

Chapter 7

Adaptation to Climate Change: Risk Management

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*Friends are like stars,
you don't always see them
but, you know they are
always there. This is for
Toshi, my very close friend.*

Abstract Adaptation to climate change is a challenge that is complex and involves increasing risk. Efforts to manage these risks involve many decision-makers, conflicting values, competing objectives and methodologies, multiple alternative options, uncertain outcomes, and debatable probabilities. Adaptation occurs at multiple levels in a complex decision environment and is generally evaluated as better–worse, not right–wrong, based on multiple criteria. Identifying the best adaptation response is difficult. Risk management techniques help to overcome these problems. Here, risk management is presented as a decision-making framework that assists in the selection of optimal strategies (according to various criteria) using a systems approach that has been well defined and generally accepted in public decision-making. In the context of adapting to climate change, the risk management process offers a framework for identifying, assessing, and prioritizing climate-related risks and developing appropriate adaptation responses. The theoretical discussion is illustrated with an example from Canada. It includes (a) the assessment of climate change-caused flood risk to the municipal infrastructure for the City of London, Ontario, Canada, and (b) analysis of adaptation options for management of the risk in one of the watersheds within the City of London – Dingman Creek.

Keywords Climate change • Flooding adaptation • Risk management

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7.1 Introduction

Several definitions of adaptation are available in the climate change literature. The following are some of the examples as summarized by Simonovic (2012) following Smit et al. (2000):

The term adaptation means any adjustment, whether passive, reactive or anticipatory, that is proposed as a means for ameliorating the anticipated adverse consequences associated with climate change.

Adaptation to climate change includes all adjustments in behaviour or economic structure that reduce the vulnerability of society to changes in the climate system.

Adaptability refers to the degree to which adjustments are possible in practices, processes or structures of systems to projected or actual changes of climate. Adaptation can be spontaneous or planned, and can be carried out in response to or in anticipation of change in conditions.

According to some of the typologies considered, adaptation can be planned or spontaneous; passive, reactive, or anticipatory; etc. According to the IPCC (2013), adaptation “has the potential to reduce adverse impacts of climate change and to enhance beneficial impacts, but will incur costs and will not prevent all damages.”

The tendency of systems (e.g., natural, social, and engineering) to adapt is influenced by certain system characteristics. These include terms such as “sensitivity,” “vulnerability,” “resilience,” “susceptibility,” and “adaptive capacity,” among others. The occurrence and the nature of adaptations are influenced by these. Adaptation is often the result of interactions between climatic and other factors. It varies not only with respect to its climatic stimuli but also with respect to other non-climate conditions. It is important to highlight that the relationship between a changed climate system (e.g., higher temperatures, altered precipitation regime, etc.) and impacts on various systems is not necessarily linear. The role of adaptation (whether reactive or anticipatory, spontaneous or planned, etc.) is crucial for assessments of potential impacts of climate change.

Adaptation to climate change is a challenge that is complex and involves increasing risk. Efforts to manage these risks involve many decision-makers, conflicting values, competing objectives and methodologies, multiple alternative options, and uncertain outcomes (Noble et al. 2005). Risk management offers a decision-making framework that assists in the selection of optimal strategies (according to various criteria) using a systems approach that has been well defined and generally accepted in public decision-making. In the context of adapting to climate change, the risk management process offers a framework for identifying, assessing, and prioritizing climate-related risks and developing appropriate adaptation responses. Vulnerability assessment is a central element of risk management. Vulnerability assessment is increasingly useful for guiding adaptation, since it helps reveal local- and larger-scale system vulnerabilities for which adaptation measures may be necessary to prevent serious adverse consequences. Unlike “adapting,” the concept “managing risks” seems, from many perspectives, much more clear. Risk management is a familiar concept, especially in disaster management, whereas

the notion of “adapting” is still poorly understood by many. Risk management provides a means for addressing uncertainties explicitly. Without a risk management view, decision-makers often receive uncertain responses to their question “what are we adapting to?” Risk management is relatively easy to apply in practice.

Climate change policy, strategy, and implementation already use language and terminology of adaptation with increasing emphasis on the need for adaptation in the face of changing average climate and climate and weather extremes (Schipper and Burton 2009). Increasing demand exists for assessment and promotion of climate change-caused disaster risk management practice that can contribute to climate change adaptation. This requires increasing synergy, merging, and complementarity between these two currently and still largely differentiated practices. The major aim of this chapter is to present a risk management as a practical approach to climate change adaptation as it relates to risk of flooding.

7.2 Methodology for Assessment of Climate Change-Caused Flood Risk to Municipal Infrastructure

The methodology presented in this chapter is based on the work conducted under the City of London (Ontario, Canada) Climate Change Adaptation Strategy Phase 1, to conduct a general risk and consequence analysis of the City’s infrastructure to flooding caused by climate change (Peck et al. 2011; Bowering et al. 2014; Peck et al. 2014).

Risk is defined as the product of hazard and vulnerability. In the case of this assessment, the hazard is the climate change-caused flood event, and the vulnerability is the ability (or lack thereof) of the municipal infrastructure to withstand flooding. Risk includes the consequence of the flooding. Consequence is the economic impact of the flood event on the infrastructure (and study area as a whole). It is a measure of both physical damage to the infrastructure and economic impact caused by a loss of function. Practically, in this assessment the risk value is the consequence multiplied by the probability of the flood event occurring.

7.2.1 Overview of the Risk Assessment Methodology

The methodology includes both qualitative and quantitative information and applies it to the calculation of risk. This enables the inclusion of information from stakeholders, city engineers, and policy makers to provide a comprehensive risk assessment. The integrated risk assessment procedure developed in this work includes: (1) climate modeling, (2) hydrologic modeling, (3) hydraulic modeling, and (4) infrastructure risk assessment. The output from each step is used as

input into the next step. Climate modeling approach based on the use of global climate model (GCM) data together with a weather generator (WG), a statistical downscaling tool, is used to provide precipitation data for a set of climate change scenarios. Precipitation data is transformed into flow data using the hydrologic model of the watershed. Flow information is processed through hydraulic analysis to obtain the extension and depth of flood inundation. Quantitative and qualitative risk calculation is performed in the next step to generate a detailed spatial distribution of flood risk to the municipal infrastructure due to climate change. The methodology in this study is specific to the flood hazard – identified as the most critical climate change impact for the City of London – but the general approach and methodology may also be applied to other hazards.

7.2.2 Climate Modeling

An original inverse impact modeling approach (Simonovic 2010) is used for assessing the vulnerability of river basin hydrologic processes to climate forcing. The approach consists of the following four steps:

- Step 1.* Identification of critical hydrologic exposures that may lead to local failures of water resource systems in a particular river basin. Critical exposures are analyzed together with existing guidelines and management practices. The vulnerable components of the river basin are identified together with the risk exposure. The water resource risk is assessed from three different viewpoints: risk and reliability (how often the system fails), resiliency (how quickly the system returns to a satisfactory state once a failure has occurred), and vulnerability (how significant the likely consequences of a failure may be). This step is accomplished in collaboration with local water authorities.
- Step 2.* In the next step, the identified critical hydrologic exposures (such as floods and droughts) are transformed into corresponding critical meteorological conditions (e.g., extreme precipitation events, sudden warming, prolonged dry spells). A hydrologic model is used to establish the inverse link between hydrologic and meteorological processes. Reservoir operation, floodplain management, and other anthropogenic interventions in the basin are also included in the model. In the City of London study, the US Army Corps of Engineers (USACE) Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) is used to transform inversely extreme hydrologic events into corresponding meteorological conditions. HEC-HMS is a precipitation–runoff model that includes a large set of mix-and-match methods to simulate river basin, channel, and water control structures.
- Step 3.* A weather generator (WG) is used to simulate the critical meteorological conditions under present and future climatic scenarios. The WG produces synthetic weather data that are statistically similar to the observed data. Since the focus is mainly on extreme hydrologic events, the generator reflects not only

the mean conditions but also the statistical properties of extreme meteorological events. The K-NN algorithm is used to perform strategic resampling to derive new daily weather data with altered mean or variability. In the strategic resampling, new weather sequences are generated from the historical record based on prescribed conditioning criteria. For a given climatic variable, regional periodical deviations are calculated for each year and for each period.

Step 4. In the final stage, the parameters of the WG are linked with GCMs, and an ensemble of simulations reflecting different future climatic conditions is generated. The frequency of critical meteorological events causing specific water resource risks is then assessed from the WG outputs.

The proposed methodology includes the assessment of climate change impacts for a range of climate scenarios (Simonovic 2010). A general suggestion is to consider the assessment of impacts for two extreme climate scenarios that will define the lower (CC_LB) and upper bound (CC_UB) of potential climate change. Two climate scenarios are derived by integrating a weather generator that perturbs and shuffles local historical data, with inputs from global climate models (GCMs). The lower-bound climate scenario (CC_LB) is obtained by perturbing and shuffling locally observed data with the assistance of a weather generator (WG) tool. Through the perturbation process, it allows the extreme (minimum and maximum) generated values to be outside of the historic range. In this way the character of the lower-bound scenario reflects the existing conditions (greenhouse gas emissions, land use, population, etc.) and their potential impact on the development of future climate. The upper-bound climate scenario (CC_UB) is derived by perturbing and shuffling historical data and combining them with the input from the global climate models. The choice of the GCM is made on the basis that the upper-bound climate scenario should represent the most critical impact of climate change for the location under consideration. The selection of the range of potential climate change through the use of two scenarios compensates for the existing level of uncertainty present in global modeling of climate change for a watershed. It is noted in the literature that the global models offer various predictions of future climate as a consequence of (1) the selected global model, (2) the selected global model simulation scenario, and (3) the spatial and temporal resolution of the selected global model. It is important to point out that both climate scenarios are equally likely as well as the range of climatic conditions between the two.

7.2.3 Hydrologic Modeling

The meteorological variables generated by the WG model are used as input data for a hydrologic model. The weather generator (WG) model generates daily precipitation and temperature variables at various stations within the river basin. However, the hydrologic model selected for the City of London study (HEC-HMS) requires extreme precipitation data with at least hourly resolution. In addition,

spatial resolution of model input data has to be adjusted too. The temporal disaggregation and the spatial interpolation schemes are implemented to provide the necessary input data. The spatial interpolation, based on the inverse distance method and the location information for the measurement stations, is applied to obtain the meteorological data for each subbasin. The disaggregation procedure based on the method of fragments is implemented to convert daily data into hourly.

For the City of London study, daily data for 200 years is generated and any given year contains a number of events. The main objective of the hydrologic analysis is to perform the flow frequency analysis of extreme annual flood events. Therefore, 5-day annual extreme events that produce the largest annual events (200 events altogether) for the entire basin are selected.

A calibrated hydrologic model, HEC-HMS, is used to convert a climate input into flow data within the City of London. The annual extreme precipitation events for each of 200 years and both climate scenarios (CC_LB and CC_UB) – a total of 400 flood events – are selected and used as input into the HEC-HMS model. For each flood event, the streamflow values are calculated for each subbasin and each control point. Each hydrologic simulation run is done using a 5-day time horizon. The simulation results provide the essential hydrologic information for each subbasin and each control point for two climate scenarios and 200 years. Within the City of London, 171 locations of interest are identified – mostly representing input profiles for the hydraulic analysis (Eum and Simonovic 2010).

The frequency analysis is used to relate the magnitude of extreme events to their frequency of occurrence. The results of the hydrologic analyses are used as input into the hydraulic model that calculates the extension and depth of flood inundation for two regulatory flood return periods, 100 and 250 years. Flood frequency analysis of the hydrologic model output is conducted to provide the input for the hydraulic analysis. The method of L moments and three extreme event probability distributions are used, Gumbel, generalized extreme value (GEV), and Log–Pearson type III (Eum and Simonovic 2010). As expected, the results of flood frequency analysis for CC_UB scenario are showing an increase in both flood frequency and flood magnitude when compared with the CC_LB scenario. The difference between the two scenarios identifies the range of climate change flood impacts that may be expected at each location. Two return period flow values (100 and 250 years) for two climate scenarios (CC_LB and CC_UB) are then provided as input into the hydraulic analysis.

7.2.4 Hydraulic Analysis

The traditional process of floodplain mapping based on the hydraulic calculations of water surface elevations is adopted for the purpose of climate change food risk assessment to the municipal infrastructure for the City of London (Sredojevic and Simonovic 2010). A standard computer software, HEC-RAS, is used for hydraulic modeling and computation of water elevation in the basin. HEC-GeoRAS, an extension of ArcGIS, is used for the preparation of spatial data for input into a HEC-

RAS hydraulic model and the generation of GIS data from the output of HEC-RAS for the use in floodplain mapping.

The climate modeling provides meteorological data (precipitation) for hydrologic analysis. The hydrologic model is used to transform the climate data generated by the WG model into flow data that is required for hydraulic analysis. The methodology used in hydraulic analyses consists of three steps: (1) pre-processing of geometric data for HEC-RAS, using HEC-GeoRAS; (2) hydraulic analysis in HEC-RAS; and (3) post-processing of HEC-RAS results and floodplain mapping, using HEC-GeoRAS.

The first step in the pre-processing stage is the creation of a digital terrain model (DTM) of the river system in a triangulated irregular network (TIN) format. The TIN also serves for the delineation of floodplain boundaries and calculation of inundation depths.

After the completion of pre-processing stage, the hydraulic analysis is performed using the HEC-RAS modeling program for the computation of water surface profiles. The analysis starts by importing geometric data (GIS layers) generated in the previous stage. The hydraulic analysis is performed using flow data for two climate scenarios (CC_LB and CC_UB). For both climate scenarios, steady flow data is used for flow return periods of 100 and 250 years. Two water surface profiles (100 and 250) are generated within the boundaries of the City of London for both climate scenarios: 100 CC_LB, 100 CC_UB, 250 CC_LB, 250 CC_UB.

The post-processing of the water surface profiles is performed using the same maps that were used for the pre-processing of geometry data. Floodplain mapping is performed within the limits of the bounding polygon using the water surface elevations generated by the HEC-RAS.

7.2.5 Risk Calculation

A comprehensive risk assessment has been undertaken to better understand climate change-caused flood impacts on the municipal infrastructure and provide a measurement of risk as the basis for the development of climate change adaptation options. The main goals of the assessment are (1) to provide the level of risk to infrastructure that may be affected by flooding and (2) to prioritize areas of high infrastructure risk for future climate change adaptation planning decisions. The methodology is based on an integrated *risk index* for each infrastructure element considered. The risk index allows for the comparison among various locations that may be flooded. Each risk level for a particular location provides the source of risk (the type of infrastructure that may be affected) and relative contribution of each source to the overall risk.

7.2.5.1 Risk Index

Risk is defined as the product between a hazard and vulnerability in the context of the presented work (Peck et al. 2011). The vulnerability is defined here as “the

shortfall in the ability of public infrastructure to absorb the negative effects, and benefit from the positive effects, of changes in the climate conditions used to design and operate infrastructure.”

An original risk measure termed the risk index, R , is defined. This index is calculated for each infrastructure element and incorporates quantitative and qualitative data to address both objective and subjective types of uncertainty. The mathematical expression of the risk index is:

$$R_{ke} = P \times \sum_{i=1}^3 (D_i \times IM_i) \quad (7.1)$$

where P is the probability of occurrence of the hazard event (dmnl); D_i is the economic loss for each impact category, i (\$); IM_i is the impact multiplier (fraction of damage sustained for each impact); e is the infrastructure element; k is the infrastructure type from 1 to 6, (building, bridge, barrier, critical facility, pollution control plant, and road); and i is the impact category, from 1 to 3, representing function, equipment/contents, and structure. For a 100-year flood event, the probability, P , of occurrence in any given year is 1 in 100, or 1 %. Similarly, the probability of a 250-year event is 1 in 250 or 0.4 %.

The risk index is tabulated and normalized for each infrastructure element across each of the scenarios (100 CC_LB, 100 CC_UB, 250 CC_LB, 250 CC_UB). These values are then combined and displayed spatially using GIS in the form of risk maps. Risk is portrayed geographically by dissemination area (DA) classification, consistent with the Statistics Canada method of representing data. There are 527 within the City of London. Each DA is defined by Statistics Canada “a small, relatively stable geographic unit comprised of one or more adjacent dissemination blocks.”

The risk index is used to aid in the prioritization of areas of infrastructure at risk. Equation (7.2) shows the calculation of risk to a dissemination area, q , for all infrastructure elements of interest (bridges, buildings, barriers, roads, critical facilities, and/or pollution control plants):

$$R_q = \sum_{e=1}^m R_{eq} \quad (7.2)$$

where q is the dissemination area and m is the number of infrastructure elements of interest.

7.2.5.2 Impact Multipliers (IM_i)

The second element of the risk equation represents the impact to the infrastructure as a result of its interaction with the flood hazard. The damages are both direct (such as a loss of structural integrity and components) and indirect (such as a loss

of functionality). Damages resulting from flooding are extremely varied and include losses ranging from inconvenience to structural damage to death. This methodology considers three variables as a measure of these consequences: the loss of function (IM_1), loss of equipment (IM_2), and loss of structure (IM_3). Each of these factors (termed impact multipliers) is measured as a percent loss and calculated using both quantitative and qualitative information. They are incorporated into the risk index as demonstrated by expanding Eq. (7.1) as shown below:

$$R_e = P \times (D_1 \times IM_1 + D_2 \times IM_2 + D_3 \times IM_3) \quad (7.3)$$

The quantitative data includes the ability of the infrastructure to withstand direct damages due to flooding in addition to actual inundation. The qualitative data includes information gathered through interviews relating to the decision-makers' expertise and experience. This includes the condition of the infrastructure and how that may affect its response to flooding. It is important to note that the measure of the impact multiplier may be different across the varying infrastructure types; however, they are consistent across any one particular infrastructure type.

Loss of function (IM_1) The loss of function impact multiplier, IM_1 , measures the degree to which the infrastructure has lost its functionality. This is defined as the degree to which the infrastructure no longer functions at an acceptable level relative to which it was originally designed, as a result of flooding. The value of IM_1 is an integer belonging to $[0,1]$ where 0 denotes no loss of function and 1 denotes the total loss of function.

Partial loss of function may occur in the case of critical infrastructure such as fire station, emergency management services (EMS), hospitals, and schools if some, but not all, of the access routes are blocked by floodwaters. The methodology assigns a fractional value of IM_1 depending on the number of incoming or outgoing major routes and the number of routes that are flooded. The relationship used to calculate IM_1 for fire stations and EMS buildings is:

$$IM_{1k} = \frac{(n - m)}{n} \quad (7.4)$$

where $k = 4$ (critical facility types); n is the total number of major access routes; and m is the number of routes obstructed by floodwaters. In the case of schools and hospitals, the loss of function multiplier is calculated based on the total number of access routes within one intersection from the building.

Loss of equipment (IM_2) The second impact multiplier, IM_2 , estimates the percent of equipment lost as a direct result of inundation. Equipment is defined as contents or nonstructural components of the infrastructure. In the case of residential buildings, this would be the housing contents or anything that would be expected to be taken in a move. Transportation infrastructure (roads, bridges, culverts, and footbridges) and flood protection structures (dikes) do not have an IM_2 component.

Buildings and critical facilities have equipment values estimated using methods based on the building type and value and are estimated as 30% of the total structure's value.

Loss of structure (IM_3) The final impact multiplier, IM_3 , measures the percent structural loss of the infrastructure. This is the degree to which the structural integrity is compromised as a result of flooding. The flood depth was used in the calculation of IM_3 in addition to the infrastructure element's condition, age, capacity, and other knowledge gained during interviews with experts in each area. IM_3 is a measure of both quantitative and qualitative structural loss. The methodology uses an innovative approach in the incorporation of qualitative and subjective data with the quantitative measures. The qualitative portion uses fuzzy set theory to allow for subjectivity and differences of opinion with respect to the condition of the infrastructure, its failure mechanisms, and its response to flooding.

The deterministic element of IM_3 is calculated using stage-damage curves. These curves use the inundation depth as input to estimate the percent damage (LS) to the infrastructure (both structural and contents) as a result of flood inundation.

The qualitative element of IM_3 is used to quantify the subjective uncertainty associated with potential failure of the infrastructure system. Assessment of subjective uncertainty is conducted with the assistance of experts for various types of infrastructure. Qualitative component of IM_3 allows for the measure of partial failure as well as the impact of the structure's current conditions on its response to flooding as perceived by experts in the field. This measurement is termed the fuzzy reliability index (Simonovic 2009). The premise for the combination of the fuzzy reliability index with the quantitative structural loss measure is that the condition of the infrastructure will affect the amount of structural damage sustained by the infrastructure during a flood. The condition of the infrastructure is not quantified by the stage-damage curves, and therefore the input of those who are the most familiar with infrastructure may provide for the more accurate assessment of the risk.

Once combined with a flood event, the condition of the infrastructure will affect its structural loss measure. Therefore, to calculate IM_3 the fuzzy risk index and the deterministic measure must be combined. To represent this inverse relationship in the calculation of the loss of structure impact multiplier (IM_3), the following equation is used:

$$IM_3(CM) = \begin{cases} 1, & CM = 0 \\ \text{Min} \left(1, LS \times \frac{1}{CM} \right), & CM > 0 \end{cases} \quad (7.5)$$

where IM_3 is the loss of structure impact multiplier used in Eq. (7.1), CM is the compatibility measure obtained through the fuzzy compatibility analysis (Peck et al. 2011), and LS is the percent loss of structure from the stage-damage curves ($LS \leq I$).

Therefore in this study when CM is 0, the structure is deemed to be completely unsafe, or experiencing a total loss ($IM_3 = I$). The stage-damage curves are assumed to represent the damage to a structure at a completely acceptable state. As such, for

CM less than 1, the risk to the infrastructure will increase proportionally. A CM value of 1 (completely safe) will yield $IM_3 = LS$.

7.2.5.3 Economic Loss

Economic loss refers to the potential monetary damage incurred by an infrastructure element as a result of a flood event. It is a value that is applied which provides a higher weight to those structures that are more expensive to repair or replace. This is in favor of the City's priority of protecting and investing in the infrastructure which could potentially cause the most interference as a result of a flood event. The economic loss factor is different for each piece of infrastructure. There is an associated economic loss value for each type of impact multiplier (IM_1 , IM_2 , IM_3) as shown in Eq. (7.3). These may be referred to as monetary losses due to loss of infrastructure's function (D_1), monetary losses associated with infrastructure's equipment (D_2), and, finally, the monetary loss incurred by damage to the infrastructure itself (D_3).

7.2.6 Results of the Analysis

The output of the analysis shows the risk to the municipal infrastructure both spatially and by itemized infrastructure. The spatial results are provided as risk maps, with the risk aggregated by dissemination area (DA). The risk values are also presented in tables accompanying the maps, which itemize the risk and consequence for each infrastructure element, by DA.

The results of the analysis (Fig. 7.1) for the City of London show that many areas of the city infrastructure are vulnerable to increased risk due to flooding caused by climate change. Under the upper-bound climate change scenario, the 1:100-year event (Fig. 7.1b) was found to be the most critical with respect to risk, while the 1:250-year event was found to be the most critical (Fig. 7.1d) with respect to damage (consequence).

7.3 Risk Management as Adaptation to Climate Change

The methodology presented in Sect. 7.2 is used to evaluate various alternative adaptation strategies through the comparison of results from the risk assessments performed for the *base scenario* flood risk areas with those from an *alternative strategy* that can be identified by the decision-makers. The *base scenario* flood footprints should be modeled both with no climate change and under the upper-bound climate change conditions. The *alternative strategy* flood footprints should be modeled solely using the upper-bound climate change conditions. The scenarios

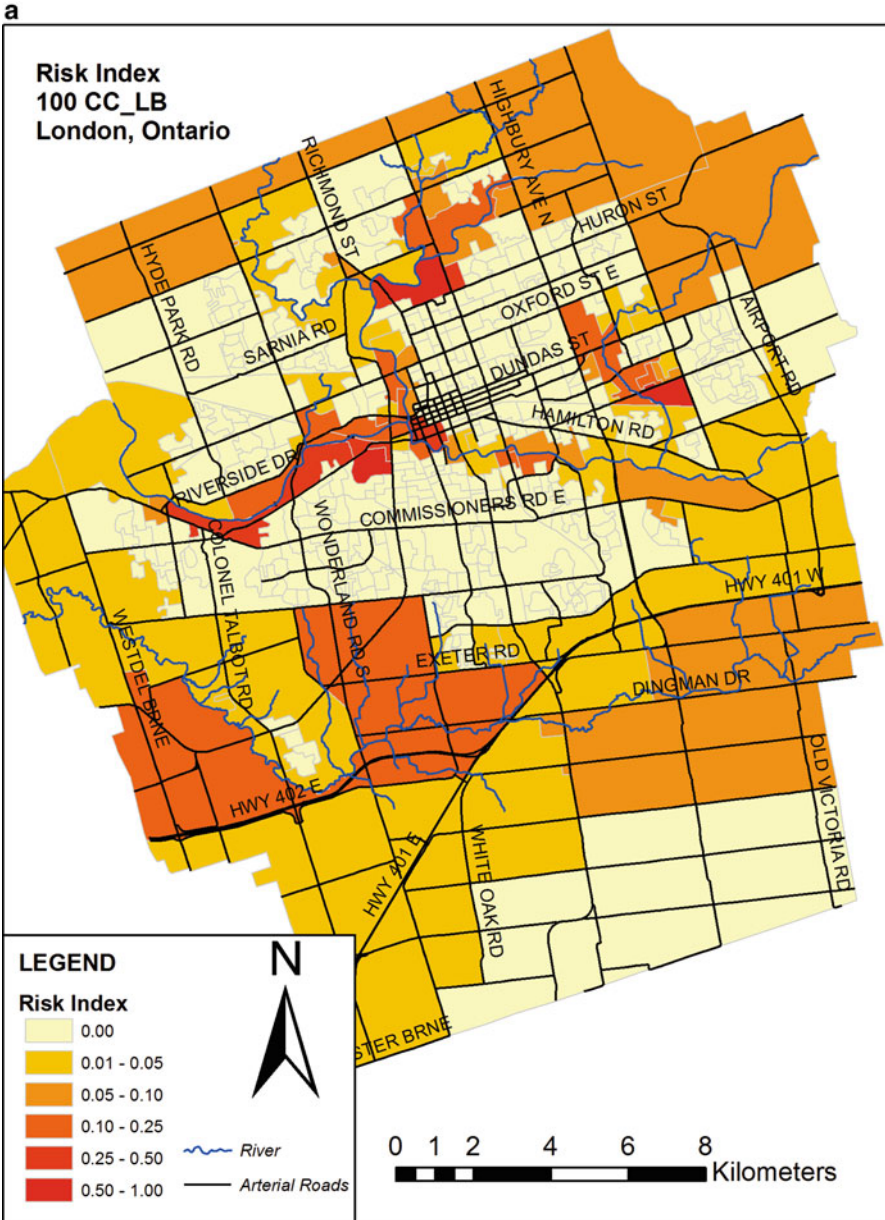


Fig. 7.1 Risk to all infrastructures for (a) 100 CC_LB, (b) 100 CC_UB, (c) 250 CC_LB, and (d) 250 CC_UB

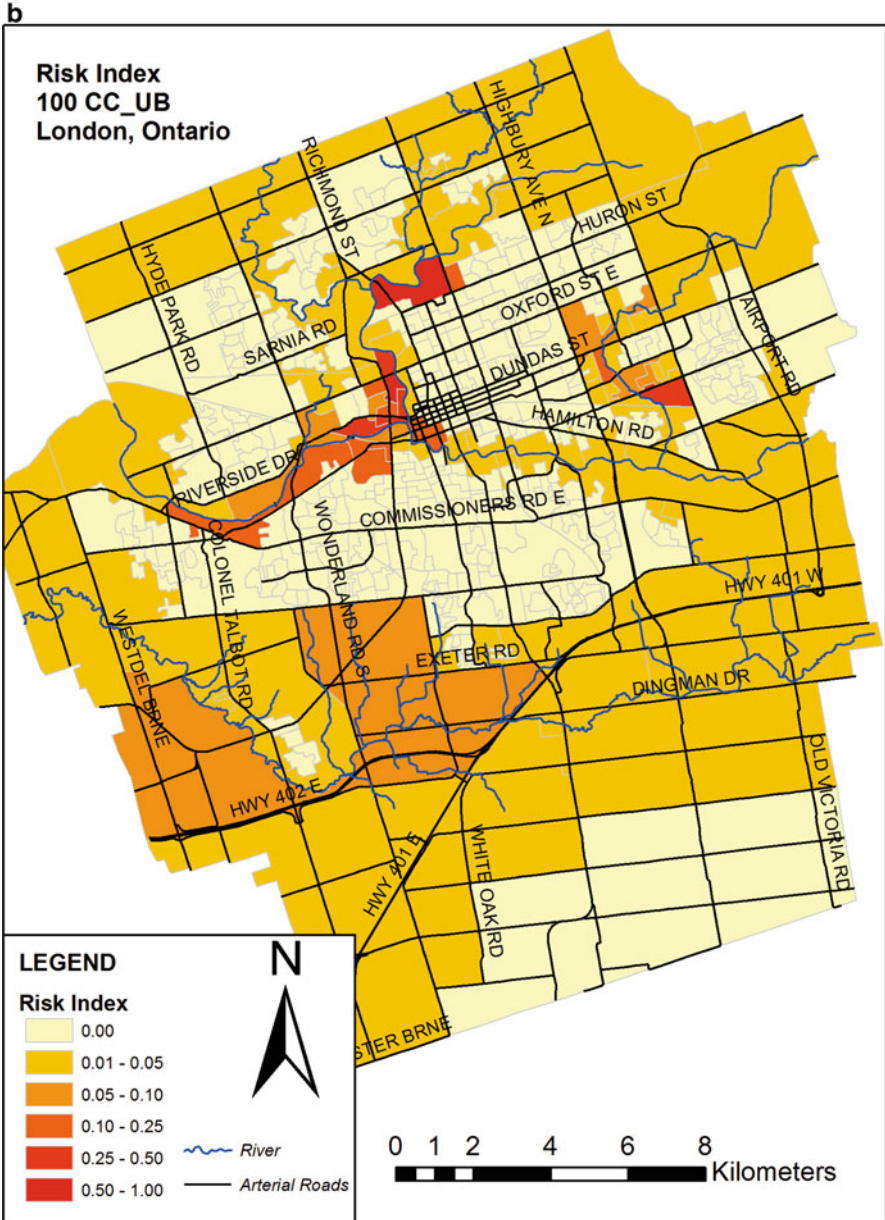


Fig. 7.1 (continued)

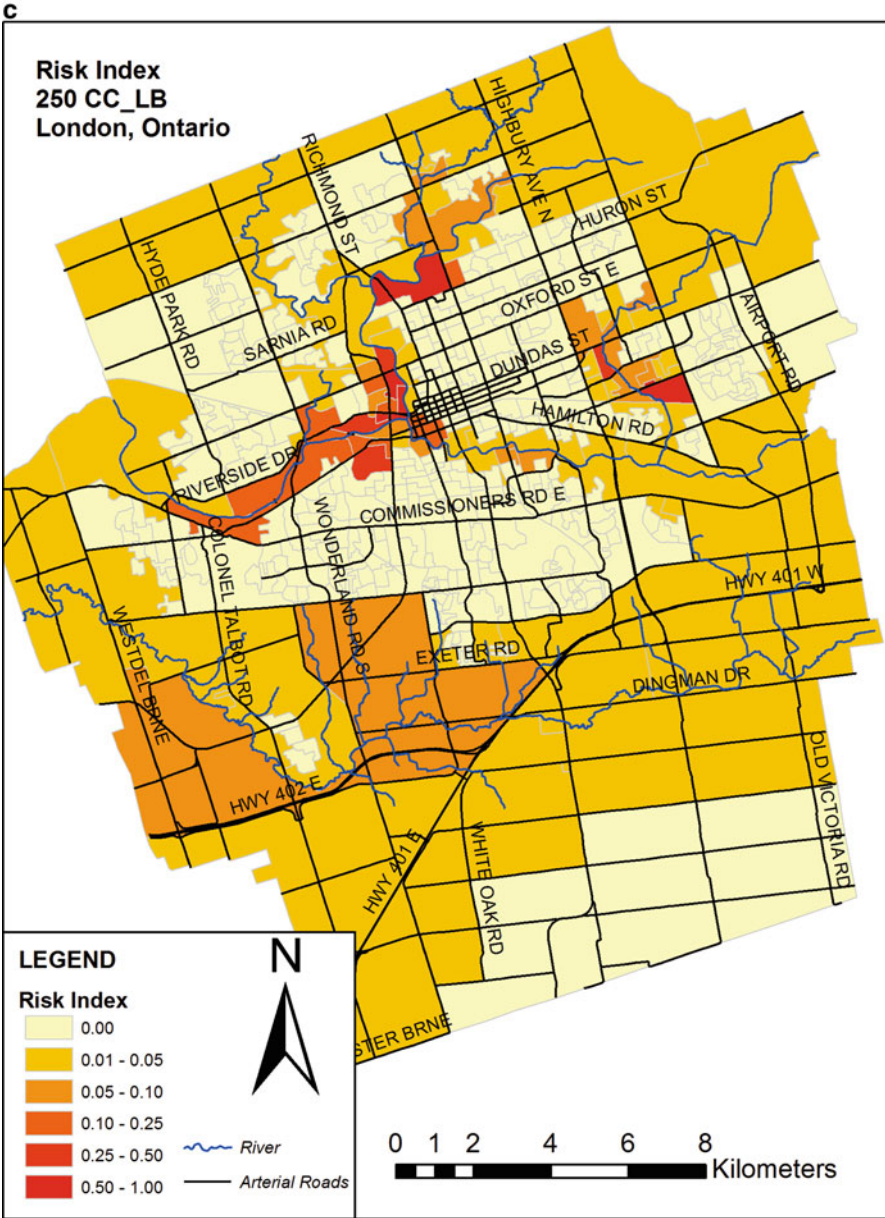


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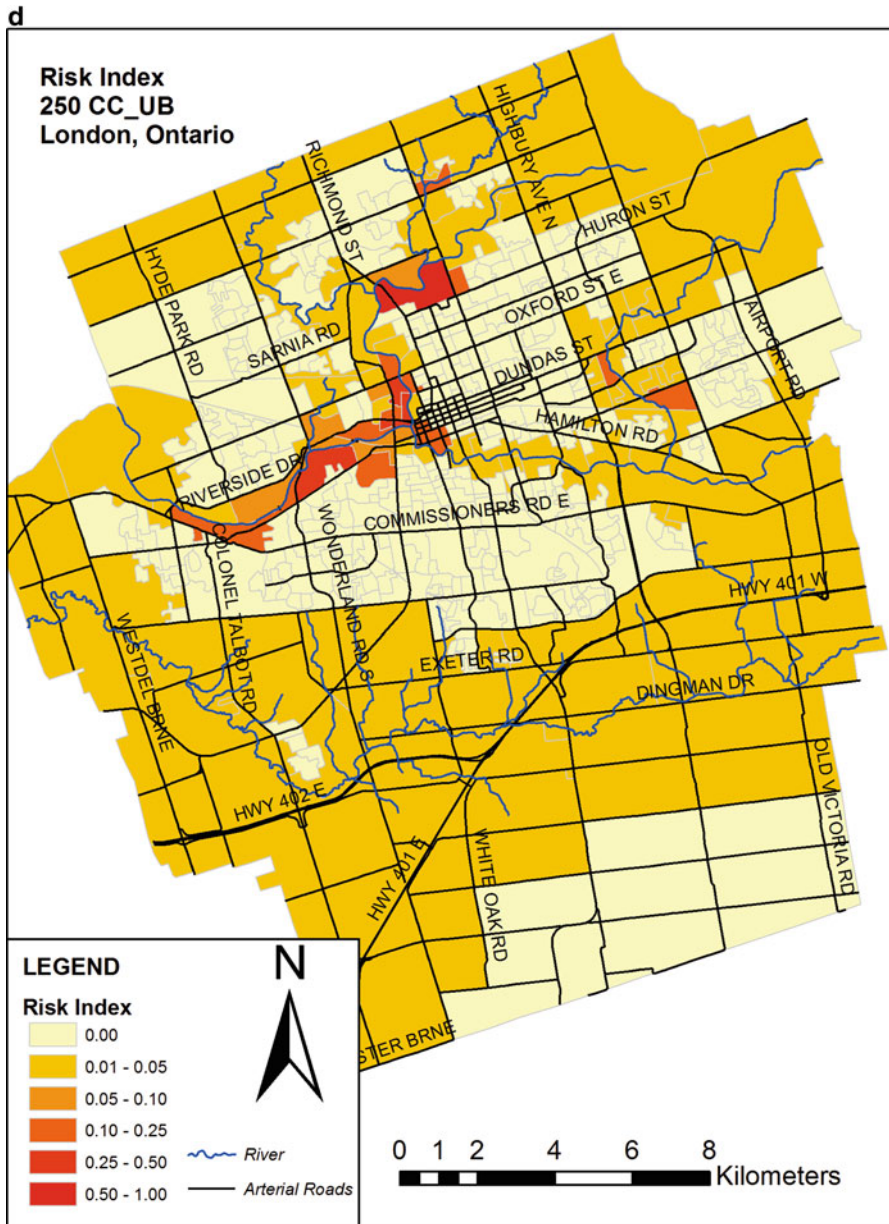


Fig. 7.1 (continued)

with no climate change represent the historical (local) precipitation conditions with perturbation of the data but no additional climate change data. Thus, the no climate change scenarios model the flood events based on locally observed data. The upper-bound climate change scenario is derived from a combination of historical data and the most critical results from various downscaled, global climate models (GCMs) as discussed in Sect. 7.2. Thus, this scenario represents the worst-case event. Either scenario is equally likely to occur; however, by modeling the worst-case event (upper-bound climate change) and the historical conditions (no climate change), a range is given which allows for better planning and risk management.

The presentation of the analysis of adaptation options for management of the risk is done using a case study of one of the watersheds within the City of London – Dingman Creek.

7.3.1 Study Area and Data

The Dingman Subwatershed spans multiple municipalities including the City of London, Middlesex Centre, and Thames Centre. The study area is the portion of the Dingman Subwatershed within the municipal boundaries of London, Ontario. The main watercourse is Dingman Creek which is a tributary of the Thames River. Smaller watercourses include Murray's Drain, Pincombe Drain, and Thornicroft Drain.

The area is mainly rural but it is continuing to develop. Highway 401 runs through the center of the area, and, as such, there is interest in the continued development of the area both commercially and residentially. Figure 7.2 (a) shows the study area and the municipal infrastructure within the study area including 16 bridges, 17 culverts, 17 schools, and 3 emergency service stations (fire, ambulance, and police). The risk analysis considered only the infrastructure impacted by the flood events including the aforementioned infrastructure as well as arterial roads, stormwater management facilities (SWMF) both existing and planned, pumping stations, manholes and outfalls, and noncritical buildings (commercial and residential).

The spatial units, dissemination areas (DAs), within the study area are shown in Fig. 7.2b. Since the DA is determined by population, it is evident that the northern portion of the study area is generally the most densely populated (many small DAs). Since the majority of Dingman Subwatershed is rural, the remaining DAs are quite large in area. This will show a generalized risk and consequence index over a large space, and as such, a detailed look into the risk tables for the results and discussion is required.

The risk analysis is performed on the base conditions with no climate change and with upper-bound climate change for two flood events (100 and 250 years) and two flood events under one alternative strategy with upper-bound climate change for a total of six different scenarios (Table 7.1). The first scenario is the future condition with the 2005 strategy in place (base conditions) for both the 1:100- and 1:250-year event with no climate change. The second scenario is the base conditions for both the

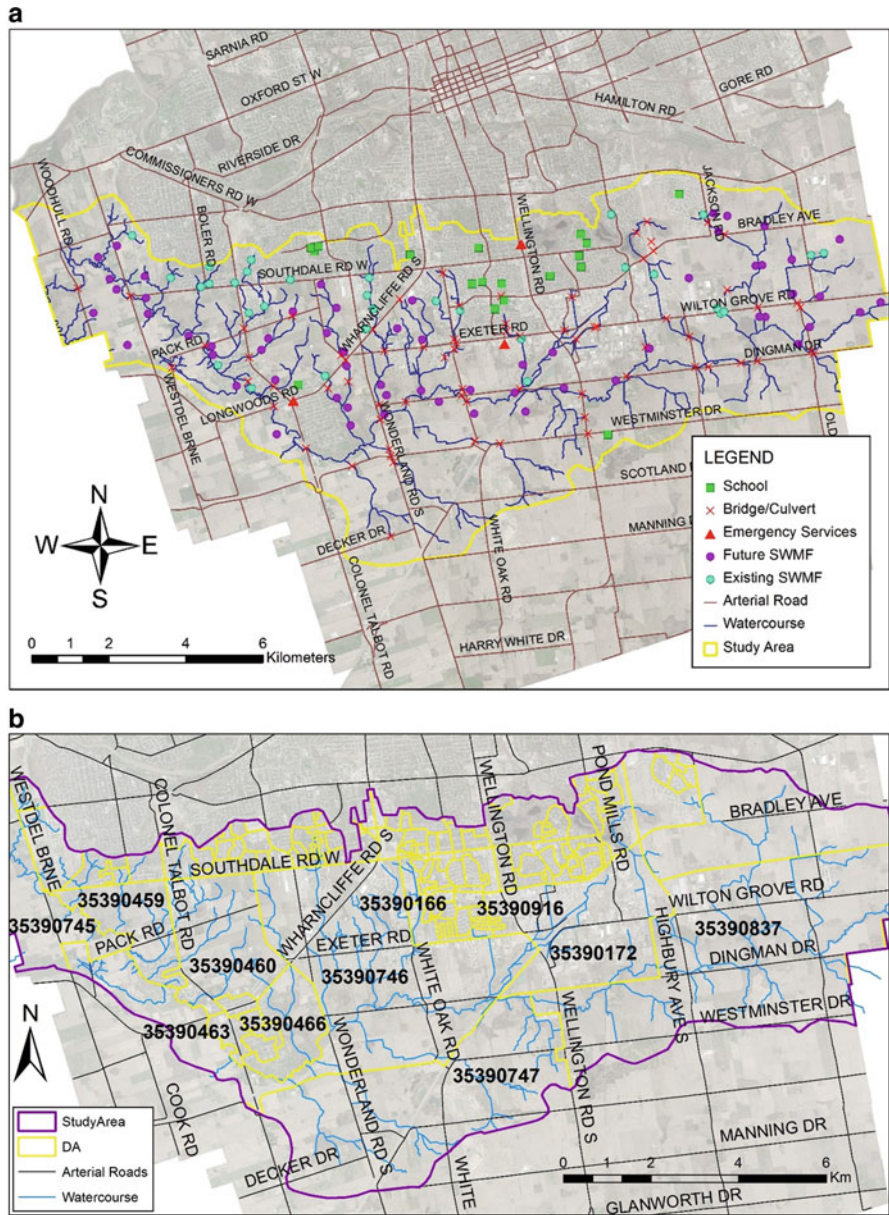


Fig. 7.2 Dingman Subwatershed: (a) study area infrastructure and (b) DAs in the study area

Table 7.1 Flood scenarios used in risk analysis

Scenario	Scenario name	Details
1	R36_100NC (base condition)	Future conditions with 2005 strategy
		1:100-year event, no climate change
		574.13 ha flood risk extent
2	R36_250NC (base condition)	Future conditions with 2005 strategy
		1:250-year event, no climate change
		670.59 ha flood risk extent
3	R36_100UB (base condition)	Future conditions with 2005 strategy
		1:100-year event, upper-bound climate change
		1072.47 ha flood risk extent
4	R36_250UB (base condition)	Future conditions with 2005 strategy
		1:250-year event, upper-bound climate change
		1192.87 ha flood risk extent
5	R39.4_100UB (alternative)	Changes in online storage
		1:100-year event, upper-bound climate change
		728.84 ha flood risk extent
6	R39.4_250UB (alternative)	Changes in online storage
		1:250-year event, upper-bound climate change
		1030.88 ha flood risk extent

1:100- and 1:250-year event with upper-bound climate change. The base condition (herein identified as R36) provides a basis from which the alternative strategy that includes climate change can be compared. The alternative strategy (herein identified as R39.4) is modeled for both the 1:100- and 1:250-year events using the climate change upper-bound scenario.

The alternative strategy was developed in the Dingman Subwatershed study as a component of the water resources, storm/drainage, and stormwater management strategy conducted by the City of London. Specifically, R39.4 addresses climate change by altering the proposed online facilities and increasing online storage to reduce flows in Dingman Creek.

Maps of each scenario showing the flood risk extent and infrastructure in the study area are available upon request. One example map is shown in Fig. 7.3 for the alternative scenario R39.4 for 1:250-year event under upper-bound climate change.

The purpose of the risk analysis is to measure the consequence and risk values of the infrastructure within the Dingman Subwatershed for each of the six scenarios. The alternative strategy can then be evaluated based on its contribution to the reduction of flood risk associated with climate change. Additionally, the impact of climate change will be shown by comparing the base condition both with and without climate change.

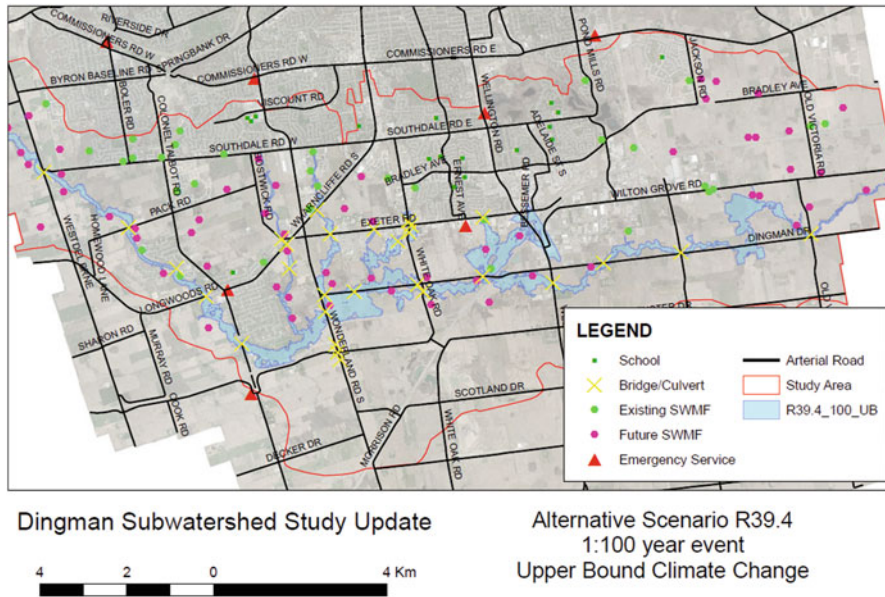


Fig. 7.3 Dingman Subwatershed: alternative scenario R39.4 inundation map

7.3.2 Results and Discussion

The results from the risk analysis for the six scenarios shown in Table 7.1 are explained here. The first section discusses the results from the comparison of the alternative strategy (scenarios 5 and 6) with the base case (scenarios 1, 2, 3, and 4) as well as the comparison of scenarios 1 against 3 and 2 against 4 to assess the impact of climate change. The second section examines the results for each of the scenarios separately. The results are available in the form of risk maps and risk and consequence tables. The tables (available upon request) can be studied along with the maps to provide complete understanding of risk. The consequence tables give damage values in CAD\$ (2012). A risk map is presented for all six scenarios along with the corresponding tables organized by dissemination area. The risk is normalized for each scenario with the darker areas indicating a higher level of risk. The normalization of risk allows for a meaningful way to rank the risk in each area. The equation used for normalization of risk in each scenario is:

$$\overline{R_{DAj}} = \frac{R_{DAj}}{R_{j\max}} \tag{7.6}$$

where $\overline{R_{DAj}}$ = normalized risk index for dissemination area (DA), scenario j; R_{DAj} = risk index for dissemination area (DA), scenario j; and $R_{j\max}$ = maximum risk index in dissemination area (DA), scenario j.

The minimum risk is always 0 and the maximum normalized risk value is 1. Using the normalized risk, it is possible to draw conclusions about the relative risk in each area within a scenario. A word of caution when interpreting the normalized index is that large values tend to suppress the smaller values. Therefore, it is necessary to look at the accompanying risk tables to gain a clear description of the risk.

The overall risk to the Dingman Subwatershed is examined by comparing the base condition (with and without climate change) to the alternative option. Scenarios 1 through 4 are also compared to each other to show the contribution of climate change. This gives six case studies described below. Additionally, all maps and tables that are not presented here are available upon request.

Case Studies Six cases are used to enable comparison between the base condition and the alternative option both with and without climate change for each event: climate change (base condition) for the 1:100-year event and 1:250-year event and R39.4 (alternative option) for the 1:100-year event and 1:250-year event.

The comparison cases are:

Case 1: Contribution of Climate Change 100 – change in risk index and consequence index from scenario 1 to scenario 3

Case 2: Contribution of Climate Change 250 – change in risk index and consequence index from scenario 2 to scenario 4

Case 3: Comparison of R39.4_100UB with Climate Change – change in risk index and consequence index from scenario 3 to scenario 5

Case 4: Comparison of R39.4_250UB with Climate Change – change in risk index and consequence index from scenario 4 to scenario 6

Case 5: Comparison of R39.4_100UB Without Climate Change – change in risk index and consequence index from scenario 1 to scenario 5

Case 6: Comparison of R39.4_250UB Without Climate Change – change in risk index and consequence index from scenario 2 to scenario 6

The equation used to determine the change in risk (R) from the existing scenario to the alternative strategy is:

$$\text{Percent Change} = 100 \left(\frac{R_{\text{alternative}} - R_{\text{existing}}}{R_{\text{existing}}} \right) \quad (7.7)$$

If there is no risk in the corresponding DA for the existing scenario ($R_{\text{existing}} = 0$), the area is given the maximum increase in risk and termed “infinite.” To determine the actual consequence of this increase, the change in consequence is used. Change in consequence is presented as \$CAD (2012) and is simply the difference in consequence between the alternative strategy and the base condition. In the first two cases, it is the difference in consequence between the base condition with climate change and without climate change. Thus, if the change is negative, the consequence has decreased relative to the base conditions. If the change is positive, the consequence has increased relative to the base conditions. The same

Table 7.2 Comparison case 1 and 2 results – contribution of climate change

		Case 1	Case 2
		Scenario 1 vs. scenario 3 (R36 100NC vs. R36 100UB)	Scenario 2 vs. scenario 4 (R36 250NC vs. R36 250UB)
		<i>Contribution of climate change</i>	
Total	Risk increase (%)	61.7	50.3
	Consequence increase (CAD2012\$)	20,863,780	20,153,250
Roads	Risk increase (%)	175.4	161.1
	Consequence increase (CAD2012\$)	43,050	52,210
Bridges and culverts	Risk increase (%)	111.3	120.9
	Consequence increase (CAD2012\$)	4,190,710	5,458,120
Buildings (noncritical)	Risk increase (%)	55.4	41.3
	Consequence increase (CAD2012\$)	16,630,20	14,642,920

is true for change in risk. To determine the total change, the summation of risk and consequence is used in the formulae as opposed to the risk per DA.

The results from the comparison are shown in Tables 7.2 and 7.3. Table 7.2 shows the contribution of climate change by comparing base conditions with and without the upper-bound climate change (cases 1 and 2). Table 7.3 shows R39.4 compared against base conditions with and without climate change (cases 3, 4, 5, and 6). The total change considers the entire infrastructure within the study area that contributes to the risk and consequence index. For each scenario in the Dingman Subwatershed, this infrastructure consists of roads, bridges and culverts, and buildings. The change for each of these categories is listed below the total. From the results below, it is evident that climate change contributes to an increase in risk and consequence. However, this increase can be mitigated by using the proposed strategy.

7.3.3 Discussion of the Results

Cases 1 and 2 show that without any mitigation measures, under the upper-bound scenario, the risk to Dingman infrastructure will increase by an estimated 62 % in the 1:100-year event and by 50 % in the 1:250-year event with climate change. This corresponds to an increase in consequence of \$20.9 M and \$20.2 M, respectively. Spatially, the increase in risk is fairly evenly distributed along the Dingman study area with the areas south of Dingman Creek consistently showing a large increase in risk – see Fig. 7.4a and b. The greatest impact, with respect to risk, is on the roads with the risk increasing by 175 % in the 1:100-year event and 160 % in the

Table 7.3 Comparison case 3, 4, 5, and 6 results – R39.4

		Case 3	Case 4	Case 5	Case 6
		Scenario 3 vs. scenario 5 (R36 100UB vs R39.4 100UB)	Scenario 4 vs. scenario 6 (R36 250UB vs. R39.4 250UB)	Scenario 1 vs. scenario 5 (R36 100NC vs. R39.4 100UB)	Scenario 2 vs. scenario 6 (R36 250NC vs. R39.4 250UB)
		<i>Online storage improvements</i>			
Total	Change in risk (%)	-19.2	-13.8	30.7	29.6
	Change in consequence (CAD2012\$)	-10,496,490	-8,294,210	10,367,290	11,859,050
Roads	Change in risk (%)	-44.9	-18.2	51.6	113.6
	Change in consequence (CAD2012\$)	-30,390	-15,390	12,670	36,810
Bridges and =culverts	Change in risk (%)	-34.6	-22.9	38.1	70.4
	Change in Consequence (CAD2012\$)	-2,755,920	-2,282,340	1,434,790	3,175,780
Buildings (noncritical)	Change in risk (%)	-16.5	-12.0	29.7	24.4
	Change in consequence (CAD2012\$)	-7,710,180	-5,996,470	8,919,830	8,646,450

1:250-year event. However, the greatest impact with respect to consequence is on (noncritical) buildings with an increase of \$16.6 M and \$14.6 M, respectively.

Cases 3 and 4 explore the changes in risk and consequence under upper-bound (UB) climate change when flood risk mitigation measures are in place. In the scenario termed R39.4, online storage is increased, and proposed online facilities are modified in order to reduce the flows in Dingman Creek. The implementation of R39.4 would cause an overall reduction in risk (compared to R36) of nearly 20 and 14 % for the 1:100UB-year event and 1:250UB-year event, respectively. For both scenarios the spatial pattern of reduction is similar with the majority of the risk reduction occurring in the central and eastern portions of the study area as shown in Fig. 7.4c and d. The largest consequence reduction, in both events, is to the buildings at -\$7.7 M (1:100UB) and -\$6 M (1:250UB). For the 1:100UB-year event, the largest decrease in risk is to the roads at 45 % (-\$30,400), while the bridges/culverts see a decrease in risk of 35 % (-\$2.76 M). For the 1:250UB-year event, the largest risk reduction is to the bridges/culverts at 23 % (-\$2.3 M), while the risk to roads is reduced by 18 % (-\$15,400). R39.4 performs the best for the 1:100-year event (in both risk and consequence mitigation), although the results are similar decreases for both events. Thus, the strategy R39.4 successfully mitigates the risk due to climate change when compared with R36.

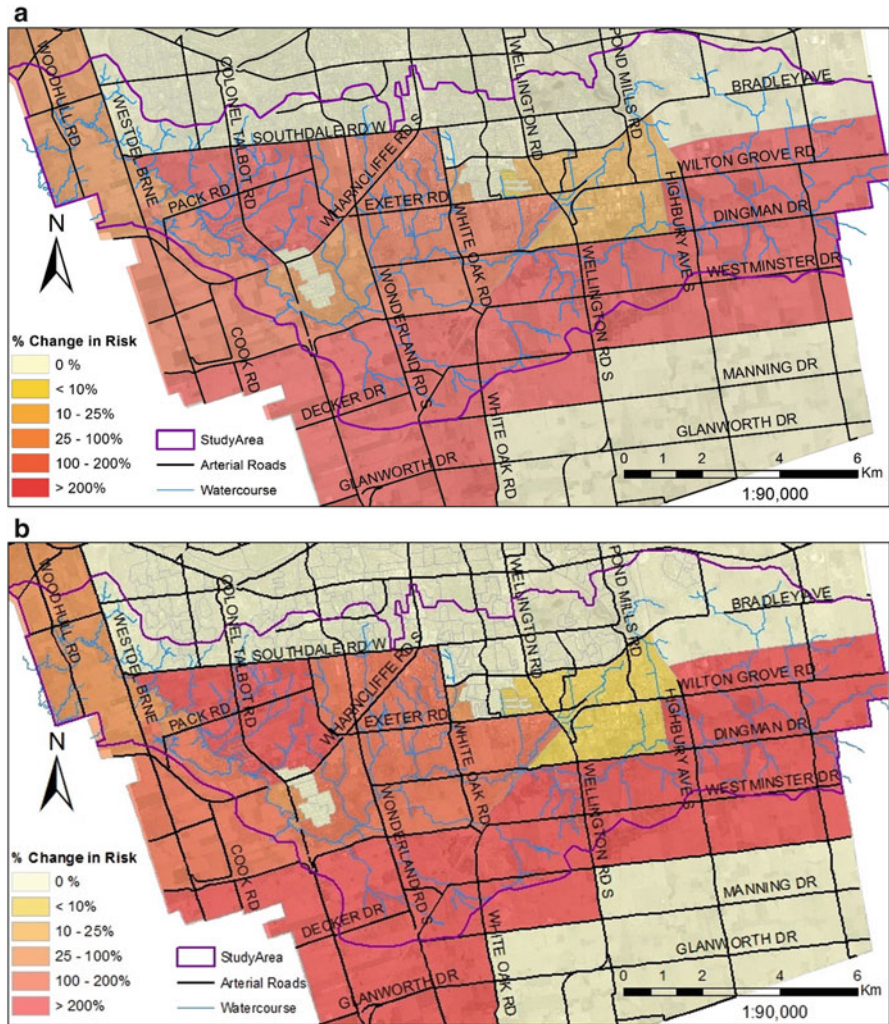


Fig. 7.4 Dingman Subwatershed: spatial distribution of change in risk (a) case 1, (b) case 2, (c) case 3, (d) case 4, (e) case 5, and (f) case 6

Cases 5 and 6 compare the results of the flood risk analysis for R39.4 (under UB climate change) against the results from R36 with no climate change. The overall risk increases by approximately 30 % for both the 1:100-year event and 1:250-year event, translating to a consequence increase of \$10.4 M and \$11.86 M, respectively. The patterns for risk mitigation are not similar for the two scenarios. In the 1:100-year event, Fig. 7.4e, the risk is unchanged for a large portion of the study area. The majority of the risk increase occurs in the eastern portion of the study area. The increase in risk to roads is 52 % (\$12,700), increase in risk to bridges/culverts is

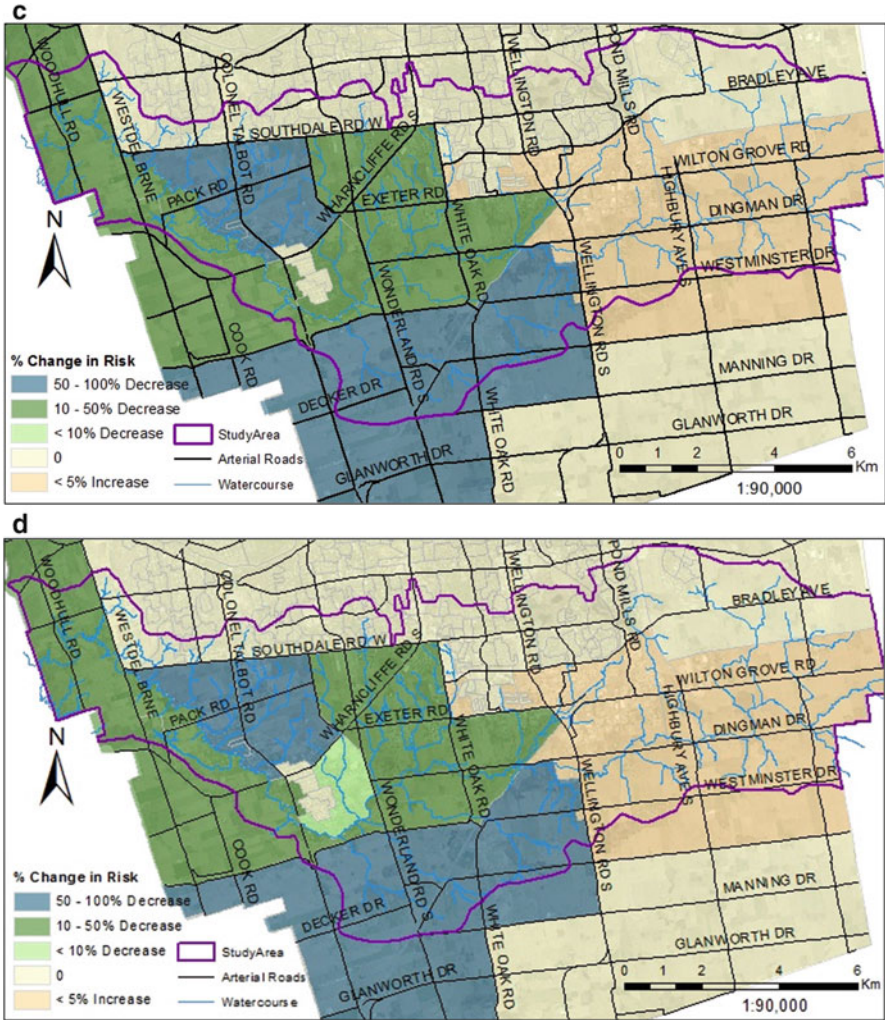


Fig. 7.4 (continued)

38 % (\$1.4 M), and increase in risk to buildings is 30 % (\$8.9 M). For the 1:250-year event, Fig. 7.4f, the distribution of risk increase is similar to that of case 2 as shown in Fig. 7.4b (base conditions compared to climate change only) but with lower overall risk increases. The majority of the increase occurs south of Dingman Creek, but the study area shows slight increases over most DAs. The risk to roads increases by 114 % (\$36,800), to bridges/culverts the risk increases by 70 % (\$3.2 M), and to buildings it increases by 24 % (\$8.6 M).

Even though the mitigation efforts are in place, the R39.4 scenarios consider UB climate change, while the R36 scenarios that are in the comparison cases 5

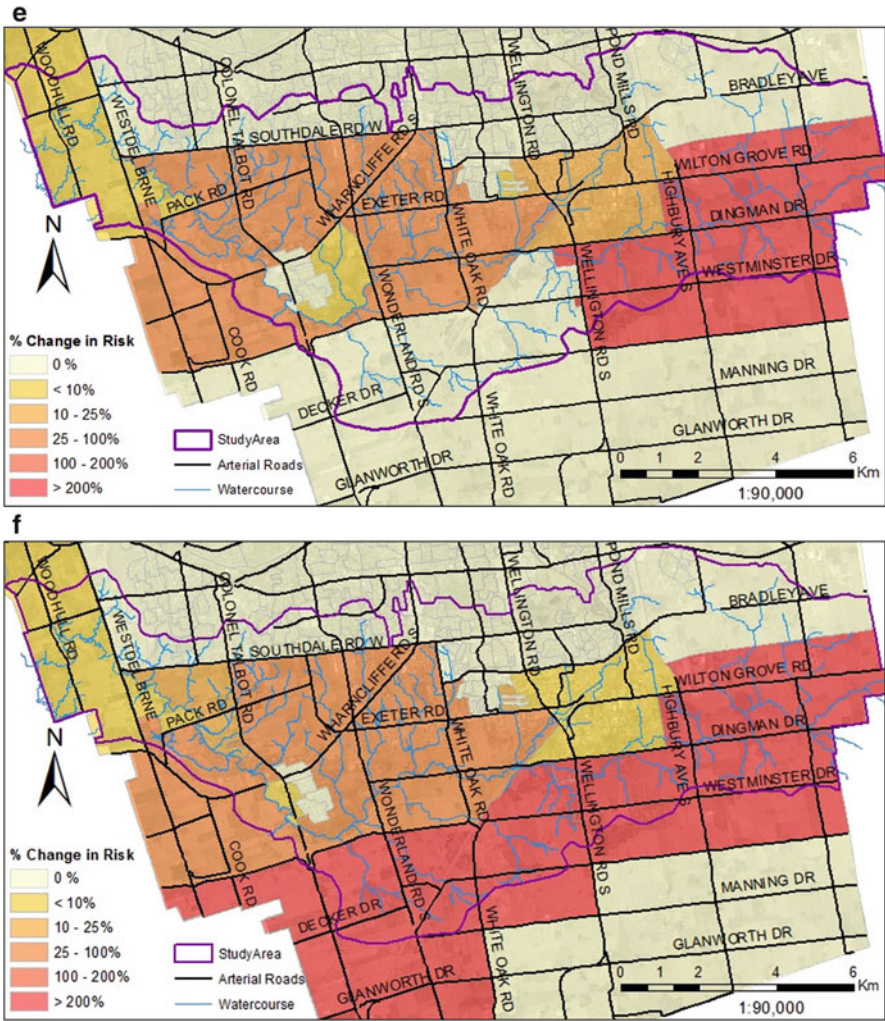


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and 6 assume no climate change. Therefore, the risk will increase because the effects of climate change are larger than the effects of the mitigation. However, it is evident that the increases in risk and consequence are still less than those in the “do-nothing” scenarios (cases 1 and 2), and as such, it is concluded that the R39.4 alternative mitigates the negative impact of climate change on the municipal infrastructure due to flooding. Additionally, in the 1:100-year event, the distribution of risk increases changes (compared to the “do-nothing” approach alternative) such that the risk is completely mitigated in the southwest portion of the study area as shown in Fig. 7.4e.

7.3.3.1 Alternative Adaptation Option R39.4

Table 7.4 summarizes the impact of different rainfall flooding events on the infrastructure within the Dingman Subwatershed study area (the first two events are without climate change; the remaining events are under the upper-bound climate change scenario).

No schools, police stations, or hospitals are affected by any flood event. The only critical facility to be affected is an emergency medical service (EMS) building. The R36 1:100-year event (without climate change) is the best-case scenario or the scenario which demonstrates the smallest flood footprint and levels of inundation that are modeled in this study. Under the remaining scenarios, the inundation only increases in this area. Although the facility experiences some loss of access, the building itself does not become inundated in any scenario. A number of pumping stations are inundated. There are also numerous existing and planned SWMF that fall within the flood risk footprints. The outfalls and manholes within the flood

Table 7.4 Summary of infrastructure impacted by flooding

	R36 100NC	R36 250NC	R36 100UB	R36 250UB	R39.4 100UB	R39.4 250UB
Extent of flood risk area (flood risk footprint)						
Total flood risk extent (ha)	574.13	670.59	1072.47	1192.87	728.84	1030.88
Roads						
Length flooded (m)	3,100	3,756	8,279	10,404	4,269	8,282
Bridges/culverts						
# affected	18	21	28	29	21	27
Buildings						
# inundated	40	50	80	90	51	77
Critical facilities						
Restricted accessibility (EMS)	1	1	1	1	1	1
Pumping stations						
# inundated	3	3	4	4	3	4
Manholes						
# SAN submerged	60	68	88	100	65	90
# STM submerged	15	20	24	29	22	27
Outfalls						
# SAN submerged	1	1	1	1	1	1
# STM submerged	26	27	32	35	32	33

Table 7.5 Contribution of infrastructure to consequence value (\$1,000 CAD2012)

<i>Alternative strategy</i>	R36	R36	R36	R36	R39.4	R39.4
<i>Flood event</i>	1:100NC	1:250NC	1:100UB	1:250UB	1:100UB	1:250UB
Roads	25	32	68	85	37	69
Bridges and culverts	3 767	4 514	7 958	9 972	5 202	7 690
Buildings (noncritical)	30 014	35 488	46 644	50 131	38 934	44 134
Total	33 806	40 034	54 670	60 187	44 173	51 893

risk area (flood risk footprint) are included for completeness. The only manholes of concern are those without flood-proofing.

Table 7.5 shows the contribution of the infrastructure to the total consequence value in each scenario. Note that the contribution of roads to the total consequence value is very low compared to the other categories. From these results it is seen that the highest consequence contributors in all scenarios are the buildings, while the lowest are the roads. Under the 1:100-year event, with upper-bound climate change, the alternative R39.4 has the lowest total consequence of \$44.2 M. Under the 1:250UB-year event, in the same scenario, R39.4 has the lowest total consequence of \$51.9 M. With no mitigation measures in place, the 1:100UB-year event experiences an estimated \$54.7 M in damages, while the 1:250UB-year event has an estimated \$60.2 M in damages (the highest of all scenarios).

Figure 7.5 shows the risk index for each scenario. The 1:100-year events show a higher risk index than the 1:250-year events under the same conditions. This is because the probability of the 1:100-year event occurring is higher than that of the 1:250-year event which counteracts the fact that the 1:250-year event has a higher consequence value. Of the scenarios under the upper-bound climate change, R39.4 has the lowest risk values for both the 1:100-year event and 1:250-year event. The scenario with the highest risk is the 1:100UB-year event under base conditions (R36). The scenario with the lowest risk is the 1:250-year event (no climate change) under base conditions (R36).

The normalized risk index and the consequence value for each scenario are obtained by DA. Figure 7.6a and b shows the relative (normalized) risk index, for base conditions (R36) and alternative option R39.4, for the 1:100-year event with upper-bound climate change. The risk has been normalized for each scenario individually, so the maps depict the relative ranking of spatial risk, independent for each scenario. Under R36 (Fig. 7.6a), the areas at highest risk are north of Dingman Creek. It is mainly due to the large number of bridges and buildings that are inundated. There is also a commercial area at the corner of Wellington and Exeter which contributes to a high-risk value in this DA.

In the R39.4 scenario (Fig. 7.6b), the areas of high risk are the same. The reasons for high risk are also due to the large number of bridges and culverts inundated as well as the commercial area at Exeter and Wellington. However, in this scenario, there is no risk south of Westminster Rd. and west of Wellington Rd S. This is

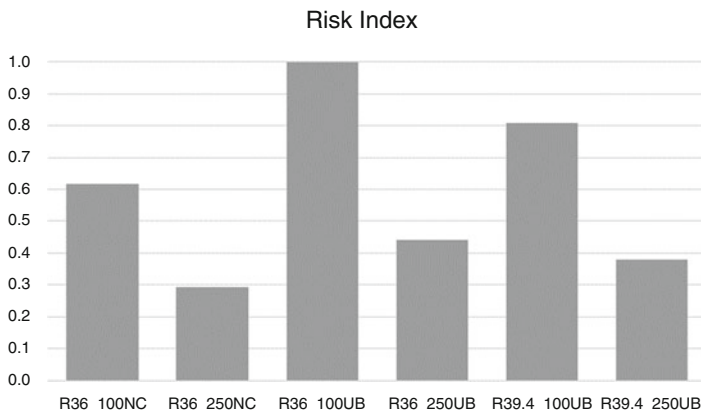


Fig. 7.5 Risk index for all scenarios

due to the fact that the mitigation measures in R39.4 prevent the flood waters from reaching this area.

Figure 7.6c and d shows the distribution of normalized risk under the 1:250-year event with upper-bound climate change. Figure 7.6c shows the distribution with base conditions (R36). The distribution is similar to that of the R36 1:100-year event. The bridges and buildings north of Dingman as well as the commercial center at Exeter and Wellington and Exeter and White Oak Rd. comprise the high-risk areas. Under R39.4 scenario, the risk distribution remains very similar. Thus, the spatial distribution of risk for all scenarios (except the R39.4 1:100-year event) is very similar due to the inundation of certain areas in all scenarios. The high-risk areas are those with a higher population density and more bridges and culverts and commercial centers.

7.4 Conclusions

A methodology is developed to quantify the risk to the municipal infrastructure from climate change-related flooding. The risk is measured using a combination of flow/frequency, stage-damage, and damage/frequency curves. The measure of risk is termed the *risk index* and calculated for each infrastructure element within a municipality. The risk is aggregated and summed by spatial unit and presented in the form of risk tables and maps. The risk index takes into account both quantitative and qualitative information obtained from research and interviews with technical experts.

The Dingman Creek case study results clearly demonstrate that climate change causes an increase in both risk and consequence with respect to the municipal infrastructure under flood conditions. The developed methodology can be effectively used

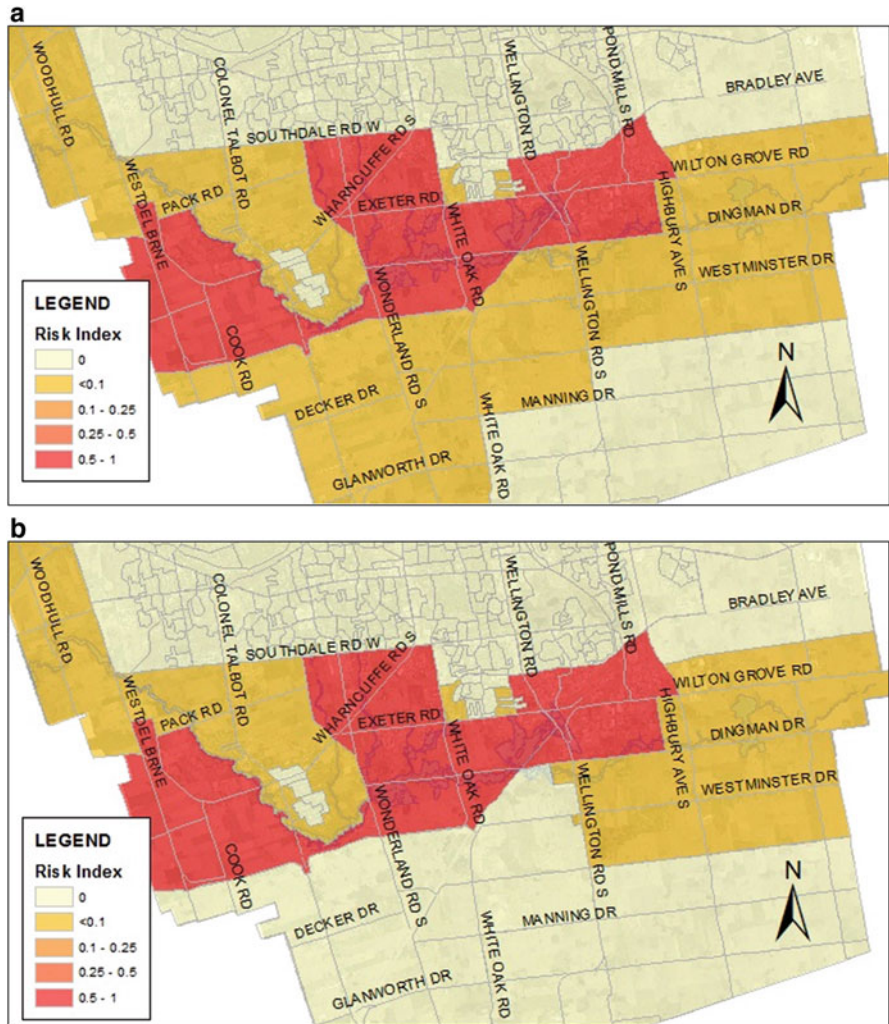


Fig. 7.6 Dingman Subwatershed: normalized risk index – (a) base conditions R36 1:100-year event UB, (b) alternative R39.4 1:100-year event UB, (c) base conditions R36 1:250-year event UB, and (d) alternative R39.4 1:250-year event UB

to assess the risk associated with various options and therefore provides support for climate change adaptation through risk management. The results from the application of the methodology to a municipality will lead to a better policy and informed decision-making.

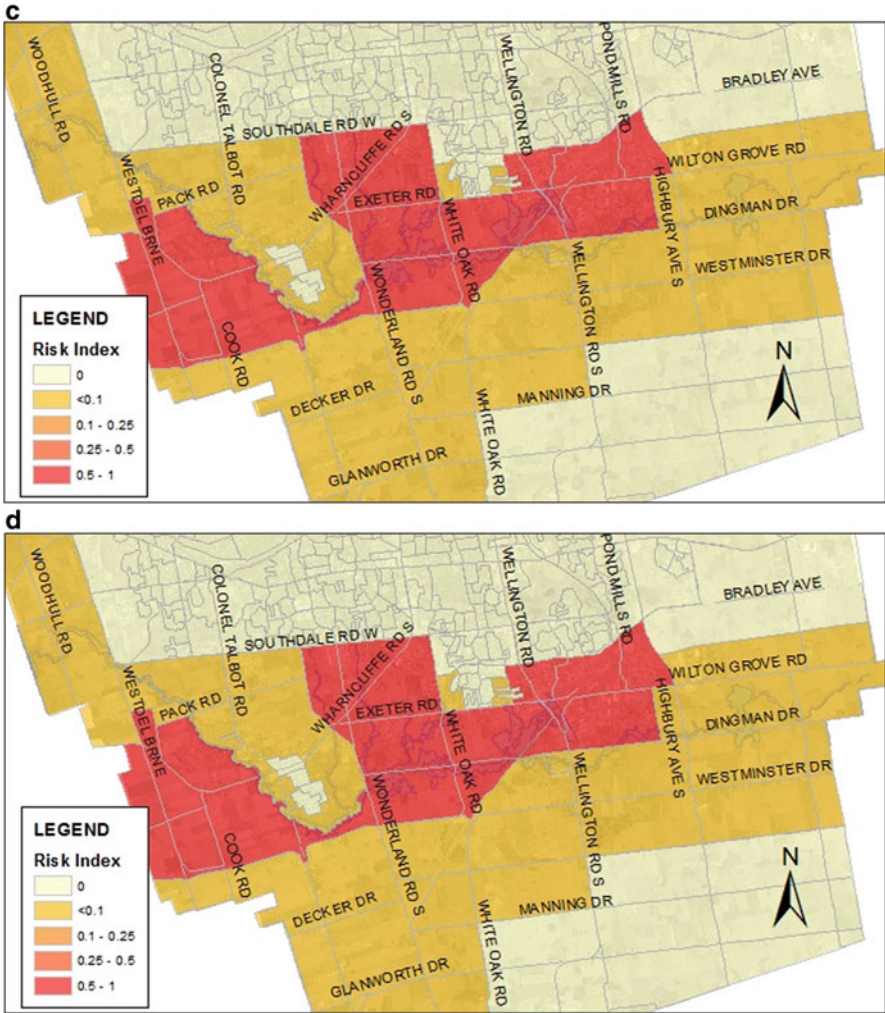


Fig. 7.6 (continued)

Acknowledgments The author would like to acknowledge the assistance provided in the preparation of this Chapter. The numerical analyses are completed by Mrs. Elizabeth Bowering-Taylor. Dingman Creek study results are obtained from the *Slobodan P. Simonovic Consulting Ltd*. The City of London provided the infrastructure data. Thank you.

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