THE UNIVERSITY OF WESTERN ONTARIO
DEPARTMENT OF CIVIL AND
ENVIRONMENTAL ENGINEERING

Water Resources Research Report

Flood Risk Management in Canadian Urban Environments: A Comprehensive Framework for Water Resources Modeling and Decision-Making

By:
Tommy Kokas
Slobodan P. Simonovic
and
Andrew Binns

Report No: 095
Date: June 2016

ISSN: (print) 1913-3200; (online) 1913-3219
ISBN: (print) 978-0-7714-3117-3; (online) 978-0-7714-3118-0

Flood Risk Management in Canadian Urban Environments: A Comprehensive Framework for Water Resources Modeling and Decision-Making

By

Tommy Kokas

Slobodan P. Simonovic

and

Andrew Binns

Department of Civil and Environmental Engineering

Western University, Canada

June, 2016

Executive Summary

Flooding is a growing concern in Canadian and American urban environments due to the effects of rapid urbanization and climate change. Greater risk of flooding will develop as population increases and as urban development persists. Reducing the risk in these environments is critical in order to minimize potential economic damages associated with urban floods. This paper introduces a comprehensive framework for flood risk management. The framework is broken down into five main sections, including: data collection, remote sensing analysis, hydrologic modeling, hydraulic modeling, and flood risk assessment. Common classifications, processes, and methods involved in the approaches and tools involved in this process are outlined along with corresponding benefits and drawbacks. This framework will assist practitioners with water resources modeling and decision making and help to improve flood risk management in urban environments.

Table of Contents

List of Figures/Tables

1. Introduction

Occurrences of flooding in urban environments continues to increase, most notably in large metropolitan areas such as Toronto, Vancouver, and Calgary in Canada, as well as Boston and New York City in the United States. Cities such as these have undergone intensive urban development over the past several decades and are now experiencing more frequent and intense flooding events (Burn and Whitfield 2015; Sandink 2015). Studies have shown that progressive urbanization increases the risk of flooding (Nirupama and Simonovic 2007; Suriya and Mudgal 2012). In urban environments, these flooding events are commonly seen as "flash floods" as a result of high levels of imperviousness, capacity of drainage systems, decreased vegetation, and localised intense rainfall. Flash floods prove to be most devastating due to their rapid response and unpredictability. In 2011, approximately 81% of Canada's total population resided in urban areas (Statistics Canada 2011) and it is projected that this number will rise to approximately 88% by the year 2050 (United Nations 2015). According to the Institute for Catastrophic Loss Reduction (ICLR), Canadian homeowners experience billions of dollars in urban flood damages every year due to riverine and basement flooding (Kovacs and Sandink 2013; Sandink 2015). Comprehensive flood risk management in Canadian urban environments is of paramount importance to develop accurate and reliable methods to protect society from the adverse effects of flooding, now and in the future.

Urbanization has significantly altered the Earth's land surface throughout the world by conversion of natural land cover into impervious surfaces. Activities such as deforestation, land-use change, and construction of infrastructure reduce infiltration rates and disrupt natural environmental processes (Chin et al. 2013). Precipitation that would naturally infiltrate into the soil now becomes stormwater runoff and is diverted rapidly into local rivers and streams. This considerable increase in flow rate results in a greater risk of flooding, but may also result in severe changes to the morphology of rivers and streams (Booth and Bledsoe 2009). Rivers naturally erode and migrate over time but urbanization can greatly accelerate this process and lead to reduced channel stability (Bledsoe and Watson 2001; Karamouz et al. 2010). Such river systems may now be more prone to flooding that could result in serious consequences to the economy, environment, and infrastructure.

Stormwater management (SWM) techniques for mitigating flooding in urban environments include artificial and more natural approaches. Channelization practices, which modifies natural waterways and creates new artificial channels, includes enlarging channels, lining banks with concrete, and stream realignment. This practice generally allows for a higher capacity of flow and reduction in flood stage (Surian 2007). Diversion channels can be seen in areas where channel migration may interfere with urban development. Concrete lining inhibits lateral movement of channels, which is a common and natural process (Charlton 2008). This is particularly important in urban areas where development is very close to rivers and streams. However, channelization has considerable adverse effects on river morphology, hydrology, ecology, and infrastructure due to the loss of natural functions and reduced ability to adapt to rapidly changing conditions (Surian 2007). Natural stormwater management (SWM) approaches consist of various measures that are incorporated into the environment to aid in the reduction of peak flows and stormwater volume while also improving water quality. Low impact development (LID) measures are one promising alternative to traditional stormwater practices due to their small-scale and cost-effective approach. Many tools have been developed to assess and understand the relationship between urbanization, flooding, and fluvial system response. Geographic Information Systems (GIS) in combination with remote sensing is a reliable method for assessing changes in land-use over a period of time.

Numerous mathematical models have been developed for evaluating both the hydrologic and hydraulic components of hydro-environmental processes. These provide a means to evaluate the rainfall-runoff response, which assists with flood risk management and land-use planning. Further, SWM features can be evaluated in these models to simulate their effects on reducing peak flows from extreme hydrological events.

The goal of this paper is to present a comprehensive framework that describes the commonly applied approaches used in the flood risk management process for water resources modeling and decision making in urban environments. This paper will describe the available tools and approaches used in this process, including remote sensing, hydrologic and hydraulic modeling. While the focus of this paper is on Canadian urban environments, this framework also applies to American urban environments due to the similarities they share in terms of climate and development patterns. This framework will provide assistance to practitioners and decision makers involved in flood risk management.

2. Characterization of Canadian Urban Environments

2.1 Urbanization of Canadian Cities

Canadian cities have evolved over time into complex environments due to the rapid advancement in technology, growing populations, and the needs of society. The development of these cities commonly originated near bodies of water as this provided early sources of transportation, water supply, and power. Today, the structure of cities generally consist of an older "inner-city" (or downtown core), the surrounding newer suburbs, and rural land with natural rivers and streams flowing through (Bunting and Filion 2006). Urban sprawl is largely responsible for this structure as a result of residents becoming increasingly attracted to the suburban lifestyle (Stone and Gibbins

2002). This is in large part due to the post World War II boom of the automotive industry and the continuous investments in expressways which has created efficient commute times (Bunting and Filion 2006).

The suburbs are continuously expanding outwards into fertile agricultural land with the construction of newer subdivisions and shopping centres. Separate sewer systems which consist of sanitary sewers and storm sewers are typically required in all new developments. Sanitary sewers convey all wastewater collected from residential, commercial, and industrial buildings to treatment facilities. Storm sewers convey excess rainfall from parking lots, roads, roofs, and sidewalks to rivers and streams. SWM measures are incorporated into the environment, such as wet ponds in subdivisions, permeable pavement in parking lots and driveways, and green roofs on top of larger buildings in order to reduce the volume of water entering storm sewers. Higher design standards are continuously being integrated into all new development as technology advances and more research is conducted.

In comparison, the downtown core is a condensed region with greater population density, lower economy, high-rise buildings, smaller homes, and a lack of pervious land. Aging infrastructure is also very common as development dates back to the 19th and 20th centuries (Bunting and Filion 2006). Combined sewers which convey both stormwater and wastewater to treatment facilities are still in operational use which poses problems for many cities across Canada. This creates a high risk for combined sewer overflows (CSOs) and bypasses to occur as the sewer system is inadequate to handle today's more frequent and intense precipitation events. Waterways running through these areas have been engineered or channelized (with minimal natural stormwater management features) in order to improve hydraulic conveyance and reduce bank erosion. These measures, however, have proven to be unable to handle today's rapidly changing environmental and hydrological conditions.

Development of Canadian cities has had a significant impact on all processes in the hydrological cycle. The decrease in infiltration caused by greater impervious area reduces groundwater recharge and impacts the base flow of rivers. Evapotranspiration and interception also decrease as vegetation is cleared and more impervious areas are introduced (Karamouz et al. 2010). Altogether, these effects have created a large imbalance in the hydrologic cycle, considerably increasing the risk of flooding. Numerous SWM practices exist today that can adapt to the dynamic, ever-changing conditions by controlling the quality and quantity of stormwater.

2.2 Effect of Climate Change on Canadian Urban Infrastructure

Urban growth in Canadian cities has put a tremendous amount of pressure on the environment with mass amounts of automobiles and industrial plants emitting harmful pollutants into the atmosphere, contributing to climate change (Statistics Canada 2008). It has been demonstrated that climate change is creating changes in precipitation patterns throughout the world (Dore 2005; Trenberth 2011; Acharya et al. 2013; Moore et al. 2015; Villafuerte II et al. 2015), including Canada (Ashmore and Church 2001; Statistics Canada 2008). More frequent and intense precipitation events are commonly experienced along with warmer temperatures across Canada. Sea levels are rising due to rapid melting of glaciers, creating much higher risk of storm surge flooding for coastal cities. Extended periods of wet weather, spring snowmelt, and ice-jams are also increasing the risk of flooding (Ouellet et al. 2012; Abraham 2015).

This changing climate is impacting Canada's water and transportation infrastructure through higher maintenance and operation costs. Intense precipitation introduces more contaminants from runoff whereas higher temperatures negatively impact the quality of water, increasing the cost of water treatment. The resulting increase in flows challenge municipal water infrastructure by increasing the risk of combined sewer overflows and placing stress on the operational abilities of pumping stations (Andrey et al. 2014). Other examples of the effect of climate change on infrastructure include: failures in permafrost highways in northern communities due to the permafrost thawing from warmer ground temperatures, increased freeze-thaw cycles in southern Ontario which greatly reduce the service life of roadways (Infrastructure Canada 2006), and failures in culverts such as that due to the intense rainfall event in Toronto on August 19, 2005 which resulted in millions of dollars in damage.

2.3 Mitigation Measures in Canadian Cities

Traditional SWM practices consist of structural and non-structural measures which can be broken down into source, lot-level, conveyance, and end-of-pipe controls. Structural measures are engineered systems that are designed to mitigate the impacts of stormwater whereas non-structural measures are practices and approaches that are implemented to reduce the occurrence of stormwater runoff while also controlling pollution at the source. Non-structural measures can be very efficient and cost-effective as they can reduce the need for expensive structural measures at a future time. Examples of non-structural measures include proper disposal of automobile products and animal waste, minimizing soil compaction, street sweeping, and lawn debris management. These measures depend on public awareness and municipality enforcement. Structural measures, such as lot-level and conveyance controls can include storage and infiltration techniques. Together, these measures help reduce stormwater quantity and improve stormwater quality by removing contaminants before they can be transported downstream. Examples of these measures include: rooftop or parking lot storage, reduced lot grading, infiltration trenches, and pervious pipe systems.

These measures are generally applied in small drainage areas and away from industrial activity to reduce the risk of failure or clogging. End-of-pipe controls enhance stormwater quality prior to discharge into rivers or streams. These controls are particularly useful for preventing flooding and erosion downstream by controlling the quantity of stormwater and releasing it at predetermined rates. Examples include wet ponds, dry ponds, and constructed wetlands. Wet ponds are commonly installed in new residential areas as they not only control the large amount of stormwater produced, but they provide an aesthetic appearance with vegetation and wildlife habitat. They can also be implemented in commercial or industrial areas where nutrient levels may be higher (Municipal Program Development Branch 1999; Strassler et al. 1999; Ontario Ministry of the Environment 2003). Depending on the characteristics of the region, constructed wetlands have the potential to mitigate floods and increase water quality through infiltration and are able to sustain a diverse ecosystem (Malaviya and Singh 2012). Natural wetlands have been decreasing in Canada, however, recent research has demonstrated the ability of wetlands to reduce peak flows (Simonovic and Juliano 2001; Qaiser et al. 2012). The success of structural SWM measures depends on numerous factors such as drainage area, soil type, topography, and water table depth (Stephens et al. 2002; Ontario Ministry of the Environment 2003).

An excellent addition to traditional SWM practices are LID measures which are small-scale structural practices that utilize natural resources and aim to mimic pre-development conditions. They are a relatively new technology that started in Prince George’s County, Maryland and are not as widespread as traditional SWM practices. LID measures are capable of reducing stormwater quantity and increasing quality through processes such as infiltration, evapotranspiration, and detention. They also reduce impervious services and increase aesthetics. LID measures are best applied in combination with traditional structural and non-structural SWM measures to achieve the best results. Common LID approaches incorporated in residential areas include grass swales, roof downspout disconnection, permeable pavement, and bioretention. A simple downspout disconnection allows precipitation to be directed to pervious areas for infiltration instead of being received by storm sewer drains. Permeable pavement is advantageous in these environments as traffic volumes are lower and there is limited space for other SWM measures. Green roofs are also commonly installed on large commercial and industrial buildings as they have greater load bearing capacities (U.S. Environmental Protection Agency 2000; Stephens et al. 2002; Toronto and Region Conservation Authority and Credit Valley Conservation 2011). Considerable research has been conducted to evaluate the capabilities of LID measures (Dietz 2007; Ahiablame et al. 2012; Jensen 2012; Zhang and Guo 2015) and simulate the performance of LID measures with modeling software (Elliot and Trowsdale 2007; Ahiablame et al. 2012).

3. Tools to Assess Flooding in Urban Environments

3.1 Spatial Analysis & Remote Sensing

Numerous tools exist to assist with flood risk management in urban environments. For example, spatial analysis systems such as GIS allow users to capture, store, analyze, and display geospatial data for purposes such as land-use planning, natural disaster management, and emergency planning (Chang 2014). In combination with remote sensing imagery, it can be a very efficient and reliable tool for assessing the spatial distribution of land-use changes over time. This assists with prediction of future growth which can aid in land-use planning (Al-Bakri et al. 2001; Weng 2002; Mengistu and Salami 2007; Reis 2008) and flood risk management (Nirupama and Simonovic 2007; Owrangi et al. 2014). As an example of an application in urban environments, Nirupama and Simonovic (2007) developed a relationship between higher peak flows and impervious areas in the

City of London. Analysis of historical remotely sensed data in combination with hydrological and meteorological data allowed for insight on the impact of urbanization on increased risks of flooding.

Remote sensing imagery such as aerial photographs and satellite imagery provide accurate snapshots of the Earth's land cover through the use of aircrafts and satellites, respectively. Aerial photographs can be analyzed with GIS software which allow for changes in land-use to be observed through manual digitizing (Al-Bakri et al. 2001). This method is sufficient for small projects seeking to obtain a general understanding of the temporal changes in development patterns. On the other hand, satellite images can be converted into pixelated raster images using automated classification techniques and programs such as IDRISI, where it is then much easier to distinguish between the different types of land cover (Nirupama and Simonovic 2007). This method is well-suited for larger projects where more accurate and detailed analysis is required. Depending on data availability, financial limitations, and the purpose of the work, aerial photography may or may not be the better option over satellite imagery. Satellite imagery is a newer technology and thus may be limited in terms of long-term historical analysis. However, satellite imagery contains multispectral attributes which allow for more advanced analyses. Once remote sensing imagery has been analyzed this information can be inputted into mathematical models to investigate hydrological processes.

3.2 Mathematical Modeling

Due to its efficiency and reliability mathematical modeling is a widely used tool for assisting with flood risk management. These models provide users with a convenient and interactive tool for understanding the environment and the response of systems to changing conditions. Mathematical models are approximations of real-world systems. These models exist in many forms, each based on specific principles. Calibration, validation, and verification are critical components of modeling applications. Calibration involves altering model parameters until the output results consistently match an observed set of data. This process relies on an extensive amount of data which is not always available for the area of interest. Model accuracy depends on the level of calibration accomplished. Validation is a comparison of output results with an independent data set, without any alterations to the model parameters. Verification involves checking that the model is functioning correctly and that the logical structure makes sense. It is also crucial to understand model operations and their capabilities since all models have unique advantages, disadvantages, abilities, and purposes. The characteristics of the study area or availability of data are large factors in selecting the appropriate modeling program. The below sections discuss hydrologic and hydraulic mathematical models as they relate to urban flood risk management.

3.2.1 Hydrologic Modeling

Hydrological modeling enables users to study the movement of water in a watershed and quantify the amount of water that is drained in a period of time. This modeling aims to mimic the hydrologic cycle by quantifying runoff, infiltration, snowmelt, groundwater, and evapotranspiration based on a meteorological event (Hingray et al. 2015). Hydrologic models are commonly used for rainfall-runoff simulations and reservoir/channel routing. Applications of hydrologic models include flood protection, flood forecasting, stream restoration, and design of reservoirs and storage ponds (Chin 2013). Hydrological models have been applied to quantify the impacts of land-use change on various hydrological processes in order to assist with the flood risk management process (see, e.g., Im et al. 2009; Wijesekara et al. 2012; Olechnowicz and Weinerowska-Bords 2014).

Hydrologic models can be classified based on criteria such as parameter relationships, treatment of space, and treatment of time. These classifications are summarized in **Table 1** which presents the advantages and disadvantages of each type along with model examples where appropriate.

Table 1. Overview of hydrologic model classifications.

	Definition	Advantages	Disadvantages	Model Examples	Comments
Type of Model					
Stochastic	• Variables follow a probability distribution (random output to same input)	• Incorporates random variations (may represent real-world conditions better)	• May be inadequate for predication when data is sparse	-	
Deterministic	• Variables have unique values (always same output to same input)	• More applicable scenarios	• Does not consider variable uncertainty	-	• More commonly used than stochastic models
Temporal Classification					
Event	• Variables change in discrete times and steps	• Easier to calibrate	• Only simulates a single hydrologic event	-	• Simple structure
Continuous	• Variables change continuously over a period of time	• Better at predicting variability • Simulates more than one hydrologic event as well as periods between events	• Requires more data (may not be available)	-	• Complex structure
Spatial Classification					
Lumped	• Parameters do not vary in space	• Minimum data input requirements • Easier to use/calibrate	• Very simplified (may not represent real-world conditions the best) • Not applicable to event-based processes	• IHACRES • SRM • WATBAL	• Simple structure
Semi-Distributed	• Parameters partially vary in space	• More physically based structure than lumped models • Less input data required than distributed models	-	• HEC-HMS • SWAT • SWMM	
Distributed	• Parameters fully vary in space	• Highest accuracy • Represent real-world conditions the best	• Considerable amount of input data required (often unavailable) • Computationally intensive	• HYDROTEL • MIKESHE • WATFLOOD	• Very complex structure

Hydrological models can be categorized as stochastic or deterministic depending on the relationship between parameters within the model. Stochastic hydrologic models are based on probability distributions so that random outputs for the same input parameters are produced. This type of modeling is useful for predicting uncertainty and is not typically used for channel routing applications. Deterministic hydrologic models are very commonly used for rainfall-runoff response and routing as they produce the same output for the same input parameters (Hingray et al. 2015). For this reason, deterministic hydrologic models will be further discussed in this paper.

Deterministic hydrologic models can be classified based on spatial characteristics as lumped, semi-distributed, or distributed models. Lumped hydrologic models do not allow the parameters to vary spatially within the watershed. In other words, the watershed is evaluated as one unit instead of as a series of individual basins. Some lumped models do not take into account all of the hydrological processes such as infiltration and snowmelt as they are a simplified representation of the real-world. However, a lumped model may be the preferred option if the application of the model is primarily to predict discharge in urban environments with a minimal amount of input data and a short computational time. Distributed hydrologic models are the most common model type used in urban environments as they allow the parameters to fully vary spatially, best representing real-world conditions. This is the most appropriate type of model for detailed and accurate analyses where flood forecasting or design of stormwater management features is the primary concern. However, this type of modeling can be data intensive and time-consuming. Semi-distributed models provide an excellent alternative since they are a combination of both types of models, providing more accuracy than lumped models yet requiring less data than distributed models (Cunderlik 2003).

Deterministic hydrologic models can be also classified based on temporal characteristics as event-based or continuous simulations. Event-based simulations model short-term hydrologic events and are typically used in flood forecasting scenarios or in the design of stormwater control facilities. Continuous simulations model the periods in between hydrologic events and simulate all conditions in the selected time period which can include anything from low flows to flood discharges (Hingray et al. 2015). These are particularly useful in long-term analyses where, for example, the determination of the water balance in a watershed is important.

Common input required for hydrologic modeling consist of precipitation, flow rates (for calibration), temperature, wind speed, evapotranspiration (if known), topographic information (slope, elevation), and thematic data (land-use, soil characteristics) (Cunderlik 2003; Hingray et al. 2015). However, the specific input will vary depending on the selected model, the goal of the modeling, and the complexity of the study area. Precipitation is the most important meteorological variable and is input in the form of a hyetograph produced from rain gages or design storms. Some models offer the capability of spatializing rainfall across a region based on various methods such as Thiessen Polygon, Inverse Distance Weighting, and Kriging. If applicable, snowmelt can be calculated from wind speed, temperature, and solar radiation parameters. The model then distributes the water to various processes based on the water balance equation which is generally expressed as

$$P + G_{in} - (Q + ET + G_{out}) = \Delta S \quad (1)$$

where P represents precipitation, G_{in} represents groundwater inflow, Q is the stream outflow, ET represents evapotranspiration, G_{out} represents groundwater outflow, and ΔS is the change in storage over the period of time (Dingman 2008). Hydrological processes that are physically calculated within these models include infiltration, evapotranspiration (if not known), groundwater flow, interception, and runoff. Infiltration can be calculated from various methods such as Horton's method expressed as

$$f_p = f_\infty + (f_o - f_\infty)e^{-\alpha t} \tag{2}$$

where f_p is the infiltration capacity into the soil [LT^{-1}], f_∞ is the minimum or ultimate value of f_p [LT^{-1}], f_o is the maximum or initial value of f_p [LT^{-1}], α is a decay coefficient [T^{-1}], and t is the time from the beginning of the storm [T] (James et al. 2010).

A runoff hydrograph is typically the desired output for these types of models. Hydrologic flow routing, which is based on the continuous solution of the continuity equation and a second equation that relates storage volume to inflow and outflow can be used to determine this output. The continuity equation can be expressed as

$$\frac{dS}{dt} = I(t) - O(t) \tag{3}$$

where S represents the storage between the upstream and downstream sections [L^3], t is time [T], $I(t)$ is the inflow rate at the upstream section [L^3T^{-1}], and $O(t)$ is the outflow rate at the downstream section [L^3T^{-1}] The simplicity and reasonable accuracy of routing within hydrologic models make them an appealing alternative to hydraulic routing (Chin 2013), which is discussed in the next section.

3.2.2 Hydraulic Modeling

Typically, the runoff hydrograph resulting from hydrologic models provides the input into hydraulic models for investigation of mechanical flow properties within a stream network. This type of modeling is capable of predicting such quantities and processes as stream power, water levels, flow velocities, water quality, and sediment transport. This information is important in determining bank stability and areas prone to higher risks of erosion or flooding. Floodplain mapping, determination of flow around hydraulic structures, and flow routing are common applications of hydraulic models. Flow routing in hydraulic models is generally preferred over hydrologic models where backwater effects are significant and where the channel is either very flat or very steep (Chin 2013). Previous research has applied hydraulic models to predict flood inundation zones, investigate bank stability, determine the benefits of reservoir storage in minimizing the risks for flooding, and assessing the effects of urbanization on channel morphology (see, e.g., Horritt and Bates 2002; Nelson et al. 2006; Yang et al. 2006; Chang et al. 2008; Owusu et al. 2013; Akbari et al. 2014).

Hydraulic models are also classified according to spatial and temporal characteristics. These classifications are summarized in **Table 2** which presents the advantages and disadvantages of each type along with model examples where appropriate.

Table 2. Overview of hydraulic model classifications.

	Definition	Advantages	Disadvantages	Model Examples	Comments
Temporal Classification					
Steady	• Flows are constant with time	• More efficient than unsteady model • Very simplified (easier to understand)	• May not represent real-world conditions	-	
Unsteady	• Flows vary with time	• More realistic conditions	• Computationally intensive • More input data required	-	
Spatial Classification					
1-Dimensional	• Assumes only longitudinal direction	• Very efficient • Simplicity of use • Low data requirements	• Can only model basic parameters • May not be most accurate	• HEC-RAS • MIKE 11	• Simple structure, used for the most basic analyses
2-Dimensional	• Assumes longitudinal and lateral directions or longitudinal and vertical directions	• Can model most required parameters	• May not be suitable for some complex modeling processes	• MIKE 21 • TELEMAC	• Good balance between 1-D and 3-D models which can simulate most required needs

3-Dimensional	• Assumes longitudinal, lateral, and vertical directions	• More complex modeling options	• Computationally intensive • Can be computationally expensive (more costs associated with input data and model calibration)	• SSIIM • MIKE 3	• Very complex structure, used for the most complex analyses

These models can be broken down into one-dimensional, two-dimensional, and three dimensional models depending on the assumed direction of flow. One-dimensional models assume only longitudinal direction. Based on this, only basic parameters can be determined such as average velocities, water surface elevation, and sediment transport loads (Papanicolaou et al. 2008). These types of models are commonly used for engineering design and flood risk analysis for open-channels (Wang and Yang 2014). Two-dimensional models assume either longitudinal and lateral directions or longitudinal and vertical directions. They are capable of calculating spatially varied water depth and bed elevations, streamwise and transverse velocity components, as well as sediment transport rates. Three-dimensional models assume longitudinal, lateral, and vertical directions, adding computational effort while allowing for more complicated analyses (Papanicolaou et al. 2008; Tonina and Jorde 2013). These types of models are capable of determining flows around hydraulic structures, flows through spillways, along with flows and sediment transport rates over complex bed morphologies (Wang and Yang 2014).

Steady and unsteady flow simulations are available in most hydraulic models. Steady simulations represent flow conditions that are constant with time whereas unsteady simulations represent flow conditions that vary with time (Sturm 2010). Steady simulations can be used for water surface profile computations in single channels, dendritic systems, or a network of channels. Unsteady simulations are most commonly used as they best-represent real-world conditions, and are capable simulating flow through a network of open channels (U.S. Army Corps of Engineers 2010).

Common input required for hydraulic modeling include flow rates (calibration), inflow hydrographs, grain size distributions, geometric data such as cross-section data, reach lengths, energy loss coefficients, junction information, boundary conditions, initial conditions, and hydraulic structure data (U.S. Army Corps of Engineers 2010). However, similar to hydrologic models, this varies depending on the selected model, the goal of the modeling, and the complexity of the study area. In hydraulic models, unsteady open-channel routing is achieved through simultaneous numerical solution of the continuity and momentum equations. These equations are commonly known as Saint-Venant equations, depth-averaged shallow water equations, and 3D Navier-Stokes equations in one-dimensional, two-dimensional, and three-dimensional models, respectively. As an example, in one-dimensional hydraulic models, the Saint-Venant equations are expressed as

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0 \tag{4}$$

$$\frac{1}{A}\frac{\partial Q}{\partial t} + \frac{1}{A}\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + g\frac{\partial y}{\partial x} - g\left(S_0 - S_f\right) = 0 \tag{5}$$

where Q is the flow rate [L^3T^{-1}], x is the distance along the streamwise direction [L], A is the cross-sectional area [L^2], t is time [T], g is the universal gravity constant [LT^{-2}], y is the flow depth [L], S_0 is the slope of the channel, and S_f is the slope of the energy grade line. When the full momentum equation is used it can also be referred to as the *dynamic model*. However, in many situations some terms in the momentum equation can be neglected due to their small or negligible values. This simplifies the numerical solution and reduces computational efforts. The *diffusion model* neglects the inertial terms whereas the *kinematic model* neglects the inertial and pressure forces. The diffusion and kinematic models are expressed as

$$g\frac{\partial y}{\partial x} - g\left(S_0 - S_f\right) = 0 \tag{6}$$

and

$$\left(S_0 - S_f\right) = 0\ , \tag{7}$$

respectively. Applicability of these models depends on the conditions present in the channel (Chin 2013). Dynamic models are ideal for complicated analyses and where the bed and water surface slopes are relatively small. Diffusion models should be used in situations where backwater effects occur and when tidal flows are not present. Kinematic models are suitable in situations where there are no backwater effects and when the slope is relatively steep (DHI Water & Environment 2009). Sediment transport rates are commonly simulated in hydraulic models in order to assess channel stability, impact on infrastructure, and in river engineering and scouring concerns. These can be broken down into bed-load, suspended load, or total load equations. The chosen approach depends on the conditions in the channel and the objective of the simulation. For example, if flows are relatively calm, then bed load equations are the appropriate approach due to the sediments being carried mostly near the bottom of the bed. For more intense flows, suspended load equations are more appropriate as the sediments will be lifted into the body of flow and transported downstream. Total load calculates both bed and suspended load together (Sturm 2010). As an example, the Meyer-Peter Müller formula is one of the most widely used equations for calculating bed-load transport and can be expressed in multiple forms. In the one-dimensional hydraulic model HEC-RAS, it is expressed as

$$\left(\frac{k_r}{k'_r}\right)^{3/2} \gamma RS = 0.047(\gamma_s - \gamma)d_m + 0.25\left(\frac{\gamma}{g}\right)^{1/3}\left(\frac{\gamma_s - \gamma}{\gamma_s}\right)^{2/3} {g_s}^{2/3} \tag{8}$$

where k_r is a roughness coefficient [dimensionless], k_r' is a roughness coefficient based on sediment grains [dimensionless], γ is the unit weight of water [$ML^{-2}T^{-2}$], R is the hydraulic radius [L], S is the energy gradient [dimensionless], γ_s is the unit weight of the sediment [$ML^{-2}T^{-2}$], d_m is the median particle diameter [L], g is the acceleration due to gravity [LT^{-2}], and g_s is the unit sediment transport rate [L^2T^{-1}] (U.S. Army Corps of Engineers 2010). These sediment transport relationships can then be used in conjunction with the sediment transport continuity equation to determine long and short-term changes in stream morphology. The sediment transport continuity equation can be expressed as

$$B(1 - p_0)\frac{\partial z_b}{\partial t} + \frac{\partial Q_t}{\partial x} = 0 \tag{9}$$

where B is the stream width [L], p_0 is the porosity of sediment bed, z_b is the bed elevation [L], t is time [T], Q_t is the total volumetric sediment discharge [L^3T^{-1}], and x is the longitudinal distance along the stream [L] (Sturm 2010). This allows for determination of change in bed elevation and bed form migration which provides valuable information for geomorphic assessment in flood risk management. In addition, calculation of wall shear stress in hydraulic models can provide insight into bank erosion, planform migration of streams and overall channel stability (Nelson et al. 2006).

4. Overview of Common Urban Stormwater Models

As examples, two of the most common models used for urban stormwater management are Storm Water Management Model (SWMM) and Hydrologic Simulation Program-FORTRAN (HSPF). Both are widely used and supported by organizations such as the U.S. Environmental Protection Agency, U.S. Geological Survey, and numerous Canadian regulatory bodies, making them appealing choices in comparison to other models with similar capabilities.

SWMM is the most widely used and accepted model for evaluating stormwater runoff quantity and quality in urban areas. SWMM was first developed in 1971 and has been continuously improved and maintained by the U.S. Environmental Protection Agency. Applications of the model are mainly focused on urban areas but the model can also be used for rural and riverine flooding studies. SWMM is a fully dynamic rainfall-runoff model that is capable of simulating hydrologic, hydraulic, and water quality components. Event-based and continuous simulation options are available in this model. Inputs include precipitation, flow rates, temperature, wind speed, substratum geology, as well as land-use and soil characteristics. The structure of the model is based off of multiple subcatchment areas where the runoff is generated from precipitation and snowmelt. Various hydrologic processes such as infiltration, evapotranspiration, and storage are also simulated from a wide availability of methods. This runoff can then be routed through such infrastructure as pipes, channels, and pumps while tracking the flow rate, flow depth, and runoff water quality. It is capable of evaluating detention storage, SWM practices, LID measures, and water treatment facilities (James et al. 2010; Mujumdar and Kumar 2012). The model has been widely used in practice and in research. For example, Denault et al. (2006) applied the SWMM model to the Mission/Wagg Creek Watershed in British Columbia with the goal of reducing future flood risk due to climate change. The study provided tremendous insight on future conditions which demonstrated the importance of implementing measures to reduce the risk of future flooding.

HSPF is a commonly used model for hydrologic and water quality simulations in streams, lakes, and artificial channels. It was developed and is currently maintained by the U.S. Environmental Protection Agency and the U.S. Geological Survey. HSPF is a process-based model that quantifies runoff and takes into account point and nonpoint sources for flow and water quality routing. Applications include storm drainage analyses, flood control planning, water quality planning and management, pollution analyses, and evaluation of SWM practices. Inputs for meteorological, hydrological, and topographical data are almost identical to SWMM other than constituent concentrations that are required for calibration. The model simulates the quantity and quality of runoff from the watershed and uses this information for further instream routing. The structure of the model can be broken down into three modules consisting of a) pervious land segments (PRLND) used for overland flow and infiltration; b) impervious land segments (IMPLND) used for overland flow; and c) free-flowing reaches or mixed reservoirs (RCHRES) used to simulate runoff in channels and reservoirs. Hydrographs and pollutographs from any point in the watershed can be output from this model. This output takes into consideration parameters such as nutrients, toxic chemicals, sediment loads, pesticides, and runoff flow rate (Bicknell et al. 1997).

5. Examples of Application of Tools in Canadian Urban Environments

This section provides a brief overview of two studies that have applied GIS, hydrologic, and hydraulic modeling techniques to Canadian cities to aid in land-use planning and flood risk management. These case studies are selected because they provide an example of the implementation of tools discussed in this paper, use specific models that are commonly used in Canadian urban environments, and apply these tools to different types of geographic regions across Canada (coastal, inland, etc.) that are sensitive to the effects of land-use change and climate change and also share the same need for improved land-use planning and urban flood risk management.

Nirupama and Simonovic (2007) demonstrated the benefits of using GIS and remote sensing imagery to assist with flood risk management and land-use planning. This study develops a relationship between higher peak flows and impervious areas by analyzing remotely sensed data with hydrological and meteorological data. The goal of this study was to use the City of London as a study site to show that the risks of flooding significantly increase due to continuous urbanization. This study collected historical Landsat images, analyzed the land-use change using computational methods, and compared the results to historical river flows and meteorological events over time. It was observed that for the earlier years, a larger precipitation event would create lower peak flows whereas the later years produced high peak flows to smaller precipitation events. Based off this observation, it was concluded that increasing urban development over the years has significantly increased the risk of flooding. This analysis has demonstrated the important relationship between increasing urban development and the risks of flooding.

Denault et al. (2006) applied the hydrologic/hydraulic SWMM model to the Mission/Wagg Creek Watershed in British Columbia in hopes of reducing the risks for future flooding due to climate change. The study predicts future climate change and then evaluates the effects on future design peak flows and drainage infrastructure. This study collected historical rainfall data, created future rainfall intensity scenarios from projected IDF curves, and then developed synthetic design storms. These storms were then input into SWMM for evaluation of future stormwater flows. Results showed that there would not be a dramatic impact on future drainage infrastructure as they would be able to adequately handle runoff from future storms. Some sections of pipe with insufficient capacity would easily be able to be upgraded over the next few decades through a long-term planning program. However, it was found that stream health would experience a significant decrease in quality. The introduction of more impervious areas will increase peak flows, and will decrease summer base flows which will have a direct impact on instream organisms. This analysis has provided tremendous insight on future conditions by allowing for measures to be taken in current time, significantly reducing the risk of future flooding.

6. Framework for Flood Risk Management in Urban Environments

Effective flood risk management involves several steps where the methodology is selected from a large number of available processes and evaluation methods. It is critical to understand the capabilities and applications of the available methods. **Figure 1** illustrates the general flood risk management process for assessing flooding in urban environments and evaluating SWM features to mitigate the effects of land-use and climate change on flood risk.

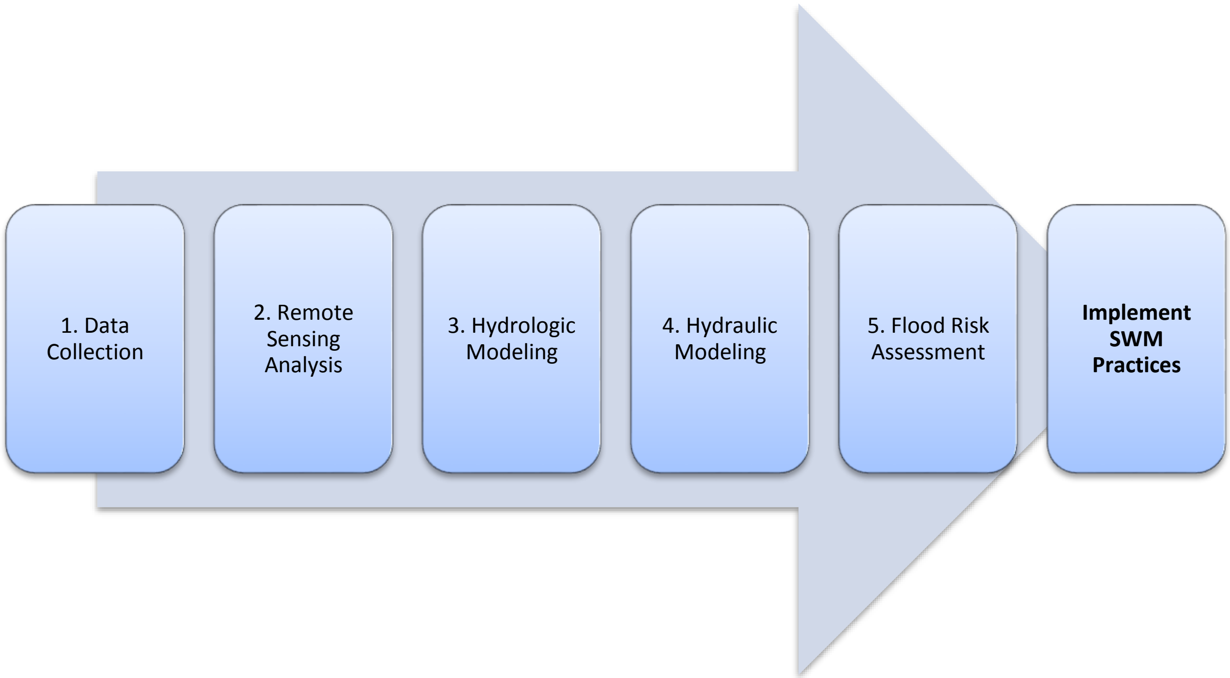

Figure 1. Flood risk management process in urban environments.

The goal of this framework is not to present an overview of all possible processes and methods, but to provide a comprehensive structure that outlines the commonly applied approaches used for urban flooding applications and provide guidance for practitioners involved with flood risk management. It is broken down into five main sections consisting of data collection, remote sensing analysis, hydrologic modeling, hydraulic modeling, and flood risk assessment.

6.1 Data Collection

Data requirements will vary depending on the type of model selected, the specific processes to be simulated, and data availability for a given site. This data, grouped into climatic or geographic data, are summarized in **Table 3**. This table summarizes the various measurement methods for determining the relevant data, together with advantages, disadvantages, and possible sources for the data.

Table 3. Data requirements for flood risk management process.

1. DATA COLLECTION	Measurement Methods	Advantages	Disadvantages	Sources
Climatic Data				
Discharge	Rating Curve	• Simple method (only need to record stage continuously from gauge) • Commonly used method by organizations who provide data publicly (government, conservation authorities)	• Reliability depends heavily on accuracy of rating curve	• Government of Canada (website)
	Velocity-Area Method	• Well known and simple technique	• Human error very possible (direct measurement) • Not recommended for complex channels • Time-consuming	• Manual measurement
	Sharp-Crested V-Notch Weir	• Reliable measurement tool (consistency in channel cross-section and depth)	• Weir equations empirically derived (chance of error) • Recommended more for smaller streams • Time-consuming	• Manual measurement
Precipitation	Rain Gauge	• Well known and simple technique • Records rainfall continuously	• Records rainfall at discrete locations only • Subject to various types of error	• Government of Canada (website)
	Radar/Satellite	• Records aerial distribution of rainfall	• Does not record rainfall continuously • Subject to various types of error	• Government of Canada (website)
Water Elevation	Stream Gauge	• Commonly used method by organizations who provide data publicly (government, conservation authorities)	• Instrumental error is possible	• Government of Canada (website)
	Field Measurements	• Security in results (doing it yourself)	• Human error very possible • Time-consuming	• Manual measurement
Evapotranspiration	Empirical Methods (e.g. Penman Monteith)	• Standard used by many • Significant amount of research on these methods exist	• Empirically derived (limitations) • Amount of required data may be extensive	• Manual calculation
	Energy Balance/Water Balance	• Standard used by many • Based off of physics/principles	• Other types of data are required to solve equation	• Manual calculation
	Lysimeter	• Well known and simple method	• Not be applicable to certain environments (forest vegetation)	• Manual measurement
Temperature, Dew Point, Relative Humidity, Wind Speed	Weather Station	-	-	• Government of Canada (website)
Geographic Data				
Aerial Photographs	Aircraft	• Suitable for projects where smaller aerial coverage is required • More likely to have historical data	• Some images may be of poor quality	• Conservation Authorities • Institutional Libraries
Satellite Imagery	Satellite	• Suitable for projects where larger aerial coverage is required • Will contain spectral properties (able to do more complicated analyses)	• Historical data may be limited	• Websites
Channel Dimensions	Field Measurements	• Security in results (doing it yourself)	• Human error very possible	• Manual measurement

			• Not very efficient	
	Remote Sensing Data	• Consistent scale	• Accessibility (may have a cost) • Accuracy (measurements taken from images)	• Manual calculation
Soil Characteristics	Published Values	• Standard used by many	• Range is usually given (difficulty in choosing appropriate value)	-
	Field Measurements	• Security in results (doing it yourself)	• Human error very possible • Not very efficient	• Manual calculation
Substratum Geology	-	• Provided from a reliable source	-	• Government of Canada (website)

Climatic data involves meteorological and hydrological information such as discharge, precipitation, temperature, water elevation and evapotranspiration. Environment Canada provides data on discharge, temperature, water levels, and other variables that may be required such as dew point, relative humidity, and wind speed. This information is provided free to the public and through a convenient interface. However, data is not available for all regions in Canada and some regions may have limited historical information depending on when the measuring instruments were implemented. In situations where data is insufficient, field measurements can be used as numerous techniques have been developed and tested extensively to accurately manually measure data in the field. Field measurements can be extremely time-consuming and may even be impractical in certain situations, however, they can provide a sufficient source of data if collected accurately.

Geographic data accounts for any spatial information that describes the physical characteristics of the region such as land-use, soil characteristics, substratum geology, slope, and elevation. Land-use information is directly obtained from analyzing raw remote sensing images, which will be further discussed in the next section. For this to occur, either aerial photographs or satellite images are required. Obtaining remote sensing images is a difficult task, especially for longer historical analyses. They are available from various sources but cost may be prohibitive. Institutional libraries provide an excellent source for these photos as they usually carry considerable historical records. Other data such as channel dimensions, soil characteristics, and substratum geology can be obtained from field measurements or published values.

6.2 Remote Sensing Analysis

Remotely sensed data provides aerial views of regions during certain time periods. However, in order to quantify land-use changes over time, these images need to be analyzed and classified into specific land-use categories. Many classification techniques have been developed and the more common methods are summarized in **Table 4**.

Table 4. Remote sensing classification techniques.

2. REMOTE SENSING ANALYSIS	**Description**	**Advantages**	**Disadvantages**	**Program Examples**
Image Classification Technique				
Supervised	• User selects sample pixels ("training sites") to represent specific classes	• More control in defining classes • More common	• Does not take into account environmental conditions (illumination, shadowing, etc.) • Considerable interaction with analyst	-
Unsupervised	• Software creates clusters of grouped pixels with similar statistical properties	• Human error is minimized • Minimal interaction with analyst • No detailed knowledge of study area is required • Classes could be created that would otherwise be undetectable by the user	• Minimal control over grouping of pixels • Large reliance on statistical and spectral properties • Some classes created may be of no interest to the user	-
Manual Digitizing	• User creates individual polygons (digitizing) to represent specific classes	• User is in complete control • Computational error is minimized	• Human error very possible • Can be time-consuming • Low accuracy for satellite images	• ArcGIS
Supervised Classification Technique				
Parallelepiped	• Pixels are assigned to a specific class based on standard deviation threshold from the mean of each class	• Simple and quick procedure	• Can't classify pixels located in overlapping "boxes" (classes) • Many pixels could be unclassified (located outside of boxes) • May not always be the most effective choice	• ENVI • IDRISI
Minimum Distance	• Pixels are assigned to a specific class based on the Euclidean distance from each pixel to the mean vector for each class	• Very efficient • All pixels are classified	• Not always accurate • Does not consider class variability	• ENVI • IDRISI

Maximum Likelihood	• Pixels are assigned to a specific class with the highest probability (based on the Bayesian probability formula)	• Most commonly used • Most accurate • All pixels are classified • Considers class variability	• Not very efficient	• ArcGIS • ENVI • IDRISI
Unsupervised Classification Technique				
ISODATA	• Pixels are iteratively assigned to a specific class using minimum distance techniques	• User only provides an initial estimate of the number of clusters • More flexible than K Means	• Can be inefficient on large datasets	• ArcGIS • ENVI • IDRISI
k-Means	• Pixels are iteratively assigned to a specific class using minimum distance techniques	• Simple procedure	• Requires number of clusters to be known	• ENVI • IDRISI

Remote sensing images are mainly classified through computer programs by supervised and unsupervised methods or by manual digitizing. Supervised classification techniques are the most common as the user manually selects sample pixels from the raw image (also known as "training site") to represent specific classes. The computer program then carries on with the analysis to group each pixel in the image to the corresponding class. These techniques are recommended for use when the user is familiar with the region and can accurately create training sites. This method also allows for more user control which may be advantageous if specific criteria are implemented that the program on its own would otherwise not recognize. However, supervised classification techniques are the most time-consuming approach due to the considerable interaction required by the analyst. Unsupervised classification techniques allow the computer programs to create clusters of grouped pixels that share similar statistical properties. This allows the computer program to do most of the work, decreasing reliance on the analyst and possibly improving quality due to a lower chance for human error. Unsupervised classification techniques are recommended for use when the user is unfamiliar with the region and is still looking for an accurate analysis. Generally, supervised classification techniques are preferred over unsupervised classification techniques due to their greater accuracy (Mather and Tso 2009). Manual digitizing has no reliance on computer algorithms but relies on the judgement of the user alone. With this approach, the user manually creates individual polygons that represent specific classes defined by the user. This can be very time consuming if the area of interest is considerably large, however, it may be the only alternative if the remote sensing images do not contain spectral properties required for supervised or unsupervised classification. This method is more commonly applied to aerial photographs than satellite images due to its higher scale and thus greater detail visible to the human eye.

The most common supervised classification techniques are parallelepiped, minimum distance, and maximum likelihood. The parallelepiped procedure is computationally efficient (Devi and Baboo 2011) and one of the simplest methods to use (Navulur 2006), however, it has many drawbacks due to its structure. This method has a tendency to classify pixels incorrectly and is only recommended if the data is well structured (no overlapping of classes) (Mather and Koch 2011) or if the user is seeking a quick procedure and only a basic understanding of the changes over time. The minimum distance technique is also simple to use and can produce fairly accurate results, but does not consider class variability which may improperly classify pixels. The maximum distance technique is the most common supervised classification method applied mainly due to its high degree of accuracy. It is also the most time-consuming method out of the three discussed in this section so it should be used in applications where accuracy is of upmost importance.

The most common unsupervised classification techniques are k-means and ISODATA. These two iterative techniques are very similar to one another. The main difference is k-means requires the number of clusters to be known initially, whereas ISODATA allows for a different number of clusters (Navulur 2006).

6.3 Hydrologic Modeling

After data collection and analysis of remotely sensed data, the next step in the flood risk management process is hydrologic modeling. The various hydrological processes evaluated in these models and the available methods are summarized in **Table 5**.

Table 5. Processes and methods encountered in hydrologic modeling.

3. HYDROLOGIC MODELING	**Method**	**Description**	**Advantages**	**Disadvantages**
Hydrologic Process				
Precipitation	Thiessen Polygon Method	• Estimated values are taken from the nearest observed points (determined from Thiessen polygons)	• Conceptually simple method • Very efficient • Low computational complexity	• Not very accurate for mountainous regions
	Inverse Distance Weighting Method	• Estimated values are based on weights given to observed points (weights decrease as distance increases)	• Conceptually simple method • Very efficient • Low computational complexity	• Sensitive to outliers
	Kriging Method	• Estimated values are determined based off of interpolation and statistical relationships between observed points	• Takes into account data clustering	• High computational complexity • More input required from user
	Polynomial Surface Method	• Estimated values are determined from a polynomial function fitted to the study area	• Very popular due to its simplicity	• Computationally expensive
	Spline Surface Method	• Estimated values are determined from a mathematical model that fits a minimum-curvature surface through observed points	• Fairly accurate results from even a few sampled points	• Sensitive to outliers
Infiltration	Horton’s Equation	• Assumes infiltration exponentially decreases from a maximum to minimum (equilibrium) rate	• Simple method • Usually gives a good fit • Widely used	• Has no physical significance • Field data required for calibration • Does not describe infiltration prior to ponding
	Green-Ampt Method	• Assumes a wetting front separates saturated soil (above) from soil with an initial moisture content (below)	• Required parameters can be physically measured • Considered to be one of the most realistic models of infiltration	• Applicability to catchment scale is physically unrealistic • Not widely used
	NRCS Curve Number Method	• Assumes an initial abstraction before ponding, related to the soil’s Curve Number (dependent on soil group, land-use, and hydrologic condition)	• Simple and efficient method • Widely used	• Does not account for rainfall intensity/duration (only volume) • Required parameters are empirical • Does not always yield reliable results
Potential Evapotranspiration	Thornthwaite Method	• Predicts evapotranspiration from air temperature and latitude data	• Widely used • Low data requirements	• Applicability is questionable due to its simplicity • Empirically based

	Linacre Method	• Predicts evapotranspiration from temperature, elevation, latitude, and dew point	• Simplification of Penman Method (less climatic data input required)	• Precision decreases on a daily basis
	Penman Method	• Predicts evapotranspiration from temperature, wind speed, air pressure, and solar radiation	• Less empirically based than Thornthwaite Method • Ease of application	• Requires a large number of meteorological variables (may be unavailable)
	Penman-Monteith Method	• Predicts evapotranspiration from temperature, wind speed, solar radiation, and relative humidity	• Physically based • Used as a standard by The United Nations Food and Agriculture Organization (FAO)	• Requires a large number of meteorological variables (may be unavailable)
	Priestley-Taylor Method	• Based off of Penman-Monteith with removal of aerodynamic terms	• Reliable in humid zones • Low data requirements	• Not recommended for arid zones
Snowmelt	Degree-Day Method	• Simple equation consisting of only temperature data	• Simple method • Very commonly used • Quite reliable if properly used	• Based off of temperature only • Can be easily misused • Empirically based • Not applicable for rain-on-snow scenarios
	Energy Balance Method	• Complex equations consisting of temperature, wind speed, and radiation data	• Comprehensive method • Physically based	• Data intensive
Overland Flow	Dynamic Wave	• Considers all terms in the momentum equation	• Considers the full Saint-Venant equation	• Computationally intensive (may not be required) • Requires more data than Diffusive or Kinematic Wave
	Diffusive Wave	• Neglects inertial terms in the momentum equation	• Suitable for backwater analysis	• Not suitable for tidal flows
	Kinematic Wave	• Neglects inertial and pressure forces in the momentum equation	• More computationally efficient than Dynamic or Diffusive Wave	• Cannot predict subsidence of flood wave • Not suitable for backwater analysis
	NRCS Curve Number Method	• Assumes an initial abstraction before ponding, related to the soil's Curve Number (dependent on soil group, land-use, and hydrologic condition)	• Simple and efficient method • Widely used	• Does not account for rainfall intensity/duration (only volume) • Required parameters are empirical • Does not always yield reliable results
Flow Routing	Muskingum Method	• Calculates storage volume in a channel by combination of prism storage and wedge storage	• Most widely used • Modest data requirements • No knowledge on riverbed geometry is required	• Routing parameters determined from calibration (measured inflow and outflow hydrographs) • Channel might be ungauged
	Muskingum-Cunge Method	• Muskingum Method with new approach for determination of coefficients	• Routing parameters based on measureable data (stage-discharge relations, cross-sectional data, etc.)	• More data required than Muskingum
	Modified Puls Method	• Method utilizes the continuity equation and a storage-outflow relationship	• Very simple and efficient method	• More commonly used for reservoir routing
Unsaturated Flow	Richards' Equation	• Non-linear partial differential equation derived by combining Darcy's Law with conservation of mass	• Most widely used	• Requires detailed soil data • Computationally intensive • No closed-form analytical solution

Groundwater	Darcy's Law	• Based on hydraulic conductivity and hydraulic gradient through a porous medium	• Most widely used and well known • Experimentally validated	• Assumes a linear relationship • Not applicable to some porous media

Precipitation is one of the most important input parameters required in hydrologic models. This information is typically input from multiple rain gauges, where the program then attempts to spatialize the rainfall across a region based on methods such as Thiessen Polygon, Inverse Distance Weighting, Kriging, Polynomial Surface, and Spline Surface. These methods distribute rainfall spatially across a region based on unique functions. For example, the Thiessen Polygon and Inverse Distance Weighting methods are more simplified methods yet can provide fairly accurate results in simple datasets. Typically, more detailed methods are required as real data can be sparse and clustered. This is where more complex methods such as Kriging, Polynomial Surface, and Spline Surface are required for use. Infiltration, which determines the amount of water that is absorbed into the ground, can be determined from methods such as Horton's Equation, Green-Ampt, and National Resources Conservation Service (NRCS) Curve Number (formerly known as Soil Conservation Service (SCS) Curve Number). The choice of these equations depends on watershed characteristics and on initial assumptions regarding the selected infiltration process to model. Potential evapotranspiration, which determines the amount of evaporation going into the atmosphere, can be determined from methods such as Thornthwaite, Linacre, Penman, Penman-Monteith, and Priestley-Taylor. The choice between these methods depends on data availability and on method availability within the selected model. Snowmelt is usually an optional module and can be determined from methods such as Degree-Day and Energy Balance. The Degree-Day method is a simple method with low data requirements, but can be inaccurate if misused. The Energy Balance method is more complex and can provide a more detailed determination of snowmelt. Overland flow (runoff) can be determined from the Dynamic Wave, Diffusive Wave, or Kinematic Wave equations. Some terms in the full Dynamic Wave equation may be ignored depending on the characteristics of the stream, which is where the Diffusive or Kinematic Wave equations may be applied. Unsaturated flow and groundwater flow can be determined from the Richards' Equation and Darcy's Law, respectively. Flow Routing is commonly determined from methods such as Muskingum, Muskingum-Cunge, and Modified Puls. The Muskingum method is commonly used for flow routing, however, for ungauged channels the Muskingum-Cunge method is recommended since the parameters can be physically measured.

6.4 Hydraulic Modeling

The output results from hydrological models are used as inputs into hydraulic models for further analyses. **Table 6** summarizes the various processes in hydraulic models and the available methods.

Table 6. Processes and methods encountered in hydraulic modeling.

4. HYDRAULIC MODELING	**Method**	**Description**	**Advantages**	**Disadvantages**
Hydraulic Process				
Sediment Transport	Meyer-Peter Müller (1948)	• Calculates bed-loads for medium to coarse sands using Shields' parameter (shear relationship) • Applicable particle size 0.4mm – 29mm	• One of the most widely used transport equations • Very simple function	• Empirically based • Tends to under predict transport of finer materials
	Yang (1973, 1984)	• Calculates total load based on stream power • Applicable particle size 0.15mm – 7mm	• Tested over a variety of flume and field data	• Very sensitive to stream velocity and fall velocity
	Engelund-Hansen (1967)	• Calculates total load based on particle size, channel velocity, bed shear stress, and unit weight of sediment/water • Applicable particle size 0.19mm – 0.93mm	• Extensively tested (fairly consistent with field data) • Relatively simple function	• Should only be applied to sand
	Ackers-White (1973)	• Calculates total load based on particle size, mobility, and transport parameters • Applicable particle size 0.04mm – 7mm	• Range of bed configurations were used during development (plane, ripples, dunes)	• Large number of parameters required
	van Rijn (1984a,b)	• Calculates bed-load and suspended load based on saltating bed particles,	• Fairly accurate considering simplified expressions are used for complicated interactions	• Based on limited field data

		sediment velocities, and concentrations • Applicable particle size 0.2mm – 2mm		
Flow Routing	Dynamic Wave	• Considers all terms in the momentum equation	• Considers the full Saint-Venant equations	• Computationally intensive (may not be required) • Requires more data than Diffusive or Kinematic Wave
	Diffusive Wave	• Neglects inertial terms in the momentum equation	• Suitable for backwater analysis	• Not suitable for tidal flows
	Kinematic Wave	• Neglects inertial and pressure forces in the momentum equation	• More computationally efficient than Dynamic or Diffusive Wave	• Cannot predict subsidence of flood wave • Not suitable for backwater analysis
Water Surface Elevations	Energy Equation	• States that the total energy is constant at any point	• Applicable in gradually varied flow situations	-
	Momentum Equation	• States that the net momentum flux plus all external forces acting on the control volume be equal to the rate of accumulation of momentum	• Applicable in rapidly varied flow situations (hydraulic jump, stream junctions, etc.)	-

Numerous sediment transport rate formulas have been developed over the past several decades. Some of the more common formulas include Meyer-Peter and Müller (1948), Yang (1973, 1984), Engelund-Hansen (1967), Ackers-White (1973), and van Rijn (1984a, b). These methods each have their advantages and disadvantages as well as typical conditions (i.e., mode of transport, particle sizes) they are suited for. These equations are chosen based on available data as well as the specific sediment characteristics in the channel of interest. Flow routing can be similarly determined from the Dynamic Wave, Diffusive Wave, or Kinematic Wave equations as discussed in Section 3 of this methodology. Water surface elevations are commonly only solved through principles such as the energy and momentum equations, and are applicable to gradually varied flow and rapidly varied flow situations, respectively.

6.5 Flood Risk Assessment

A very important part of the flood risk management process is the development of a flood risk assessment (FRA). The concept of risk includes the probability of a hazard occurring along with its corresponding impacts. This paper focusses on hazard analysis only and not of exposure and vulnerability which relate to the impacts. FRAs utilize the results from land-use change analyses and hydrologic and hydraulic modeling simulations to evaluate the flood risk in a given region and provide recommendations on proper flood mitigation measures. They determine the potential flood risk in urban areas or in proposed development scenarios and can also evaluate the effectiveness of various SWM practices before implementation. Quantifying historical land-use change allows for prediction of future changes, which assists in hazard analyses by providing insight into the level of development that could exist in the future. This plays a major role in selecting the appropriate SWM practices to be proposed and evaluated through means of hydrologic and hydraulic modeling. FRAs can range in structure from simple written statements to detailed analyses.

7. Conclusions

Future land-use change and climate change will continue to present hydrologic issues in Canadian urban environments. The risks of flooding will continue to increase and will impact the service life of infrastructure while also producing significant amounts of economic damage. It is important to be able to reduce these risks through proper flood risk management and land-use planning techniques. This paper presented a detailed integrated framework that outlines various classifications, processes, and methods involved in the flood risk management process. This framework will assist in land-use planning, decision making to implement appropriate stormwater management features and improve water resources modelling capabilities to decrease future flood risk in Canadian urban environments.

Acknowledgements

The authors would like to thank FloodNET for their funding as well as the Toronto and Region Conservation Authority (TRCA) for their continuous communication and support.

References

Abraham, J. (2015). *The Impact of Climate Change on Canadian Municipalities and Infrastructure.* Canadian Climate Forum.

Acharya, A., Lamb, K., & Piechota, T. C. (2013). Impacts of Climate Change on Extreme Precipitation Events over Flamingo Tropicana Watershed. *Journal of the American Water Resources Association, 49*(2), 359-370. doi:10.1111/jawr.12020

Ahiablame, L. M., Engel, B. A., & Chaubey, I. (2012). Effectiveness of Low Impact Development Practices: Literature Review and Suggestions for Future Research. *Water Air and Soil Pollution, 223*(7), 4253-4273. doi:10.1007/s11270-012-1189-2

Akbari, A., Mozafari, G., Fanodi, M., & Hemmesy, M. S. (2014). Impact of Landuse Change on River Floodplain Using Public Domain Hydraulic Model. *Modern Applied Science, 8*(5), 80-86. doi:10.5539/mas.v8n5p80

Al-Bakri, J. T., Taylor, J. C., & Brewer, T. R. (2001). Monitoring land use change in the Badia transition zone in Jordan using aerial photography and satellite imagery. *The Geographical Journal*, *167*(3), 248-262. doi:10.1111/1475-4959.00022

Andrey, J., Kertland, P., & Warren, F. (2014). Water and Transportation Infrastructure. In F. J. Warren, & D. S. Lemmen (Eds.), *Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation* (pp. 233-252). Ottawa, ON: Government of Canada.

Ashmore, P., & Church, M. (2001). *The Impact of Climate Change on Rivers and River Processes in Canada.* Ottawa, ON: Natural Resources Canada.

Bicknell, B. R., Imhoff, J. C., Kittle, J. R., & Donigian, A. S. (1997). *Hydrological Simulation Program - Fortran.* Athens, GA: U.S. Environmental Protection Agency.

Bledsoe, B. P., & Watson, C. C. (2001). Effects of Urbanization on Channel Instability. *Journal of the American Water Resources Association, 37*(2), 255-270. doi:10.1111/j.1752-1688.2001.tb00966.x

Booth, D. B., & Bledsoe, B. P. (2009). Streams and Urbanization. In L. A. Baker, *The Water Environment of Cities* (pp. 93-123). Springer US. doi:10.1007/978-0-387-84891-4_6

Bunting, T., & Filion, P. (Eds.). (2006). *Canadian Cities in Transition: Local Through Global Perspectives* (3rd ed.). Don Mills, ON: Oxford University Press.

Burn, D. H., & Whitfield, P. H. (2015). Changes in floods and flood regimes in Canada. *Canadian Water Resources Journal*, 1-12. doi:10.1080/07011784.2015.1026844

Chang, C. K., Aminuddin, A. G., Rozi, A., & Nor, A. Z. (2008). Sediment transport modeling for Kulim River - A case study. *Journal of Hydro-environment Research, 2*(1), 47-59. doi:10.1016/j.jher.2008.04.002

Chang, K.-T. (2014). *Introduction to Geographic Information Systems* (7th ed.). New York, NY: The McGraw-Hill Companies, Inc.

Charlton, J. (2008). *Fundamentals of Fluvial Geomorphology*. New York, NY: Routledge.

Chin, A., O'Dowd, A. P., & Gregory, K. J. (2013). Urbanization and River Channels. (J. Shroder, & E. Wohl, Eds.) *Treatise on Geomorphology, 9*, 809-827. doi:10.1016/B978-0-12-374739-6.00266-9

Chin, D. A. (2013). *Water-Resources Engineering* (3rd ed.). Upper Saddle River, NJ: Pearson Education, Inc.

Cunderlik, J. (2003). Hydrologic Model Selection for the CFCAS Project: Assessment of Water Resources Risk and Vulnerability to Changing Climatic Condition. *Water Resources Research Report*, 046.

Denault, C., Millar, R. G., & Lence, B. J. (2006). Assessment of Possible Impacts of Climate Change in an Urban Catchment. *Journal of the American Water Resources Association, 42*(3), 685-697. doi:10.1111/j.1752-1688.2006.tb04485.x

Devi, M. R., & Baboo, S. S. (2011). Land Use and Land Cover Classification using RGB&L Based Supervised Classification Algorithm. *International Journal of Computer Science & Engineering Technology (IJCSET), 2*(10), 167-180.

DHI Water & Environment. (2009). *MIKE 11: A Modelling System for Rivers and Channels - User Guide.* DHI Water & Environment.

Dietz, M. E. (2007). Low Impact Development Practices: A Review of Current Research and Recommendations for Future Directions. *Water, Air, and Soil Pollution, 186*(1-4), 351-363. doi:10.1007/s11270-007-9484-z

Dingman, S. L. (2008). *Physical Hydrology* (2nd ed.). Long Grove, IL: Waveland Press, Inc.

Dore, M. H. (2005). Climate change and changes in global precipitation patterns: What do we know? *Environmental International, 31*(8), 1167-1181. doi:10.1016/j.envint.2005.03.004

Elliot, A. H., & Trowsdale, S. A. (2007). A Review of Models for Low Impact Urban Stormwater Drainage. *Environmental Modelling and Software, 22*(3), 394-405. doi:10.1016/j.envsoft.2005.12.005

Hingray, B., Picouet, C., & Musy, A. (2015). *Hydrology: A Science for Engineers* (1st ed.). Boca Raton, FL: CRC Press.

Horritt, M. S., & Bates, P. D. (2002). Evaluation of 1D and 2D numerical models for predicting river flood inundation. *Journal of Hydrology, 268*(1-4), 87-99. doi:10.1016/S0022-1694(02)00121-X

Im, S., Kim, H., Kim, C., & Jang, C. (2009). Assessing the impacts of land use changes on watershed hydrology using MIKE SHE. *Environmental Geology, 57*(1), 231-239. doi:10.1007/s00254-008-1303-3

Infrastructure Canada. (2006). *Adapting Infrastructure to Climate Change in Canada's Cities and Communities: A Literature Review.* Canada: Infrastructure Canada, Research and Analysis Division.

James, W., Rossman, L. E., & James, W. R. (2010). *Water Systems Models: User's Guide to SWMM5.* Guelph, ON: Computational Hydraulics International.

Jensen, C. A. (2012). *A Hydrologic Assessment of using Low Impact Development to Mitigate the Impacts of Climate Change in Victoria, BC, Canada.* Victoria, BC: University of Victoria.

Karamouz, M., Moridi, A., & Nazif, S. (2010). *Urban Water Engineering and Management* (1 ed.). Boca Raton, FL: CRC Press. doi:10.1201/b15857-8

Kovacs, P., & Sandink, D. (2013). *Best Practices for Reducing the Risk of Future Damage to Homes from Riverine and Urban Flooding.* Toronto, ON: Institute for Catastrophic Loss Reduction (ICLR).

Malaviya, P., & Singh, A. (2012). Constructed Wetlands for Management of Urban Stormwater Runoff. *Environmental Science and Technology, 42*(20), 2153-2214. doi:10.1080/10643389.2011.574107

Mather, P., & Koch, M. (2011). *Computer Processing of Remotely-Sensed Images: An Introduction* (4th ed.). West Sussex, UK: John Wiley & Sons.

Mather, P., & Tso, B. (2009). *Classification Methods for Remotely Sensed Data* (2nd ed.). Boca Raton, FL: CRC Press.

Mengistu, D. A., & Salami, A. T. (2007). Application of remote sensing and GIS inland use/land cover mapping and change detection in a part of south western Nigeria. *African Journal of Environmental Science and Technology, 1*(5), 99-109.

Moore, N., Andresen, J., Lofgren, B., Pijanowski, B., & Kim, D.-Y. (2015). Projected land-cover change effects on East African rainfall under climate change. *International Journal of Climatology, 35*(8), 1772-1783. doi:10.1002/joc.4117

Mujumdar, P. P., & Kumar, D. N. (2012). *Floods in a Changing Climate: Hydrologic Modeling.* Cambridge, UK: Cambridge University Press.

Municipal Program Development Branch. (1999). *Stormwater Management Guidelines for the Province of Alberta.* Edmonton, AB: Municipal Program Development Branch.

Navulur, K. (2006). *Multispectral Image Analysis Using the Object-Oriented Paradigm.* Boca Raton, FL: CRC Press.

Nelson, P. A., Smith, J. A., & Miller, A. J. (2006). Evolution of channel morphology and hydrologic response in an urbanizing drainage basin. *Earth Surface Processes and Landforms, 31*(9), 1063-1079. doi:10.1002/esp.1308

Nirupama, N., & Simonovic, S. P. (2007). Increase of Flood Risk due to Urbanisation: A Canadian Example. *Natural Hazards, 40*(1), 25-41. doi:10.1007/s11069-006-0003-0

Olechnowicz, B., & Weinerowska-Bords, K. (2014). Impact of Urbanization on Stormwater Runoff from a Small Urban Catchment: Gdansk Malomiejska Basin Case Study. *Archives of Hydro-Engineering and Environmental Mechanics, 61*(3-4), 141-162. doi:10.1515/heem-2015-0009

Ontario Ministry of the Environment. (2003). *Stormwater Management Planning and Design Manual.* Queen's Printer for Ontario.

Ouellet, C., Saint-Laurent, D., & Normand, F. (2012). Flood events and flood risk assessment in relation to climate change and land-use changes: Saint-François River, southern Québec, Canada. *Hydrological Sciences Journal*, *57*(2), 313-325. doi:10.1080/02626667.2011.645475

Owrangi, A. M., Lannigan, R., & Simonovic, S. P. (2014). Interaction between land-use change, flooding and human health in Metro Vancouver, Canada. *Natural Hazards, 72*(2), 1219-1230. doi:10.1007/s11069-014-1064-0

Owusu, P. A., Odai, S. N., Annor, F. O., & Adjei, K. A. (2013). Reservoir storage for Managing Floods in Urban Areas: A Case Study of Dzorwulu Basin in Accra. *Hydrological Processes, 27*(11), 1615-1625. doi:10.1002/hyp.9286

Papanicolaou, A. N., Elhakeem, M., Krallis, G., Prakash, S., & Edinger, J. (2008). Sediment Transport Modeling Review - Current and Future Developments. *Journal of Hydraulic Engineering, 134*(1), 1-14.

Qaiser, K., Yuan, Y., & Lopez, R. D. (2012). Urbanization Impacts on Flooding in the Kansas River Basin and Evaluation of Wetlands as a Mitigation Measure. *American Society of Agricultural and Biological Engineers*, *55*(3), 849-859.

Reis, S. (2008). Analyzing Land Use/Land Cover Changes Using Remote Sensing and GIS in Rize, North-East Turkey. *Sensors, 8*(10), 6188-6202. doi:10.3390/s8106188

Sandink, D. (2015). Urban Flooding and Ground-Related Homes in Canada: An Overview. *Journal of Flood Risk Management*. doi:10.1111/jfr3.12168

Simonovic, S. P., & Juliano, K. M. (2001). The Role of Wetlands during Low Frequency Flooding Events in the Red River Basin. *Canadian Water Resources Journal*, *26*(3), 377-397. doi:10.4296/cwrj2603377

Statistics Canada. (2008). *Human Activity and the Environment: Annual Statistics.* Ottawa, ON: Minister of Industry.

Statistics Canada. (2011). *Population, urban and rural, by province and territory (Canada)*. Retrieved from Statistics Canada: http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/demo62a-eng.htm

Stephens, K. A., Graham, P., & Reid, D. (2002). *Stormwater Planning: A Guidebook for British Columbia.*

Stone, L., & Gibbins, R. (2002). *Tighening Our Beltways: Urban Sprawl in Western Canada.* Canada West Foundation.

Strassler, E., Pritts, J., & Strellec, K. (1999). *Preliminary Data Summary of Urban Storm Water Best Management Practices.* Washington, DC: U.S. Environmental Protection Agency.

Sturm, T. W. (2010). *Open Channel Hydraulics* (2nd ed.). New York, NY: McGraw-Hill Higher Education.

Surian, N. (2007). River Channelization. In S. W. Trimble, *Encyclopedia of Water Science* (2nd ed., pp. 986-990). CRC Press. doi:10.1201/NOE0849396274.ch241

Suriya, S., & Mudgal, B. V. (2012). Impact of urbanization on flooding: The Thirusoolam sub watershed - A case study. *Journal of Hydrology, 412-413*, 210-219. doi:10.1016/j.jhydrol.2011.05.008

Tonina, D., & Jorde, K. (2013). Hydraulic Modelling Approaches for Ecohydraulic Studies: 3D, 2D, 1D and Non-Numerical Models. In I. Maddock, A. Harby, P. Kemp, & P. Wood (Eds.), *Ecohydraulics: An Integrated Approach.* Chichester, UK: John Wiley & Sons.

Toronto and Region Conservation Authority and Credit Valley Conservation. (2011). *Low Impact Development Stormwater Management Planning and Design Guide.* Toronto, ON: Toronto and Region Conservation Authority and Credit Valley Conservation.

Trenberth, K. E. (2011). Changes in precipitation with climate change. *Climate Research, 47*, 123-138. doi:10.3354/cr00953

U.S. Army Corps of Engineers. (2010). *HEC-RAS River Analysis System Hydraulic Reference Manual.* Davis, CA: U.S. Army Corps of Engineers.

U.S. Environmental Protection Agency. (2000). *Low Impact Development (LID): A Literature Review.* Washington, DC: U.S. Environmental Protection Agency.

United Nations. (2015). *World Urbanization Prospects: The 2014 Revision.* Department of Economic and Social Affairs, Population Division. New York: United Nations.

Villafuerte II, M. Q., Matsumoto, J., & Kubota, H. (2015). Changes in extreme rainfall in the Philippines (1911-2010) linked to global mean temperature and ENSO. *International Journal of Climatology, 35*(8), 2033-2044. doi:10.1002/joc.4105

Wang, L. K., & Yang, C. T. (Eds.). (2014). *Modern Water Resources Engineering* (Vol. 15). New York, NY: Springer Science & Business Media. doi:10.1007/978-1-62703-595-8

Weng, Q. (2002). Land use change analysis in the Zhujiang Delta of China using satellite remote sensing, GIS and stochastic modelling. *Journal of Environmental Management, 64*(3), 273-284. doi:10.1006/jema.2001.0509

Wijesekara, G. N., Gupta, A., Valeo, C., Hasbani, J.-G., Qiao, Y., Delaney, P., & Marceau, D. J. (2012). Assessing the impact of future land-use changes on hydrological processes in the Elbow River watershed in southern Alberta, Canada. *Journal of Hydrology*, *412-413*, 220-232. doi:10.1016/j.jhydrol.2011.04.018

Yang, J., Townsend, R. D., & Daneshfar, B. (2006). Applying the HEC-RAS model and GIS techniques in river network floodplain delineation. *Canadian Journal of Civil Engineering, 33*(1), 19-28. doi:10.1139/L05-102

Zhang, S., & Guo, Y. (2015). SWMM Simulation of the Storm Water Volume Control Performance of Permeable Pavement Systems. *Journal of Hydrologic Engineering*, *20*(8), 06014010. doi:10.1061/(ASCE)HE.1943-5584.0001092

List of Previous Reports in the Series

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

In addition to 78 previous reports (No. 01 – No. 78) prior to 2012

Samiran Das and Slobodan P. Simonovic (2012). Assessment of Uncertainty in Flood Flows under Climate Change. Water Resources Research Report no. 079, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 67 pages. ISBN: (print) 978-0-7714-2960-6; (online) 978-0-7714-2961-3.

Rubaiya Sarwar, Sarah E. Irwin, Leanna King and Slobodan P. Simonovic (2012). Assessment of Climatic Vulnerability in the Upper Thames River basin: Downscaling with SDSM. Water Resources Research Report no. 080, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 65 pages. ISBN: (print) 978-0-7714-2962-0; (online) 978-0-7714-2963-7.

Sarah E. Irwin, Rubaiya Sarwar, Leanna King and Slobodan P. Simonovic (2012). Assessment of Climatic Vulnerability in the Upper Thames River basin: Downscaling with LARS-WG. Water Resources Research Report no. 081, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 80 pages. ISBN: (print) 978-0-7714-2964-4; (online) 978-0-7714-2965-1.

Samiran Das and Slobodan P. Simonovic (2012). Guidelines for Flood Frequency Estimation under Climate Change. Water Resources Research Report no. 082, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 44 pages. ISBN: (print) 978-0-7714-2973-6; (online) 978-0-7714-2974-3.

Angela Peck and Slobodan P. Simonovic (2013). Coastal Cities at Risk (CCaR): Generic System Dynamics Simulation Models for Use with City Resilience Simulator. Water Resources Research Report no. 083, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 55 pages. ISBN: (print) 978-0-7714-3024-4; (online) 978-0-7714-3025-1.

Roshan Srivastav and Slobodan P. Simonovic (2014). Generic Framework for Computation of Spatial Dynamic Resilience. Water Resources Research Report no. 085, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 81 pages. ISBN: (print) 978-0-7714-3067-1; (online) 978-0-7714-3068-8.

Angela Peck and Slobodan P. Simonovic (2014). Coupling System Dynamics with Geographic Information Systems: CCaR Project Report. Water Resources Research Report no. 086, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 60 pages. ISBN: (print) 978-0-7714-3069-5; (online) 978-0-7714-3070-1.

Sarah Irwin, Roshan Srivastav and Slobodan P. Simonovic (2014). Instruction for Watershed Delineation in an ArcGIS Environment for Regionalization Studies.Water Resources Research

Report no. 087, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 45 pages. ISBN: (print) 978-0-7714-3071-8; (online) 978-0-7714-3072-5.

Andre Schardong, Roshan K. Srivastav and Slobodan P. Simonovic (2014).Computerized Tool for the Development of Intensity-Duration-Frequency Curves under a Changing Climate: Users Manual v.1 Water Resources Research Report no. 088, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 68 pages. ISBN: (print) 978-0-7714-3085-5; (online) 978-0-7714-3086-2.

Roshan K. Srivastav, Andre Schardong and Slobodan P. Simonovic (2014). Computerized Tool for the Development of Intensity-Duration-Frequency Curves under a Changing Climate: Technical Manual v.1 Water Resources Research Report no. 089, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 62 pages. ISBN: (print) 978-0-7714-3087-9; (online) 978-0-7714-3088-6.

Roshan K. Srivastav and Slobodan P. Simonovic (2014). Simulation of Dynamic Resilience: A Railway Case Study. Water Resources Research Report no. 090, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 91 pages. ISBN: (print) 978-0-7714-3089-3; (online) 978-0-7714-3090-9.

Nick Agam and Slobodan P. Simonovic (2015). Development of Inundation Maps for the Vancouver Coastline Incorporating the Effects of Sea Level Rise and Extreme Events. Water

Resources Research Report no. 091, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 107 pages. ISBN: (print) 978-0-7714-3092-3; (online) 978-0-7714-3094-7.

Sarah Irwin, Roshan K. Srivastav and Slobodan P. Simonovic (2015). Instructions for Operating the Proposed Regionalization Tool "Cluster-FCM" Using Fuzzy C-Means Clustering and L-Moment Statistics. Water Resources Research Report no. 092, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 54 pages. ISBN: (print) 978-0-7714-3101-2; (online) 978-0-7714-3102-9.

Bogdan Pavlovic and Slobodan P. Simonovic (2016). Automated Control Flaw Generation Procedure: Cheakamus Dam Case Study. Water Resources Research Report no. 093, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 78 pages. ISBN: (print) 978-0-7714-3113-5; (online) 978-0-7714-3114-2.

Sarah Irwin, Slobodan P. Simonovic and Niru Nirupama (2016). Introduction to ResilSIM: A Decision Support Tool for Estimating Disaster Resilience to Hydro-Meteorological Events. Water Resources Research Report no. 095, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 66 pages. ISBN: (print) 978-0-7714-3115-9; (online) 978-0-7714-3116-6.