network with a branch configuration. An additional power transmission line will be added to make this section of the system more redundant with a reduction in disturbance time from 5 days to 10 h. The total direct and indirect disruption for the 350-year return period case, for example, is reduced from 350,874 person × days to 106,628 person × days, a reduction of 65%. The expected annual disruption decreases from 16,388 person × days to 8953 person × days with a reduction of 44%.

The flexibility measure to be tested is a change of the power distribution in terms of equipment and capacity to respond to flooding. When some equipment is flooded power can often be restored with a reconfiguration of the network. This is reflected in a reduction of the time of the power outage due to flooding for redundant parts of the network. This could also be reduced somewhat for non-redundant parts with additional availability of spare parts and personnel to repair equipment when power cannot be provided through other lines. Assuming a 50% reduction in the time of disturbance for each power substation the effect of adding flexibility on the total direct and indirect disruption for the 350-year return period case, for example, is a reduction of the disruption days from 350,874 person × days to 203,777 person × days. A reduction of 43%**.** The EAD decreases from 16,388 to 11,216 person × days with a reduction of 30%.

The robustness measure tested is the addition of a protection wall around a power site in the study area which, is in a non-redundant part of the power network. This is a measure which the power company has already applied to another site through a wall built between equipment and the Don River. As can be seen from the change in the disruption metric in Table 6, the addition of robustness to part of the power network also reduces disruption. The total direct and indirect disruption for the 350-year return period case for example is reduced from 350,874 person × days to 84,424 person × days a reduction of 76%. The EAD_{IS} decreases from 16,388 to 8309 person × days with a reduction of 48%. Also, the change of impact with increased severity is more gradual.

Table 6. Contributions of events with different severity to disruption calculations measured in person × days for the LDTC study area

AEP (1/Years)	Disruption Base Case (Person × Days)	Disruption w/Added Redundancy (Person × Days)	Disruption w/Added Flexibility (Person × Days)	Disruption w/Added Robustness (Person × Days)
0.3%	350,874	106,628	203,777	84,424
1.0%	341,741	97,496	194,645	75,291
2.0%	332,628	88,382	185,531	66,178
4.0%	57,081	57,081	43,209	57,081
10.0%	20,255	20,255	20,255	20,255
20.0%	11,187	11,187	11,187	11,187
50.0%	480	480	480	480
EAD_{IS}	16,037	8953	11,216	8309
	Improvement	44%	30%	48%

These relative quantifications with the addition of measures are summarized in Table 6 and the graphic representation of disruption due to flooding is in Figure 10. As can be seen from the summary table the greatest improvement according to the EAD_{IS} metric is the addition of robustness or redundancy to the power system. The improvements gained from the addition of robustness and redundancy are similar, with improvements of 48% and 44% respectively for EAD_{IS}. As can be seen from the system response curve in Figure 10, the disruption for the system with a robustness measure added is the lowest for the more extreme event of AEP 0.3% (350-year RP). Important to note, however, is that this would increase rapidly again (i.e., to the same total disruption as for the base case) for very extreme events when the protective wall is overtopped. In other words, this would result in a disproportionate response. This points to a higher level of resilience for the system with added redundancy when both the EAD_{IS} metric and curve are considered.

These impacts are described in Table 7 with the affected CI for each case listed. The CI affected are the same for some cases, although the disruption times increase with the severity of the event. The grouping of effects highlights some of the thresholds for functioning. For example, with added robustness, the second power substation is protected, which is why the affected CI is different following the addition of that measure.

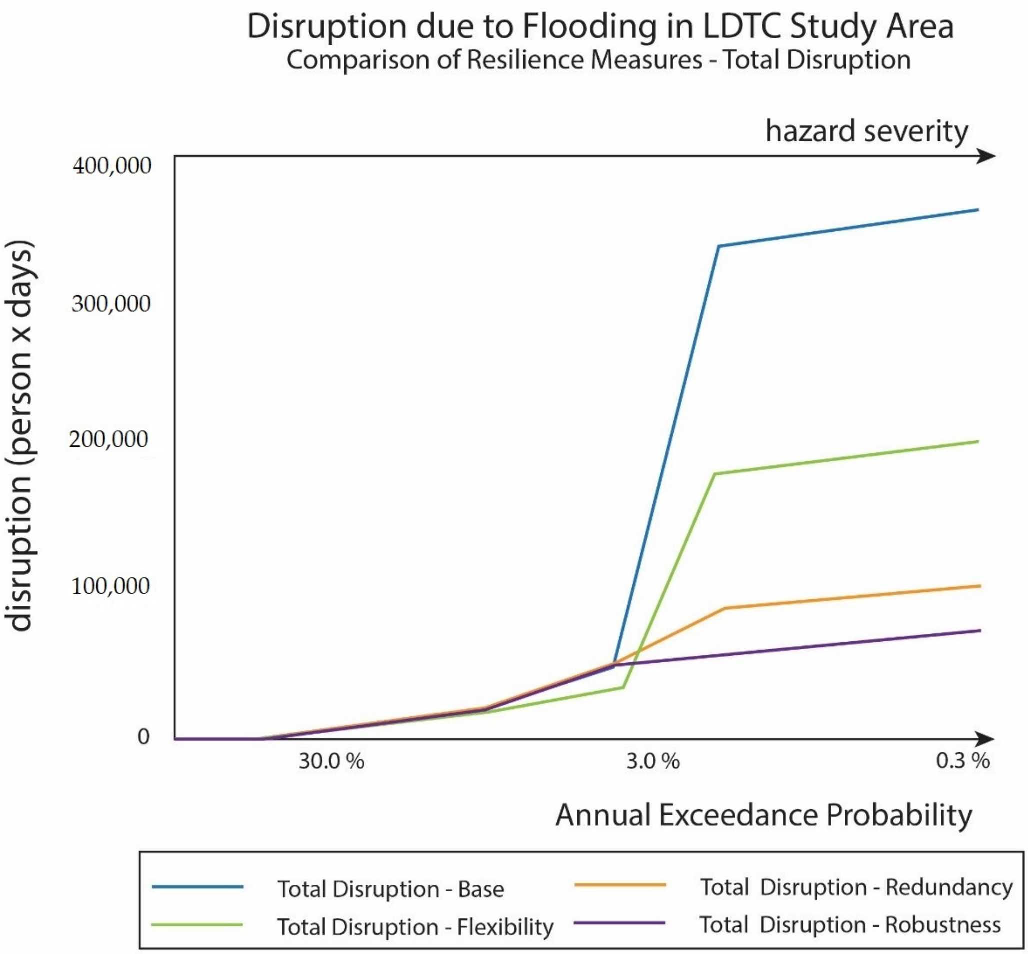

Figure 10. Disruption due to flooding in LDTC with measures.

Table 7. Disrupted CI for base case, redundant case, flexibility case, and robustness case.

AEP (1/Years)	Non-Functioning CI Base Case	Non-Functioning CI Redundancy	Non-Functioning CI Flexibility	Non-Functioning CI Robustness
0.3% 1.0% 2.0%	Rail, secondary road, highway, telecom, traffic signaling, emergency services, two power sub stations			Rail, secondary road, highway, telecom, traffic signaling, emergency services, one power sub station
4.0%	Rail, secondary road, highway, telecom, traffic signaling, emergency services, one power sub station			
10.0% 20.0%	Rail, secondary road, highway, telecom, traffic signaling, emergency services			
50.0%	Rail, secondary road			

6. Discussion

6.1. Reflection on Innovation, Method, and Applications

The resilience of systems to flooding has been quantified before using several methods including the amplitude of state change, graduality of recovery, and duration of recovery [18]. CI resilience specifically has been quantified in terms of reduced losses with resilience enhancing measures [11], but not specifically for flood hazard. This paper applies an innovative quantification of CI resilience to flooding using a system response curve method.

The strength of this method is that it uses open data and input from stakeholders throughout the data gathering process. This means that the method can be applied for many locations in the world that are working on assessing the resilience of their infrastructure to flooding and is it not tied to the availability of specific local or national data sets. In addition, this method takes into account interdependencies through the application of the CIrcle tool for data collection and visualization. This is important because the indirect impacts of flooding are often the greater of the two in terms of spatial extent as well as duration and mostly transferred through the interdependencies of CI. There are many reasons why this has not been previously addressed, including difficulty in accessing information about CI networks. Also, this problem is highly multidisciplinary and requires knowledge pertaining to not only flooding but also power, transportation, and other CI systems. The knowledge of the functioning of these systems spans several disciplines of engineering including electrical, mechanical, civil, as well as local operational knowledge.

The use of person × days as a unit for the disruption and resilience metric is an important innovative contribution of this method. For example, the method applied in this paper differs from that of Bristow and Hay [11] in that disruption to people is used as the metric for resilience instead of cost. The present study also explicitly takes into account direct as well as indirect impacts of flooding. This paper used inputs from the fields of resilience and CI and combined these to assess the resilience of CI and the effect of measures on this resilience. Important elements of resilience such as robustness, flexibility, and redundancy were used to guide the identification of measures and while these properties have been assessed before using resilience metrics, using a graph model and EAD_{IS} for flood hazard represents a novel approach. Resilience defined as the ability of the CI system to cope with floods, was quantified by using as an indicator the disruption days: the number of people affected by the disruption in CI services multiplied by the days of disruption. The results show that the indicators used are suitable to evaluate the system's resilience and the effect of various measures on this resilience.

The method employed here in which structured workshops and interviews were used to gather and link information from a wide range of actors proved to be a useful starting point for assessment. For this study stakeholder engagement was limited to one group workshop and several individual meetings. This helped to establish a basic understanding of interdependencies and thresholds. As stated by [17] the main limitation of this method is that it is data and judgement dependent. However, this method addresses the persistent challenge in the field of lack of data. One area of improvement would be to implement other CI systems modelling approaches such as a network model or agent based model [17]. The purpose to this process was a first test of the method, however, for decision making or other applications additional follow up and validation is recommended. For the case study area used, a flood occurred in 2013 and several reports of impacts from flooded infrastructure have been reported. In addition, some studies on the vulnerability of the power network have been conducted which help to validate the understanding of the network developed for this application [31].

This paper seeks to quantify resilience in terms of disruption for multiple flood events using a response curve approach for CI in the study area. This is an innovative contribution of the present research given that multiple hazard severities are considered. The application to a case study area in Toronto demonstrated that the proposed method, which consists of an EAD_{IS} metric and curve, can enable decision makers to gain insight into the current resilience of CI to flooding and the effect of potential measures. The EAD_{IS} metric is based on disruption to people over time and the probabilities of those events. The available modelling for the Don River included events up to 0.3% AEP and most of the effects are experienced between this upper limited and 10% AEP. It would improve the understanding of the system and the graphical representation of the study area resilience to include several more severe events with more rare likelihoods of occurring, meaning less than 0.3% AEP. This would not greatly influence the EAD_{IS} metric, however, since the AEP multiplier would be so low. On the other hand, a resilience approach needs to focus both on these more frequent, less severe, events as well as the more rare and severe events. Indeed, the consequences of flooding, represented by the system response curve, are important, and not only the probabilities of the hazard. The consequences of many cumulative moderate events can be significant, as are the consequences of a single large and rare event. With a focus on consequences, these rare and extreme events should be included in additional modelling as well as factored into the selection of resilience enhancing measures.

The proposed method can be used as a guide to assess the relative improvements with adaptation measures rather than as a predictor of future disruption. There are also many sources of uncertainty within this method and it is difficult to validate resilience assessments. A few of these sources, such as vehicle occupancy, are addressed with reasonable assumptions such as single vehicle occupancy and rush hour commuting traffic flow. Other sources of uncertainty include the number of people affected by a power outage, for example. These estimates were made with open data and assumptions about Toronto's transmission network. More detailed network information would help improve these estimates. This study includes many complex elements and so there is a need to strategically simplify while addressing uncertainties where possible.

6.2. Reflection on Practical Relevance and Limitations

Many regions of the world are working to become more resilient to disasters [32]. If an area wants to be more resilient to shocks they should explicitly consider and test measures which have been shown to effectively enhance resilience with a solid grounding in the local context. The method proposed in this study would help to analyze those measures. An advantage of this approach is that it lends itself to a quantitative comparison of options to enhance resilience.

The method also has several limitations. First, given that it is based on the input of experts within stakeholder organizations, it depends on their contribution. If areas are very large with many stakeholders, efficient workshops and discussions become more complex since many people must be present. Furthermore, workshops only work efficiently if the right people are present and can contribute their knowledge. The likelihood that experts give opinions and participate in discussions in a meeting with stakeholders from different disciplines and institutions differs per culture and society. In the present study, only one workshop and sever individual meetings were used to collect CI network information. In would be important to conduct follow up meetings in order to improve the quality of the consultation and validate the findings from earlier meetings. Another limitation is that, in the present study, all types of disturbances are valued equally, although they may not all being perceived as equally important: delays may be considered less severe than having no power, stress, or fear of becoming hurt may be considered more important than not being able to reach a destination and so on. In this initial study, there was no differentiation made between types of disturbances for the purpose of quantification. However, if stakeholders would want to differentiate between various types of disturbances, it would be possible to add a weighing factor or qualitative assessment.

The TRCA is now working with local partners to address the impacts of flooding in the LDTC. Some of the preliminary findings from this study could help support this endeavor. In addition, there should be a focus on the consequences of larger, more rare events beyond the severity included in this study and beyond what is often considered for regulatory purposes. It is, therefore, expected that both the $\mathrm{EAD_{IS}}$ metric and curve will have added value in practice as one of the tools that decision makers can use when considering possible measures. The metric, for example, can help to determine the relative resilience of different areas for comparison or (as a follow-up) for prioritization. A metric based on disruption from flood events due to failure of CI provides an idea of the scale of the issue in the study area, however, it is hard to judge whether this is satisfactory. Indeed, the question should be asked, "How much disruption is too much disruption?" Answering this question is a matter of public discourse. The disruption for the 0.3% AEP (350-year RP) event is 350,874 person × days which is equivalent to 16% of the population of the city of Toronto being affected for one day. These kinds of impact-based metrics could support discussions of tolerance for the future. Similarly, tolerances to hazard are often specified in terms of stormwater guidelines for rainfall hazards and regulatory floodplains for fluvial hazards [33]. This is, however, a method which works well in a data rich environment with some open data on CI and hydraulic modelling results. In an area with no flood hazard maps or limited CI network data, it could be possible to adapt the method but it would be difficult to produce meaningful results for decision making.

Although the approach of using a metric and curve can be helpful for comparison and prioritization, it does not address some of the need in cities for community engagement and education around flood resilience. This is one of the drawbacks as it is a tool for decision makers. It could, however, fit into a larger strategy on measure prioritization with community engagement and quantitative prioritization. In general, practitioners tend to prefer protection measures as they are visible and familiar. However, the method in the present study can help to make the case for other approaches to disaster risk reduction.

7. Conclusions

This study yielded two critical key findings, (1) that the resilience of CI to flooding can be quantified, and (2) that this metric can be used to compare the effectiveness of resilience enhancing measures. This is useful for both research as well as practical applications. Developing and applying methods to quantify and enhance resilience to flooding is a topic of interest in current research and is also receiving increased attention from decision makers. Increasingly, there is an interest in adopting a resilience approach and developing a better understanding of how to do so. For infrastructure, this approach is one which focuses on maintaining the continued functioning and/or recovery of assets rather than targeting measures which aim to only reduce the cost of damages. Flood resilience in this study refers to the ability of an urban area to cope with flood hazards and increased resilience refers reducing the duration of disruption to people from flooding. Improving infrastructure resilience to flooding is one aspect that contributes to improving the overall flood resilience of cities. Other factors—such as social, economic, and environmental resilience—are also important factors.

The present study sought to answer the question, "How can CI resilience to flooding be quantified?" While there are many qualitative methods that address this question, there is a gap in the literature for quantitative methods specifically for flooding and CI. Some studies already applied spatial resilience metrics, however, they failed to take into account infrastructure interdependency and network effects [16]. Other studies focused on modelling CI networks from an all hazards approach [11,17] but did not specifically address disruption caused by flooding to people or flood specific characteristics of CI resilience.

To identify potential resilience enhancing measures, the resilience characteristics robustness, redundancy, and flexibility were used. These are discussed as properties of resilience systems in several sources in the literature [3,11,16]. The effect of these measures on the resilience of CI in the case study area was demonstrated using a disruption curve and metric. The curves moved to the right and were lowered due to the measures studied. To effectively apply this method and the insights it provides to improve understanding of CI resilience it should be tested with other CI networks as well and for other geographical locations. In the case study of Toronto, the resilience enhancing measures were tested for the power system only since this was the most the crucial system in that area. However, assessing the effect of redundancy or robustness for roads of rail would be important to demonstrate the full application of the method for this area in particular. Furthermore, the EAD_{IS} metric was tested for this small case study area but could be applied at a city level. If this were to be done, it could potentially be used as a metric to compare the CI resilience of cities. Also, considering other hazards would help make the method more robust and relevant for disaster risk reduction, which is in line with the Sendai Framework.

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