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POLYTECHNIQUE MONTRÉAL
affiliée à l'Université de Montréal

Integrated modeling of short-term flood forecasting in the Ottawa river

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Mémoire présenté en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*
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Ce mémoire intitulé :

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présenté par **Hamza OUSOUKHMAN**
en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*
a été dûment accepté par le jury d'examen constitué de :

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DEDICATION

I dedicate this work to
my parents, my brother and my sisters who were always supportive of my decisions.

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RÉSUMÉ

Les inondations sont considérées comme l'un des risques naturels les plus dangereux au monde. Plusieurs pays souffrent des conséquences néfastes des inondations. Au Canada, plusieurs provinces ont subi des inondations au cours du siècle dernier. Par exemple, la rivière des Outaouais a été confrontée à de nombreuses inondations comme en 2017 et 2019. La population d'Ottawa continue à augmenter d'une année à l'autre. C'est pour cela que nous avons choisi la rivière des Outaouais comme étude de cas pour ce projet dans le but de protéger la société contre les risques causés par les inondations.

Les pays adoptent plusieurs solutions basées sur différentes méthodes afin de minimiser les dommages causés par les crues. La plupart des scientifiques s'accordent que la prévision des crues est la meilleure façon de limiter les conséquences des crues. Les systèmes de prévision des crues sont indispensables dans les pays fréquemment confrontés à des crues. Ils visent à fournir un long délai d'exécution et à fournir aux autorités et aux décideurs des informations suffisantes. Par conséquent, ils auront suffisamment de temps pour prendre les mesures adéquates pour sauver la vie de la population et limiter les catastrophes économiques dues aux inondations.

Cette étude présente un système intégré de modélisation hydraulique et hydrologique pour la prévision de l'impact des crues. Dans ce système, le modèle hydrodynamique bidimensionnel est développé en utilisant le logiciel Delft3D et le modèle hydrologique est développé avec le logiciel HEC-HMS. Ensuite, le modèle hydrodynamique est connecté à un modèle hydrologique et à des données d'observation pour fournir un échange automatique de données et de résultats. Les logiciels Delft3D et HEC-HMS ont été choisis pour cette étude car ils étaient utilisés dans plusieurs projet de prédiction des crues et ils produisaient des bons résultats. De plus, ils ont été appliqués dans plusieurs études de prévision des crues et fournissent de bons résultats. Les données météorologiques de prévision et les caractéristiques des bassins versants fournissent les données d'entrée au modèle hydrologique pour prédire les conditions d'écoulement, qui sont ensuite automatiquement introduites dans le modèle hydrodynamique. Le modèle hydrodynamique modélise les caractéristiques des crues telles que le niveau d'eau, le champ de vitesse moyen en profondeur et l'étendue des crues. Le système est appliqué à la rivière des Outaouais. Les données bathymétriques de diverses sources sont combinées et interpolées au modèle hydrodynamique Delft3D. Le modèle hydrodynamique est validé par rapport au niveau d'eau et aussi par rapport aux profils de vitesse d'eau mesurés dans différentes coupes transversales le long de la rivière. Les résultats de Delft3D montrent une bonne performance par rapport aux données observes que ce soit pour le niveau d'eau ou les profils de vitesse. Les modèles hydrologiques ont été élaborés pour les sous-bassins versants les plus importants d'Ottawa. Ensuite, ils ont été calibrés et validés par rapport au débit observé dans différents exutoires de sous-bassin versant. La fiabilité des modèles hydrologiques a été évaluée à l'aide de plusieurs indicateurs de performance tels que le coefficient de régression (R^2), l'erreur quadratique moyenne (RMSE), l'erreur quadratique moyenne relative (RRMSE) et Nash-Sutcliffe (NSE). En général, les modèles hydrologiques ont montré de bons résultats dans les tests de validation. Le modèle hydrodynamique est ensuite couplé aux modèles hydrologiques et à des sources de données climatiques via une plateforme de modélisation unifiée modulaire. Le système de prévision des crues Delft FEWS a été utilisé comme une plateforme pour intégrer les modèles hydrodynamiques et hydrologiques aux données de prévision météorologique. Enfin, tous les modèles et la prévision météorologique numérique seront manipulés à l'aide de la plateforme DELFT-FEWS.

ABSTRACT

Floods are one of the most catastrophic natural disasters in Canada and around the world that can cause loss of life and damages to properties and infrastructures. Saguenay flood (1996), southern Alberta flood (2013), and Ottawa floods (2017, 2019), are a few examples of Canadian floods with tremendous socio-economic impacts. Flood forecasting and predicting its characteristics (e.g., its magnitude and extent) has an important role in preventing and mitigating such flood impacts. Particularly, short-term forecasting is crucial for early warning systems and emergency response to floods.

This study presents an integrated hydraulic-hydrologic modeling system for flood prediction. In this system, the Delft3D two-dimensional hydrodynamic model is connected with a HEC-HMS hydrologic model and observation data to provide an automatic exchange of data and results. Delft3D and HEC-HMS were chosen for this study because they were widely used and provided good results. In addition, they were applied in several flood forecasting studies. The prediction weather data and watershed characteristics provide input to the hydrological model to predict streamflow conditions, which are then automatically fed into the hydrodynamic model. The hydrodynamic model simulates the flood characteristics such as water level, 2D depth-averaged velocity field, and flood extent. The system is applied to the Ottawa River. The bathymetric data of various sources are combined and interpolated to the Delft3D hydrodynamic model. The hydrodynamic model is validated against the measured water level and velocity profiles, showing a good agreement. The hydrological models were developed for the main Ottawa watershed. Then, they were calibrated and validated against observed discharge in different sub-watershed outlets. The reliability of hydrological models was assessed using several performance indicators. Generally, HEC-HMS hydrological models showed a good result in validation tests. The hydrodynamic model is then coupled with a hydrological model and data sources through a modular unified modeling platform. The flood forecasting system Delft-FEWS was used as a platform to integrate hydrodynamic and hydrologic models with weather prediction data. Finally, these models will be integrated into the flood forecasting system Delft-FEWS. They aim to forecast flood characteristics such as the flow in the watershed outlet, water level, and velocity in the Ottawa River.

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OPG	Ontario Power Generation
HQ	Hydro-Québec
MELCC	Ministère de l'Environnement et de la Lutte contre les changements climatiques of Quebec
PSPC	Public Services and Procurement Canada
R^2	Regression coefficient
RMSE	Root Mean Square Error
RRMSE	Relative Root Mean Square Error
NSE	Nash-Sutcliff
HSG	Hydrologic Soil Groups
HMS	Hydrologic Modeling System
DEM	Digital Elevation Model
PADDS	Pareto Archived Dynamically Dimensioned Search
Tc	Time of Concentration
QC	Quebec
ON	Ontario
CN	Curve Number
FEWS	Flood Early Warning System
NWP	Numerical Weather Prediction
XML	eXtensible Markup Language
GDPS	Global Deterministic Prediction System
UTM	Universal Transverse Mercator
WGS	World Geodetic System
EPSG	European Petroleum Survey Group
NWS	National Weather Service
WSC	Water Survey of Canada
ADCP	Acoustic Doppler Current Profiler

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CHAPTER 1 INTRODUCTION

1.1 Flood

Flood is considered as one of the most dangerous and deadliest natural disasters after earthquakes and tsunami [12] [13] [14] [15] [16]. The flood intensities and damages depend on several factors such as watershed characteristics, the mainstream, and location [12]. These disasters cause significant damage to the environment, infrastructure, the economy, and the health and safety of the population. Floods represent around half of the natural disasters caused by water [4] as it is shown in the Figure 1.1.

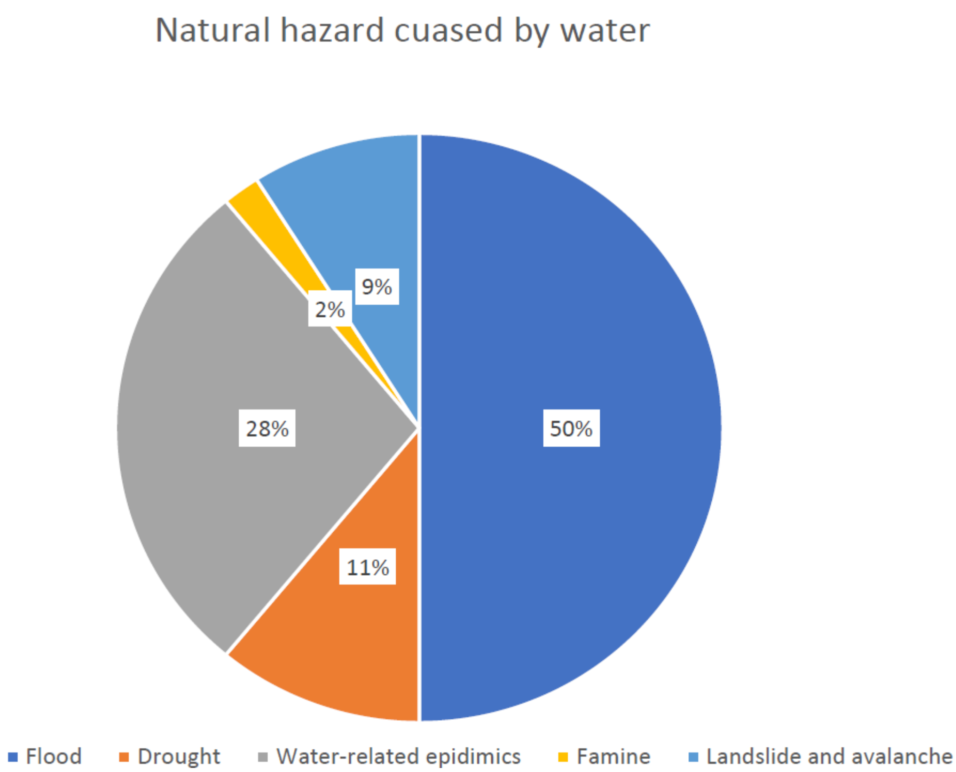


Figure 1.1 The main Natural Hazard caused by water [4]

Flood can be classified into several types including flash floods, coastal floods, estuarine flooding, and more [17]. The main flood type and their main causes are summarized in the Figure 1.2.

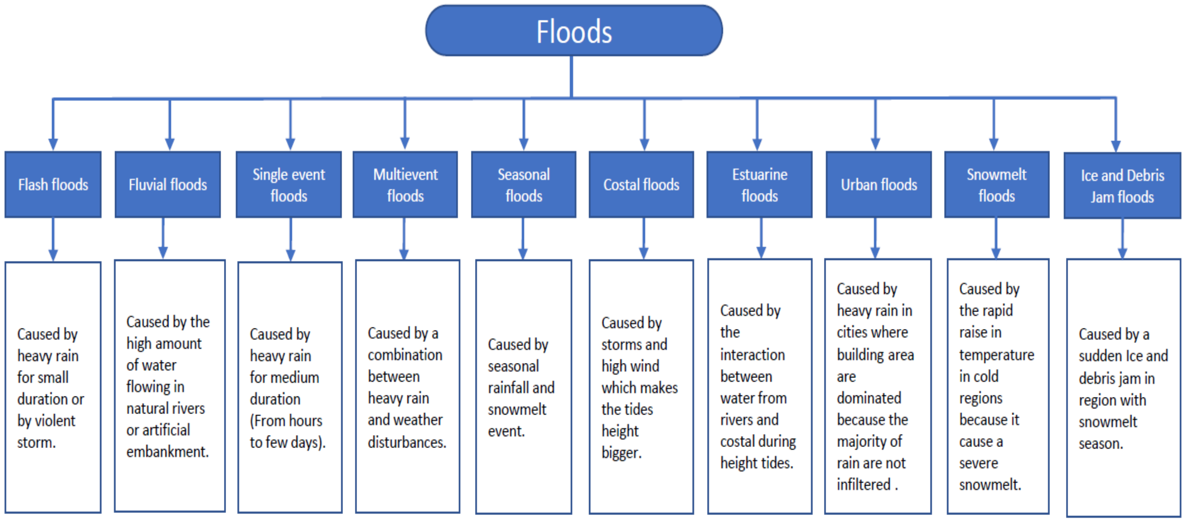


Figure 1.2 The main flood types and their causes [4]

The main causes of flooding are generally the heavy rains, snowmelt run-off [14] [18] [19], ice jams and other natural dams which lead to excessive runoff [20]. In addition, thunderstorms, coastal storms, and overwilling jams can cause flood in some cases [12]. These natural hazards cost losses in terms of human life and billions of dollars in terms of infrastructure damages [21]. Moreover, they can cause water pollution, destruction of aquatic habitat, losses in agricultural productivity, and interruption of transport means [17]. However, in very few cases, floods can present benefits such as transporting nutrients to the agricultural lands [17]. Many countries faced frequent flood events every year. For example, in 2002, in European countries, the damages caused by floods have been estimated at more than 7 billion [20]. In Germany, in June 2013, a flood caused a loss of around 10 billion in the Elbe and Danube catchments [22]. Also, in China (2015), a widespread flood in the Yangtze River Delta resulted in a dramatic economic damage [23].

Flood hazards are the most recurrent natural disasters in the majority of Canadian provinces [24] [12]. Ottawa watershed contains large flood areas from Ontario and Quebec sides. These areas have been often affected by spring flooding characterized by a high level of residential instability [25]. For example, between 1886 and 1965, ice jams caused floods in the St. Lawrence River in Montreal, that cost millions of dollars of damages and 5 deaths [14]. In 1954, in the Don and Humber rivers (Toronto), heavy rains and hurricane Hazel generated flooding hazards that caused losses in human life (around 80 deaths) [14]. In the spring of 1974, precisely in the Gatineau, Ottawa, St. Lawrence, Saint-Maurice, Richelieu, Châteauguay, and Chaudière rivers more than 300 municipalities were affected, and 7,000 people were evacuated [14]. In August 1996, a recorded flood disaster caused damages estimated around CAD $21,308 million [26]. Canadian floods in 2002 caused over $2 billion, and more than 198 lives lost [27]. Only between 2003 and 2012, floods caused around $20 billion (CAD) of losses [28]. More recently, in April 2019, several provinces of Canada have faced extreme spring floods. About 9,500 residents were evacuated from the province of Quebec [29].

Floods are likely to increase in volume, frequency, magnitude and duration in the future due to changing climate [20] [30] [17]. Climate change affects the spatial and temporal distribution of precipitation and temperature which lead to a remarkable effect on the glacier and snowmelt process [31]. Moreover, a lot of studies showed that climate change has huge impacts on the timing and magnitude of floods [18] [32] [33]. In recent decades, flood losses have increased in several areas and led to a growth of vulnerability [34]. Extreme Canadian floods in 2017 and 2019 are linked to climate change [28]. Climate change alters the magnitude of peak events, in Spring, Summer, and Fall as it is examined in Châteauguay watershed [35], and in the Red River basin in Manitoba [36]. In addition, it also affects surface storage of water capacity and the process of snowmelt [20].

A lot of research was carried out to develop advanced methods for flood prediction in purpose lessen catastrophically damage [15]. Several studies were conducted to examine changes in floods in Canada using methods such as the partial duration series to understand the flood behaviors [37], the timing and magnitude of flood trends in Canada with seasonal scale [18], machine learning in flood prediction [15], peak stream discharge to determine the level of flood risk [38], the stochastic extreme-value model and regional analysis to provide a physical description of the flood phenomenon [38]. These tools help Governments make suitable decisions on prevention and preparedness in order to create accurate risk flood mapping [39] [16].

Flood damages are expected to be higher in the future years. Consequently, scientists and decision-makers struggle to find suitable solutions that can alleviate these hazards [16]. Flood risk management starts primarily by controlling flood with infrastructure and managing behavior with laws and regulations [40] [41]. Hazard mapping is an essential step to facilitate flood management. It helps to detect dangerous and vulnerable areas. It leads to making adequate decisions [34], such as getting people out of the dangerous area. For example, in Mississippi, a buyout program aimed to evacuate 7700 properties in Missouri and Illinois [34]. Studying flood damage is becoming more important to determine the region vulnerable by creating flood risk maps [42].

1.2 Ottawa River Basin

Ottawa River Basin is one of the biggest watersheds in Canada. The Ottawa population is estimated around 2 million people [43]. Ottawa river is one of the largest rivers in eastern Ontario with a length of around 1130 km. It originates at Lake Capitmitchigama in Quebec and its outflow is located in the confluence with St. Lawrence River [44]. Ottawa river is considered as a natural provincial border between Ontario and Quebec. It starts from Lake Temiscaming to Carillon for a distance of around 580 km [45]. The Ottawa watershed has a surface area of approximately 146,000 km^2, 65% of which is located in Quebec and the rest in Ontario. The average annual flow is around 1968 m^3/s, the annual average of precipitation in the Ottawa River Basin is estimated to be 880 mm, and the vertical descent was estimated about 365 m [46]. Along the Ottawa River, existence hydro-electric stations and dams were constructed [47]. The Ottawa River is one of the main St. Lawrence tributaries. The total drainage area of the Ottawa River represents 11.2 % of the St. Lawrence River drainage area [46]. It is estimated around $(1,315,000\ km^2)$ [48]. It is one of the biggest drainage areas in Canada. Seven hydroelectric dams were built between Lake Temiscaming to Carillon from the 1880s to 1964 [3]. Dams are created in the Ottawa River mainly to produce electricity and for flood mitigation [3]. The main dams in Ottawa River Basin are illustrated in Figure 1.5 and their information are presented in Table 1.2. In addition, there are several dams with strong and low capacity as it is shown in Figure 1.4. There are around 28 of the main Ottawa River tributaries as it is shown in the following Table 1.1. Regarding to the main tributaries of the interesting section of the Ottawa River, the Ottawa River Basin is divided into seven main subwatershed as it is illustrated in Figure 1.3.

The Upstream Ottawa River basin is the main Ottawa sub-watershed. It springs from lake Capitmitchigama in Quebec and its outlet is located around Chaudière dam. It drains an area of 95 528 km^2.

The Rideau Valley Watershed is located in Eastern Ontario. It drains an area of over 4 000 km^2 of Eastern Ontario. The river rises from Upper Rideau Lake near Newboro and flows to the north to join the Ottawa River. The length of the longest part of the Rideau basin is estimated at 180 kilometers. The elevation varies from approximately 250 to 50 m above the mean sea level [49] [50] [51].

The Lievre River basin is a tributary of the Ottawa River. It drains an area of around 9133 km^2. The Lievre River is estimated at around 350 km.

The Gatineau River watershed is located in southwestern Quebec. It originates from Baskatong Reservoir and flows to join the Ottawa River. The total river length is about 400 km and the total drain area is estimated at 23 700 km^2. It covers an area of 26 785 km^2 which can be subdivided into six sub-catchments: Ceizur (6 840 km^2), Cabonga (2 662 km^2), Baskatong(6 200 km^2), Maniwaki (4 145 km^2), Paugan (2 790 km^2) and Chelsea (1 148 km^2) [52] [53].

The Petite Nation River basin is a tributary of the Ottawa river. It drains an area of around 2249 km^2. The Lievre River is estimated at around 128.5 km.

The Rouge River basin springs from Lac de la Fougère. The river length is estimated at around 161 kilometers and it joins the Ottawa river at the head of Long-Sault. The Rouge River drainage area is estimated around 5583 km^2 [54] [55].

The South Nation basin is located in eastern Ontario, Canada. The South Nation watershed has an area of around 3900 km^2. The basin is drained by the South Nation River to join the watershed outlet in the Ottawa River.

Table 1.1 Ottawa river tributaries [1]

Ottawa river tributaries in Ontario	**Ottawa river tributaries in Quebec**
Blanche River	Rivière Camichigama
Montreal River	Rivière Kanijevie
Matabitchuan River	Rivière Kipawa
Jocko River	Rivière Dumoine
Mattawa River	Rivière Schyan
Petawawa River	Rivière Noir
Indian and Muskrat River	Rivière Coulonge
Bonnechere River	Rivière Quyon
Madawaska River	Rivière Gatineau
Mississipi River	Rivière du Lievre
Rideau River	Rivière Blanche
South Nation River	Rivière du Petite Nation
Rigaud River	Rivière Rouge
Raquette River	Rivière du Nord

1.3 Problem statement

A lot of studies were carried out on how to minimize the flood effect in Canada generally and in the Ottawa River Basin specifically as reviewed in Table 2.2. Most of these studies aim to study a specific point such as simulating floodplains by developing hydraulic models, implementing hydrological models to assess the response of some Ottawa subwatershed to

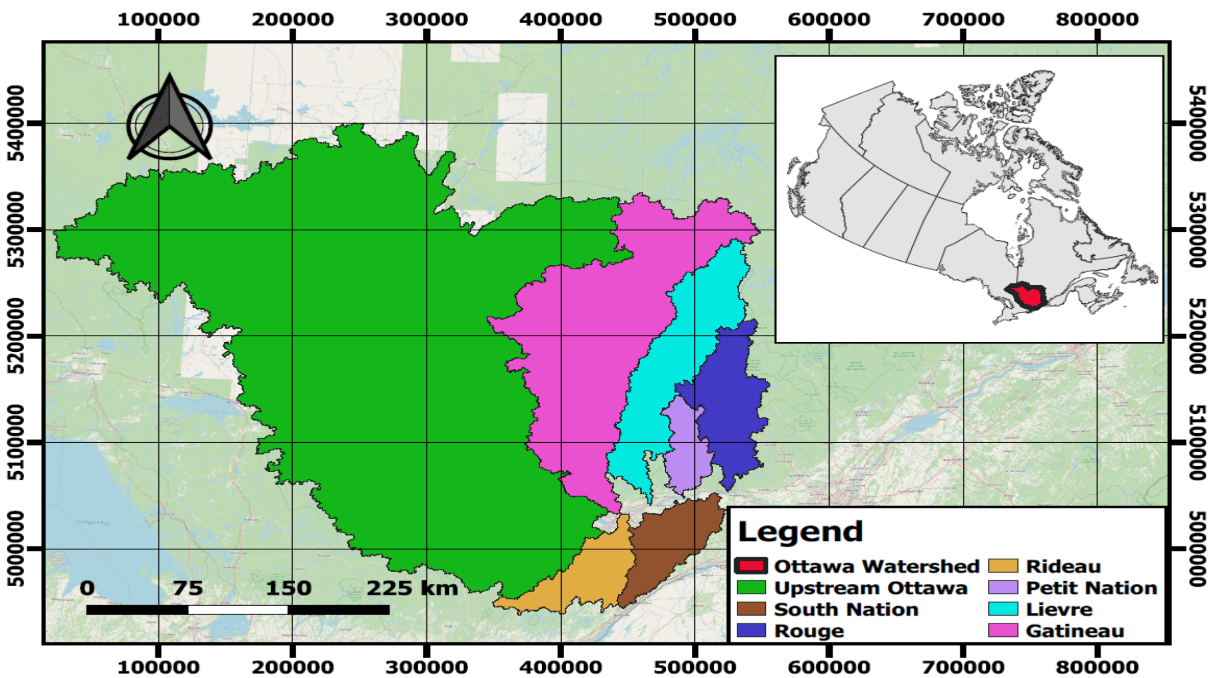


Figure 1.3 Location of Ottawa Watershed with Subbasin Delineations

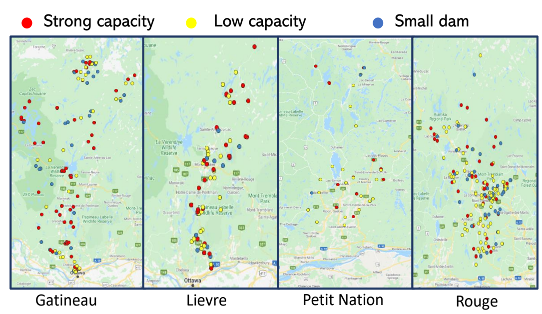


Figure 1.4 Dams in Quebec watersheds: source [www.cehq.gouv.qc.ca]

the rain event, or analyzing flood frequency, duration, and magnitude under historical and future climate data. This work sheds light on the flood forecasting system. Flood forecasting provides us with useful information related to flood characteristics. In short term, this predicted information helps authorities and decision-makers have more time to make the right decisions. This work consists of developing an integrated flood forecasting system that will be connected to hydraulic, hydrological models, and numerical weather prediction with the purpose to predict short-term early warnings and emergency response by providing flood characteristics. So, the authorities and decision-makers will have enough information and time to make the right decisions in purpose save the population's life and minimizing the economic losses.

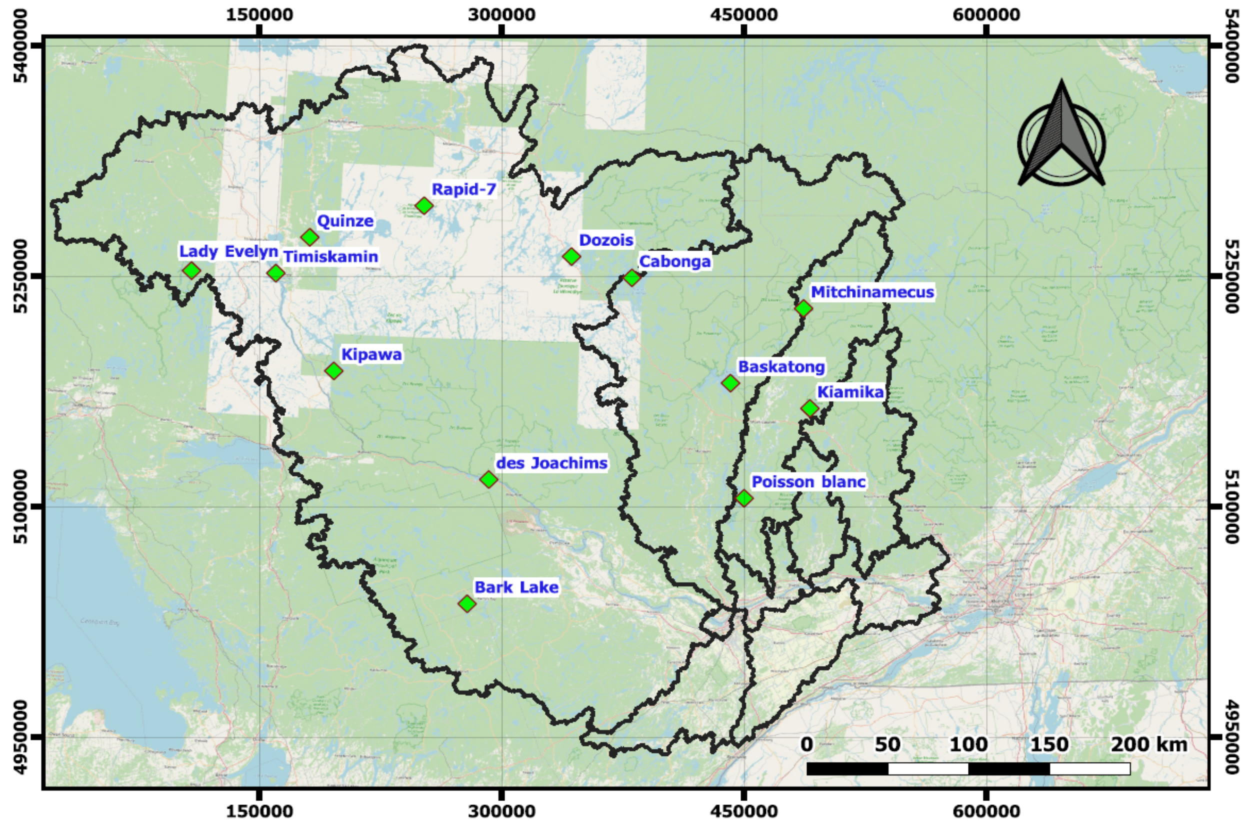


Figure 1.5 The location of the main dams in Ottawa River Basin

Table 1.2 The main dams in Ottawa River Basin : source [www.ottawariver.ca] and [www.cehq.gouv.qc.ca]

River	Dam name	Dam capacity (Mm^3)	Year of built	Agency Owned
Ottawa	Dozois	1 863	1949	HQ
	Rapide 7	371	1941	
	Quinze	2 750	1914	MELCC
	Timiskaming	1 217	1911	PSPC
	Des Joachims	229	1950	OPG
Montreal	Lady Evelyn	308	1925	
Kipawa	Kipawa	673	1912	MELCC
Madawaska	Bark Lake	374	1942	OPG
Gatineau	Cabonga	1 565	1928	HQ
	Baskatong	3 049	1926	
Lievre	Mitchinamecus	554	1942	MELCC
	Kiamika	379	1954	
	Poisson Blanc	625	1930	

CHAPTER 2 LITERATURE REVIEW

2.1 Hydraulic Model

A lot of research has been done to ameliorate the numerical models in the modeling of deep and shallow water. In addition, several hydrodynamic models were developed in order to simulate the water behavior in different cases such as the HEC River Analysis System (HEC-RAS) developed by the US Army Corps of Engineer's Hydrologic Engineering Center, MIKE11, and MIKE-21 from the Danish Hydraulic Institute, SOBEK-1D created by Delft Hydraulics, TELEMAC-2D and Delft3D [56]. These models solve the partial derivative Navier-Stokes equations. Unfortunately, there isn't yet an analytic solution for these equations. Consequently, these models use several Computational Fluid Dynamics (CFD) methods in order to discretize the Navier-Stokes equations for instance finite difference, finite volume, finite element, mesh-free particle, and moving particle semi-implicit methods [57]. CFD methods became an important numerical tool in different fields such as fluid mechanics, oceanography, flood mapping, turbomachinery, and aircraft design [58].

In this study, a bidimensional hydrodynamics model was developed using the open-source software Delft3D software. It is one of the powerful and widely used for a range of applications of simulating shallow water behaviors. Delft3D was tested and validated in several research works such as testing it with ferry and field measurements measurements [59] [60] [61]. Also, its capability was evaluated in nearshore flows [62] [63]. In addition, Delft3D performed well as commercial software, it showed good results against Mike21 in the case of river modeling [64] or in the study of A. M. Symonds et al. [65] where its performance was evaluated in comparison with Delft3D FM and MIKE 21 FM in Australia. Delft3D-Flow was widely used in several research works for hydrodynamics river modeling [66] [67] [64] [68] [69] [70]. Moreover, it was used in different simulation such as coastal and estuary modelling [71] [72] [73] [74] [75] [76], modeling sand and sediment transport [77] [78] [79] [80], tidal modeling [81] [82] , tidal turbines simulation [83] [84] [85], morphological modeling [86], hydrodynamic lake models [87], irrigation system modeling [88], storm modeling [89], evaporation simulation [90], salt intrusion modeling [91].

In hydrodynamics studies, model selection is an import step to start with. It aims to identify an adequate model that can simulate the water behavior with high accuracy as the reality. This work was conducted using Delft3D software. Then, we move to data collection which is very important to work in a study area where data is available. This data usually needs to be preprocessed. After that, we could start developing the hydrodynamics model then calibrating and validating with measured data and the final step is post-processing. These steps were summarized in the following diagrams 2.1.

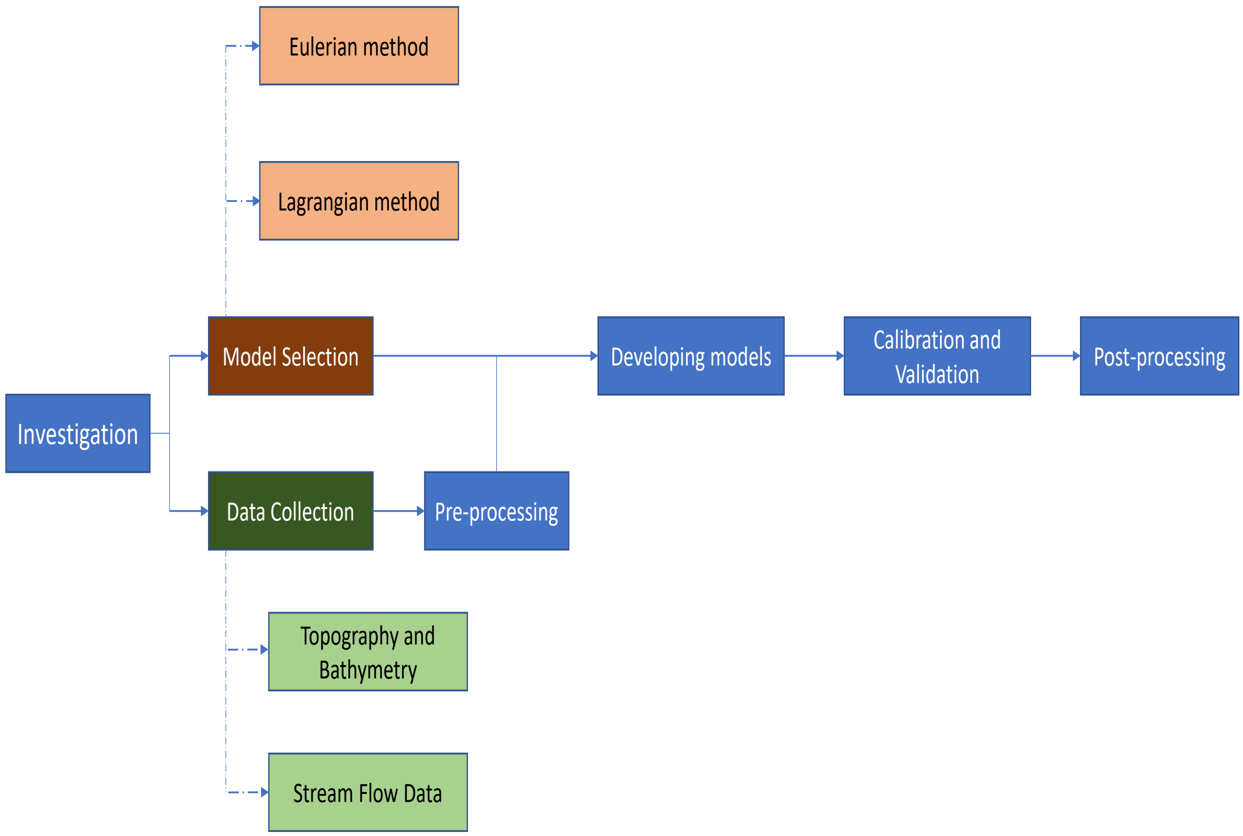


Figure 2.1 The main hydraulic model steps

2.1.1 Governing equations

The majority of hydrodynamic models used for river flow simulation discretize the Navier-Stokes equations for an incompressible fluid. There are two equations: the continuity equation and the momentum equation as it is shown below.

Continuity equation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{2.1}$$

Momentum equation

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = g_x - \frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{\mu}{\rho}\nabla^2 u \tag{2.2}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial u}{\partial z} = g_y - \frac{1}{\rho}\frac{\partial p}{\partial y} + \frac{\mu}{\rho}\nabla^2 v \tag{2.3}$$

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} = g_z - \frac{1}{\rho}\frac{\partial p}{\partial z} + \frac{\mu}{\rho}\nabla^2 w \tag{2.4}$$

Where: **u**, **v** and **w** are the components of the velocity along the x,y and z directions.
$g = (g_x, g_y, g_z)^T$ is the gravitational force per unit mass.
μ is the dynamic viscosity.
p is pressure.
∇^2 is a laplacian operator where $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$

The shallow water equation is given in the equation 2.5. For more information about demonstration please refer to the Open-Channel Flow book written by M. Hanif Chaudhry [92]:

$$\frac{\partial \underline{U}}{\partial t} + \frac{\partial \underline{E}}{\partial x} + \frac{\partial \underline{F}}{\partial y} + S = 0 \tag{2.5}$$

Where:

$$\underline{\mathrm{U}} = \begin{pmatrix} h \\ uh \\ vh \end{pmatrix} \quad ;\underline{\mathrm{E}} = \begin{pmatrix} uh \\ u^2h + \frac{1}{2}gh^2 \\ uvh \end{pmatrix}; \quad \underline{\mathrm{F}} = \begin{pmatrix} Vh \\ uvh \\ v^2h + \frac{1}{2}gh^2 \end{pmatrix}; \quad \mathrm{S} = \begin{pmatrix} 0 \\ -gh(S_{ox} - S_{fx}) \\ -gh(S_{oy} - S_{fy})\frac{1}{2}gh^2 \end{pmatrix}$$

and (uh) and (vh) are momenta convected in x- and y-directions. Using Manning equation S_{fx} and S_{fy} are defined as follow:

$$S_{fx} = \frac{n^2 u\sqrt{u^2+v^2}}{C_o^2 h^{1.33}} \qquad S_{fy} = \frac{n^2 v\sqrt{u^2+v^2}}{C_o^2 h^{1.33}}$$

For more detail please refer to Delft3D FLOW manual [93].

2.2 Watershed hydrology

Hydrology is the science that studies the water cycle, from its occurrence, circulation, and distribution. Hydrological models consist of understanding water behavior in watersheds and estimating flow in the catchment outlets [94]. The Stanford Watershed Model (SWM) was one of the first hydrological modeling programs. These programs aim to predict streamflow using observed meteorological data such as precipitation and temperature [95]. Scientists often aim to develop hydrological models with simple structures [96]. There are several applications of hydrological models. For instance, flood forecasting, design and planning, and flood protection [95]. Hydrological models aim to simulate natural processes with a greater goal of estimating river flow [95]. Flow discharge and volume is often used to evaluate floods, droughts, erosion, sedimentation, water pollution, deterioration of lakes, and more [95].

2.2.1 Hydrological model

Several hydrological models were developed all over the world. They differ significantly from each other depending on the purpose which are used for. In addition, the choice of a suitable hydrological model depends on several factors such as model structure, data availability, data quality, and computing time. For instance, the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) is widely used in the U.S for different purposes such as designing drainage systems. Moreover, it was widely used to simulate hydrological phenomena and to support engineering works such as in Canada [97], in China [98], in Morocco [99] and in more countries around the world. The National Weather Service (NWS) model is designed for flood forecasting applications. The Hydrological Simulation Program Fortran (HSPF) serves the Environmental Protection issue. The Modular Modeling System (MMS) model of the USGS is widely used for water resources planning and management applications. The distributed hydrological model (WATFLOOD) is widely used in Canada for hydrological simulation. The runoff routing model (RORB) and WBN models are effective for dealing with flood forecasting, drainage design, and evaluating the effect of land-use change in Australia. In many European countries, the standard hydrological models are TOPMODEL and SHE. In Scandinavian countries, The HBV model is known for its application flow forecasting works. The ARNO, LCS, and TOPKAPI models are known in Italy. The Tank models and Xinanjiang model are popular in Japan and in China, respectively [95]. Table 2.1 illustrates the main strengths and weaknesses of different hydrology model types.

Several hydrological models were adopted in Ontario and Quebec provinces. The famous ones were reviewed in Z. Zahmatkesh et al. [12]. For example, in Ontario, we found WATFLOOD [100], Distributed System Hydrologique European (SHE) [101] and HEC-HMS [102]. In Quebec, we have WATFLOOD [103] and HBV [103]. Moreover, a lot of studies were conducted in implementing hydrological models in Quebec and Ontario. For example, the Soil and Water Assessment Tool (SWAT) model was implemented in the Canard River Watershed in Quebec. This model aims to assess and understand the hydrologic regime and the

Table 2.1 Comparison of the main rainfall-runoff models type [2].

Hydrology Model Type	**Strength**	**Weakness**	**Best case of use**
Empirical	Require not many parameters to develop models. It is fast and accurate	No connection between physical catchment.	Adequate for ungauged catchment.
Conceptual	The model has a simple structure and it is easy to calibrate it	Spatial variability is not taken into consideration within the watershed.	When Data or the computational ability are limited.
Physical	Include temporal and spatial variability	Dealing with high number of parameters which make the calibration more challenging.	The availability of high-resolution data.

future climate change's impact on the hydrology process [104]. Another study was conducted to understand the climate change impact on the hydrology of the southern Ontario basin (Spencer Creek watershed). Several hydrological models were developed such as SAC-SMA, IHMS–HBV, and HEC-HMS [105]. Moreover, the distributed model HYDROTEL, the lumped model HSAMI, HMETS, MOHYSE, and GR4J were developed for 192 watersheds in the province of Quebec, these models were developed with high resolution climate data to assess the reliability of distributed and lumped models to simulate streamflow in basin outlets [106]. Four hydrological models HSAMI, HYDROTEL, WASIM-ETH, and PROMET were implemented in the Saumon watershed in order to understand the effect of the hydrological model on uncertainty using ensemble approach [107]. Furthermore, the distributed hydrological model HYDROTEL was used in several catchments in Quebec such as in the Chute du Diable watershed [108], in the Chaudière watershed [109] and in the Necopastic watershed [110].

2.3 Flood Forecasting

The flood forecasting process aims to forecast flood events that are likely to happen in the future. It consists of using numerical weather prediction, streamflow data, the rainfall-runoff, and hydraulic models to predict flow and water level for a future time, generally for a few hours to days [12] [111]. This process helps convert extreme events to warnings which helps authorities to make the right actions [5]. The flood forecasting system contains several components which start from collecting data, simulation, and forecasting. Data is collected, pre-processed, and displayed through flood forecasting systems such as WISKI or DELFT-FEWS. The forecasting result provides us with some warnings that should be transferred to decision-makers. These steps can be summarized in the following Figure 2.2.

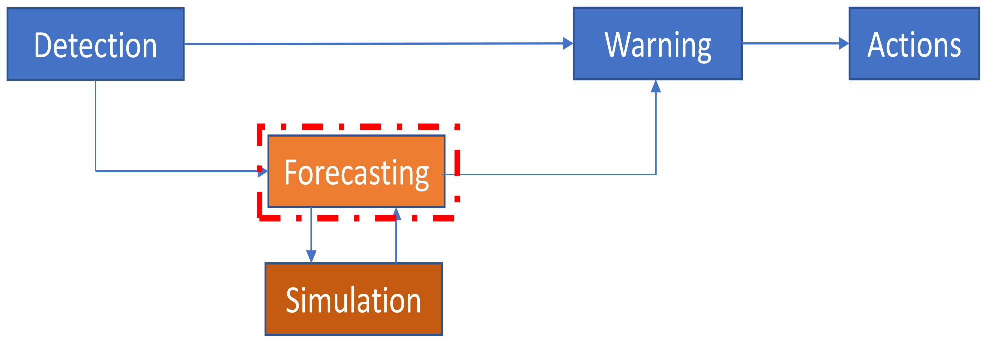


Figure 2.2 The Main Flood Forecasting Steps

Flood forecasting program is crucial for countries that face flood events regularly. Canadian provinces are developing their center for collecting and managing meteorological and hydrometric data. Moreover, they develop hydrological and hydraulic models by using the watershed characteristics and data availability [12]. FloodNet is a multi-disciplinary research network related to floods in Canada (www.nsercfloodnet.ca). FloodNet efforts consist of having a good understanding of flood hazards and improving flood forecasting and warning technology [12].

Generally, all flood forecasting programs are respecting the seven main steps: Monitoring, Flood Forecasts, Forecast Interpretation, Warning Communication, Response, and Further Dissemination. In this section, we will make some comparisons between different flood forecasting programs in several countries such as Canada (Ontario, Saskatchewan, Manitoba, Alberta, and British Columbia), the United States (Colorado), Australia, and Europe (France, Netherland, and Switzerland). We observe that every country is developing its local agencies for collecting data for its region. Data is very important to be available with high accuracy in order to forecast extreme events with small uncertainty. For example, in our study area Ontario, Organizations that are responsible for Monitoring steps are the National Oceanic and Atmospheric Administration, Environment Canada, Water Survey of Canada, as shown in the Figure 2.3. The majority of countries have a Forecast Centre which is responsible for Flood Forecasts, Forecast Interpretation, Warning Construction, and Warning Communication. Local Governments, Infrastructure Owners, Dam Operators, and Emergency are those who take action. Finally, in Further Dissemination, we find Public and Mass Media. The Flood forecasting programs are listed in Annex A and for more information please refer to "Flood Forecasting Jurisdictional Review Improving Flood Forecasting in Alberta April 30, 2014" [5].

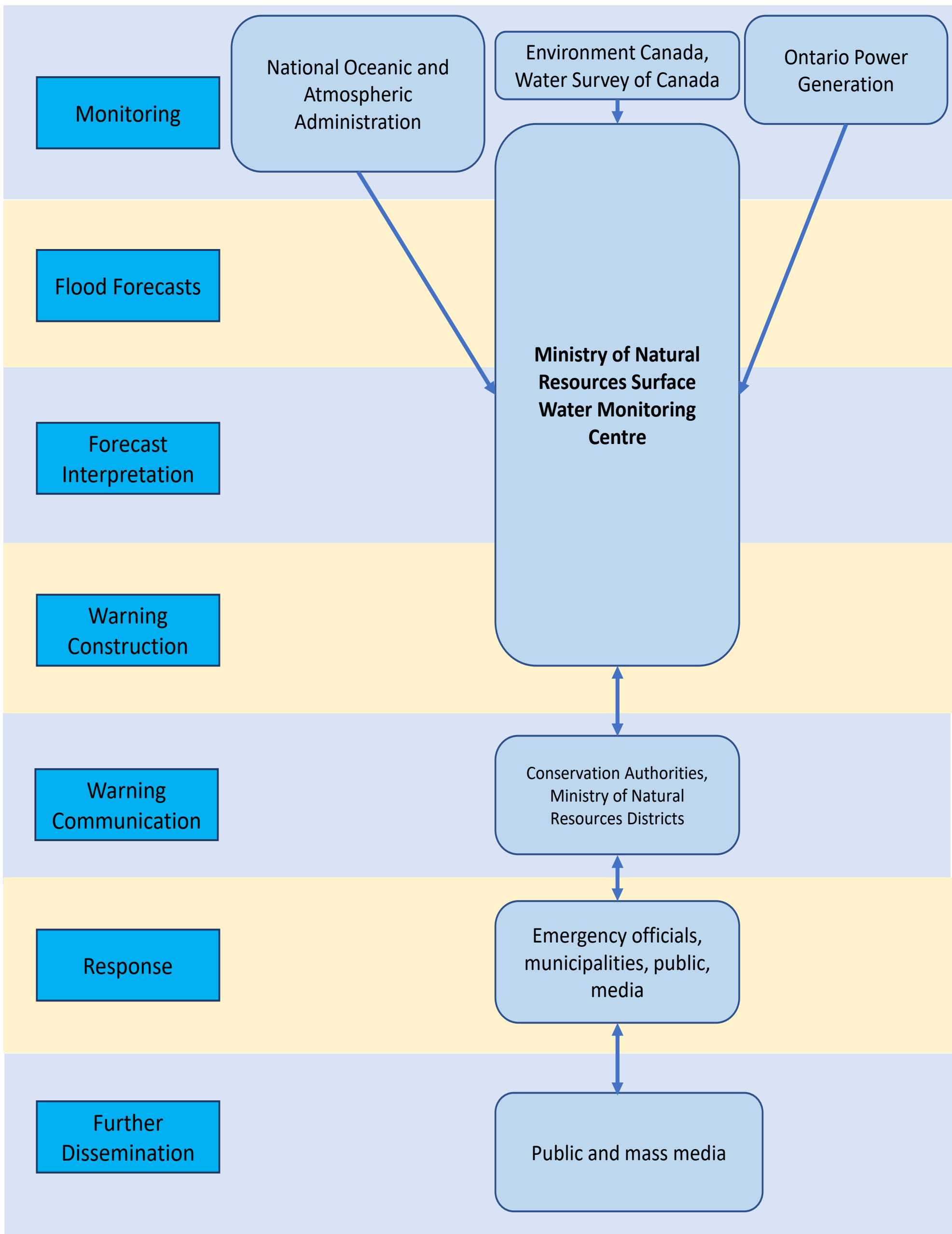


Figure 2.3 The Ontario Flood Forecasting Program [5]

2.3.1 Flood forecasting and warning

Flood forecasting systems are crucial in hydrology because of their importance in decreasing flood impacts, they were developed and used in many countries around the world [111]. For example, European countries use several hydrological models: LISFLOOD, HBV, TOPKAPI, and LISFLOOD-2D for hydrodynamic modeling in their flood forecasting [112], it is connected to numerical weather prediction for the rainfall input in order to provide flood information up to 15 days in the future [111]. In Nepal, HEC-RAS and MIKE 11 were used for hydrodynamic modeling and MIKE NAM was used as a semi-distributed hydrological model with telemetry and satellite rainfall forecast [113] [111]. URBS distributed hydrological model and SWIFT Continuous hydrological model has been used in the Australian operational flood forecasting systems since 2015 [114]. In the Netherlands, Deltares developed an open-shell system DELFT-FEWS for managing and handling time series data. Several hydraulic and hydrological models can be connected to DELFT-FEWS and it was implemented in several countries including Canada [115].

DELFT-FEWS was chosen to be the flood forecasting system for this study. It was adopted by different flood forecast agencies all over the world. The Netherlands is one of the famous countries that use the flood forecasting system DELFT-FEWS for its flood forecasting program. For example, DELFT-FEWS is used in the Netherlands in sewage spilling applications and for developing an integrated platform that ensures a real-time connection between external models and weather prediction data [116] [117]. Then, it was applied in several flow forecasting systems in different countries such as England, Wales, Scotland, Germany, Switzerland, Taiwan, Italy, USA, Austria, Sudan Singapore, Russia, Spain, in the Mekong basin and Canada [118] [117]. In USA DELFT-FEWS was applied in 13 river forecasting centers by the National Weather Service River Forecasting System [119] [117], In Sudan, it was used to develop a flood warning system for Blue Nile River [120] and was used for the Punjab in Pakistan [115] [117] too. It was applied in several research projects in Europe [112] [117]. Moreover, DELFT-FEWS was applied in the Environment Agency in Wales and Scotland [121] [117]. It is not only applied in its main purpose (flood forecasting) but also it was used in different applications for example groundwater management, water quality forecasting, water information system and more [118].

2.4 Research review in Ottawa River Basin

Several research studies were carried out in the Ottawa River Basin. These researches focus on different domains such as hydrological, hydraulic, and flood modeling as summarized in the following Table 2.2. This review study shows that the integrated flood forecasting system with DELFT-FEWS will be implemented in the Ottawa River Basin for the first time.

Table 2.2 Key case studies related to hydrological model in Ottawa River Basin

Study Type	Study area	Study objectif	Reference
Hydrological Modeling	Ottawa	This study aims to assess the role of heavy rain on the spring flood 2019.	M. C. Kirchmeier-Young, H. Wan et X. Zhang [122]
	Ceizur	This study was conducted in the snow dominate watershed Ceizur River Basin (Sub-basin of Gatineau watershed) in order to assess and understand the uncertainty of hydrological models in climate change impacts.	A. Poulin et al. [123].
	Gatineau	This study aims to estimate the snow water equivalent using the hierarchical Bayesian method.	O. Seidou et al [124]
		This work consists of developing a method using Neural Network in purpose to infill missing precipitation data.	P. Coulibaly et N. Evora [125]
		This study assesses the uncertainty of several hydrological models structure in the climate change studies.	A. Poulin et al [123]
	Rideau	Developing a hydrological model using the SWMHYMO model	F. Ahmed et al [126] [127]
		Developing a hydrological model using the Mike 11 model for the main Rideau subwatershed.	F. Ahmad [128] [129]
		Accurate precipitation data are very important in hydrological modeling. This study aims to make a comparison of different spatial interpolation methods for precipitation over the rideau valley.	M. Ramey [130]

Table 2.3 Key case studies related to hydrological, hydraulic and flood modeling in Ottawa River Basin

Study Type	Study area	Study objectif	Reference
Hydrological Modeling	South Nation	Many hydrological models need land use information to generate Curve Number grids. This study aims to predict land use series of maps using the land-use allocation algorithm of the Dyna-CLUE.	A. Alodah [131]
		Climate change is crucial in hydrological modeling. It helps to understand streamflow and water behavior within the catchment. This study aims to develop different climate change scenarios.	A. Alodah [132]
	Include Ottawa River Basin	This Study aims to make future projections for changes in flood properties . It uses 21 General Climate Models in order to estimate streamflow for historic and future periods across Canada.	A. Gaur et al. [28]
Hydraulic Modeling	Upstream-Ottawa	Developing a hydraudynamic and water Quality model using Mike FM.	M. Taghipour et al. [133]
		Developing a hydrodynamic and water Quality model using Mike21	Baird [134]
	Downstream Ottawa	Developing a hydrodynamic and water Quality model using Mike21.	Baird [135]
	Ottawa river	This study aims to evaluate the reliability pressure assumption (hydrostatic versus non hydrostatic) in Ottawa river by using Delft3D software.	P. Parsapour-Moghaddam et C. Rennie [69]
	Rideau	Developing hydrodynamic model using Mike 11	F. Ahmad [49]
Flood Modeling	Ottawa	Statistics Canada generates flood maps for the most regions affected by flood events using the Canadian Space Agency and Natural Resources Canada data.	I. Olthof et al. [136] and Statistics Canada [137]
	Gatineau	This study aims to produce flood maps using the height above the nearest drainage model and machine learning.	M. Esfandiari et al. [138]

Table 2.4 Key case studies related to flood forecasting in Ottawa River Basin

Study Type	Study area	Study objectif	Reference
Flood Forecasting	Ottawa	Developing hydrodynamic model using HEC-RAS.	F. Ahmad et al. [139] [140] [126] [127]
		Developing Near-real-time flood forecasting using satellite precipitation products in the purpose to minimize flood damages.	N. Belabid et al. [141]
	Gatineau	This study makes a comparison between several conceptual models. It shows that the height above the nearest drainage network model provides a good flood prediction.	H. McGrath et al. [142]
		This study consists of making a comparison between ensemble and deterministic hydrological data in flood forecasting.	M.-A. Boucher et al. [52]
		This study aims to develop a forecast hydrological system using Hydrotel hydrological model with ensemble precipitation forecast data.	M.-A. Boucher et al. [143]
		This study consists of making a comparison between for different hydrological forecasting systems in purpose to assess the hydro-economic.	M.-A. Boucher et al. [144]
	Ottawa and Gatineau rivers	This study aims to produce Near-real-time flood forecasting by using satellite precipitation products.	N. Belabid et al. [141]
	Rideau	This study aims to develop short-term snowmelt river flood forecasting using a cross-wavelet analysis method.	J. F. Adamowski [145]

CHAPTER 3 OBJECTIVES AND ORGANIZATION OF WORK

3.1 Research objectives

The main goal of this study is to develop an integrated flood modeling system for the Ottawa River, to predict short-term early warnings and emergency response by providing flood characteristics such as water level, and flood extend. This information help authorities and decision-makers to have enough information and time to make the right actions.

This work is organized to address several objectives, as listed below:

- Data acquisition and processing: identifying and collecting the topographic, bathymetric, hydrometric, and climatic data (required for configuration and validation of the models) for the study region.
- Developing and validating a 2D hydraulic model based on Delft3D software in Ottawa river.
- Developing, calibrating, and validating a hydrological model based on the HEC-HMS model for the main Ottawa River sub-watershed
- Interconnecting the hydraulic model, hydrological model, and the weather prediction data through a unified modeling platform in our case the flood forecasting system DELFT-FEWS was used.

3.2 Organization of the work

This work consists of three major tasks, the first part aims to develop a hydraulic model for the Ottawa River using Delft3D software. Delft3D was used to develop hydraulic models for two sections of the Ottawa River: about 20km upstream and about 120km downstream of the Chaudiere dam. The second part includes the development of hydrological models for the main Ottawa subwatershed. Finally, the third part aims to connect the hydraulic, hydrologic models and real-time numerical weather prediction in the flood forecasting system DELFT-FEWS. These models will be connected to a Flood Forecasting System. In our case, we choose to work with the DELFT-FEWS platform.

There are several intermediate tasks either to prepare data, to post-processing results, or make model files compatible with the Flood Forecasting System DELFT-FEWS. The main tasks of this project are summarized in the following diagram 3.1.

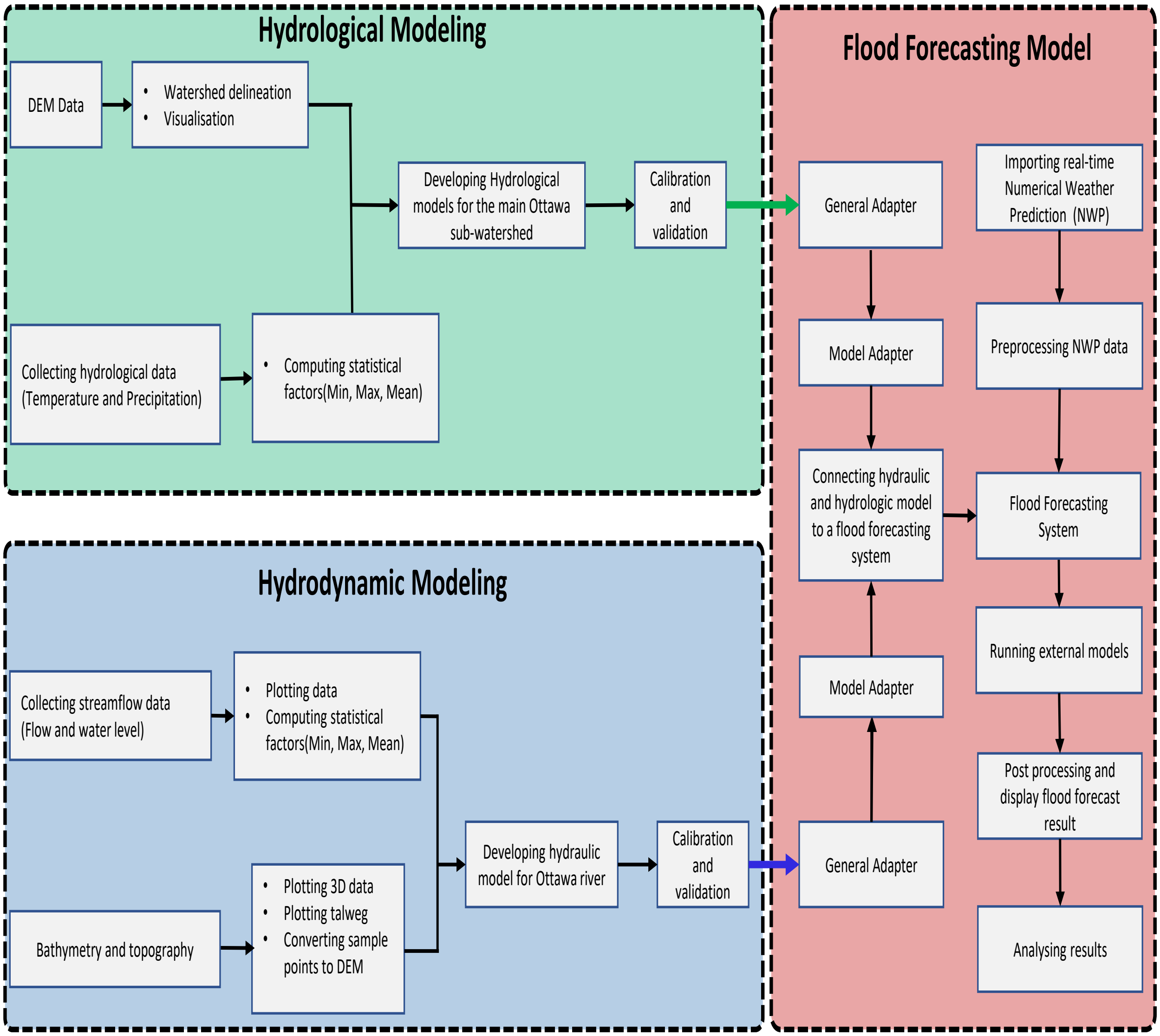


Figure 3.1 The organization of the main tasks to develop integrated flood forecasting system.

CHAPTER 4 HYDRAULIC MODEL FOR OTTAWA RIVER

4.1 Introduction

This chapter presents the hydraulic model of this study. The model has been developed, based on the Delft3D, for the Ottawa River. Two hydraulic models will simulate the water behavior in the two sections of the Ottawa River: about 20km upstream and about 120km downstream of the Chaudière dam. This work is organized as follows: Firstly, by presenting the study area of hydraulic models. Then, describing the structure of the numerical model Delft3D and the data used to develop hydraulic models. Finally, the Delft3D results will be discussed and validated in the important flood event (2017 and 2019) in Ottawa River.

4.2 Study area

Ottawa River has a length estimated at around 1130 km. It springs from lake Capitmitchigama in Quebec and its outflow is located in the confluence with St. Lawrence River [44]. Ottawa river is considered as a natural provincial border that separates Ontario and Quebec. It starts from Lake Temiscaming to Carillon for a distance of around 580 km [45]. The Ottawa River is one of the main St. Lawrence tributaries. My work aims to develop a hydraulic model for two sections of the Ottawa River: about 20 km upstream from Chat Fall to Chaudière Dam as it is shown in Fig.4.2 and about 120 km downstream of the Chaudière dam from Chaudière Dam to Carillon Dam as it is illustrated in Fig.4.1.

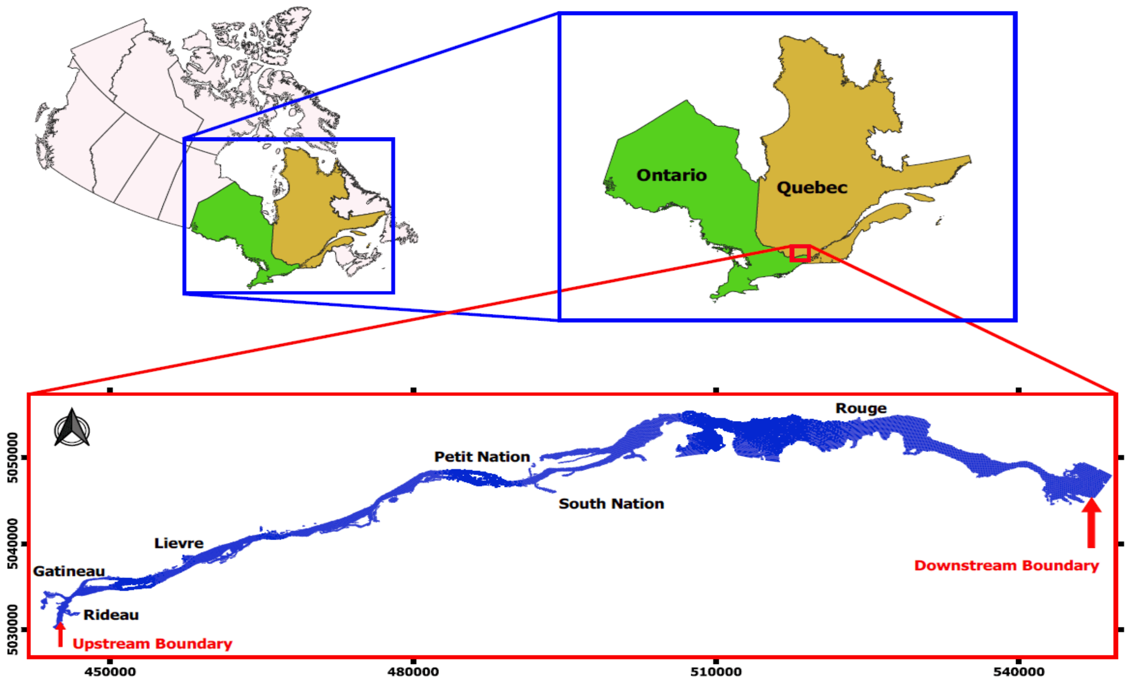


Figure 4.1 Downstream Ottawa River from Chaudière Dam to Carillon Dam [6]

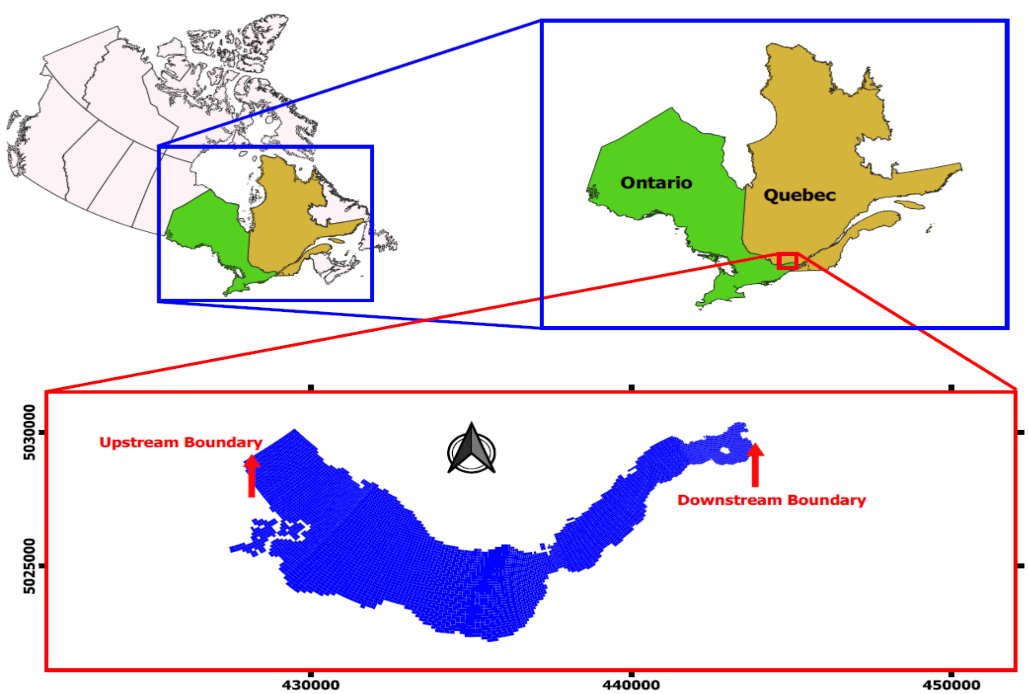


Figure 4.2 Upstream Ottawa River from Chat Fall to Chaudière Dam [6]

4.3 Numerical model Delft3D

Delft3D is an open-source 2D/3D modeling software, developed by the Deltares institute. Delft3D-Flow is one of the most widely used hydrodynamic models for river flow simulation. It simulates hydro-morphodynamic processes on a rectilinear or a curvilinear grid. Delft3D's flow module code solves the Navier-Stokes equations using shallow water assumptions and the Boussinesq approximation. It is based on the finite difference method and solves the partial differential equation depending on initial and boundary conditions [146].

4.3.1 Delft3D Structure

Delft3D is a software package that was designed to model the water flow and its quality. It contains many modules in the order to provide two- and three-dimensional results of flow, surface wave, water quality, ecology, sediment transport, and coastal areas simulations.

There are three main modules integrated into Delft3D software (Delft3D-FLOW, Delft3D-WAVE and Delft3D-WAQ). Here is a brief description of these modules :

- **Delft3D-FLOW** is the hydrodynamic module in the Delft3D package. It calculates nonsteady flow based on shallow water equation as it mentioned in the equation 2.5 [60].

- **Delft3D-WAQ** is the water quality package in Delft3D. It is widely used in water quality management and integrated management [147].

- **Delft3D-WAVE** is a numerical model in the Delf3D package. It simulates coastal waves and provides an estimation wave parameter from given stationary wind, bottom, and current conditions. It uses the HISWA-model [148] [60].

In this study, the Delft3D-FLOW module will be used as a hydrodynamics model for the Ottawa River simulation. Some additional tools are used to prepare files or display results. These programs are contained in the Delft3D package.

4.3.2 Pre-processing

For pre-processing, two main tools help to prepare the main Delft3D input files.

- **RGFGRID** is a tool that provides users the ability to manipulate and visualize orthogonal, curvilinear model grids for the Delft3D-FLOW.

- **QUICKIN** is a tool that aims to create, manipulate and visualize model bathymetry. Moreover, it helps to alter or to prepare the Delft3D input files such as depth, initial velocity or water level, and roughness.

4.3.3 Post-processing

The post-processing is done with Delft3D self-developed MATLAB routines named Quick-Plot, this tool helps to show simulation results with reasonable and relative accurate comparisons with the measurements.

There are several tricks that the Delft3D user should be respected to avoid numerical simulation issues as instability.

- Gridlines must intersect perpendicularly
- Grid spacing must vary smoothly (M- and N smoothness) over the computational region.
- The orthogonality coefficient should be below (< 0.04)

4.3.4 Numerical stability

Stability is very crucial in hydrodynamics models. For this reason and to have an accurate result, it is suggested that the Courant Number should be inferior to 10 [146].

$$C_t = 2\Delta t\sqrt{gh\Big(\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2}\Big)} \tag{4.1}$$

Where:

C_t	: Courant number
Δt	: Time step
g	: Gravitational acceleration
h	: Water depth
$\Delta x, \Delta y$	: Horizontal grid size in respectively x and y-direction

4.3.5 Governing equation for Delft3D-FLOW

The software used in the hydrodynamic model is Delft3D. Delft3D-FLOW is the package responsible of solving the Navier Stokes equations for incompressible fluid [149] [146].

Continuity equation

$$\frac{\partial \zeta}{\partial t} + \frac{\partial [hU]}{\partial x} + \frac{\partial [hV]}{\partial y} = 0 \tag{4.2}$$

Horizontal momentum equation

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} = -g\frac{\partial \zeta}{\partial x} + fV + v_H + \left[\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2}\right] + \frac{gU\sqrt{U^2+V^2}}{HC^2} + \frac{\rho_{air} C_d W_x \sqrt{W_x^2 + W_y^2}}{\rho_0 H} \tag{4.3}$$

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} = -g\frac{\partial \zeta}{\partial y} + fU + v_H + \left[\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2}\right] + \frac{gU\sqrt{U^2+V^2}}{HC^2} + \frac{\rho_{air} C_d W_y \sqrt{W_x^2 + W_y^2}}{\rho_0 H} \tag{4.4}$$

Where: ζ is the water level according to the reference level, d is the depth towards reference level, H is the total water depth, U and V are the depth average velocity in respectively x and y-direction, W_x and W_y are the wind speed in respectively x and y-direction, f is the Coriolis parameter, g is the acceleration gravity, C is the Chezy-coefficient, C_d is the wind shear stress coefficient, ρ_0 the density of water, ρ_{air} is the density of air, v_H is the horizontal eddy viscosity.

For more information about the capability of Delft3D you can be referenced to the Delft3D-FLOW user manual [93] [146].

4.4 Numerical Data

Generally, hydrodynamic models need Bathymetry, topography, and hydrometric data. These data will be presented and discussed in the following section.

4.4.1 Bathymetry and Topography data

For this study, the Ottawa River bathymetry was obtained from three different sources: Canadian Hydrographic Service [150], Baird & Associates [151] and GeoBase [152]. Then, it was merged by giving the priority to bathymetry then to topography. The final results of the bathymetry for both sections of the Ottawa River are illustrated in the Figures 4.3 and 4.4.

- **First bathymetry**: This bathymetry is taken from Canadian Hydrographic Service [150]. It has a 20 meters resolution and covers the area from the west of the Rideau Canal (by Parliament Hill) along the Ottawa River to the Saint Lawrence, all the way to Sorel-Tracy, QC. Also, it includes parts of the Richelieu River and the Canadian portion of Lac Memphrémagog. The data is given in the projection of EPSG 4326 (WGS 84) [150].

- **Second bathymetry**: The digital elevation data were surveyed by W.F. Baird & Associates Coastal Engineers Ltd. ("Baird & Associates") for the City of Ottawa as part of the Ottawa Surface Water Vulnerability Study. this data covers the area from Shirley's Bay to Chaudière Dam. The data is given in the projection of UTM Zone 18N WGS84 [151].

- **Topography**: The Canadian Digital Elevation Model (CDEM) is part of Natural Resources Canada's altimetry system. CDEM covers generally the whole Canadian territory. The base resolution for CDEM data is 20 m [152].

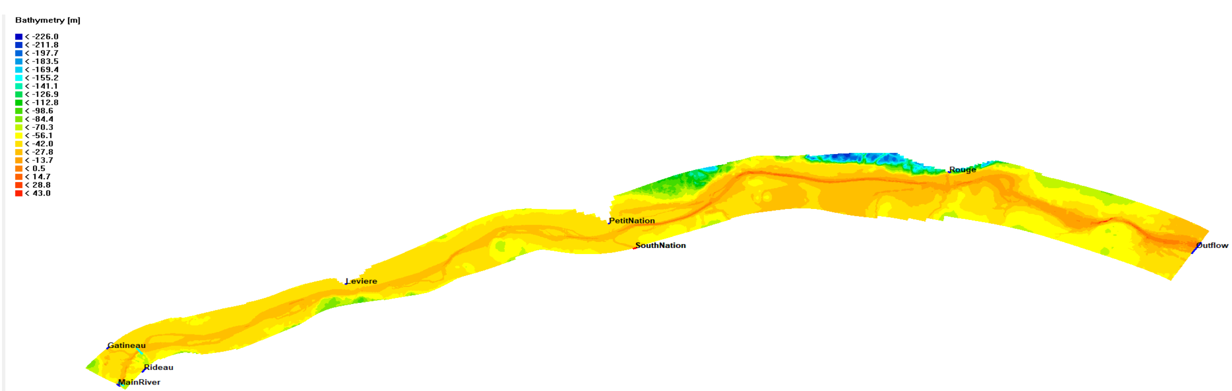


Figure 4.3 The bathymetry of downstream Ottawa River from Chat Fall to Chaudière Dam

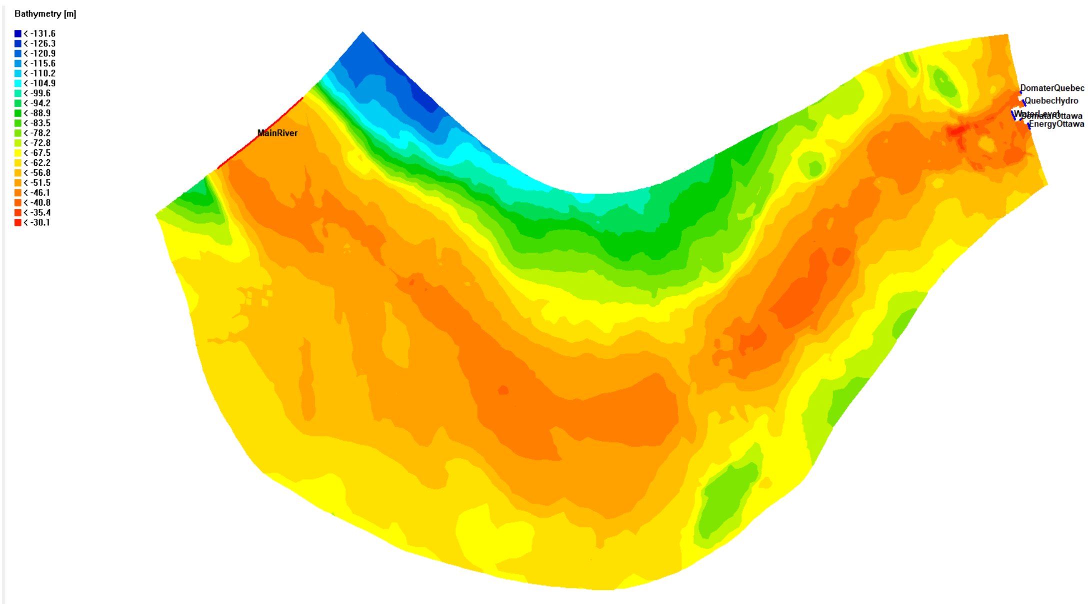


Figure 4.4 The bathymetry of Downstream Ottawa River from Chat Fall to Chaudière Dam

4.5 Hydromertic data

Streamflow data are crucial in hydraulic modeling. It serves to define the boundary conditions. For this study, data was collected from several sources as it is shown in Table 4.1 which presents the main Ottawa River tributaries with their main annual discharge. A Flow Duration study was applied for the streamflow data to assess their contribution to the Ottawa River. The results are shown in Figure 4.6. It is shown that Gatineau is the main Ottawa River tributary with an annual discharge estimated at 368 m^3/s. Then, South Nation and Rouge have a high discharge in the first 5% as it is clearly shown in the flow duration Figure4.6. Moreover, the tributaries' time-series flow data for the last five years from the beginning of 2015 to 2020 were plotted as it is shown in Figure 4.5. It showed that the peaks were recorded in 2017 and in 2019 which are corresponding to the recent flood event in the Ottawa River.

The station named 'OTTAWA RIVER AT BRITANNIA' (www.wateroffice.ec.gc.ca) was used for this study as a boundary condition for the main Ottawa River. Its data was investigated, the annual mean flow and the water level were calculated as it is presented in Figures 4.7 and 4.8. It showed that the peak flow is recorded for the period starting from March to the end of June which is the flood period in the Ottawa River.

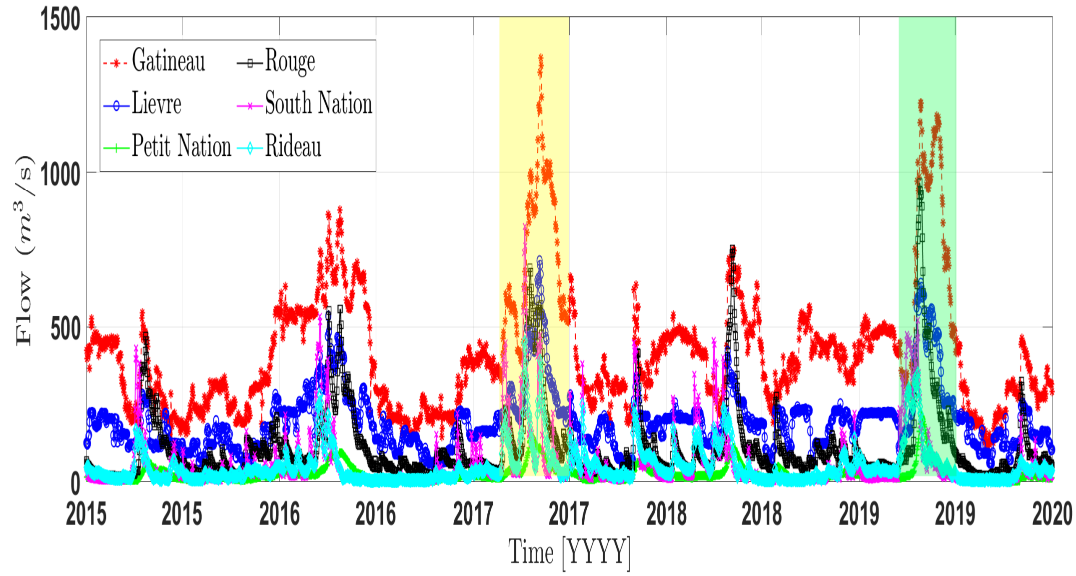


Figure 4.5 Plotting the time series flow data for the main Ottawa River: The yellow and green highlight correspond to the main flood events

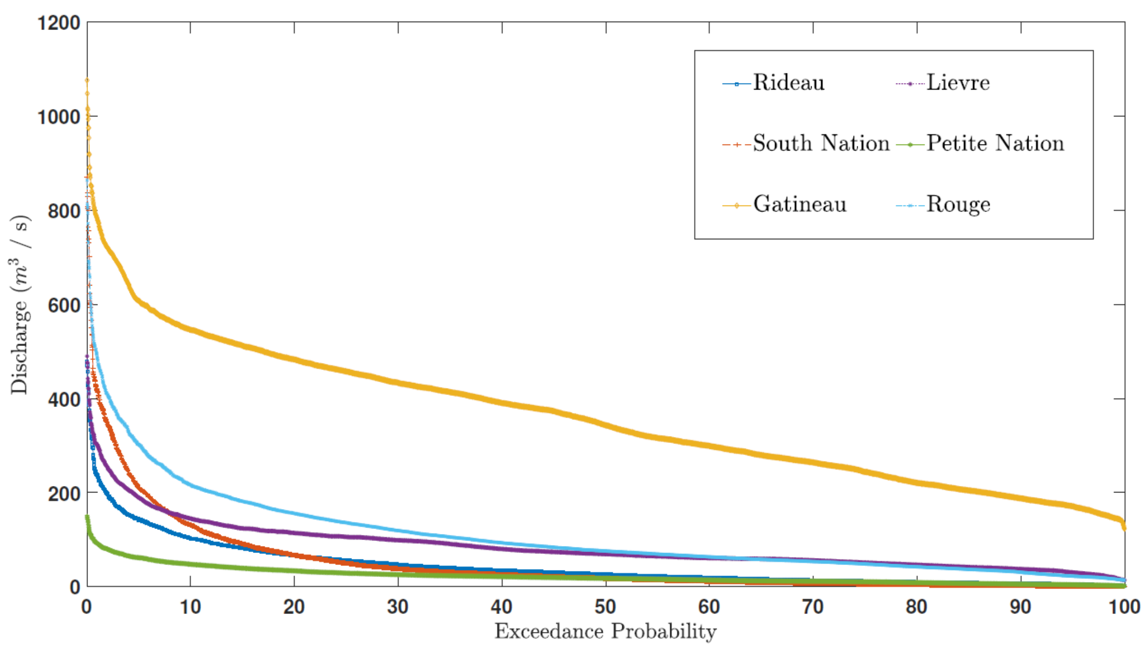


Figure 4.6 Flow duration for the main Ottawa River

Table 4.1 The main Ottawa River tributaries

Tributary	**Station Name**	**Station Number**	**Mean Discharge (m^3/s)**	**Source of data**
Gatineau	CHELSEA	————	368	Provided by Hydro-Quebec
Lievre	MASSON	————	177	Provided by Evolugen
Petite Nation	PETITE NATION (RIVIERE DE LA) AU PONT A 1,6 KM EN AMONT DE RIPON	02LD005	24	Water Survey of Canada (WSC)
Rouge	ROUGE (RIVIERE) EN AMONT DE LA CHUTE MCNEIL	02LC029	109	Water Survey of Canada (WSC)
South Nation	SOUTH NATION RIVER NEAR PLANTAGENET SPRINGS	02LB005	51	Water Survey of Canada (WSC)
Rideau	RIDEAU RIVER AT OTTAWA	02LA027	46	Water Survey of Canada (WSC)

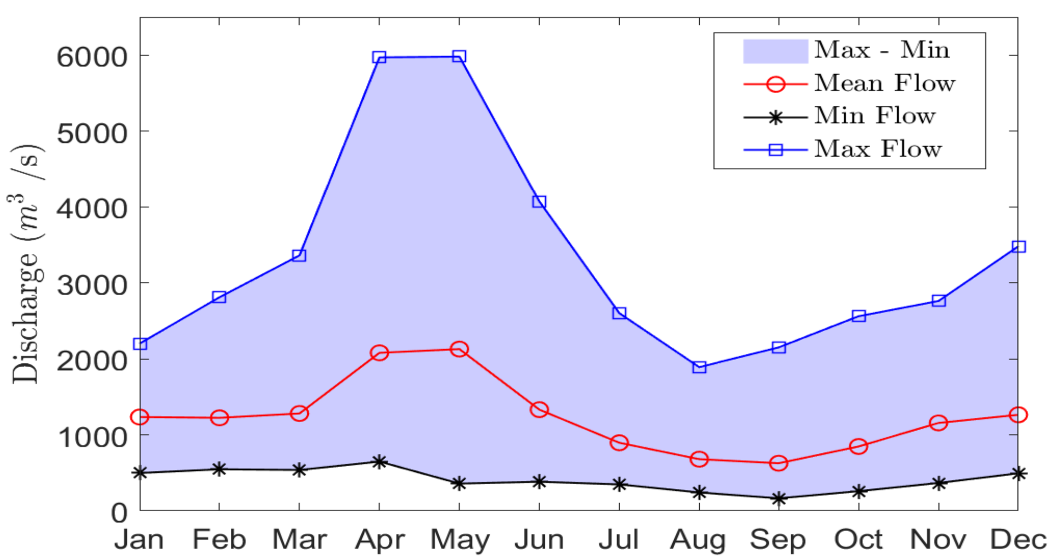


Figure 4.7 The annual mean of the flow data of the Ottawa River

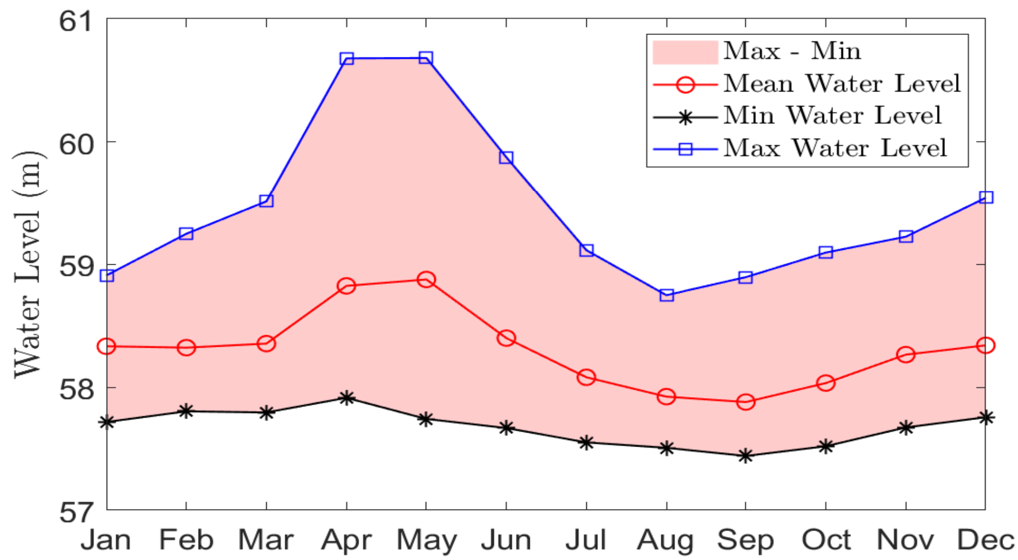


Figure 4.8 The annual mean of the water level data of the Ottawa River

4.5.1 Boundary conditions.

The Ottawa River model is driven by water level and discharge boundaries. The flow open boundaries will be set in the Upstream of the river sections and the main tributaries. Moreover, the water Level boundary was set for the downstream boundaries.

4.5.2 Computational grid

Delft3D-FLOW uses a staggered grid to calculate the water properties such as water level and velocity in both directions x and y.

A curvilinear grid was constructed for both Ottawa River sections as it is shown in the Figures 4.10 and 4.11. They contain 231 * 80 nodes for the Upstream section and 108 *1671 nodes for the Downstream section, respectively.

4.5.3 Initial Condition

Hydrodynamics models start the simulation from the initial condition that should be defined for all grid nodes. For our case, the Delft3D initial conditions are to zero for the velocity in both directions and the initial water level was provided from the water surface elevation which is available in the topography information.

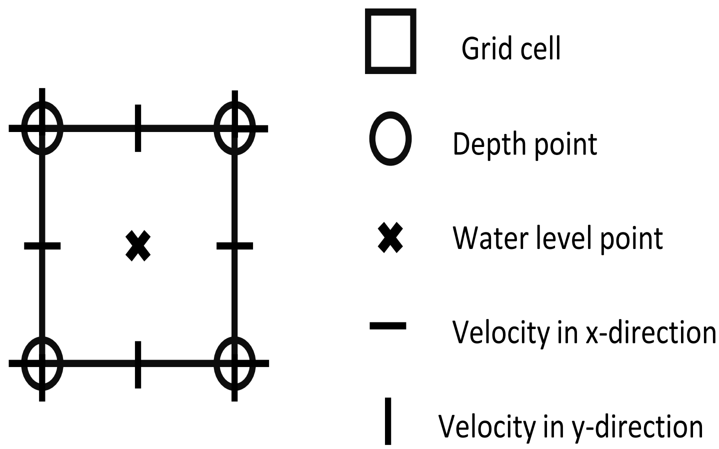


Figure 4.9 Delft3D-FLOW staggered grid

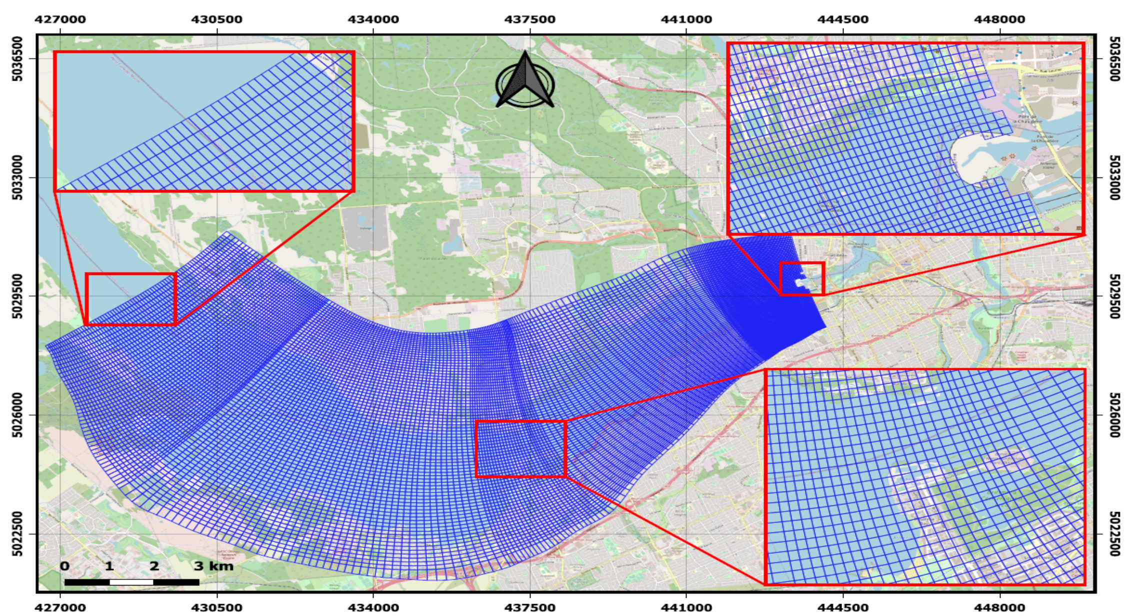


Figure 4.10 Computational gird of the Upstream Ottawa River model area

4.5.4 Monitoring in Delft3D

In this work, many monitoring points were used in several cross-sections throughout the Ottawa River. They aim to provide the time series water properties such as velocities and water level.

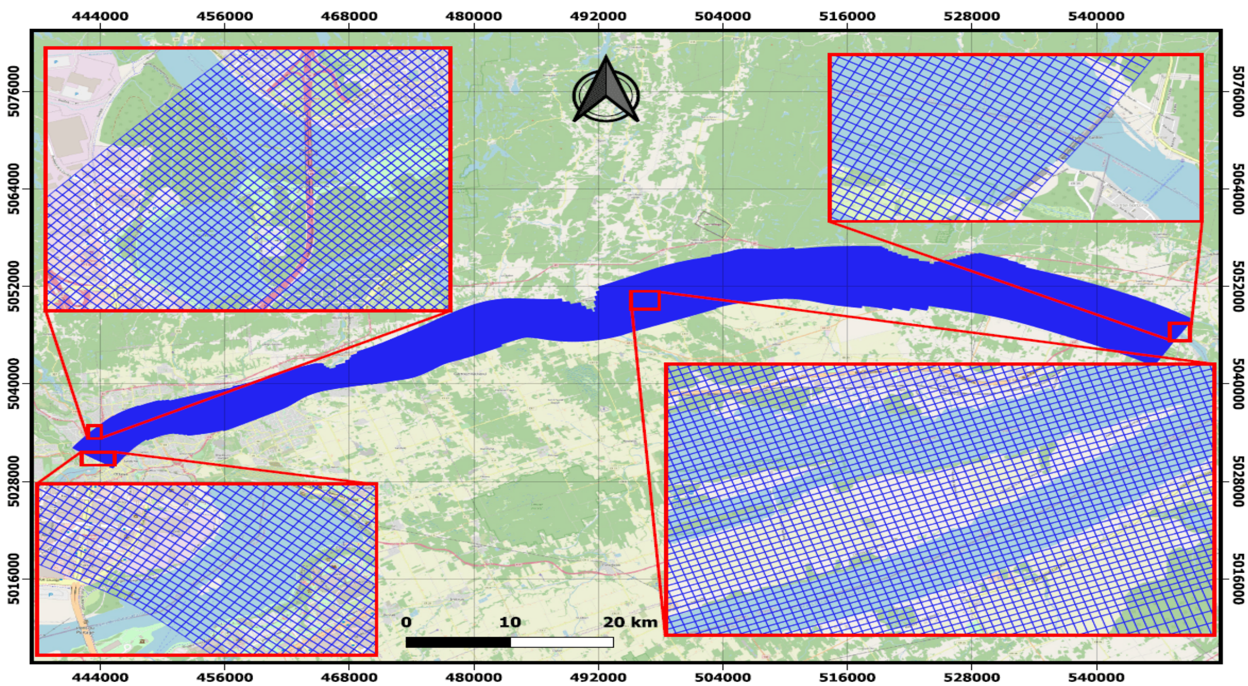


Figure 4.11 Computational gird of the Downstream Ottawa River model area

4.5.5 Parameter settings

The physical parameters used in the Delft3D hydraulic model are summarized in the Table 4.2.

Table 4.2 Physical parameters

Parameters	**Values**	**Unites**
Gravity	9.81	m/s^2
Viscosity	0.28	m^2/s
Water density	1000	kg/m^3
Manning's Roughness	0.013 - 0.035	
Model Time step	1	minute
Simulation time	1	year

4.6 Results and Discussions

Delft3D hydraulic model successfully simulates water behavior in the Ottawa River. Figures 4.13 to 4.21 compare the current simulated velocity profiles in several cross-sections with

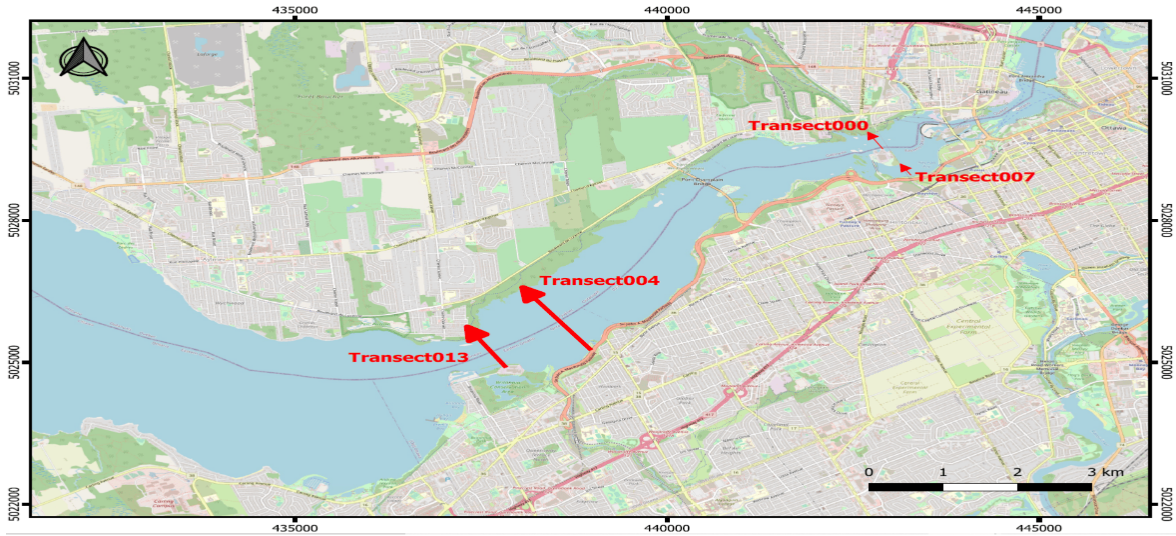


Figure 4.12 The location of the different cross section for measured velocity profile along the Upstream Ottawa River

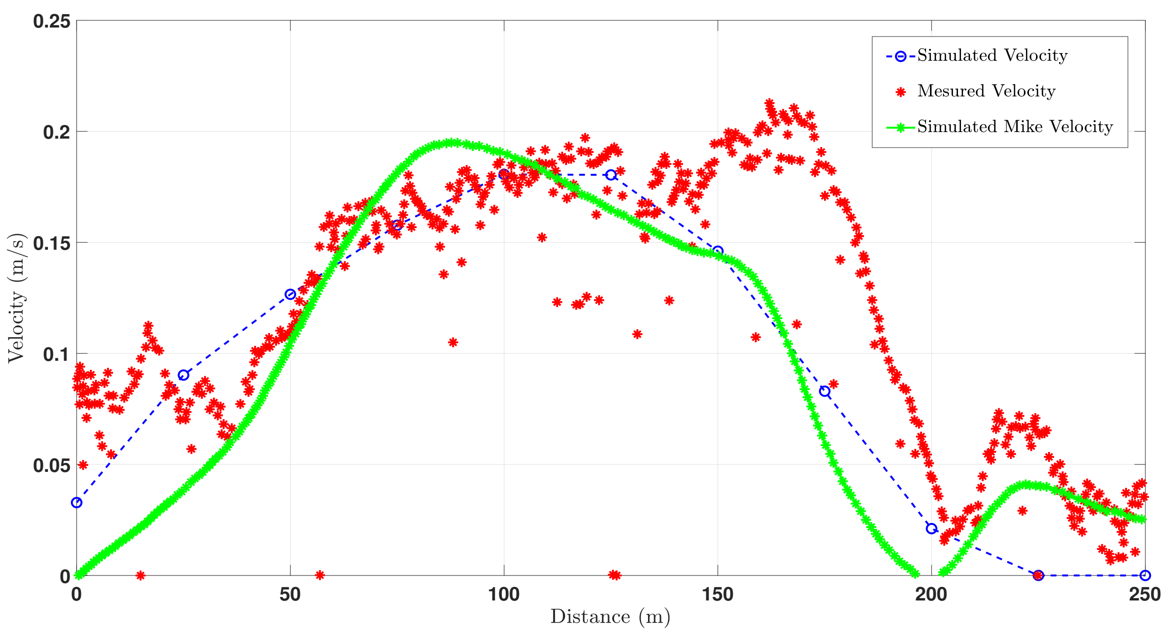


Figure 4.13 Validating Delft3D hydraulic model with velocity profile data for the section Transect007

those from measurements [135] [134] as well as the simulated results of Taghipour et al. [133] (achieved using Mike21 model). They show good compatibilities. The measured depth-averaged velocity was surveyed using Acoustic Doppler Current Profiler (ADCP). Delft3D

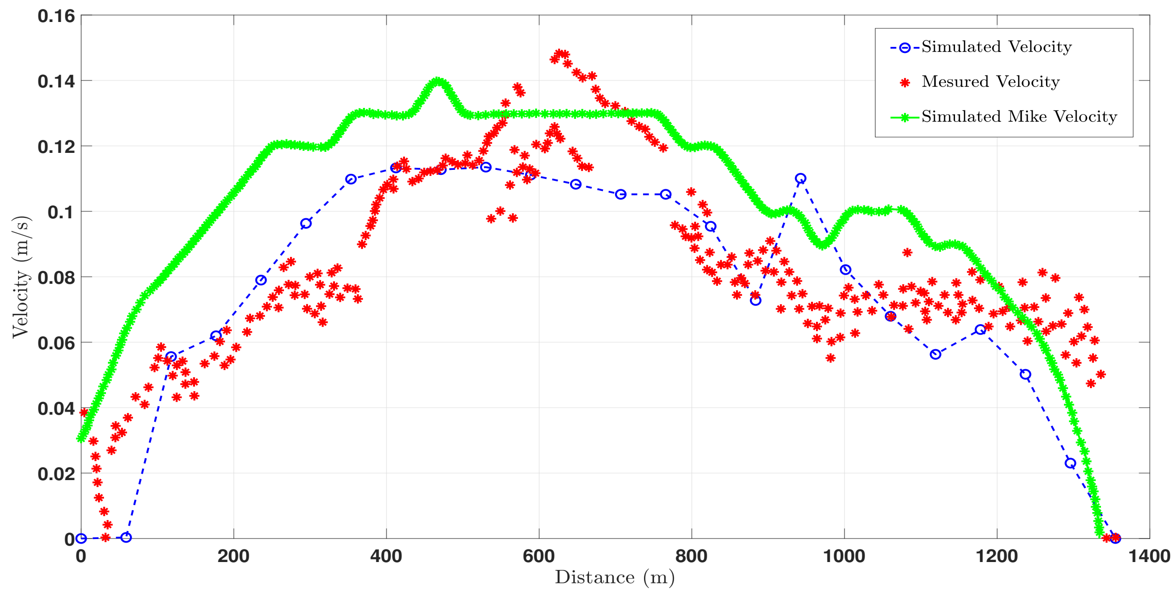


Figure 4.14 Validating Delft3D hydraulic model with velocity profile data for the section Transect004

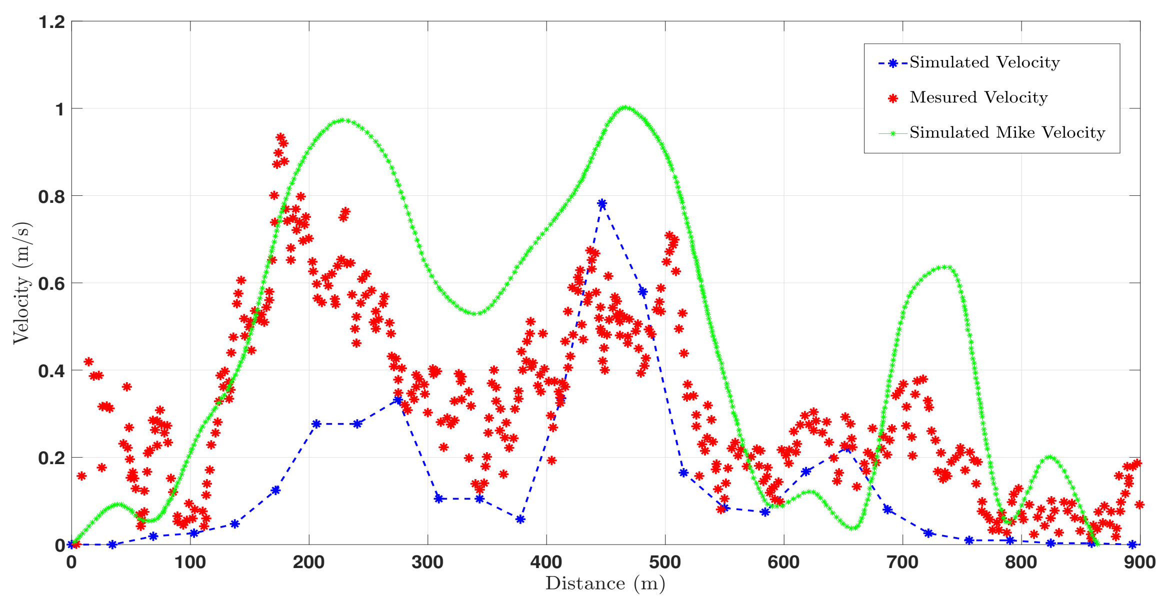


Figure 4.15 Validating Hydraulic Model with velocity profile data for the section Transect013

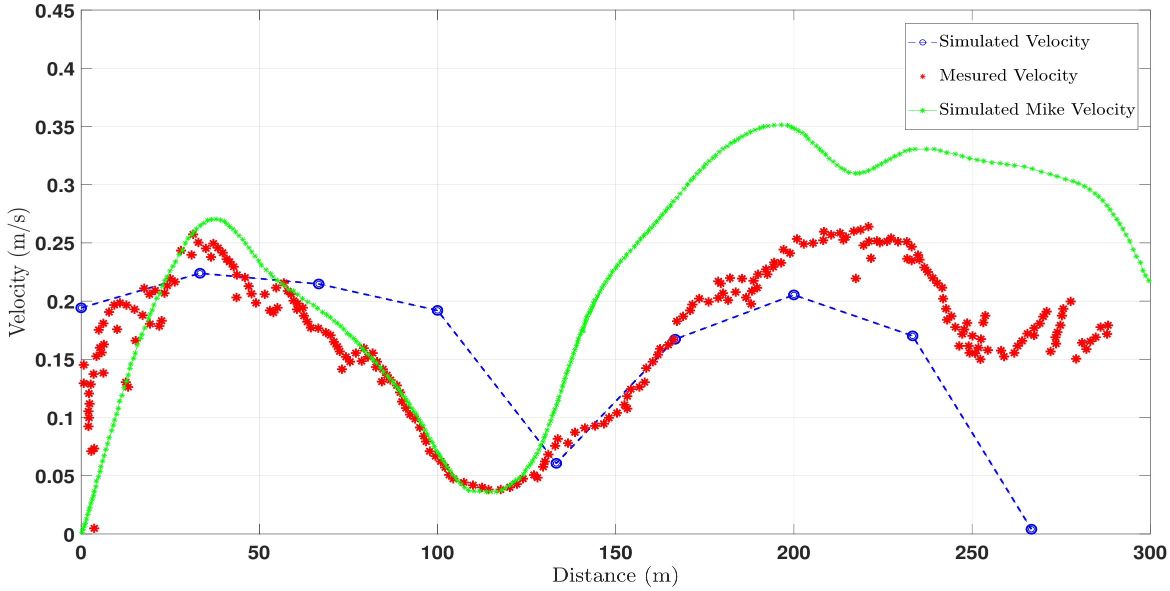


Figure 4.16 Validating Delft3D hydraulic model with velocity profile data for the section Transect000

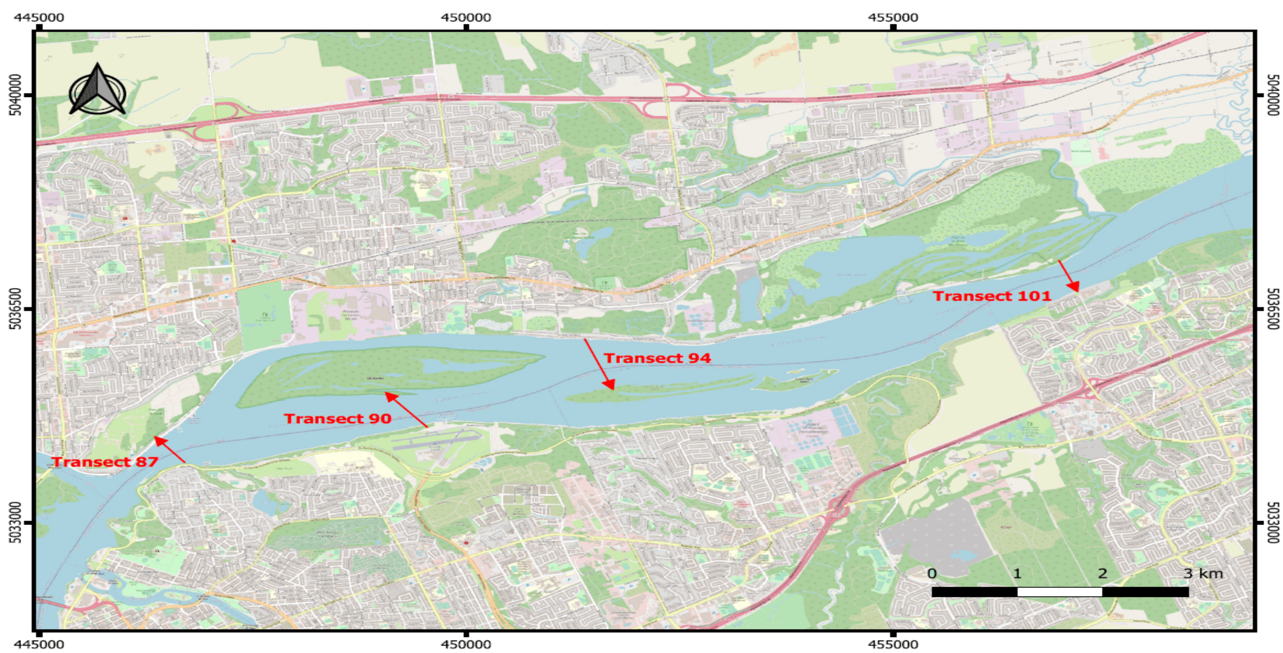


Figure 4.17 The location of the different cross section for measured velocity profile along the Downstream Ottawa River

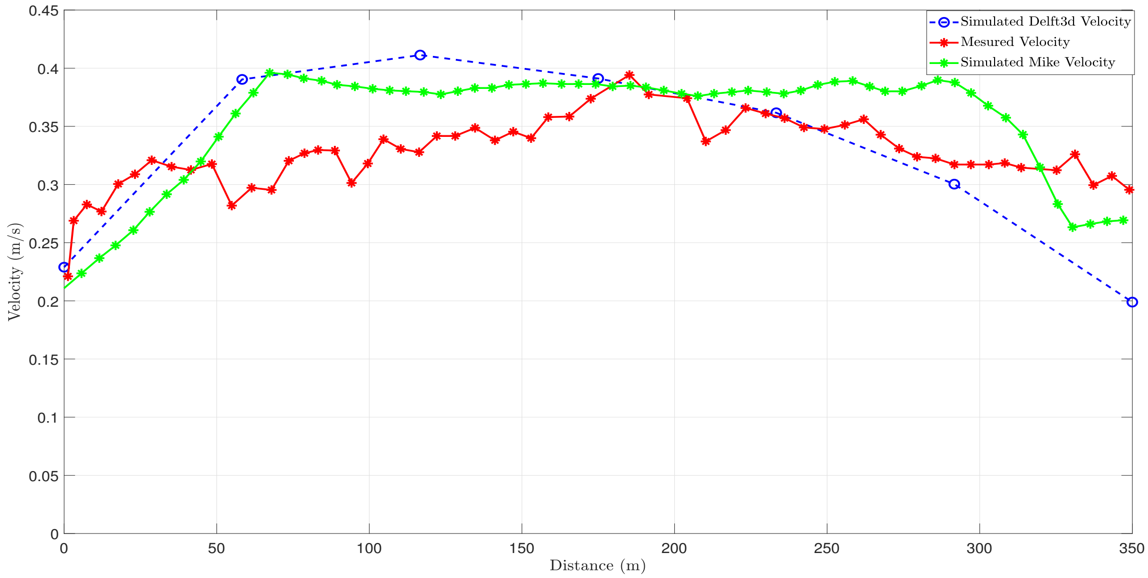


Figure 4.18 Validating Delft3D hydraulic model with velocity profile data for the section Transect87

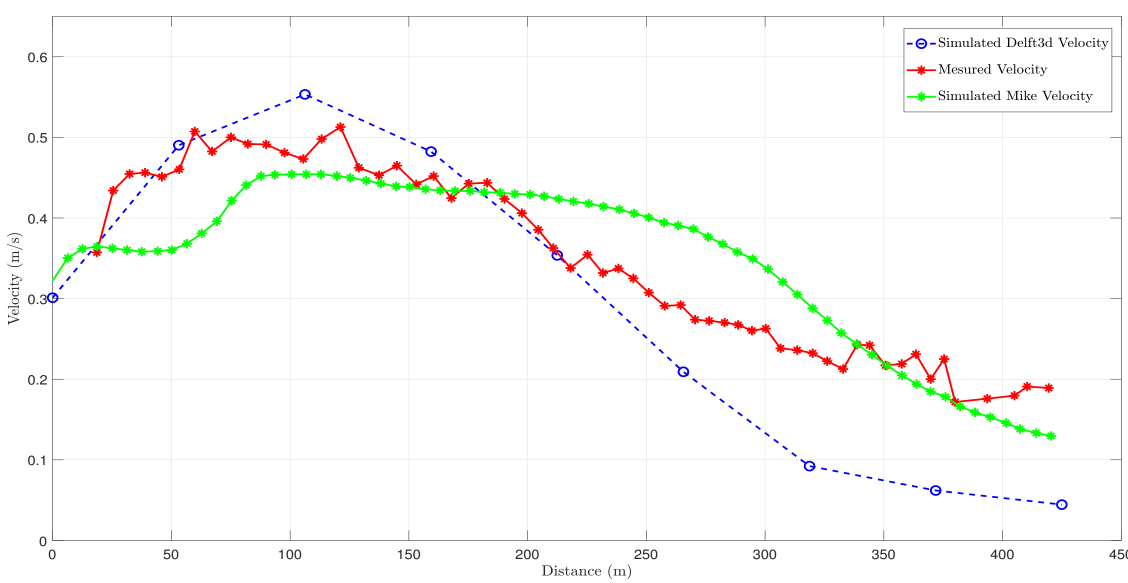


Figure 4.19 Validating Delft3D hydraulic model with velocity profile data for the section Transect90

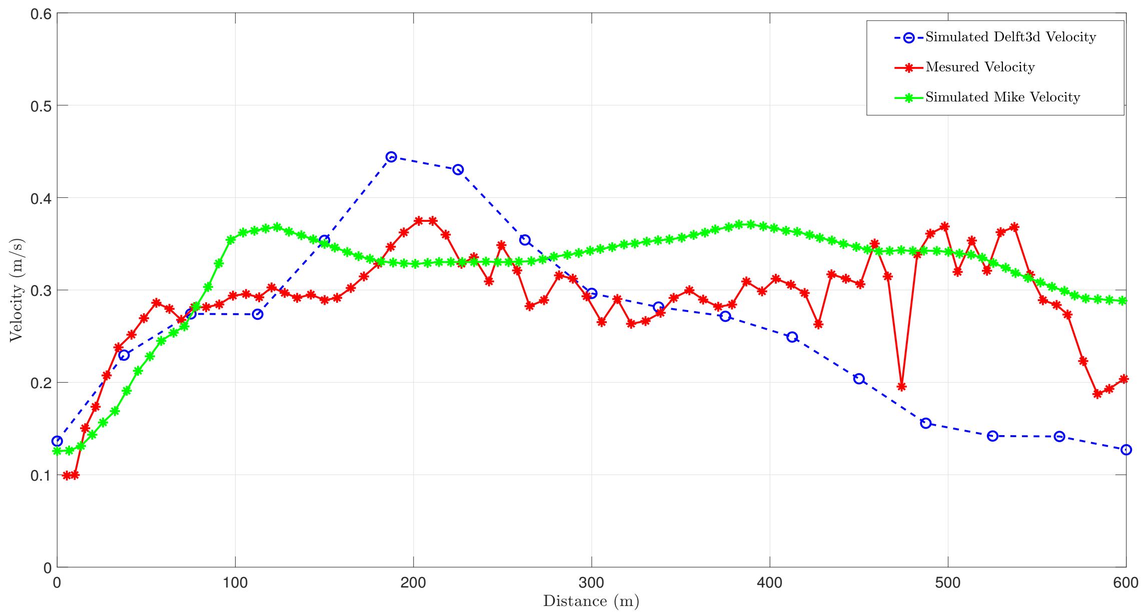


Figure 4.20 Validating Hydraulic Model with velocity profile data for the section Transect94

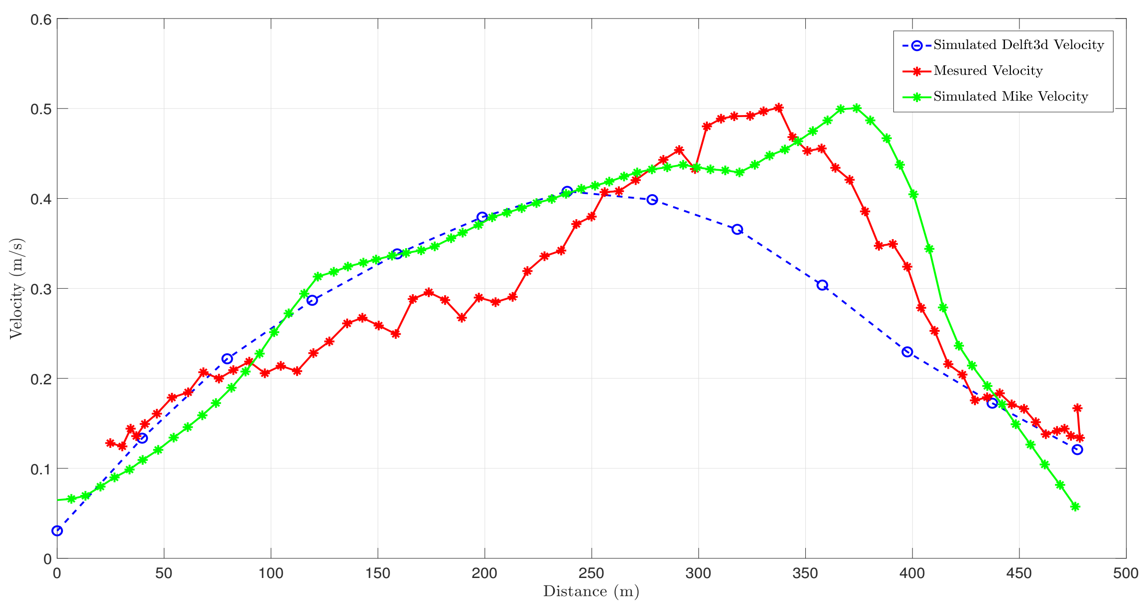


Figure 4.21 Validating Hydraulic Model with velocity profile data for the section Transect101

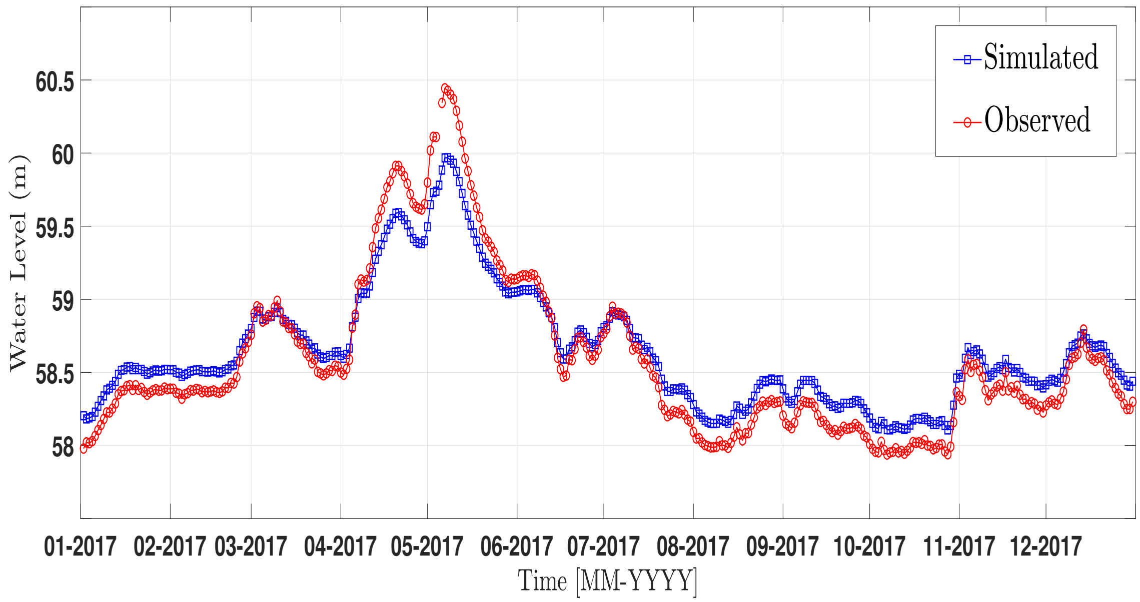


Figure 4.22 Validating Delft3D hydraulic model against observed water level during 2017 flood event in the Upstream Ottawa River

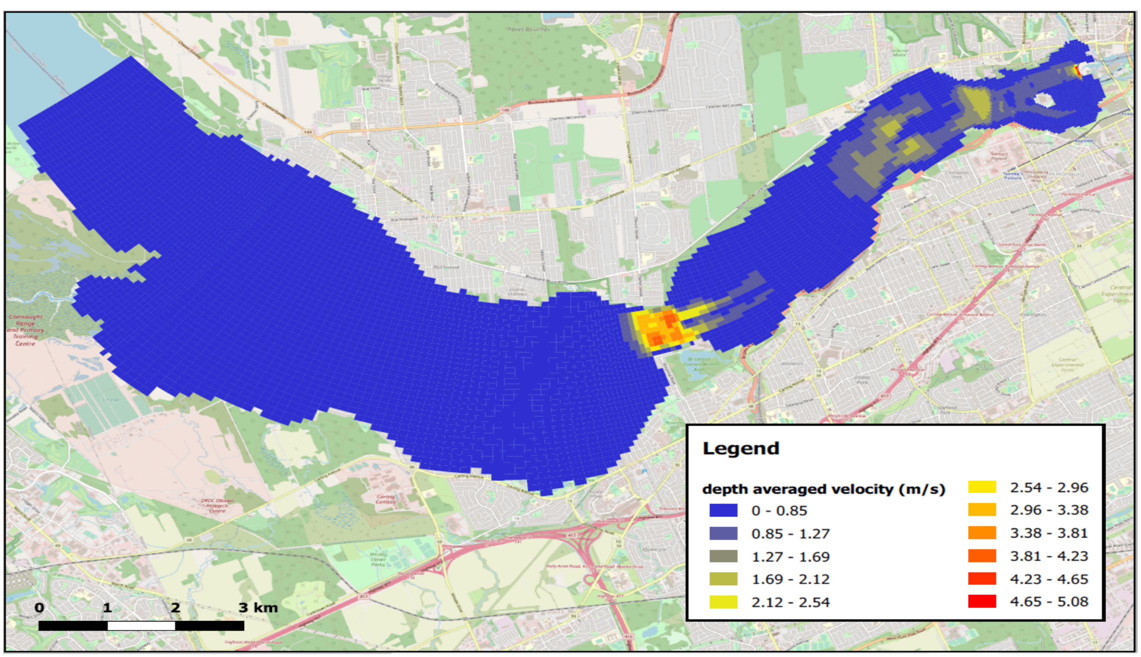


Figure 4.23 Depth averaged velocity in Upstream Ottawa River during 2017 flood event

results fit with the measured velocity profile. The simulated velocity is underestimated in the south side of the river and showed a good performance on the north side for the Transect 94

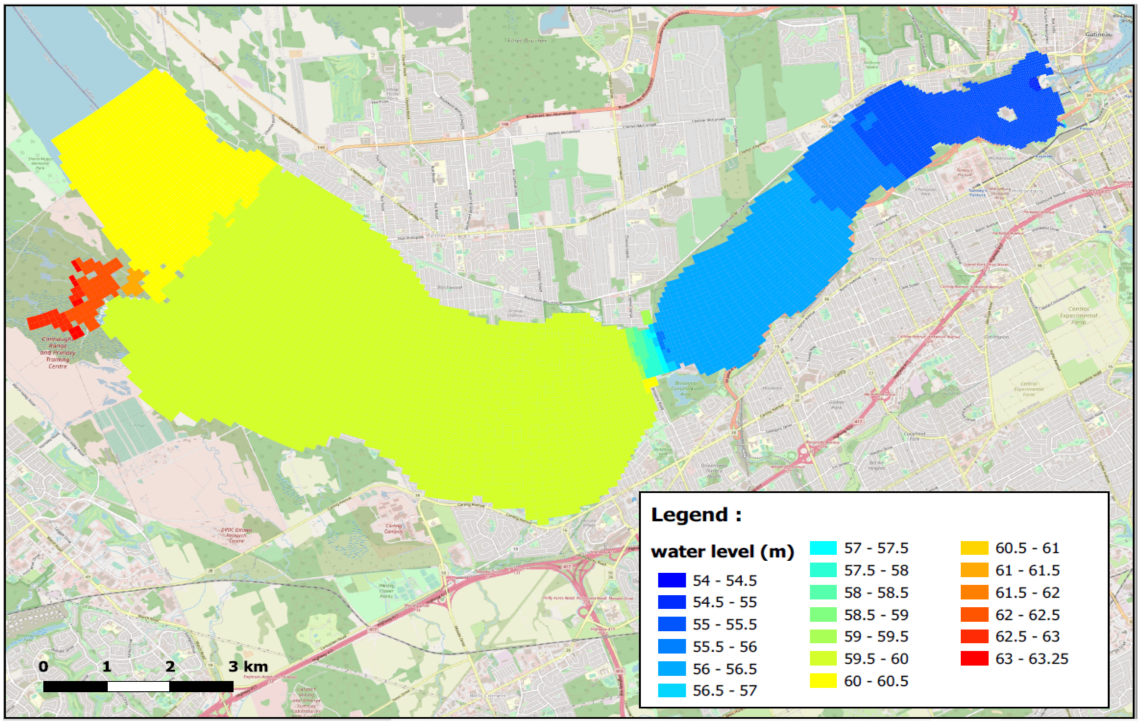


Figure 4.24 Water level in Upstream Ottawa River during 2017 flood event

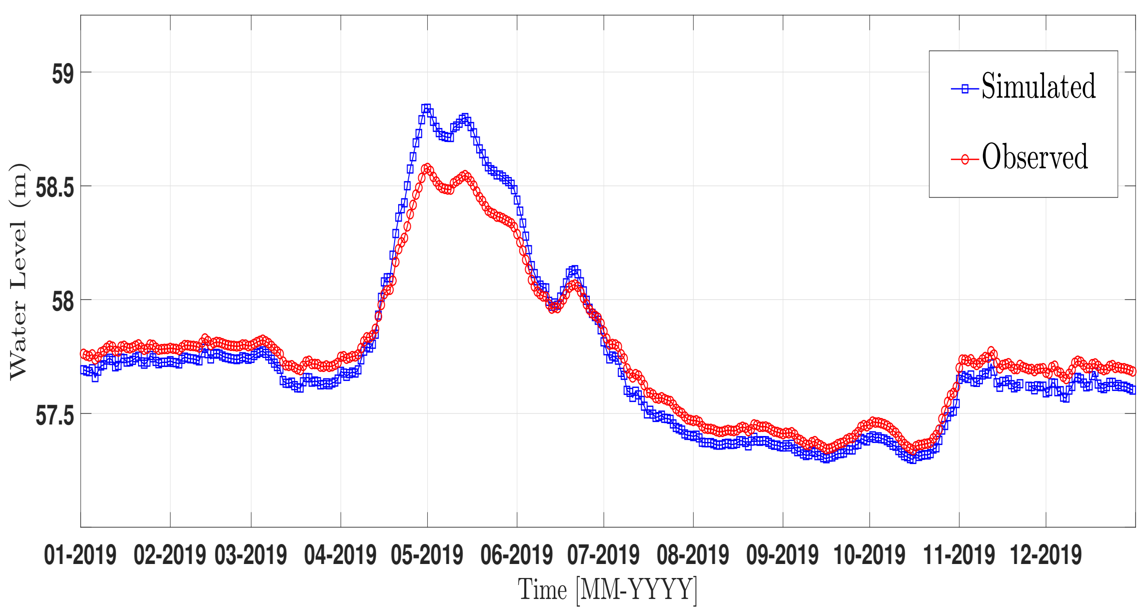


Figure 4.25 Validating Delft3D hydraulic model against observed water level during 2019 flood even in the Upstream Ottawa River

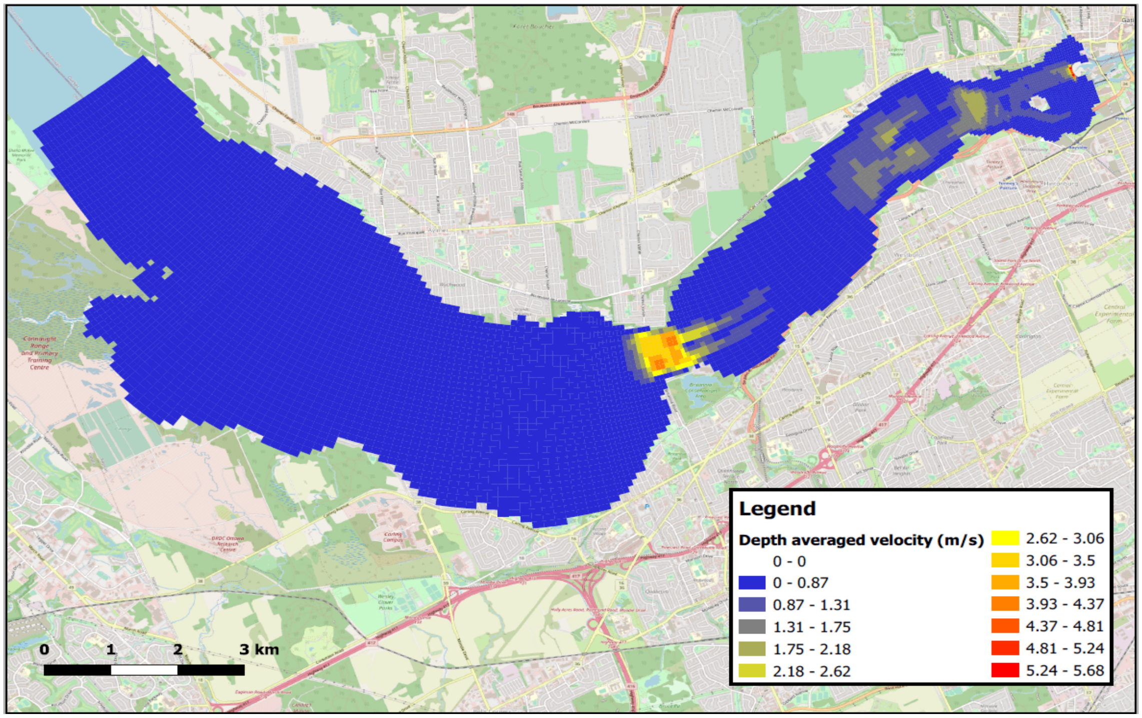


Figure 4.26 Depth averaged velocity in Upstream Ottawa River during 2019 flood event

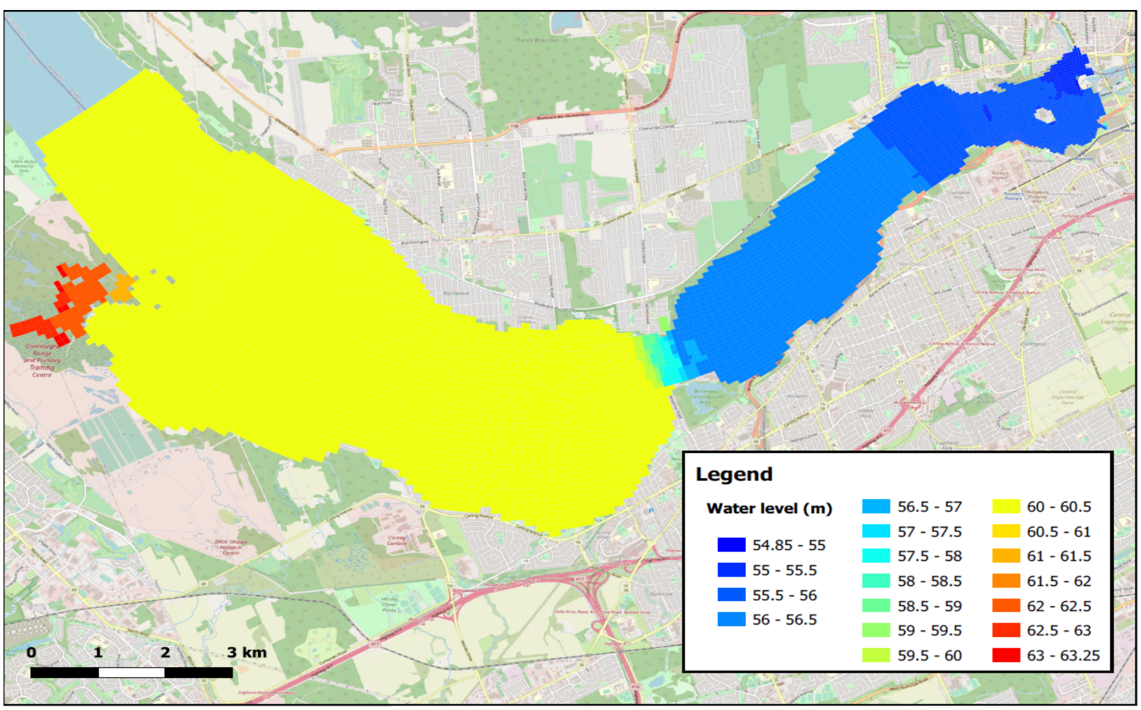


Figure 4.27 Water level in Upstream Ottawa River during 2019 flood event

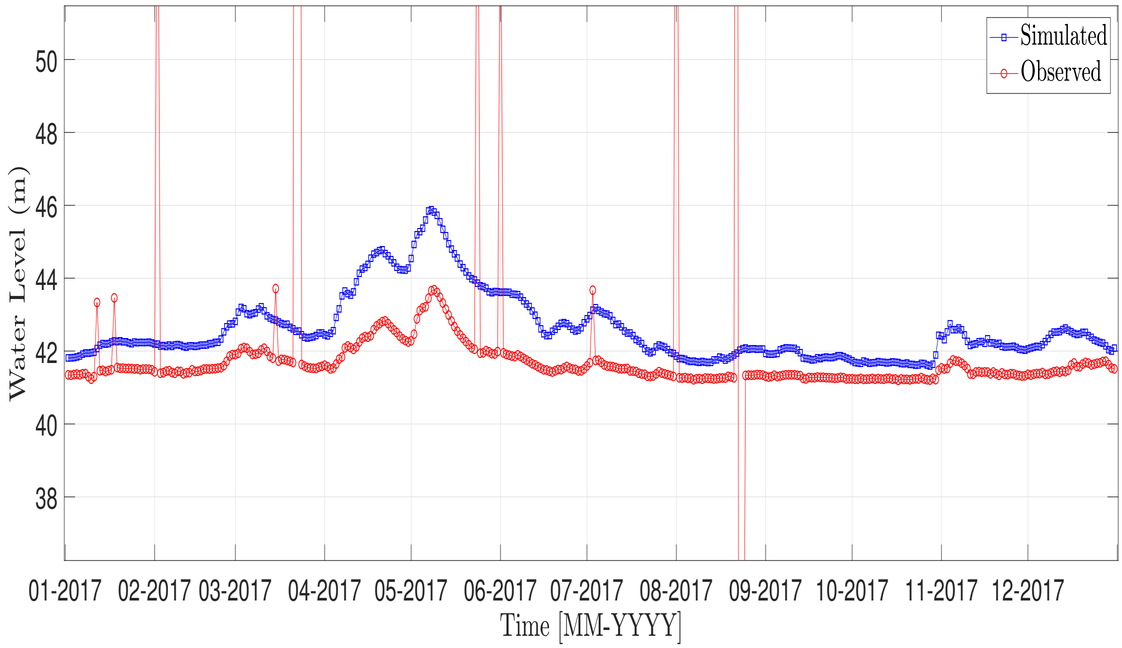


Figure 4.28 Validating Delft3D hydraulic model against observed water level during 2017 flood event in the Downstream Ottawa River

and this can be caused by the supercritical flow regime as it is shown in Figure 4.20. In the Transect000, simulated depth-averaged velocity fits with measured velocity tendency with a small underestimate while Mike overestimates velocity in the north side of the river and this could be due to the Chaudière dam effect. Furthermore, note that the Mike21 results have been achieved using a much finer mesh, which has been possible considering the much smaller spatial and temporal scales of simulations. In addition, it is hard to determine the place of the cross-sections.

The Ottawa River faced frequent flood events. In the last decade, 2017 and 2019 were considered as the most devastating natural hazard that was recorded. The Delft3D hydrodynamic models were validated against measured water level and it showed good results for both flood events as it is well illustrated in the Figures 4.24 and 4.25. The two dimensional results of water level and depth-averaged velocity was presented in the Figures 4.24, 4.27, 4.26 and 4.23. These figures present just the active cells in the computational grid. The water level reached a record of 60.5 m in the Upstream as it is shown in the Figures 4.24 and 4.27 for 2017 and 2019 flood events. The depth-averaged velocity was presented in the Figures 4.26 and 4.23 where the maximum velocity was estimated around 4.5 m/s for the 2017 flood event

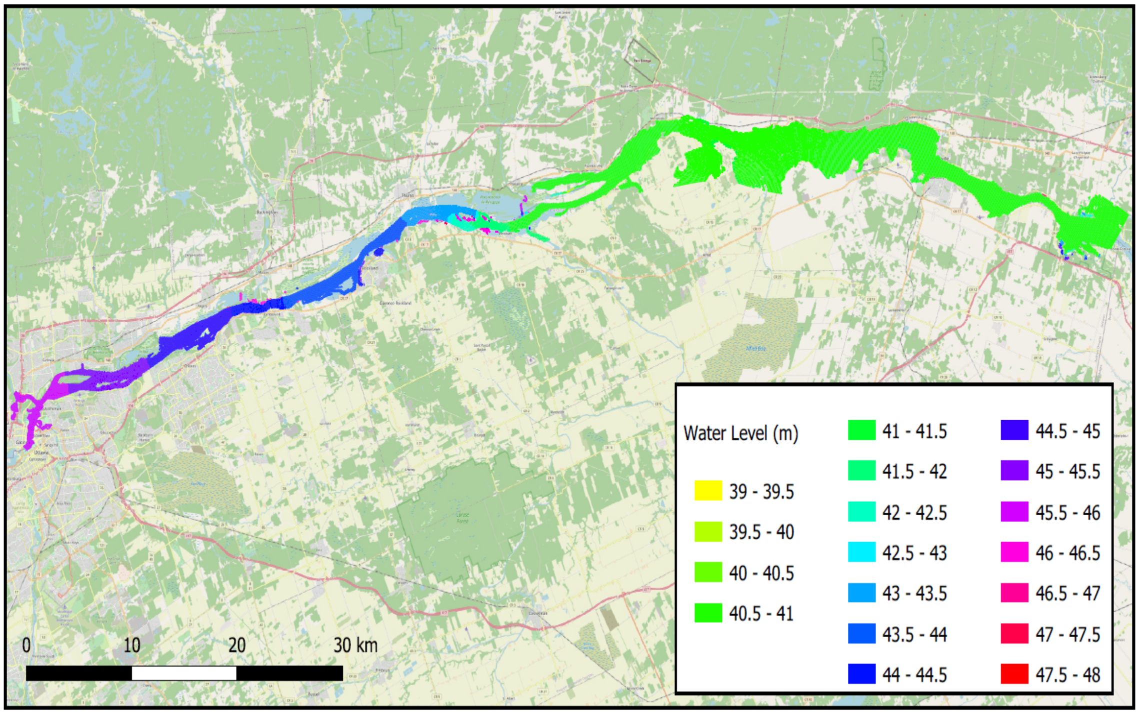


Figure 4.29 Water level in Downstream Ottawa River during 2017 flood event

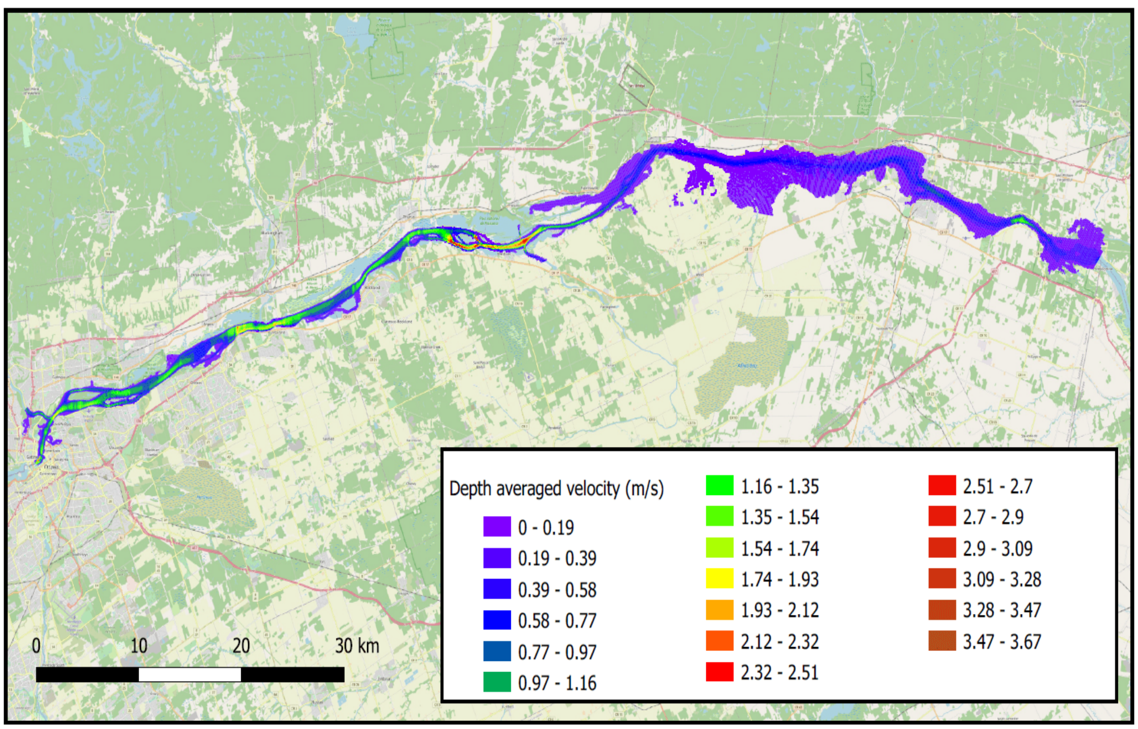


Figure 4.30 Depth averaged velocity in Downstream Ottawa River during 2017 flood event

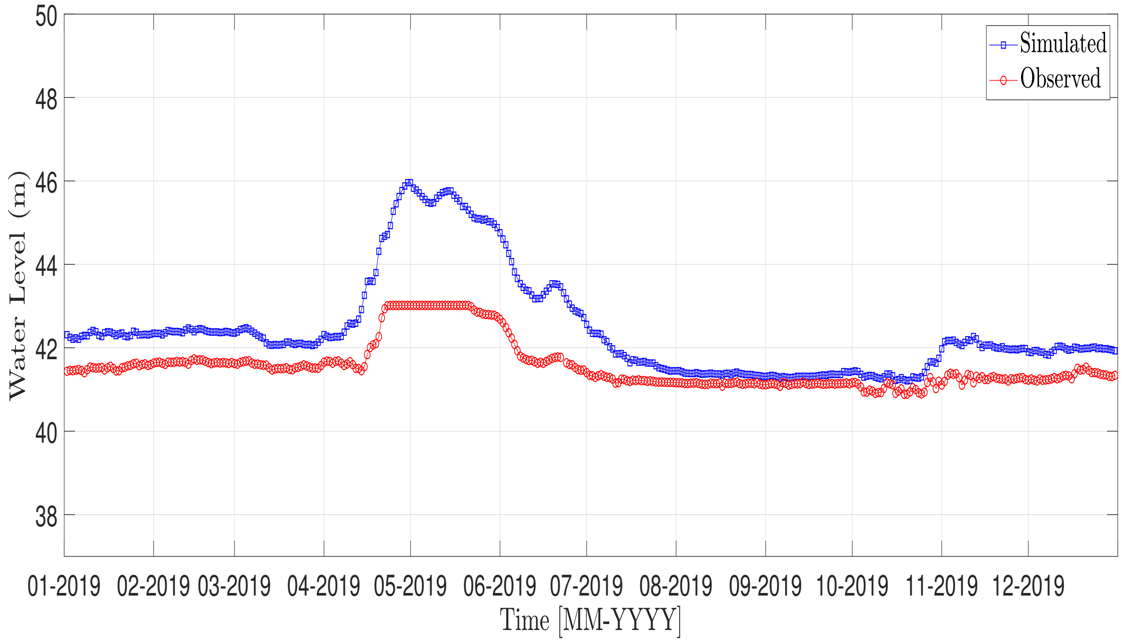


Figure 4.31 Validating Delft3D hydraulic model against observed water level during 2019 flood event in the Downstream Ottawa River

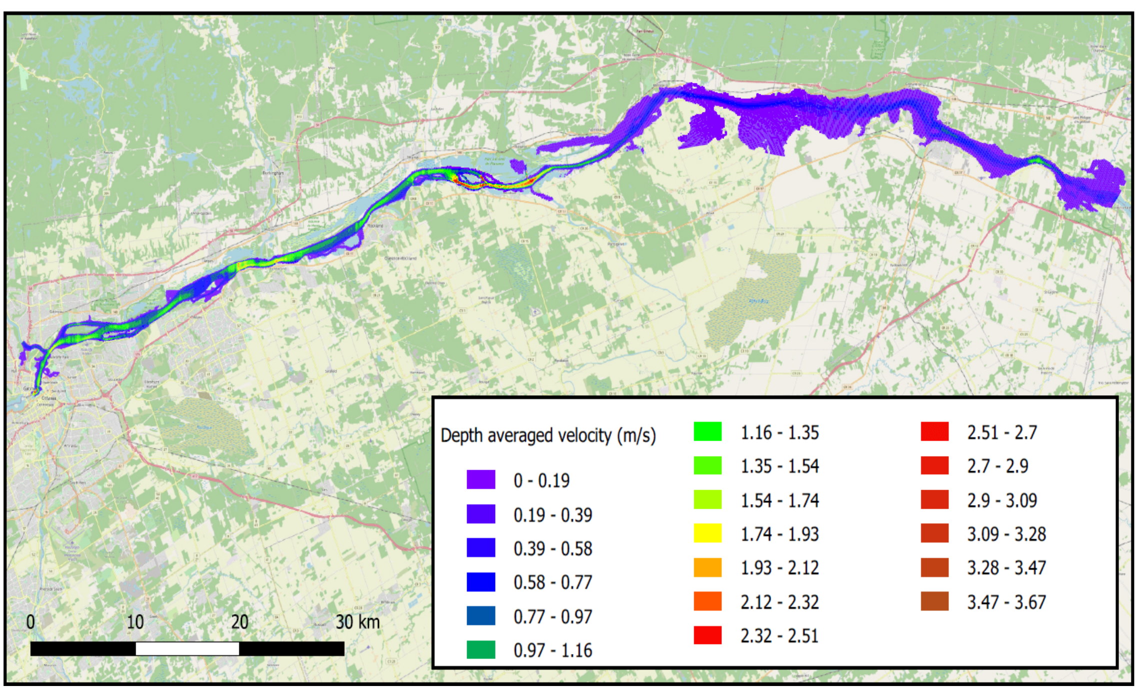


Figure 4.32 Depth averaged velocity in Downstream Ottawa River during 2019 flood event

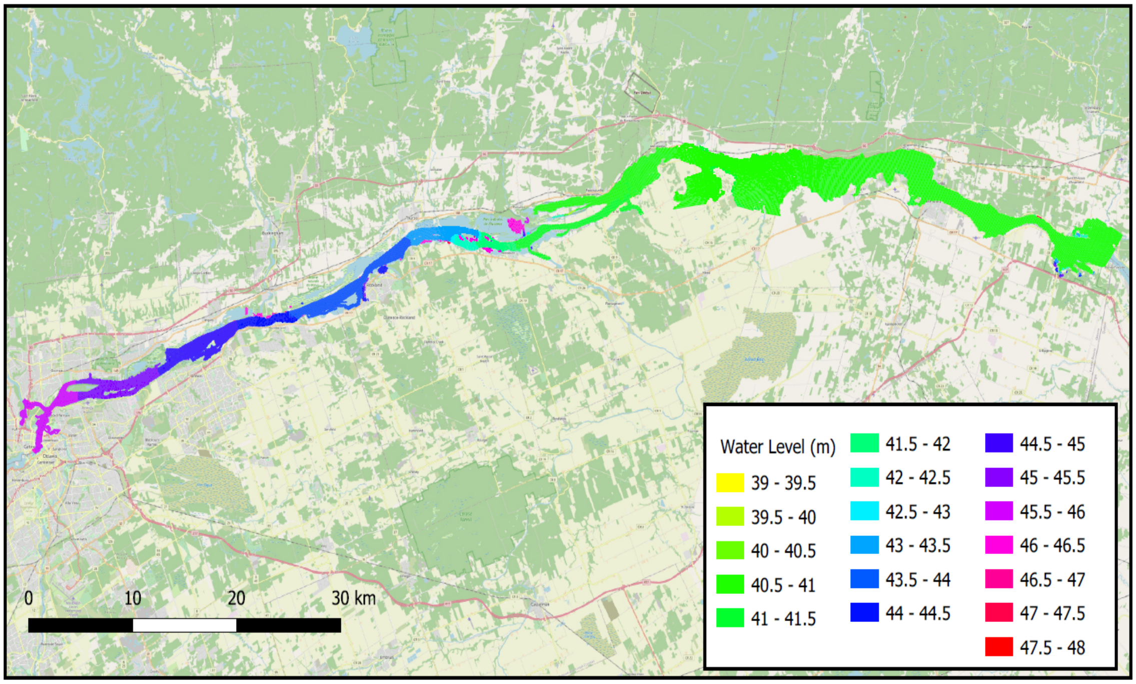


Figure 4.33 Water level in Downstream Ottawa River during 2019 flood event

and around 5 m/s for the 2019 flood event.

The Delft3D hydrodynamic model for the downstream Ottawa River simulates the flood event of 2017 and 2019. The flow of the station named " OTTAWA RIVER AT BRITANNIA" was used as an upstream boundary condition due to the lack of the daily flow data at the Chaudière dam. The Delft3D hydrodynamic model showed good results. The simulated results follow the same profile observed with a small overestimation as it is illustrated in the Figures 4.28, 4.31. This overestimation could be caused due by the lack of hydrometric data in Chaudière data and also to the quality of water level in Thurso station where it contains several outliers as it is shown in the Figure 4.28 or a constant value for a long period as it is illustrated in the Figure 4.31. The water level and the depth-averaged velocity was mapped in the Figures 4.30, 4.29, 4.33 and 4.32 for both flood event 2017 and 2019, respectively. The water level in the upstream part of the river is around 46 m while the downstream is regulated around 41 m by the Carillon dam effect. The evolution of water level during the flood events of 2017 and 2019 are presented in the Annexes B, C, D and E.

4.7 Conclusion

In conclusion, this chapter presents the Delft3D hydrodynamic models for the Ottawa River. The Delft3D models performed well for two sections of the Ottawa River. They were validated against observed water level and depth-averaged velocity in several cross-sections along the river. Moreover, they were validated during the recent flood event in Ontario in 2017 and 2019. The simulated Delft3D results fit against hydrometric data with some small difference that could be due to the dam effect such as Chaudière and Carillon dam, the quality of the streamflow, bathymetry and topography data, or the difference between the spatial and temporal resolution of Mike21 results for the case of depth-averaged velocity.

CHAPTER 5 HYDROLOGICAL MODEL FOR THE MAIN OTTAWA WATERSHED

5.1 Introduction

In this chapter, hydrological models were implemented for the main Ottawa subwatershed using the HEC-HMS model. These models were calibrated and validated against observed discharge in the subwatershed outlets. The HEC-HMS model showed good performance and reliability for most of the Ottawa subwatershed. They were developed in order to be integrated into the flood forecasting system DELFT-FEWS.

5.2 Hydrological Model

In this study, the hydrology model which was used in this study is HEC-HMS. HEC-HMS was widely used, applied in several flood forecasting studies, and provided good results [97] [98] [99]. It was used to estimate streamflow in the main Ottawa River subwatershed which are illustrated in Figure 5.9 and Table 5.1. The digital elevation of the Ottawa River Basin was presented in the Figures 5.1 which was created in the projection WGS/UTM zone 18N. HEC-HMS was developed by the Hydrologic Engineering Center of the Army Corps of Engineers. It was implemented in several applications such as the design of urban drainage, flow forecasting, flood damage mitigation, and more phenomena. HEC-HMS has a Graphic User Interface (GUI) which makes the simulations more structured and simplified [153]. It is based on solving the continuity equation 5.1 [153].

$$\underbrace{\frac{dS(e)}{dt}}_{\text{Storage}} - \overbrace{\sum_i Q_i(t)}^{\text{Inflow}} + \underbrace{\sum_j Q_j(e,t)}_{\text{Outflow}} = 0 \tag{5.1}$$

where S denotes reservoir storage; t for time; e for the water surface elevation in the reservoir; Q_i for flow for each inflow i; Q_j for outflow for each outlet j.

In brief, a portion of precipitation contributes to runoff. Another portion is returned to the atmosphere by evapotranspiration which is related principally to temperature and it is important in water bodies, vegetation, and land use. Moreover, in cold regions like Canada, an important part of precipitation is converted to snow during the cold period. Finally, the

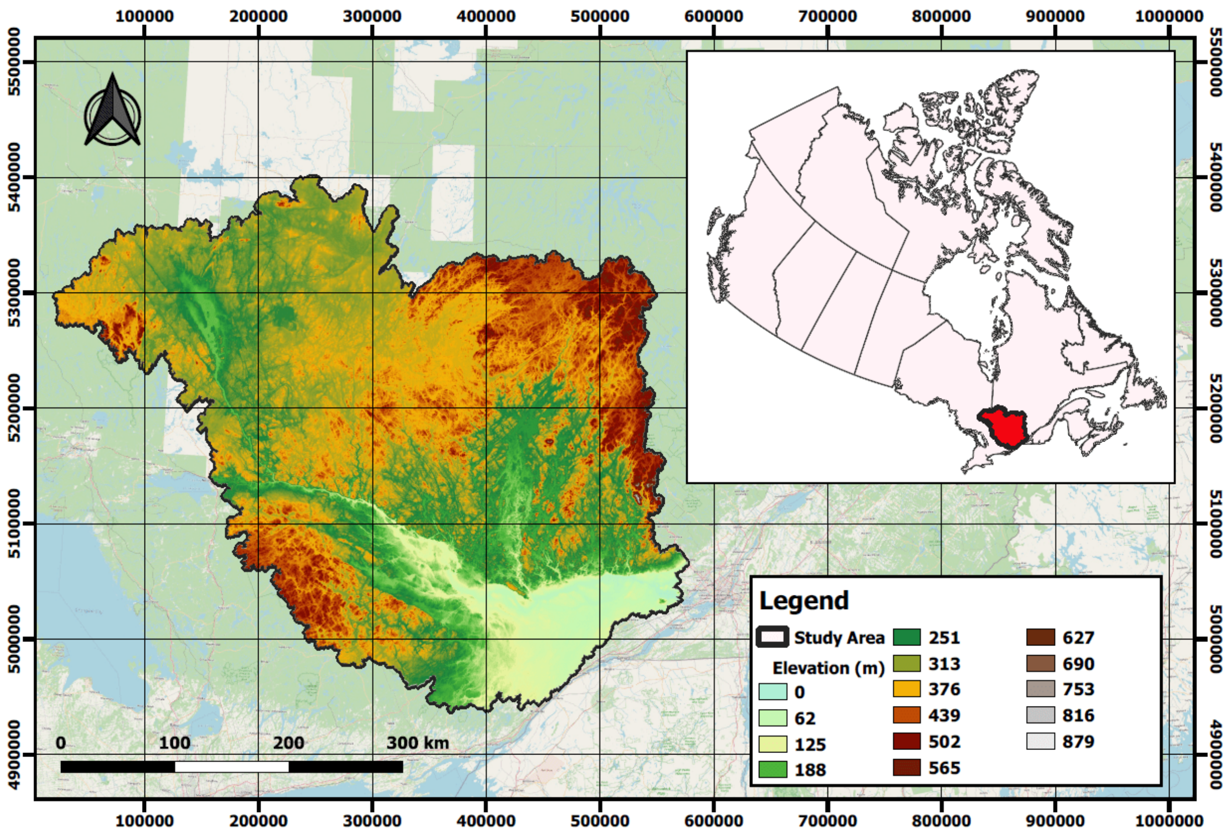


Figure 5.1 Digital elevation of Ottawa River Basin

Table 5.1 The main Ottawa river tributaries [3]

Tributary	**Drainage Area** (km^2)	**Mean Discharge** (m^3/s)	**Dam controlled**	**Reach**
Gatineau	23129.2	368	Yes	Dollard des Ormeaux
Lievre	9133.9	177	Yes	
Petite Nation	2249.6	24	No	
Rouge	5583.3	109	—	
South Nation	3963.5	51	—	
Rideau	3987.7	46	Yes	

rest is infiltrated to the ground [8] as it is illustrated in the Figure 5.3. The HEC-HMS model consists of two major components: The meteorological component discriminates between snow and rainfall which contribute to runoff and the basin component is responsible for conceptual modeling as it is presented in Figure 5.5.

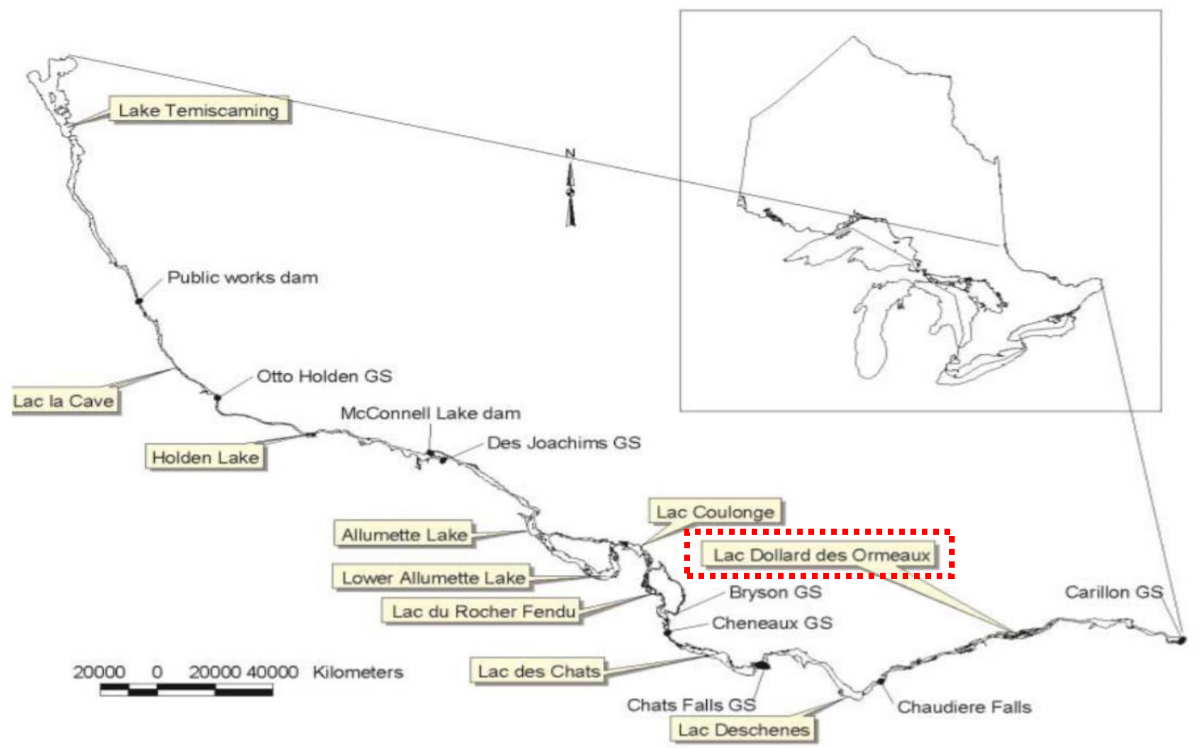


Figure 5.2 The main dams and lakes in the Ottawa river :Image source [7]

HEC-HMS can also simulate snowmelt using the temperature index approach. It is based on the degree-day approach [8]. The structure of the snowpack is illustrated in Figure 5.4. For more information please refer to HEC-HMS documentation in (www.hec.usace.army.mil). It is defined by the following equation [153].

$$q = M_R(T - T_B) \tag{5.2}$$

Where q denotes the volume of melted snow; M_R for melt rate in volume per degree Celsius; T for air temperature in degrees Celsius; T_B for the base temperature above which snow melts.

Curve Number in the Soil Conservation Service is used to estimate the incremental losses. HEC-HMS calculated the accumulated precipitation excess using the following equation:

$$P_e = \frac{(P - I_a)^2}{P - I_a + S} \tag{5.3}$$

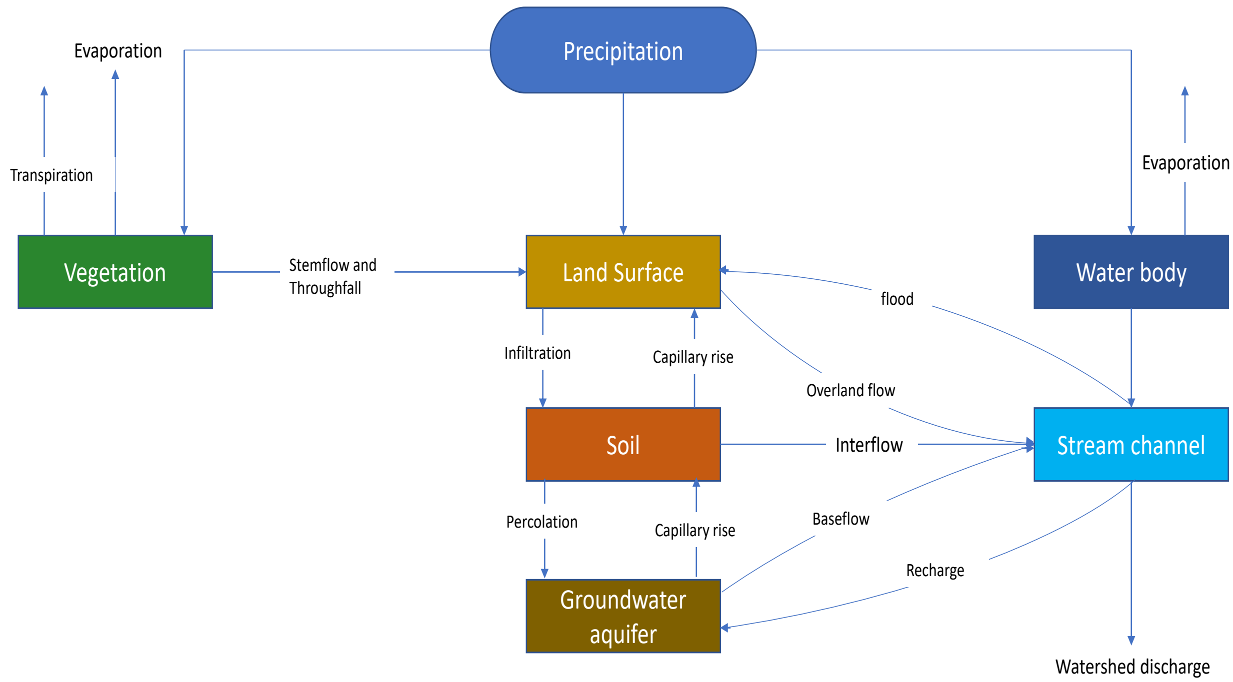


Figure 5.3 The runoff Process of HEC-HMS software [8]

where P_e is accumulated precipitation excess at time t, P is the accumulated rainfall depth at time t, I_a is the initial abstraction (initial loss), and S is the potential maximum retention [8], The initial abstraction can be estimated by the following relation with potential maximum retention as it is given in the following equation 5.4:

$$I_a = 0.2 * S \tag{5.4}$$

Then, the equation 5.3 can be written as follow :

$$P_e = \frac{(P - 0.2 * S)^2}{P - I_a + S} \tag{5.5}$$

The potential maximum retention (S) is estimated in function of curve number (CN). It is represented in SI units:

$$S = \frac{25400 - 254CN}{CN} \tag{5.6}$$

The Curve number grid was created from the land use and soil classification data as it is

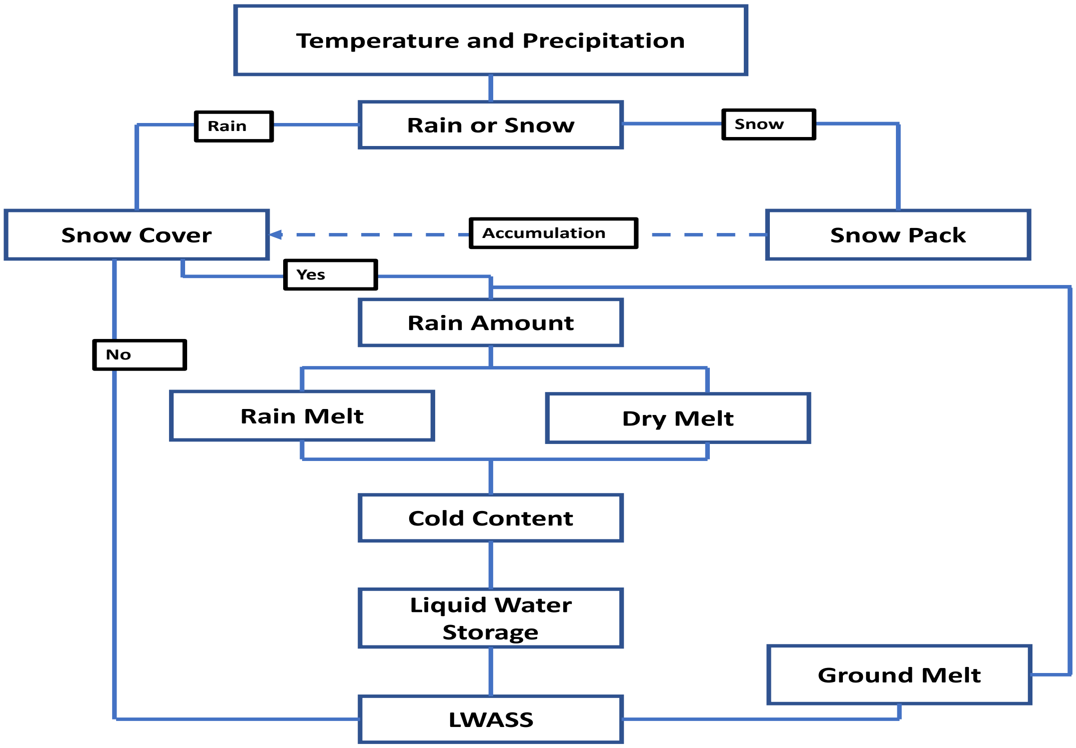


Figure 5.4 The snowmelt module of HEC-HMS software [8]

presented in Figure 5.8. Natural Resources Canada produces land cover by using remote sensing data (www.nrcan.gc.ca), the Land-use for Ottawa River Basin is illustrated in Figure 5.6. The source of soil data is Harmonized World Soil Database [154] which was used to generate soil classification map for Ottawa River Basin with respect of classification of HSG presented in Table 5.2 as it is illustrated in Figure 5.7. The equivalent curve number for each subwatershed is summarized in Table 5.3.

Table 5.2 Classification of HSG with Soil texture

HSG	Soil textures
A	Sand, Loamy sand, or sandy loam
B	Silt loam or loam
C	Sandy clay loam
D	Clay loam, silty clay loam, sandy clay, silty clay, or clay

The curve number for each subwatershed was estimated using the following equation:

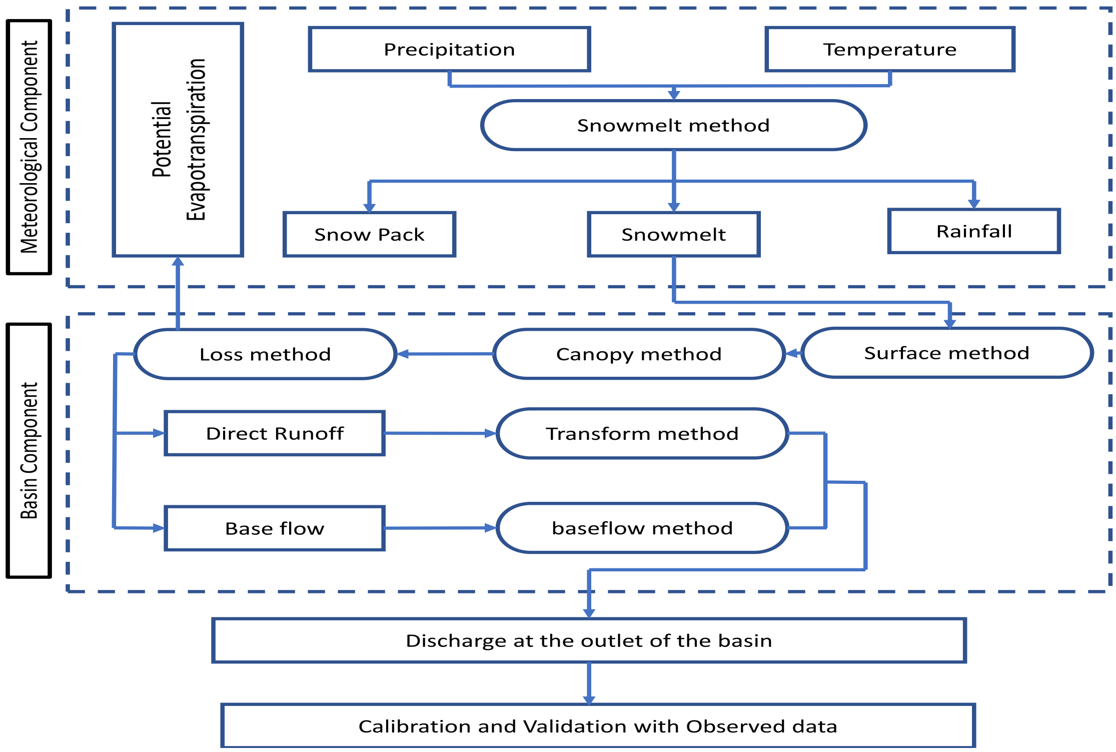


Figure 5.5 The general structure of HEC-HMS software [9] [10] [11]

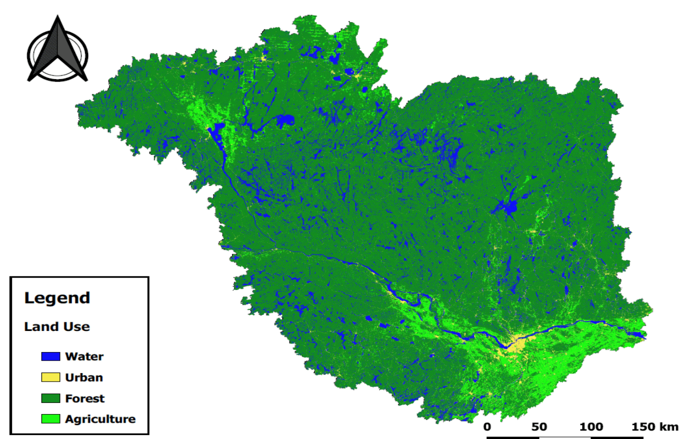


Figure 5.6 Land use for Ottawa River Basin

$$CN = \frac{\sum_i (CN_i * A_i)}{\sum_{i=n}^{n} A_i} \tag{5.7}$$

where CN denotes the area-weighted curve number; A_i is the area for each land use soil polygon; CN_i is the curve number for each land use soil polygon.

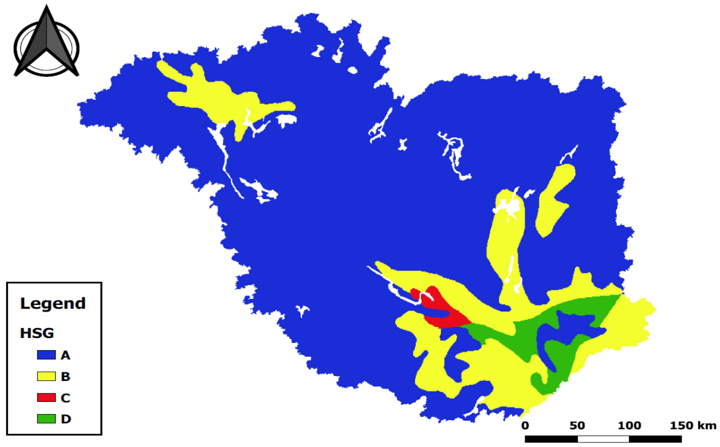


Figure 5.7 Soil classification map for Ottawa River Basin

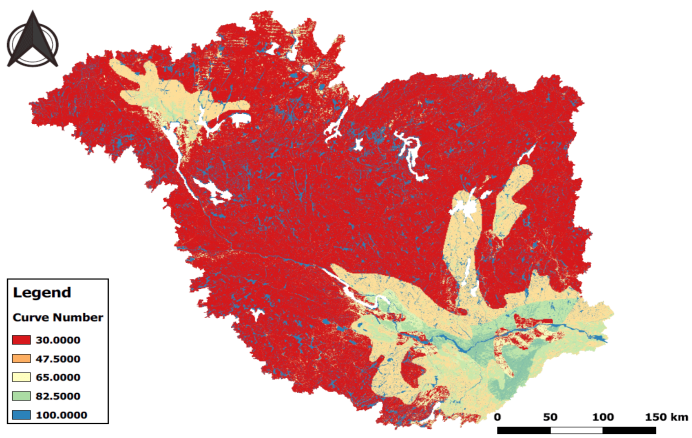


Figure 5.8 Curve number for the Ottawa River Basin

Table 5.3 The curve number value for the main Ottawa subwatershed

Watershed	**Curve Number (CN)**
Rideau	61
Petite Nation	55.4
South Nation	72.3
Rouge	41.6
Lievre	43.3
Gatineau	42.2
Upstream Ottawa	42.8

5.3 Meteorological data

The hydrological model was calibrated and validated using climate data provided from ERA5-Land data. ERA5-Land was available from 1981 to 2-3 months before the present date. In the Ottawa River Basin, there is an insufficient station density to estimate the average climate data for the main subwatersheds. In this context, the ERA5-Land has been chosen for this study because of its high horizontal spatial resolution of the data which is 9 km [155] and it showed a good similarity to that of meteorological stations in Ottawa River Basin [156].

In this work, the climate data that was obtained from ERA5-Land are precipitation and temperature. The mean precipitation was calculated using the Thiessen polygon method. This method is based on area weighting. The average precipitation using the Thiessen polygon method is estimated by the following equation 5.8.

$$P_{mean} = \frac{\sum_i^n P_i A_i}{\sum_i^n A_i} \tag{5.8}$$

Where P_{mean} is the weighted average; P_i is the precipitation in the polygon i; A_i is the area of polygon i and n is the number of polygons generated using Thiessen polygon.

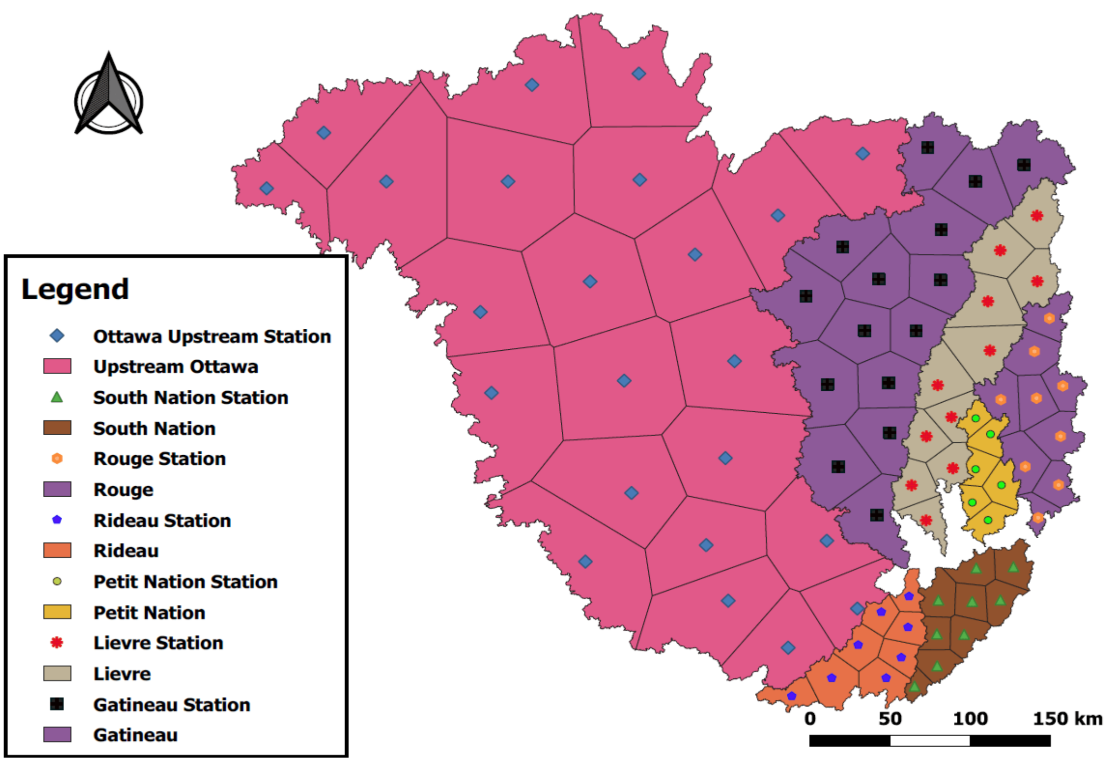


Figure 5.9 The location of the main Ottawa sub-watershed with the Era-5 sample point

The evapotranspiration was calculated using Hargreaves equation [157] with Era5 temperature data.

The ERA5 -Land and measured data in four stations Angers, Luskville, Kemptville and Ottawa CDA are compared here. See Figures 5.10, 5.11, 5.12 and 5.13, also by using a statistical measures as in Tables 5.4 and 5.5.

Table 5.4 Comparison of the precipitation data of ERA5-Land with the observed data of several station

	Angers		**Luskville**		**Kemptville**		**Ottawa CDA**	
	ERA5	**Station**	**ERA5**	**Station**	**ERA5**	**Station**	**ERA5**	**Station**
Min	0	0	0	0	0	0	0	0
Mean	2.868	2.793	2.704	2.63	2.537	2.852	2.732	2.38
Max	80.68	105.4	69.423	58.4	99.953	81.9	54.259	59
STD	6.225	6.788	5.711	5.575	6.48	6.26	5.754	5.588

Table 5.4 represents a comparison between the precipitation provided from ERA5-Land and the measured in four stations Angers, Luskville, Kemptville, and Ottawa CDA. This comparison is based on four statistical parameters minimum (Min), maximum (Max), mean (Mean), and standard deviation (STD). For the precipitation case, the Min does not provide much information as the minimum is recorded during the days without precipitation, so all of them have the 0 mm value. The mean and the standard deviation are almost the same for the four locations. For the extreme precipitation, we observe that ERA5-Land underestimates precipitation in Angers and Ottawa CDA by around 25 mm and 5 mm, respectively. Moreover, it overestimates in Luskville and Kemptville by around 11 mm and 18 mm, respectively. Generally, ERA5-land precipitation data is almost the same as the measured ones with some differences regarding the peak data.

Table 5.5 represents a comparison between the temperature provided from ERA5-Land and the measured in the same location and with the same statistical parameters as it was done for precipitation. For temperature, there are big similarities regarding the fourth parameter with a small difference in the mean and maximum values in Angers and Luskville locations.

Table 5.5 Comparison of the temperature data of ERA5-Land with the observed data of several station

	Angers		**Luskville**		**Kemptville**		**Ottawa CDA**	
	ERA5	**Station**	**ERA5**	**Station**	**ERA5**	**Station**	**ERA5**	**Station**
Min	-27.42	-30	-22.935	-24	-27.543	-26.7	-22.637	-22.4
Mean	7.127	4.726	7.458	4.863	6.96	6.35	7.955	7.312
Max	29.46	27	30.676	26.5	28.678	27.2	31.231	31.1
STD	12.578	12.608	11.382	11.639	12.434	12.26	11.466	11.464

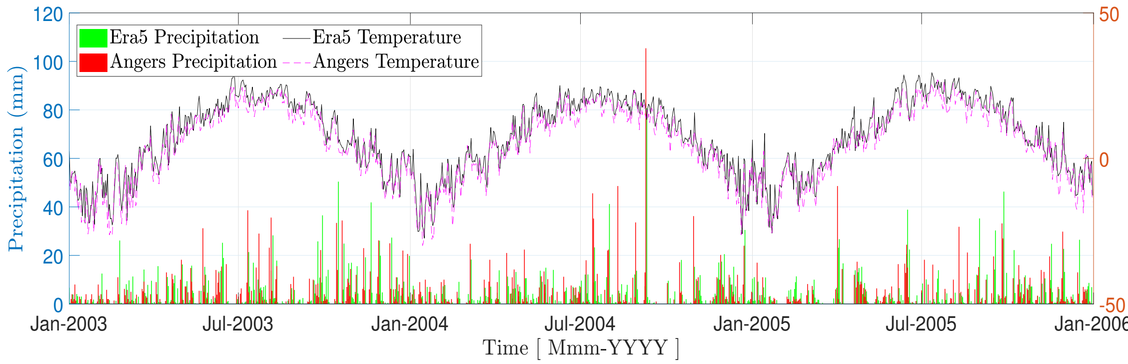


Figure 5.10 Comparing temperature and precipitation between Era-5 and observed climate data in Angers station (Latitude 45°33′00N Longitude 75°33′00W)

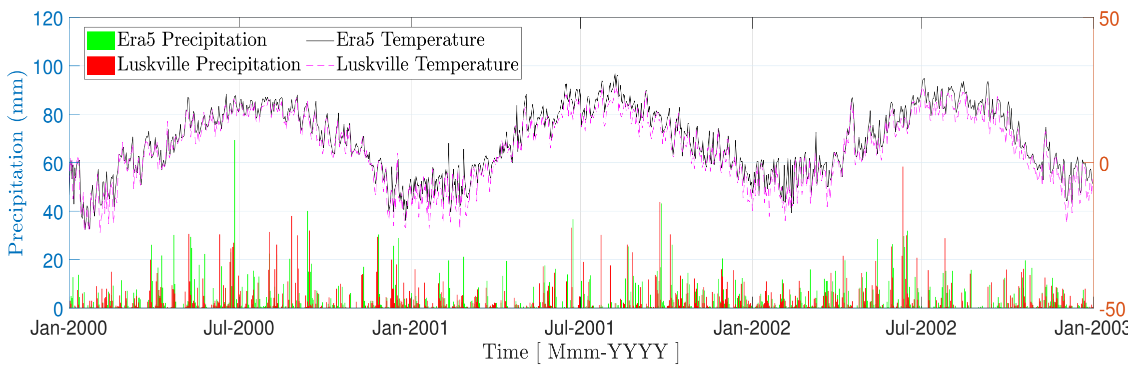


Figure 5.11 Comparing temperature and precipitation between Era-5 and observed climate data in Luskville station (Latitude 45°32′00N Longitude 76°03′00W)

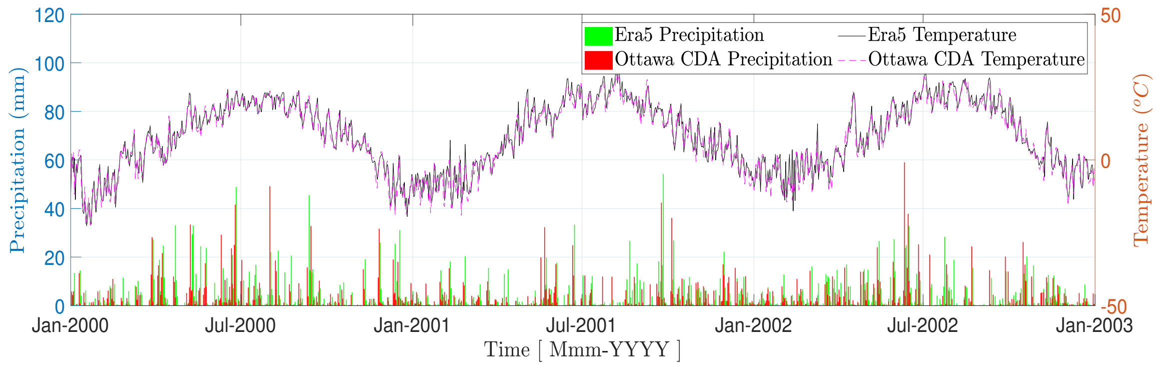


Figure 5.12 Comparing temperature and precipitation between Era-5 and observed climate data in Ottawa CDA station (Latitude $45^o23'00$N Longitude $75^o43'00$W)

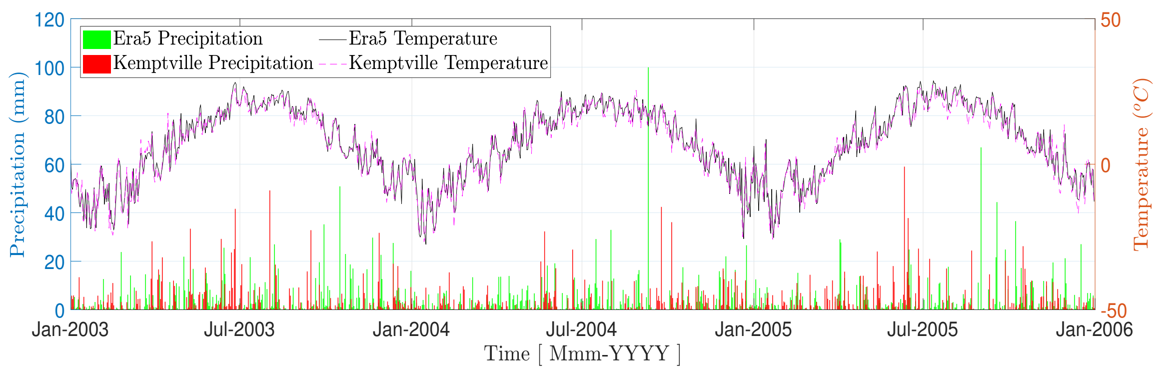


Figure 5.13 Comparing temperature and precipitation between Era-5 and observed climate data in Kemptville station (Latitude $45^o00'00$N Longitude $75^o38'00$W)

5.4 Time of Concentration

Time of concentration is a key parameter used in hydrology. It represents the required time for a drop of water to travel from the most remote point to the watershed outlet. Time of concentration aims to estimate the response of watersheds [158] [159] [160] [161].

There are several empirical equations to estimate the time of concentration such as Haktanir–Sezen [162] Williams [163], Kirpich [164], the Johnstone–Cross [165], Kerby [166], Chen and Womg [167] and more [159]. These equations are based on the watershed parameters such as watershed drainage area, channel length, watershed or channel slope and watershed shape parameters [164] [168] [159].

In this study, the Johnstone–Cross [165] equation was used for the subwatershed with an area between 64,7 and 4206,1 km^2 (Rideau, Petite Nation, and South Nation) and Bransby-Williams [169] equation was used for the big subwatershed (Gatineau, Lievre Rouge, and Upstream Ottawa).

Johnstone–Cross equation is given in the following equation:

$$Tc = 3.258 * (\frac{L_c}{S_c})^{0.5} \tag{5.9}$$

Where Tc denotes for time of concentration in (minutes); L_c for river length in (km); S_c for slope in (m/m) and A for watershed area (km^2)

Bransby-Williams formula is given in the following equation:

$$Tc = 58.5 * L_c * A^{-0.1} * S_c^{-0.2} \tag{5.10}$$

Where: Tc denotes for time of concentration in (minutes); L_c for river length in (km); S_c for slope in (m/km) and A for watershed area (km^2)

The time of concentration of the main Ottawa subwatershed are listed in the flowing Table 5.6:

Table 5.6 The time of concentration for the main Ottawa subwatershed

Watershed	**Area (km^2)**	**Equation**	**Time of concentration (hour)**
Rideau	3987.7	Johnstone–Cross	28.54
Petite Nation	2249.6		14.95
South Nation	3963.5		41.45
Rouge	5583.8	Bransby-Williams	70.01
Lievre	9133.9		132.29
Gatineau	23129.2		163.25
Upstream Ottawa	95528.6		260.46

5.5 Calibration

The hydrological models were calibrated by using the HEC-HMS optimization algorithm (Nelder Mead) to optimize basin and snowmelt parameters. In addition, this optimization was improved with an automatic optimization by using Pareto Archived Dynamically Dimensioned Search (PADDS) algorithm [170]. The calibration algorithm (PADDS) is integrated into a MATLAB script created by S. Sahraei et al. [171]. The calibration process is described in Figure 5.14.

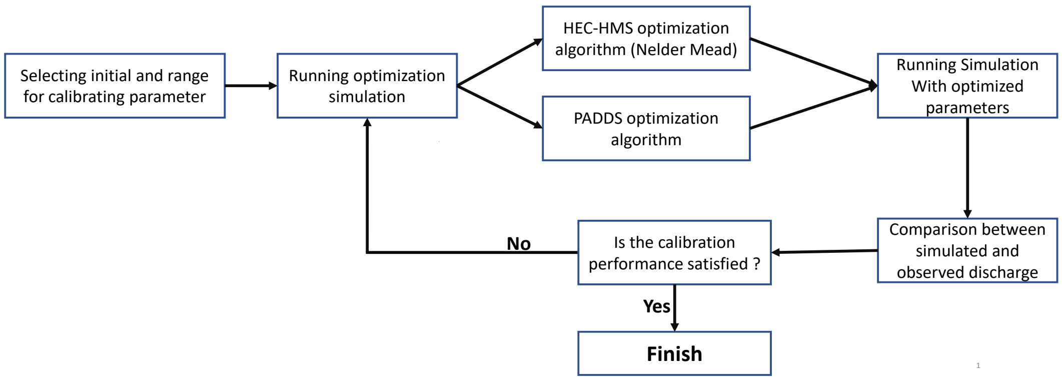


Figure 5.14 The schematization of the calibration process

For more information about calibration parameters, please refer to HEC-HMS documentation [10].

5.6 Results and Discussions

The performance measures that were used in this study to assess the reliability of hydrological models are Pearson correlation coefficient (R^2), Root Mean Square Error (RMSE), Relative Root Mean Square Error (RRMSE), and Nash-Sutcliff (NSE).

The Pearson correlation coefficient (R^2) is a statistical parameter. It takes values in the range between 0 and 1. It indicates good performance more it is close to 1 [172].

$$R^2 = \left[\frac{\sum_{i=1}^{n}(Q_{obs_i} - \overline{Q}_{obs})(Q_{sim_i} - \overline{Q}_{sim})}{\sqrt{\sum_{i=1}^{n}(Q_{obs_i} - \overline{Q}_{obs})^2}\sqrt{\sum_{i=1}^{n}(Q_{sim_i} - \overline{Q}_{sim})^2}} \right]^2 \tag{5.11}$$

Root Mean Square Error (RMSE) and also called root-mean-square deviation (RMSD). It assesses the magnitudes of the errors between observed and simulated time series data. The lower the RMSE is, the more the model is performing well [173].

Table 5.7 The ranges of the main calibrating parameters of HEC-HMS model

Type	Parameter	Unit	Range
Basin	Initial Storage	%	0 – 100
	Max Storage	MM	0 – 1500
	Crop Coefficient	–	0.01 – 1.5
	Initial Abstraction	MM	0 – 500
	Imprevious	%	0 – 100
	Storage Coefficient	HR	0.01 – 1000
	Initial Discharge	$M^3/s/Km^2$	0 – 100
	Recession Constant	–	0.01 – 1
SnowMelt	WET Meltrate	MM / DEG C-DAY	0 – 100
	Rain Rate Limite	MM / DAY	0 – 6000
	ATI-Meltrate Coefficient	–	0 – 0.9
	Cold Limit	MM / DAY	0 – 6000
	Water Capacity	%	0 – 100
	GroundMelt Method	MM / DAY	0 – 100
	Lapse Rate	DEG C / 1000 M	0 – 15
	Initial Cold Content ATI	DEG C	0 – 45
	Initial Melt ATI	DEG C - DAY	0 – 100

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Q_{sim_i} - Q_{obs_i})^2}{n}} \tag{5.12}$$

Relative Root Mean Square Error (RRMSE) is defined as RMSE, however, it is normalized by the average value of observed data. It gives more information about the scatter relative to the mean.

$$RRMSE = \frac{1}{\overline{Q}_{obs}}\sqrt{\frac{\sum_{i=1}^{n}(Q_{sim_i} - Q_{obs_i})^2}{n}} \tag{5.13}$$

The Nash–Sutcliffe model efficiency coefficient (NSE) is one of the famous performance indicators to assess the hydrology model. It was introduced by Nash and Sutcliffe [174]. NSE normally ranges are from -inf to 1. When NSE < 0, it indicates that the mean observed value is a better indicator than the model results. The acceptable NSE range is between 0 and 1 which is the optimal value.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_{sim_i} - Q_{obs_i})^2}{\sum_{i=1}^{n}(Q_{obs_i} - \overline{Q}_{obs})^2} \tag{5.14}$$

Where :

Q_{obs_i} : Observed Flow in the i^{th} day
Q_{sim_i} : Simulated Flow in the i^{th} day
$\overline{Q}_{obs}$: Average of the observed flow

The HEC-HMS hydrological models were successfully developed for the main Ottawa sub-watershed. The reliability of hydrological models was assessed using several performance indicators. Hydrological models were successfully done for almost the main Ottawa subwatershed as it is listed in Table 5.8. The validation and calibration were done with daily data for different periods. The simulation period was chosen to cover the longest period possible. Also, the period choice is depending on the data availability and quality (without missing data). The error measures were calculated based on daily values.

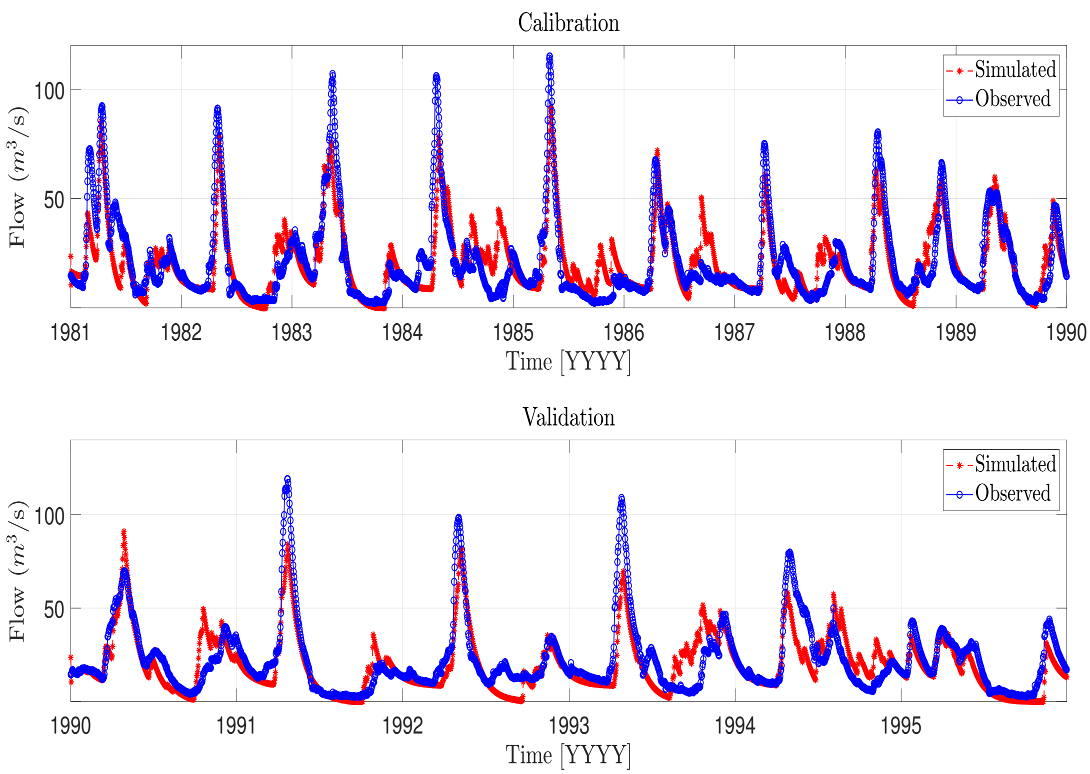


Figure 5.15 Observed and simulated flow results for Petite Nation hydrological model during calibration and validation process

Figure 5.15 presents the results of the hydrological model for the Petit Nation watershed and Figure 5.17 shows the scatter plot between measured and simulated flow results. HEC- HMS

Table 5.8 The performance of hydrological models

Subwatershed	**Simulation purpose**	**Performance Indicators**			
		NSE	R^2	RMSE (m^3/s)	RRMSE
Petite Nation	Calibration	0.687	0.689	11.17	0.515
	Validation	0.655	0.675	11.22	0.495
Ottawa Upstream	Calibration	0.440	0.444	482.85	0.404
	Validation	0.605	0.615	572.58	0.383
Gatineau	Calibration	0.377	0.45	114.12	0.313
	Validation	0.476	0.511	149.9	0.356
Rouge	Calibration	0.546	0.555	67.71	0.642
	Validation	0.526	0.528	68.11	0.673
Rideau	Calibration	0.531	0.538	37.67	0.857
	Validation	0.633	0.65	37.54	0.716
South Nation	Calibration	0.405	0.419	73.94	1.54
	Validation	0.416	0.432	60.5	1.25
Lievre	Calibration	0.295	0.316	64.98	0.376
	Validation	0.306	0.3	80.53	0.416

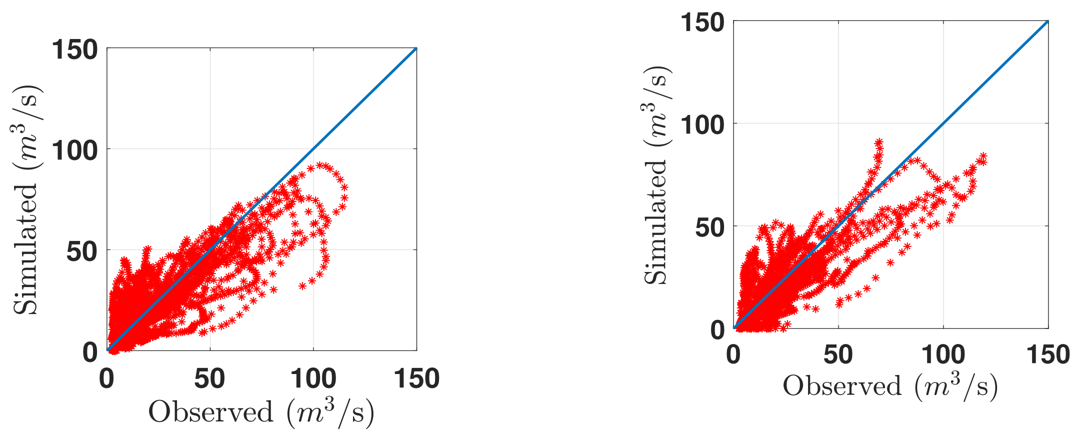


Figure 5.17 Scatter-plot of measured against simulated discharge for Petit Nation hydrological model (a) during calibration period (b) during validation period

performed well during calibration and validation with a Nush-Sutcliff coefficient estimated at 0.687 and 0.655, respectively. It well simulates the peak flow below 90 m^3/s and we observe an underestimation for fitting to the extreme flow below 90 m^3/s. Moreover, it reaches good regression values which were around 0.687 and 0.655 during calibration and validation, respectively. Hydrological model for Petite Nation watershed provide good results because water is not regulated [3].

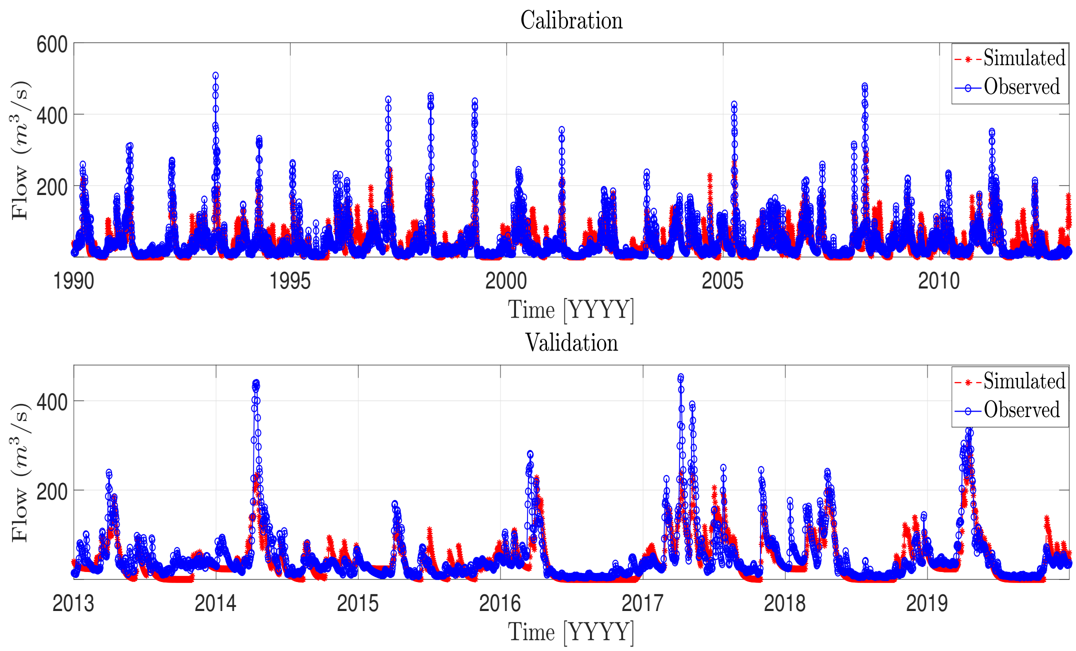


Figure 5.18 Observed and simulated flow results for Rideau hydrological model during calibration and validation process

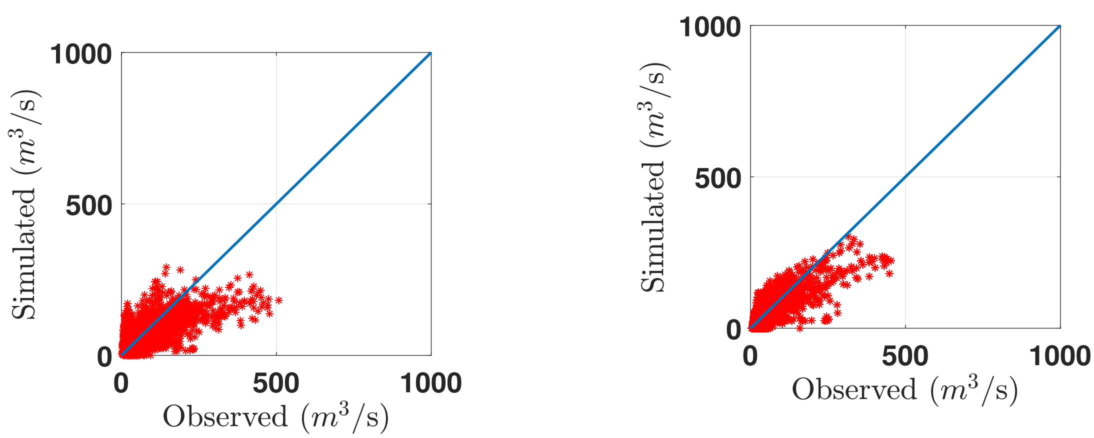


Figure 5.20 Scatter-plot of measured against simulated discharge for Rideau hydrological model (a) during calibration period (b) during validation period

Figure 5.18 depicts the results of the hydrological model for the Rideau watershed during the calibration and validation periods. The HEC-HMS model was calibrated for 20 years which contained seven peak flows. The hydrological model succeeds in simulating the flow below 200 m^3/s but it suffers to simulate with the extreme peak flow. Generally, the model performed well with a Nush-Sutcliff coefficient estimated at 0.531 and 0.633 during calibration and validation, respectively. Figure 5.20 illustrates the scatter plot between measured and simulated flow results. It is shown that during calibration there is divergence regarding the peak flows, but the simulated results fit better to the observed data during the validation period.

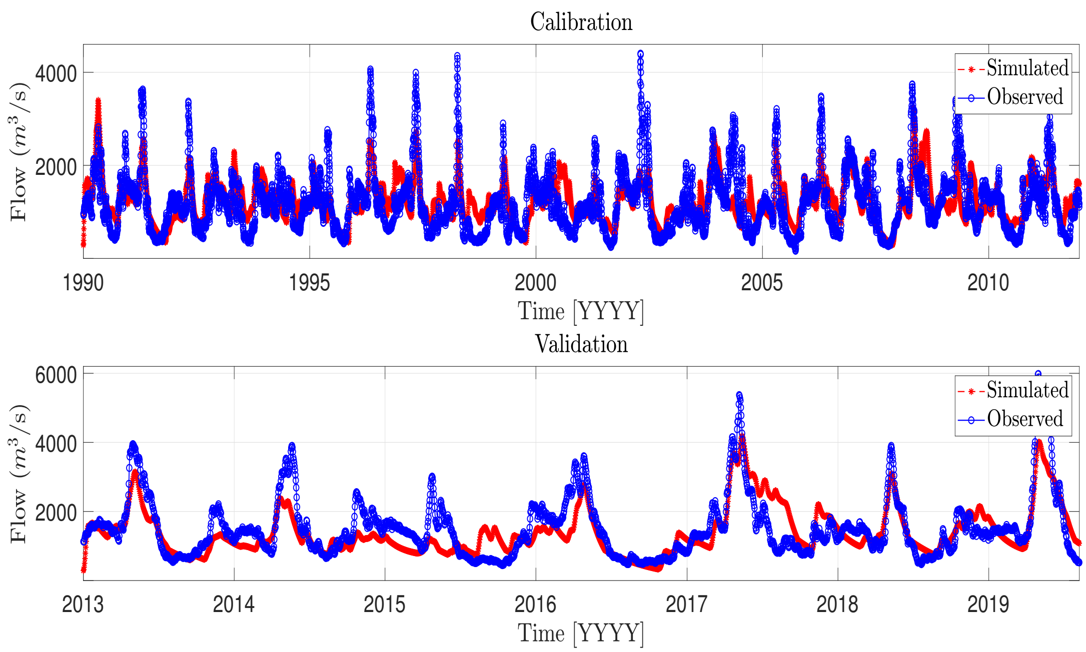
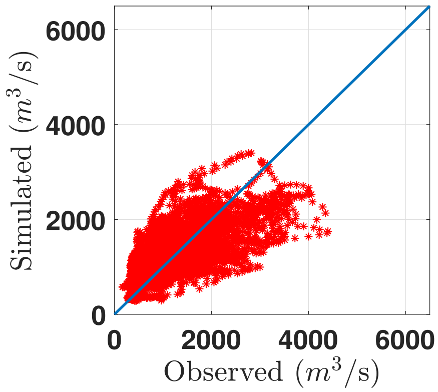


Figure 5.21 Observed and simulated flow results for Upstream Ottawa hydrological model during calibration and validation process

Figure 5.21 shows the results of the hydrological model for the Upstream Ottawa watershed during the calibration and validation periods. The Upstream Ottawa is the biggest Ottawa subwatershed and its outlet is located in the main Ottawa river with an important discharge rate which is around 1968 m^3/s. The Upstream Ottawa showed a good result for the calibration with NSE around 0.605 and a regression coefficient around 0.615. HEC HMS model has good results for simulation of the peaks flow with a small underestimation as shown in the Figure 5.23.

Figure 5.24 presents the results of the hydrological model for the Rouge watershed during



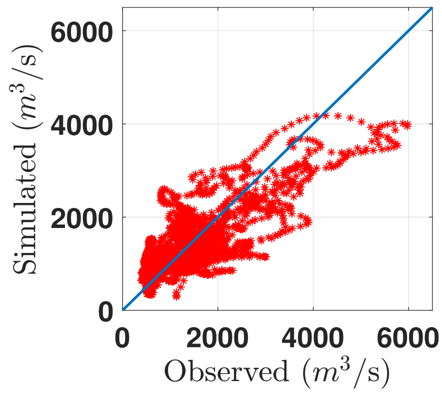


Figure 5.23 Scatter-plot of measured against simulated discharge for Upstream Ottawa hydrological model (a) during calibration period (b) during validation period

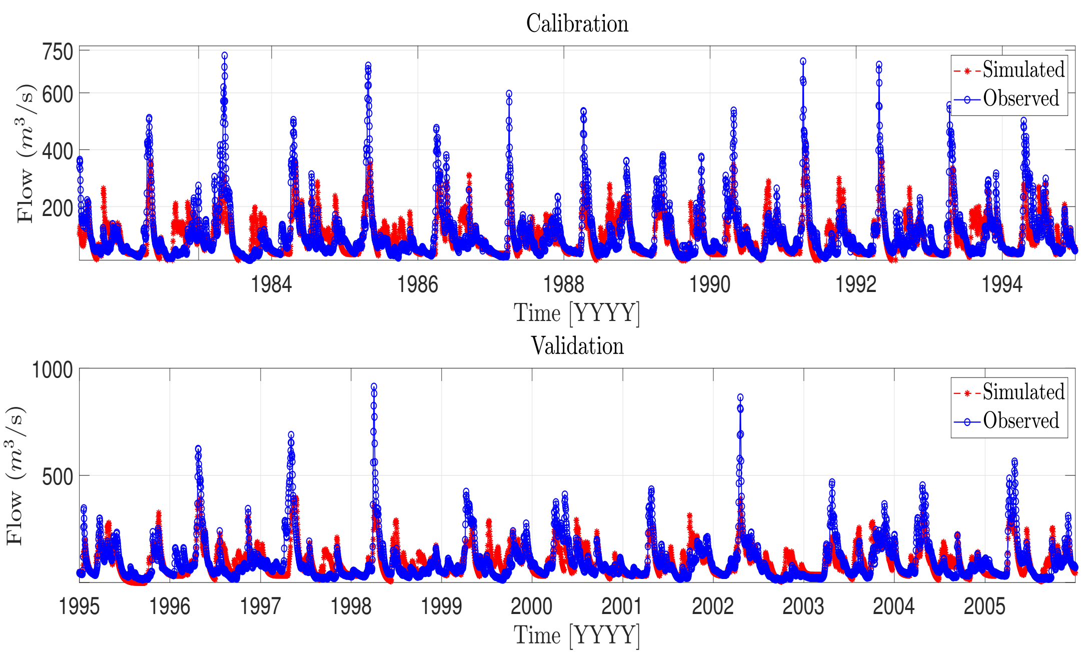
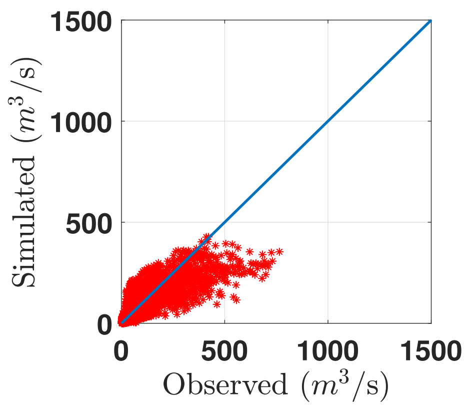


Figure 5.24 Observed and simulated flow results for Rouge hydrological model during calibration and validation process

the calibration and validation periods. The HEC HMS model was calibrated for 14 years and it was validated during 11 years. The simulation period characterizes by high peaks during short periods and the HEC-HMS model suffers to fit with extreme flow data as illustrated in



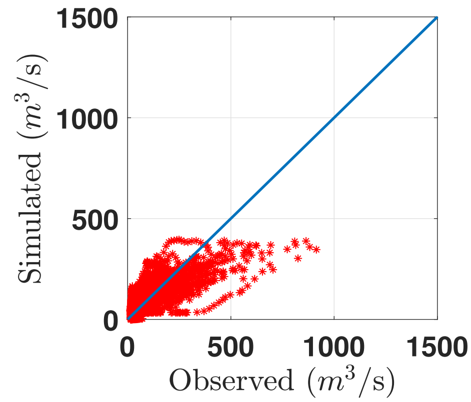


Figure 5.26 Scatter-plot of measured against simulated discharge for Rouge hydrological model (a) during calibration period (b) during validation period

Figure 5.26. Generally, it provides a satisfactory result. For the NSE, it reaches 0.546 and 0.526 during calibration and validation, respectively.

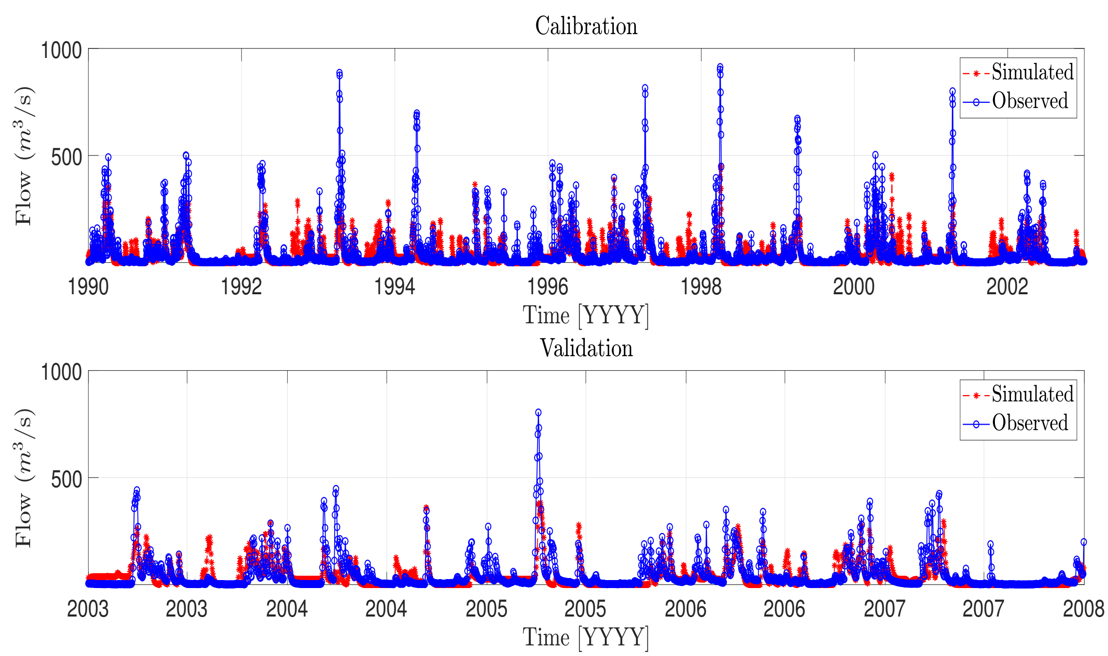


Figure 5.27 Observed and simulated flow results for South Nation hydrological model during calibration and validation process

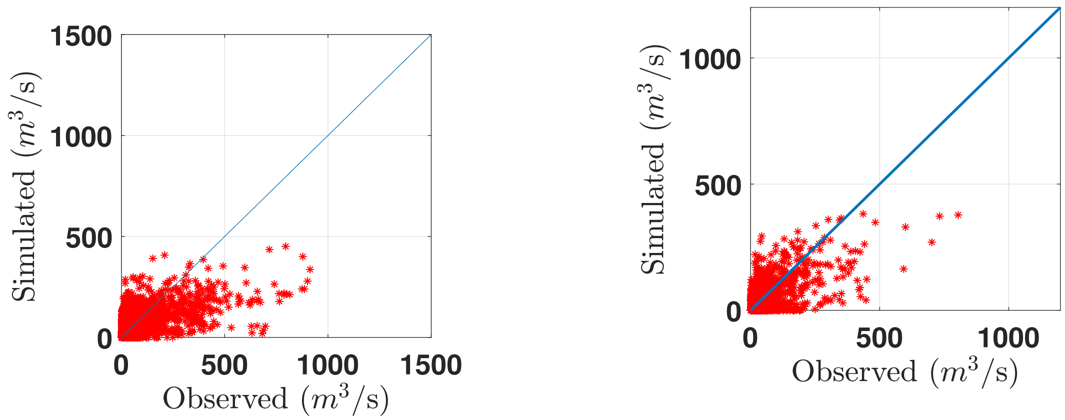


Figure 5.29 Scatter-plot of measured against simulated discharge for South Nation hydrological model (a) during calibration period (b) during validation period

Figure 5.27 illustrates the results of the hydrological model for the South Nation watershed during the calibration and validation periods. The hydrological model was calibrated for 13 years from 1990 to 2002, during this period 6 extreme flows were recorded. The HEC-HMS provides satisfactory results during calibration and validation with an underestimation to the peak flows as it is illustrated in the Figure 5.29.

Figure 5.30 displays the results of the hydrological model for the Gatineau watershed during the calibration and validation periods. The hydrological model was calibrated for 15 years with the measured flow data in Chelsea hydroelectric station which is regulated. The hydrological model provides satisfactory results. It fits well to the peak flows with a small underestimation as it is illustrated in the Figure 5.32.

Figure 5.33 shows the results of the hydrological model for the Lievre watershed during the calibration and validation periods. The hydrological model was calibrated for 11 years with the measured flow data in Masson hydroelectric station which is regulated. The HEC-HMS model suffers to provide good results for this case. It underestimates much the peak flows which are illustrated with a large divergence as it is presented in the Figure 5.35.

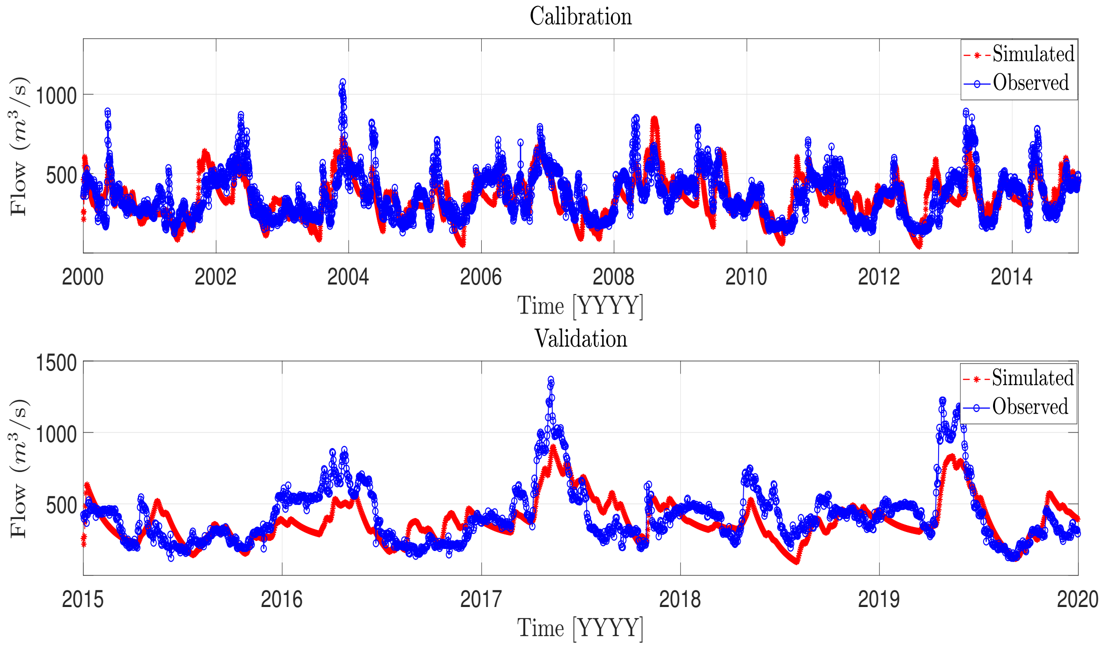


Figure 5.30 Observed and simulated flow results for Gatineau hydrological model during calibration and validation process

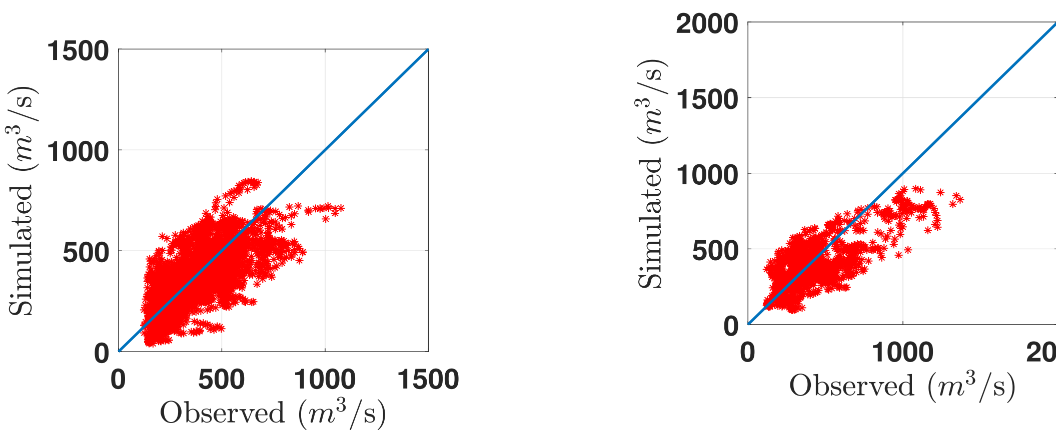


Figure 5.32 Scatter-plot of measured against simulated discharge for Gatineau hydrological model (a) during calibration period (b) during validation period

Regarding the results presented in the Figures from 5.15 to 5.35, we observe that HEC-HMS hydrological models underestimate the peak flows in some cases. This underestimation can be justified by several reasons. Firstly, because of the lack of information about lakes, dams, and

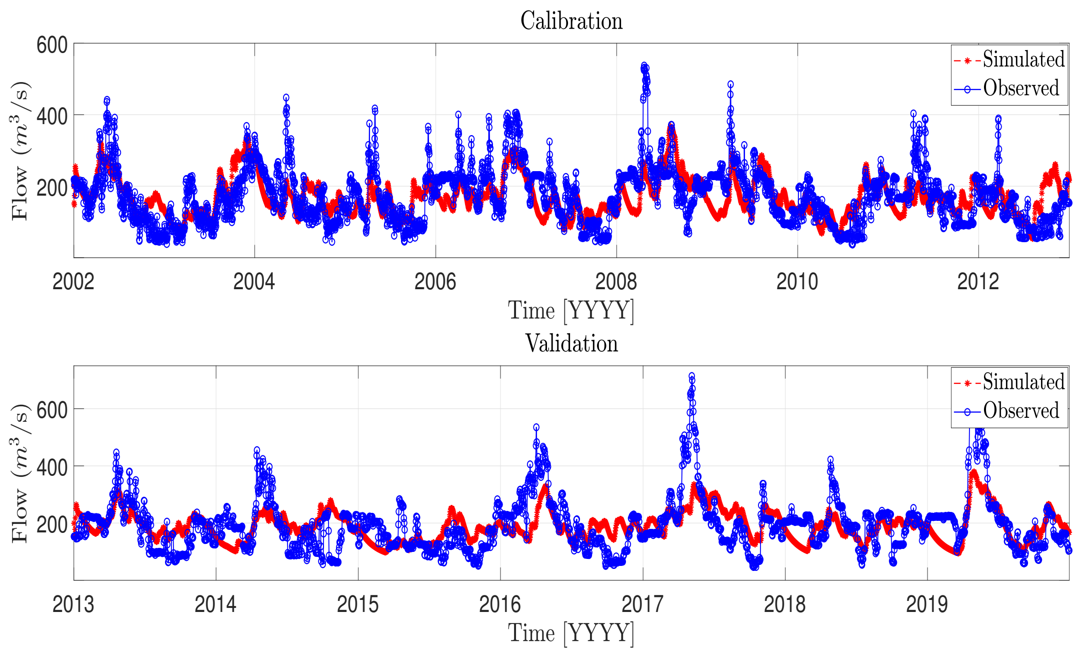


Figure 5.33 Observed and simulated flow results for Lievre hydrological model during calibration and validation process

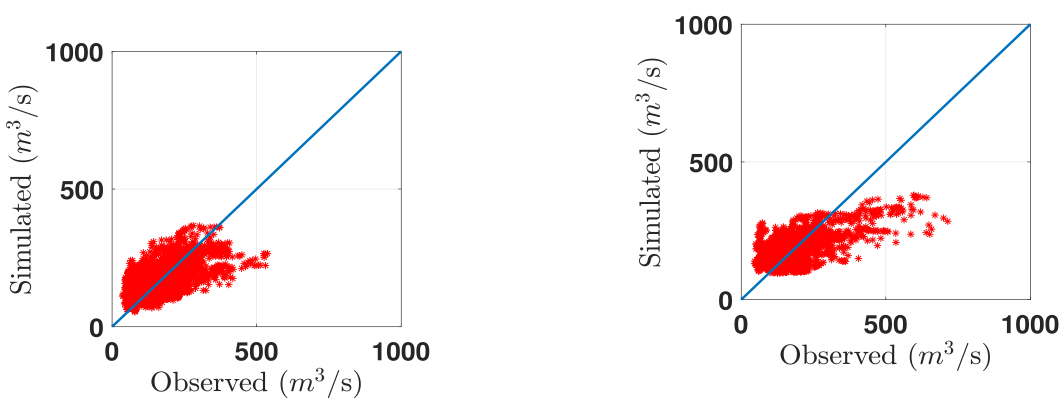


Figure 5.35 Scatter-plot of measured against simulated discharge for Lievre hydrological model (a) during calibration period (b) during validation period

hydroelectric stations which were located in the Ottawa River Basin. For example, several dams and hydroelectric stations were constructed in Quebec provinces as it is illustrated in Figure 1.4, the same for the Rideau watershed [128]. Moreover, the streamflow data quality affects the performance of hydrological models. For example, the Lievre watershed was validated with the daily averages of the total spilled flow calculated at the Masson station which does not represent the natural behavior of water in reality. Furthermore, these underestimations can be due to the difference between precipitation from ERA-5 Land and observed stations data as it is illustrated in Tables 5.5 and 5.5. In addition, every hydrological model has its limitations depending on its process structure schemes. HEC-HMS is based on a simple model formulation and flow representation. It could be due to models' limitations in representing hydrological processes such as snowmelt processes, infiltration to frozen soil, and curve number method can have its influence on results as it is based on soil texture and land use data which change year after year.

5.7 Conclusions

In conclusion, this chapter presents the HEC-HMS models developed for the main Ottawa subwatershed. The reliability of these models was assessed using different performance indicators: Pearson correlation coefficient (R^2), Root Mean Square Error (RMSE), Relative Root Mean Square Error (RRMSE), and Nash-Sutcliff (NSE). Generally, The HEC-HMS hydrological models simulate low and mean flows properly in most watersheds. It showed a good performance to simulate peak flows in only the Petit Nation watershed. The other models provide satisfactory results which showed an underestimation to fit extreme flow in some cases. This underestimation is due to several factors. Firstly, the flow data quality was not good for all models such as in the case of Lievre watersheds, the model was calibrated and validated with the daily averages of the total spilled flow calculated at Masson station. This is the reason that justifies the results of HEC HMS in Lievre Basin because the observed data is regulated and does not represent the natural behavior of water. Simulating extreme flow is an issue for most hydrological models [11]. The underestimation of HEC-HMS for the extreme flow event is due to its simplified process structure due to models' limitations in representing hydrological processes such as snowmelt processes and infiltration to frozen soil. Moreover, the lack of information about lakes, dams, and hydroelectric stations which are constructed with high numbers in the Ottawa River Basin affects the performance of hydrological models. In addition, it can be caused due to the difference between meteorological data of Era-5 Land and observed station data.

CHAPTER 6 INTEGRATING HYDRAULIC AND HYDROLOGICAL MODELS TO FLOOD FORECASTING SYSTEM DELFT-FEWS

6.1 Introdution

With the goal of developing an integrated flood forecasting system for the Ottawa River Basin, this chapter presents the automatic interconnections of the models and data using the DELFT-FEWS platform. This platform will provide the connection between the models (hydraulic and hydrologic) and the data (e.g., real-time weather forecasting data) to forecast the flood events and their characteristics in the Ottawa River.

6.2 Flood Forecasting System DELFT-FEWS

DELFT-FEWS is a real-time flood forecasting system. It is widely used for operational water management and flood forecasting applications. DELFT-FEWS itself is not a model. However, it is an open-shell system that can be connected to several models and also to different data types [175]. It aims to organize data processes from input to forecast, to dissemination, as it is illustrated in Figure 6.1. DELFT-FEWS is based on configurable files which are written in eXtensible Markup Language (XML). The configurable nature of DELFT-FEWS makes it the state of the art of data handling and warning system. Its major strengths are presented in Table 6.1. Flood forecasting systems aim to increase the lead time and also make predictions with high accuracy to support the decisions of decision-makers as it is presented in Figure 6.2.

6.3 Handling numerical weather prediction in DELFT-FEWS

DELFT-FEWS is capable of importing different data types e.g., numerical weather product, meteorological gages, remote sensor data) and formats (CSV, NetCDF, Grib, Xml, Open-DAP, ...). Connecting the flood forecasting models to the numerical weather prediction data will allow short-term flood forecasting, needed for emergency responses. Numerical weather prediction is integrated into DELFT-FEWS through several steps and by configuring multiple files as it is well structured in Figures 6.4 and 6.5. The main process of data through the flood forecasting system DELFT-FEWS could be described in these main steps. Data collection is the first step in flood forecasting, it can be several types such as precipitation radar, telemetry, or external forecasts. Then, this data is preprocessed with multiple data transformation

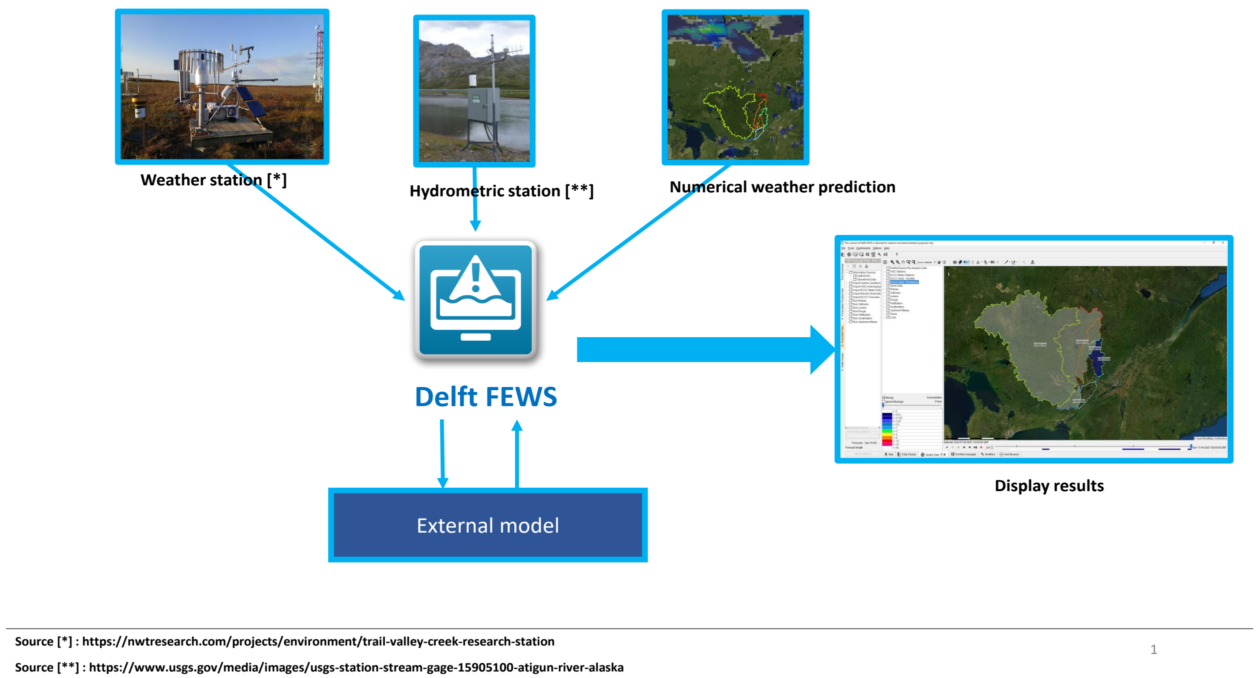


Figure 6.1 The main structure of DELFT-FEWS

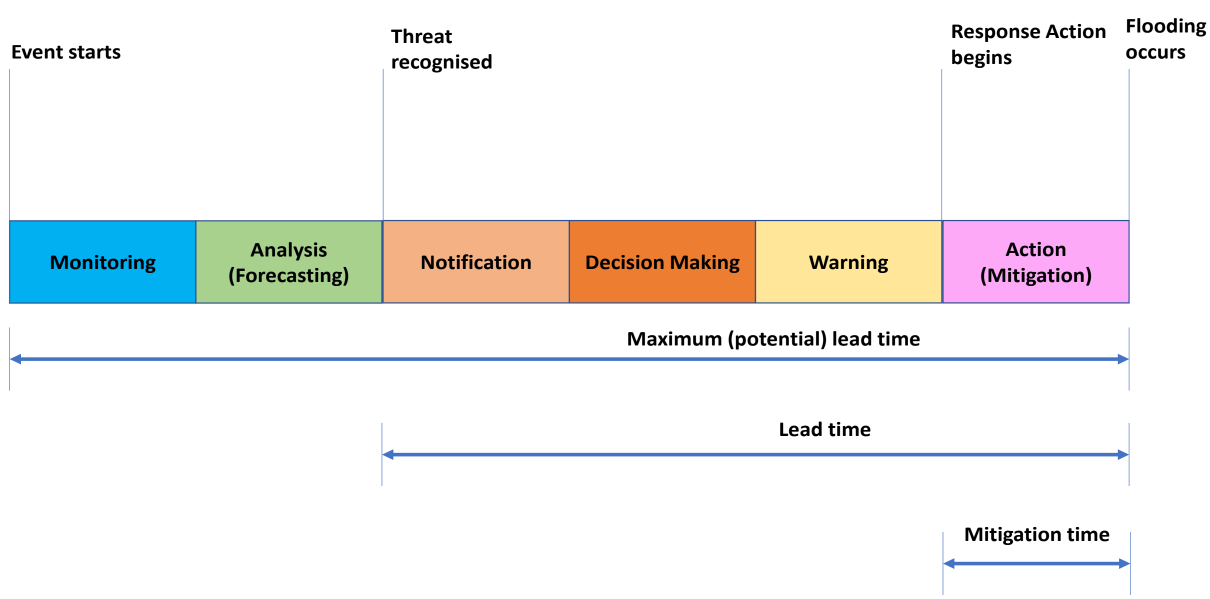


Figure 6.2 Lead time in flood forecasting system (www.publicwiki.deltares.nl)

which is available in DELFT-FEWS, for example: InterpolationSpatialAverage is a transformation method that aims to compute the average of a time series data within a specific area,

Table 6.1 The strengths and weakness of flood forecasting system DELFT-FEWS

Strength	**Weakness**
• XML data formats allow for robust verification of the exchange of data through applicable XML-schemas. • Support different data type and format. • It can be connected to the majority of water management models.	• It is based on configurable files which are organized in different folders. Consequently, it takes time to figure out the files that should be modified to do a specific task.

toggle Merge consists of merging a set of time series data, and daySample aims to make a daily sample from an input time series. Furthermore, data is ready to be integrated into connected hydrological, hydraulic, or overland flow models. Then, the models' results must be analyzed such as floodplain and threshold crossing. These steps are described in Figure 6.3. For more information, the DELFT-FEWS wiki page (www.publicwiki.deltaresota.nl) is the first source of documentation to be consulted.

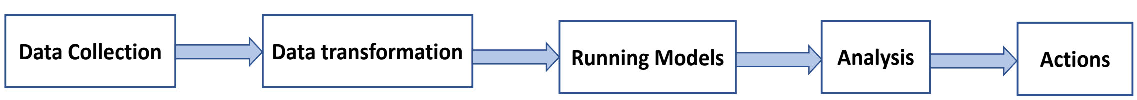


Figure 6.3 The sequence of the main forecasting steps in DELFT-FEWS

In this study, the Global Deterministic Prediction System (GDPS) was used to feed our hydrological models with forecasting data (precipitation and temperature) as a numerical weather prediction. GDPS was chosen for this work because it is provided from Environment and Climate Canada under physical calculations and has a high temporal resolution of 3 hours. It provides data for 10 days in the future. Its horizontal resolution is defined by 25 and 15 km [176]. The spatial display of the GDPS data is illustrated in Figure 6.6. Then, the GDPS climate data is pre-processed using a catchment average for temperature and precipitation as it is presented in Figure 6.7.

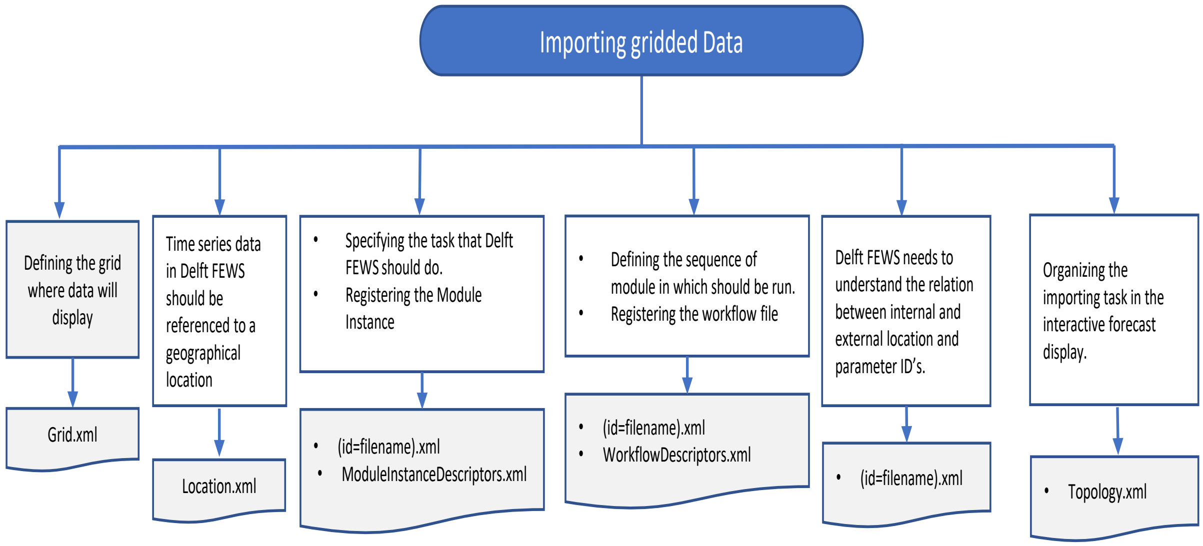


Figure 6.4 The organization of the main tasks to import NWP DELFT-FEWS

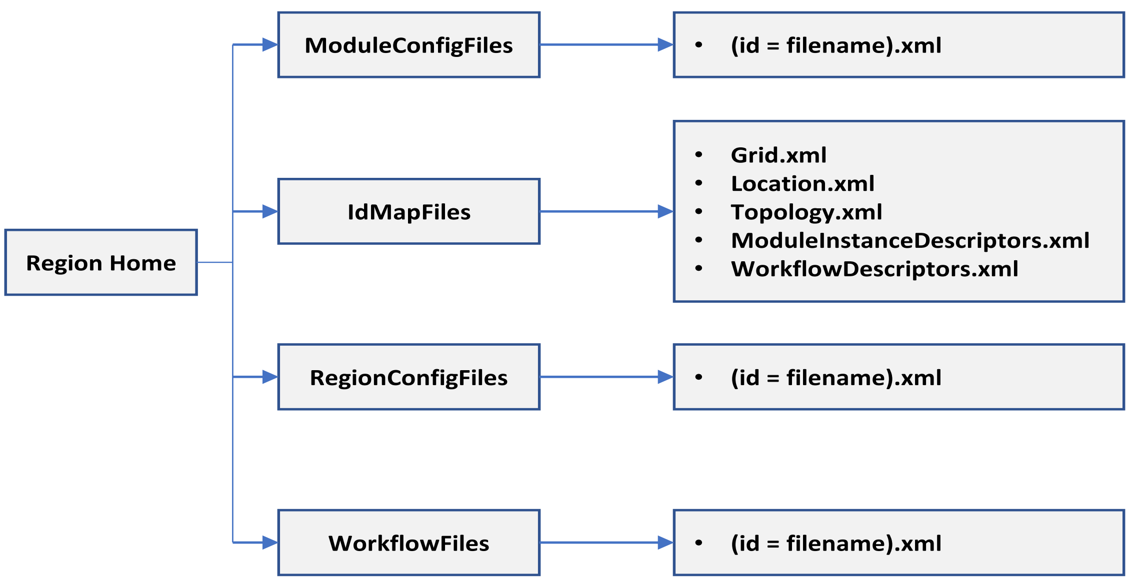


Figure 6.5 Directories for the main files to import NWP into Delft-FEWS

6.4 Connecting external models to DELFT-FEWS

DELFT-FEWS is capable of being connected to several external models such as hydrological, hydraulic, reservoir, and flood simulation models thanks to the General Adapter (GA). The general adapter aims to generate time series input and output in the XML files format and also to execute the Model Adapter (MA). The model adapter allows communication with

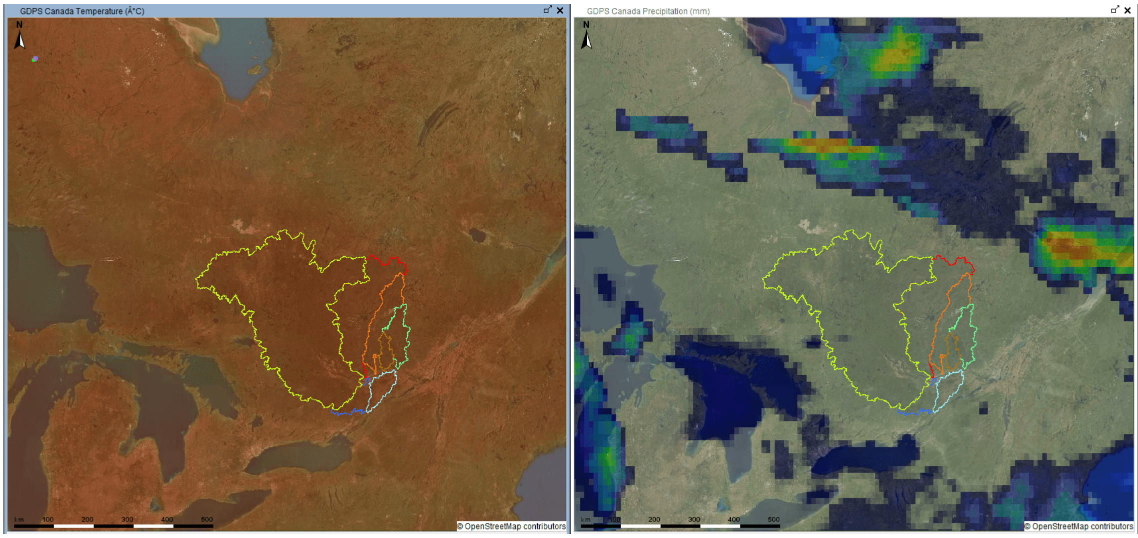


Figure 6.6 Spatial display of the GDPS data

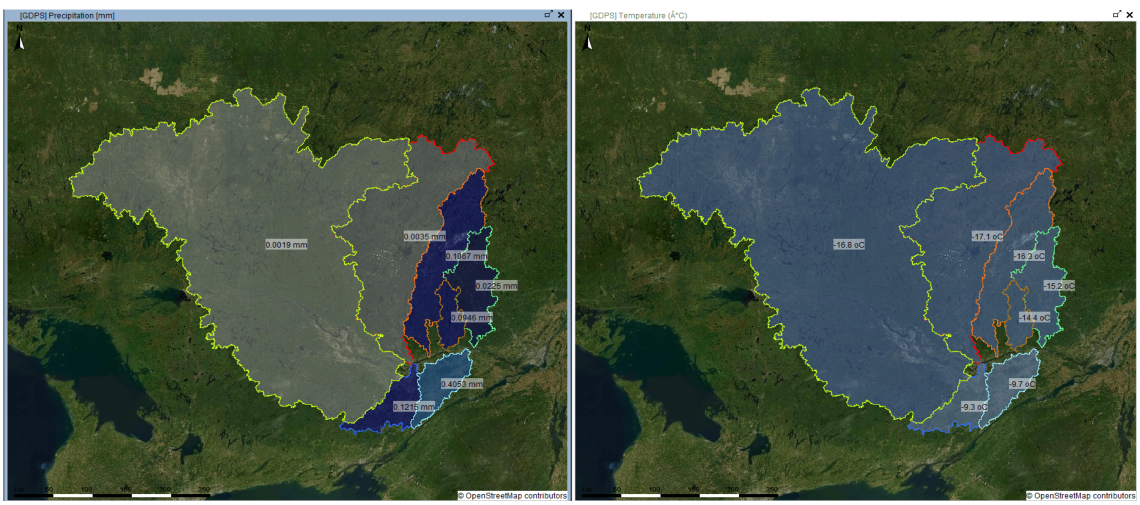


Figure 6.7 Catchment average of GDPS Data for temperature and precipitation

external models and converting data from DELFT-FEWS to native models format as it is illustrated in the Figure 6.8.

In this study, the hydrological model HEC-HMS will be connected to DELFT-FEWS to predict flow in the main Ottawa river tributaries. The flood forecasting results are illustrated in the Figures 6.9 to 6.15.

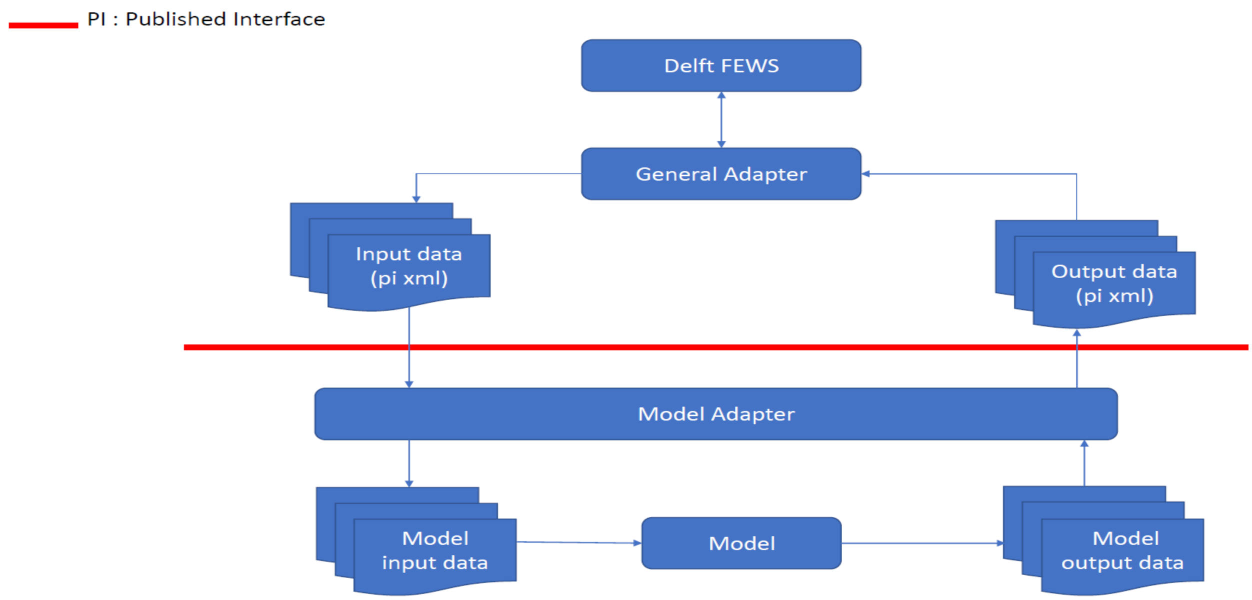


Figure 6.8 The structure of connecting external model to DELFT-FEWS

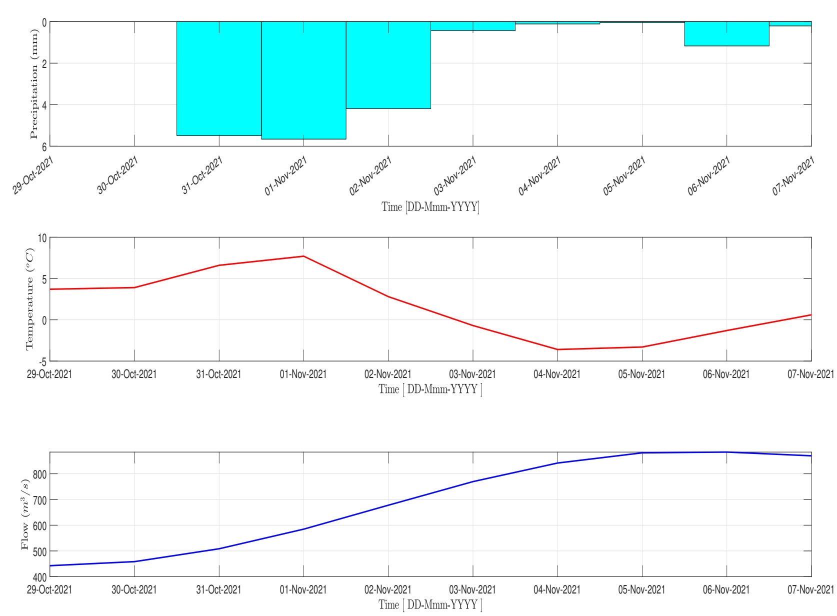


Figure 6.9 Forecast flow resulted from Gatineau hydrological simulation in connection with the numerical weather prediction.

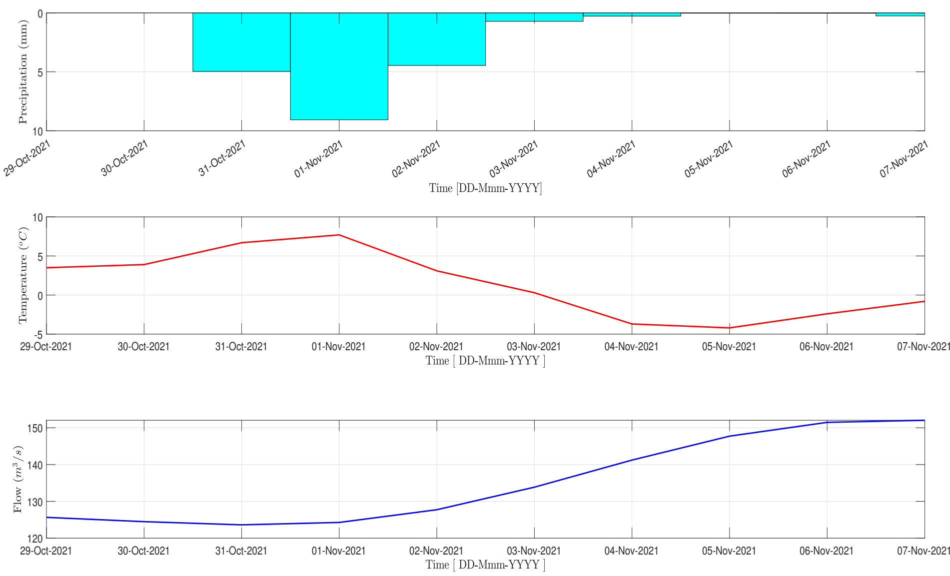


Figure 6.10 Forecast flow resulted from Lievre hydrological simulation in connection with the numerical weather prediction.

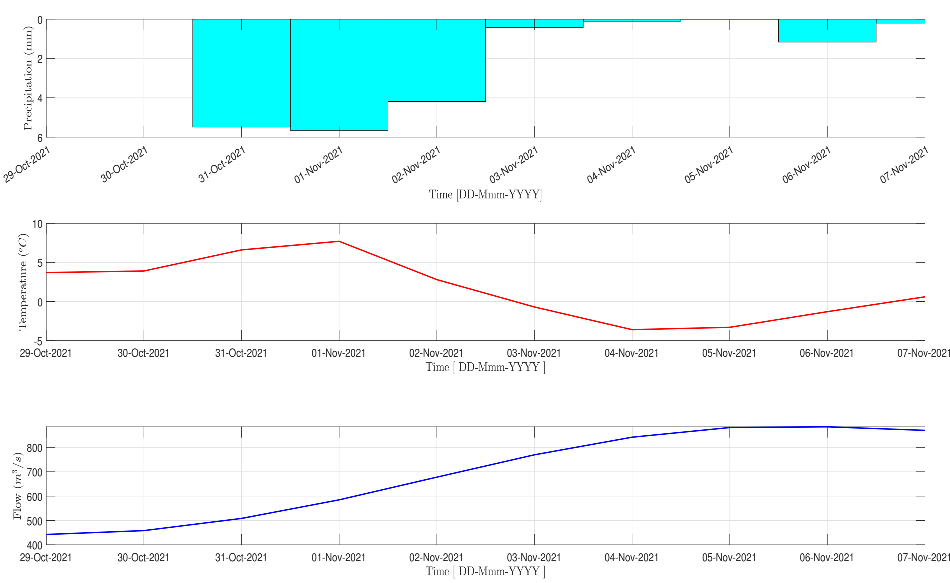


Figure 6.11 Forecast flow resulted from Rideau hydrological simulation in connection with the numerical weather prediction.

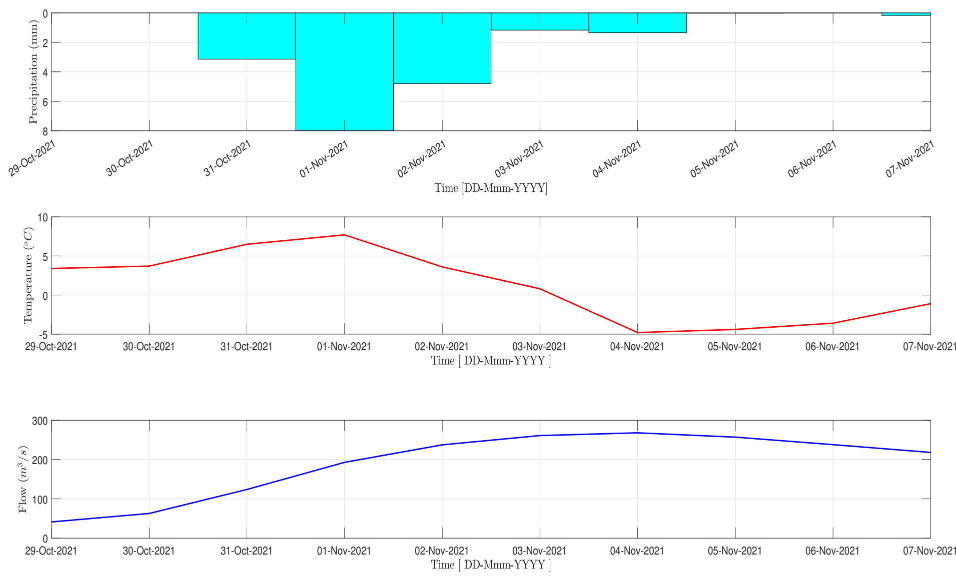


Figure 6.12 Forecast flow resulted from Rouge hydrological simulation in connection with the numerical weather prediction.

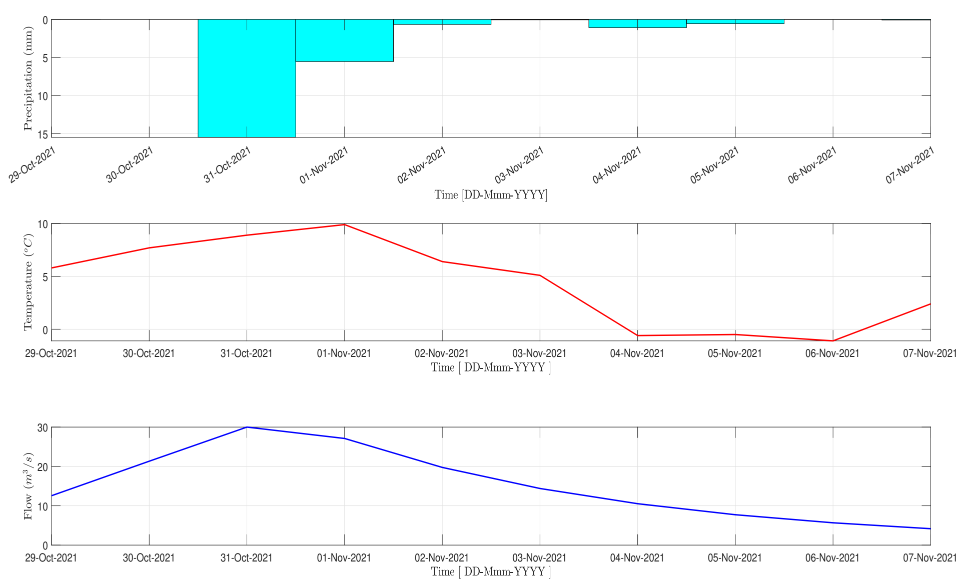


Figure 6.13 Forecast flow resulted from South Nation hydrological simulation in connection with the numerical weather prediction.

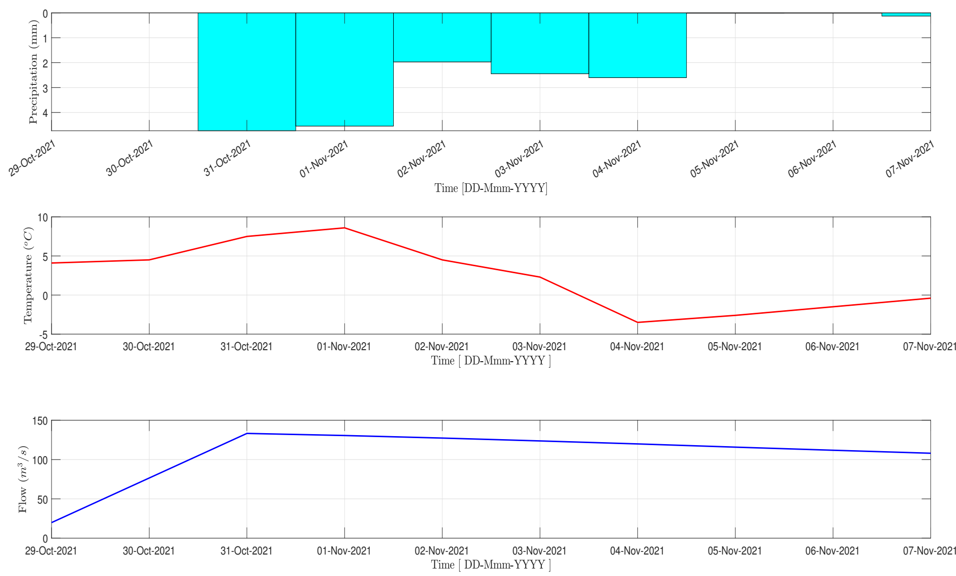


Figure 6.14 Forecast flow resulted from Petite Nation hydrological simulation in connection with the numerical weather prediction.

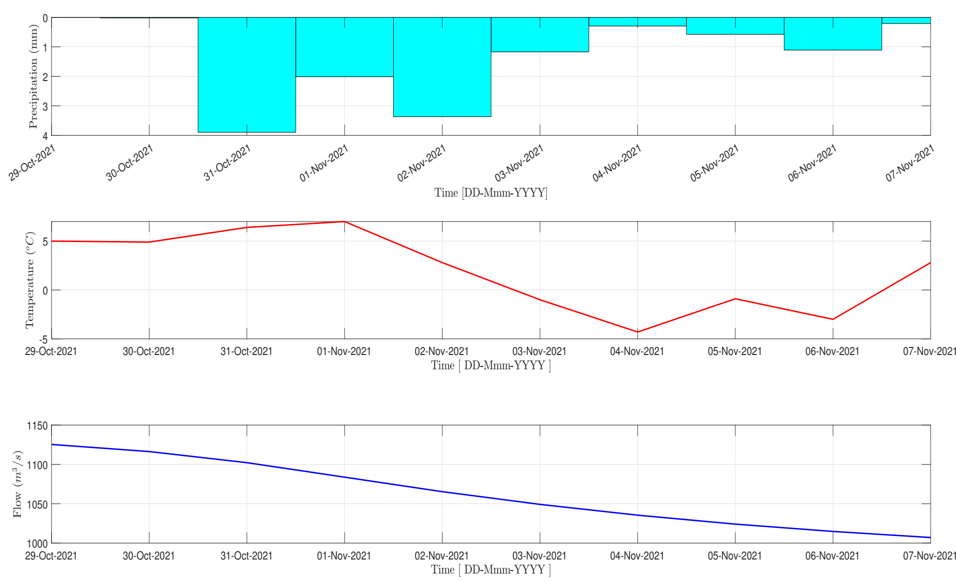


Figure 6.15 Forecast flow resulted from Upstream Ottawa hydrological simulation in connection with the numerical weather prediction.

6.5 Conclusion

The DELFT-FEWS philosophy is based on providing the state of the art of data managing, forecasting, and warning processes. It was applied for the Ottawa River Basin in order to conduct a flood forecasting study in this region for the first time. The numerical data was successfully connected to DELFT-FEWS. Then, it was fed to hydrological models in order to estimate forecast discharge in outlets of the main Ottawa subwatershed. The next step will be to use DEFT-FEWS to provide the interconnection between the developed hydraulic model (i.e. based on Delft3D) and the hydrologic model. This will provide the opportunity to translate the short-term weather prediction data to the flood hydrodynamic characteristic (e.g., water level and velocity and inundation extent).

CHAPTER 7 CONCLUSION AND FUTURE WORK

7.1 Conclusion

This thesis's main objective was to develop an integrated flood modeling system for the Ottawa River, to predict short-term early warnings and emergency response. In addition, to provide flood characteristics such as water level, and land inundation flow discharge too. So, the authorities and decision-makers will have enough time to make the right decisions. This study started in the first step by data acquisition and processing the topographic, bathymetric, hydrometric, and climatic data required for the configuration and validation of the models for the Ottawa River Basin. Then, developing and validating a 2D hydraulic model based on Delft3D software in Ottawa River. In addition, developing, calibrating, and validating a hydrological model based on the HEC-HMS model for the main Ottawa River subwatershed.

Two hydrodynamic models have been successfully developed, based on the Delft-3D software for Ottawa River. It will simulate the water behavior in the two sections of the Ottawa River: about 20km upstream and about 120km downstream of the Chaudière dam. The two Delft3D models performed well for two sections of the Ottawa River. They were validated against observed water level and depth-averaged velocity in several cross-sections along the river. Moreover, they were validated against water levels during the recent flood event in Ontario in 2017 and 2019. The simulated delft3D results fit against hydrometric data with some small differences that could be due to the dam effect such as Chaudière and Carillion dam, the quality of the streamflow, bathymetry, and topography data.

The second part of this study consists of developing hydrological models for the main Ottawa river basin. These models were successfully developed using the HEC-HMS software. The reliability of these models was assessed depending on different performance indicators such as R^2, RMSE, RRMSE, and NSE. The HEC HMS hydrological models performed well for simulating peak flows for the case of the Petite Nation watershed. The other hydrological models provide satisfactory results which suffer to simulate the extreme flow in some cases. The model's underestimation is due to several factors. Firstly, the flow data quality was regulated in several models such as in the case of Lievre watersheds where the model was calibrated and validated with the daily averages of the total spilled flow calculated at Masson station. These data do not represent the natural behavior of water and this was the main reason that justified the results of HEC HMS in Lievre Basin. Simulating peak flow is an issue for most hydrological models. The simplified process structure of HEC-HMS could influence this underestimation. In addition, the lack of information about lakes, dams, and hydroelectric stations which were located in the Ottawa River Basin with high numbers, affects the results on the hydrological model's performance. Also, the difference between meteorological data of Era-5 Land and observed station data could contribute to this underestimation.

7.2 Future work

In this thesis, the hydraulic model was not yet connected to the flood forecasting system Delft FEWS due to a configuration issue. HEC-HMS model and the numerical weather data were successfully connected to Delft FEWS. In the future, the author is working to interconnect the hydraulic model Delft3D with hydrological models, and the weather prediction data through the unified modeling platform Delft FEWS.

Furthermore, in this thesis, the Ottawa river Basin was subdivided into the main subwatershed. A lumped hydrological model was developed for each subwatershed. It is recommended to develop different hydrological models with different structures and types and assess their performances against what was presented in this study.

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APPENDIX A FLOOD FORECASTING PROGRAMS

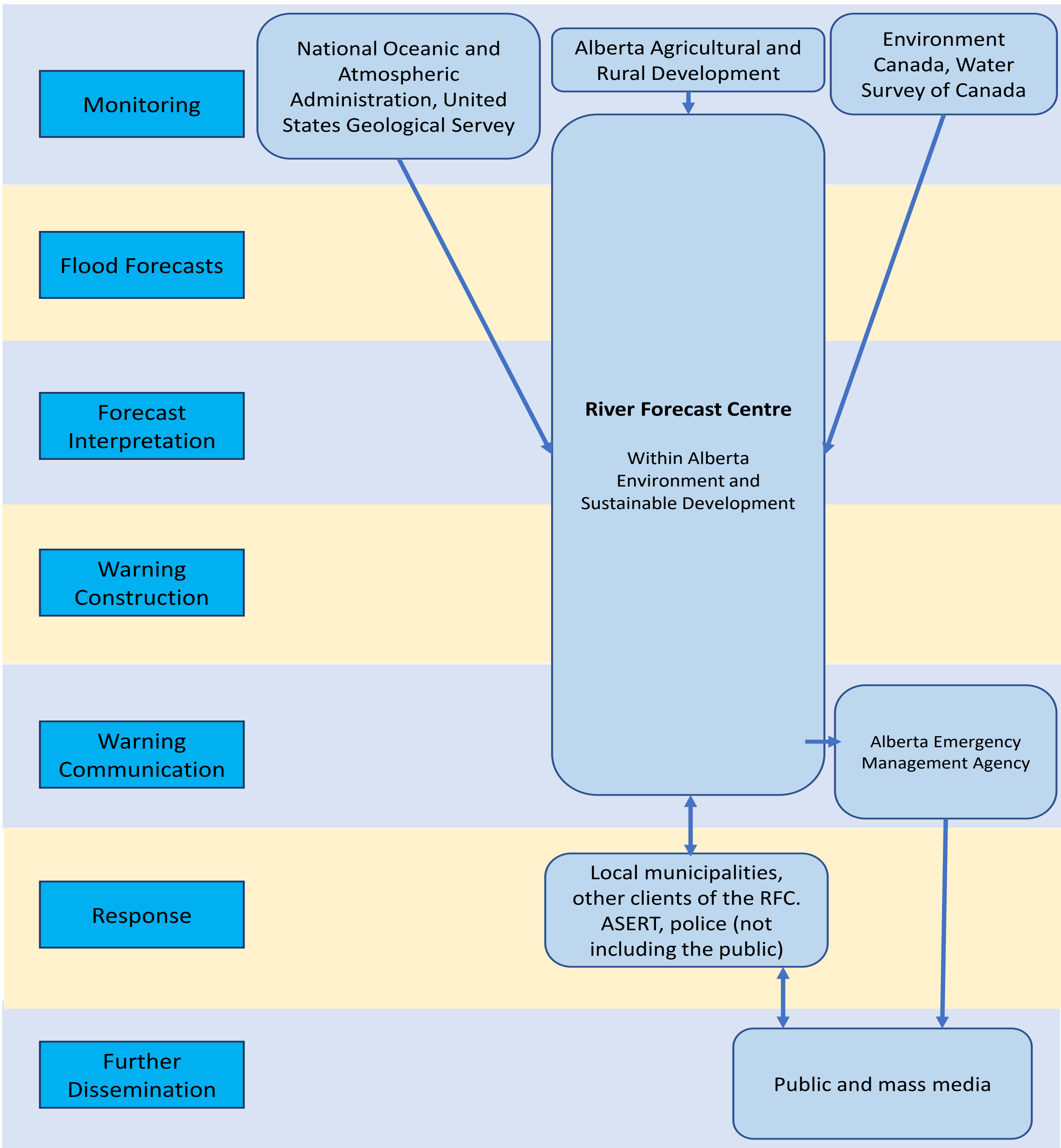

Figure A.1 The Alberta Flood Forecasting Program [5]

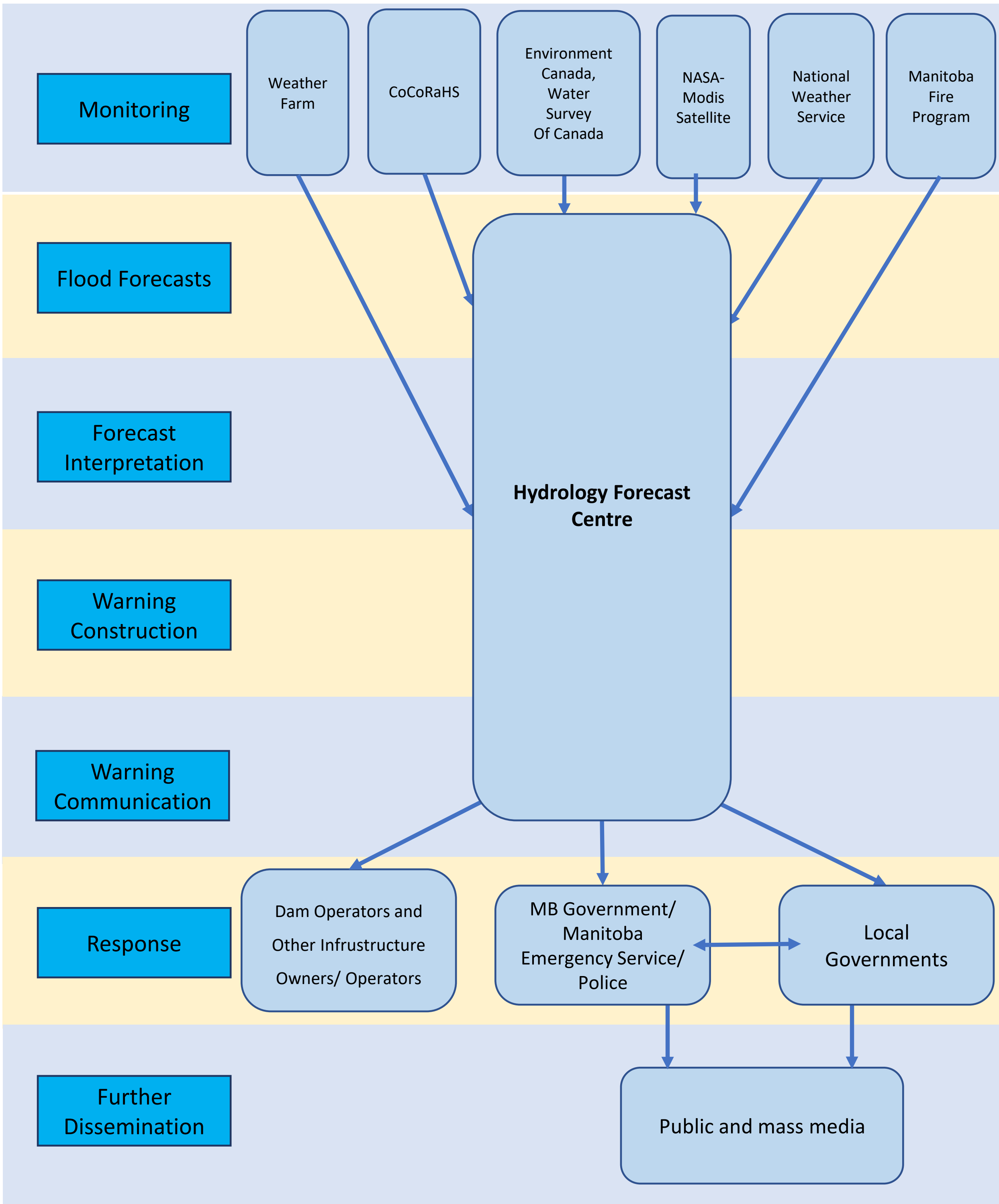

Figure A.2 The Manitoba Flood Forecasting Program [5]

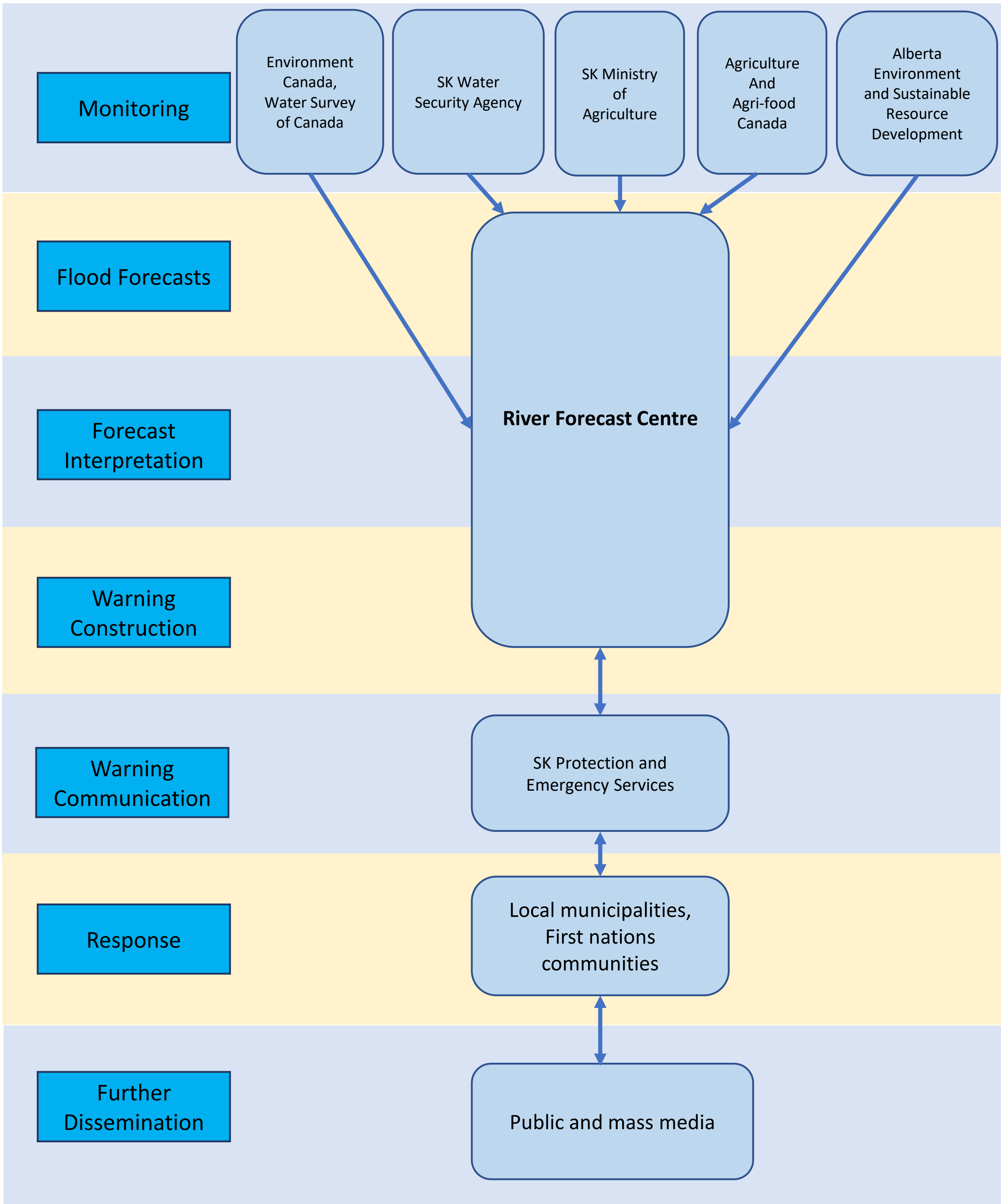

Figure A.3 The Saskatchewan Flood Forecasting Program [5]

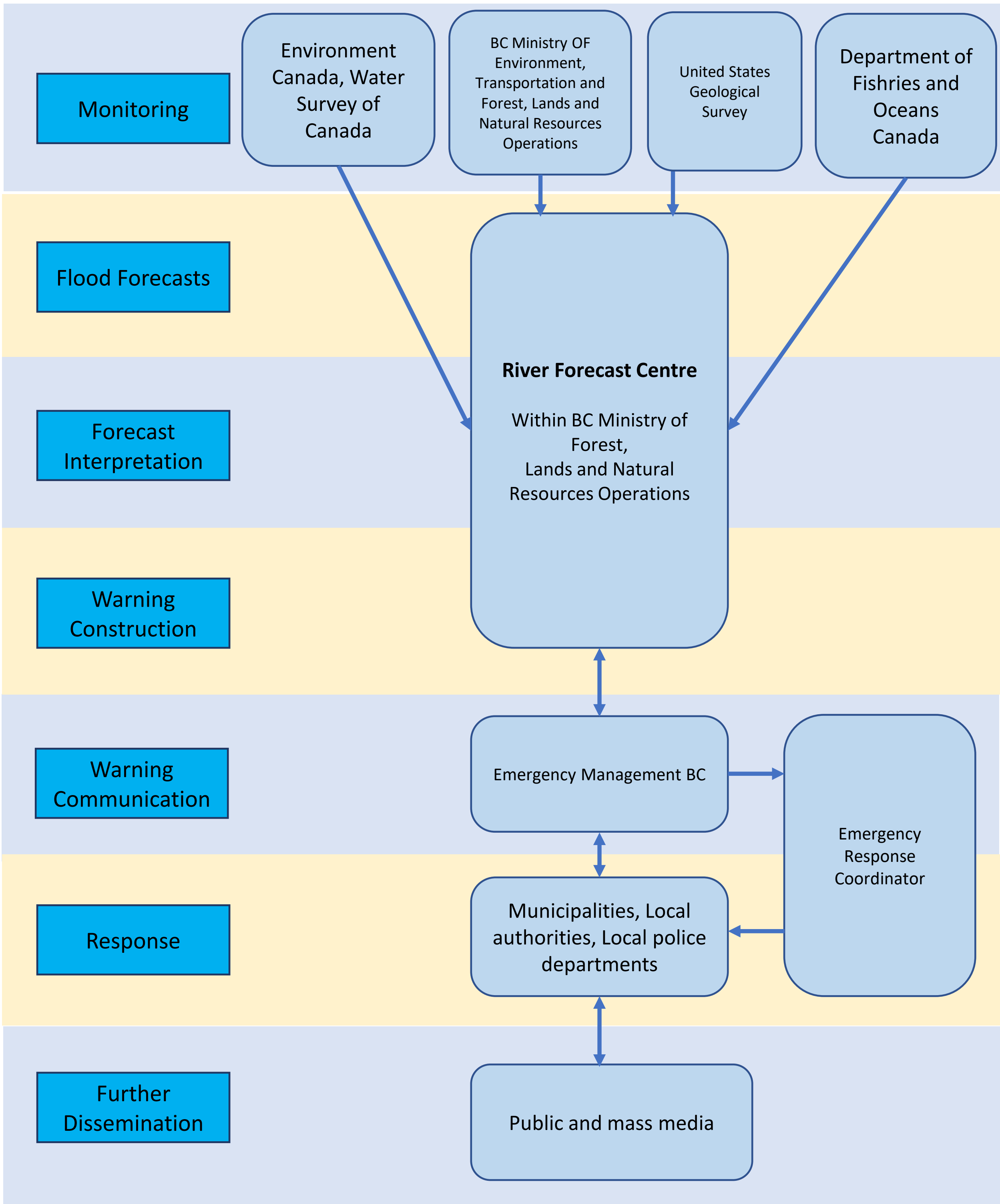

Figure A.4 The British Columbia Flood Forecasting Program [5]

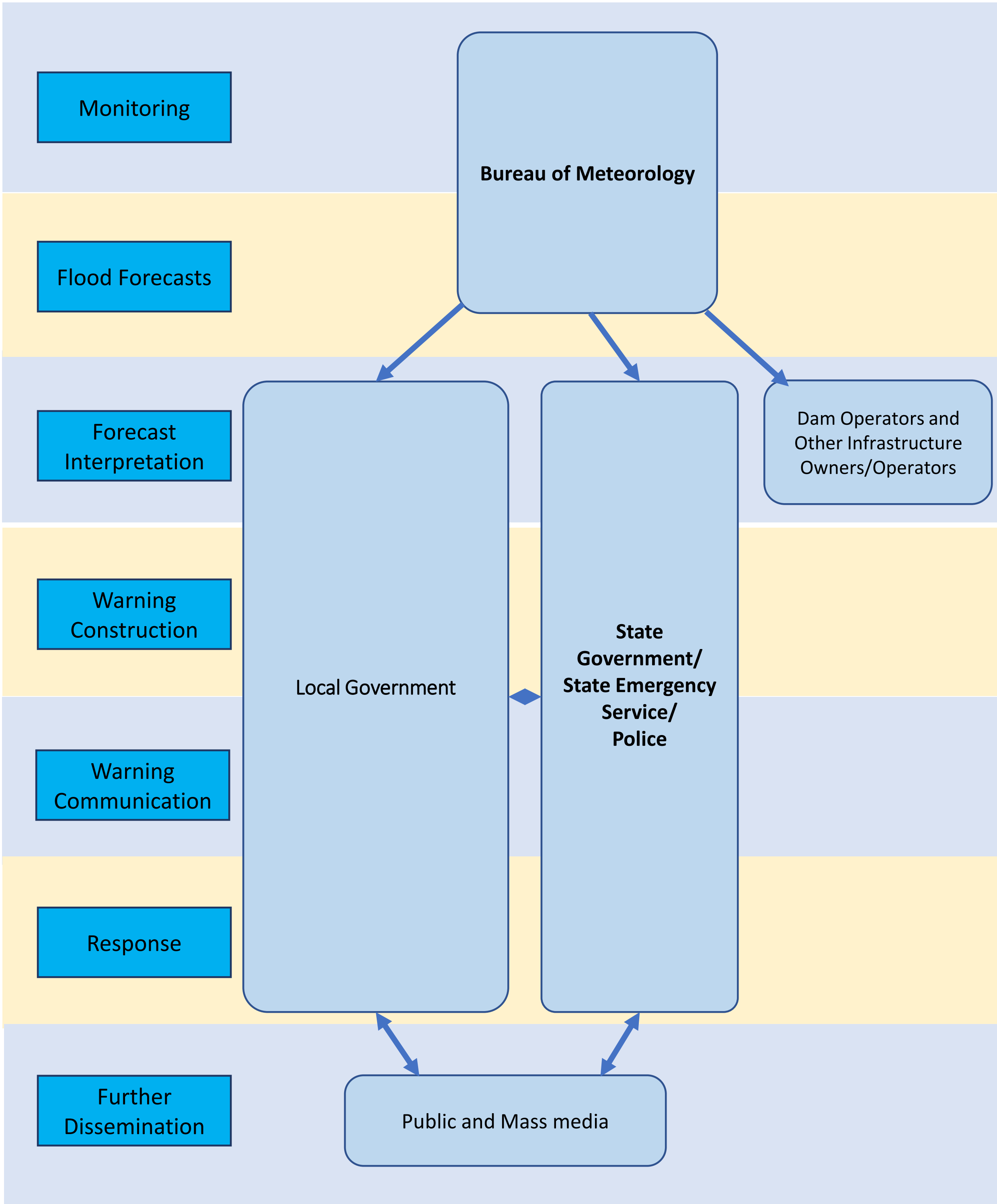

Figure A.5 The British Columbia Flood Forecasting Program [5]

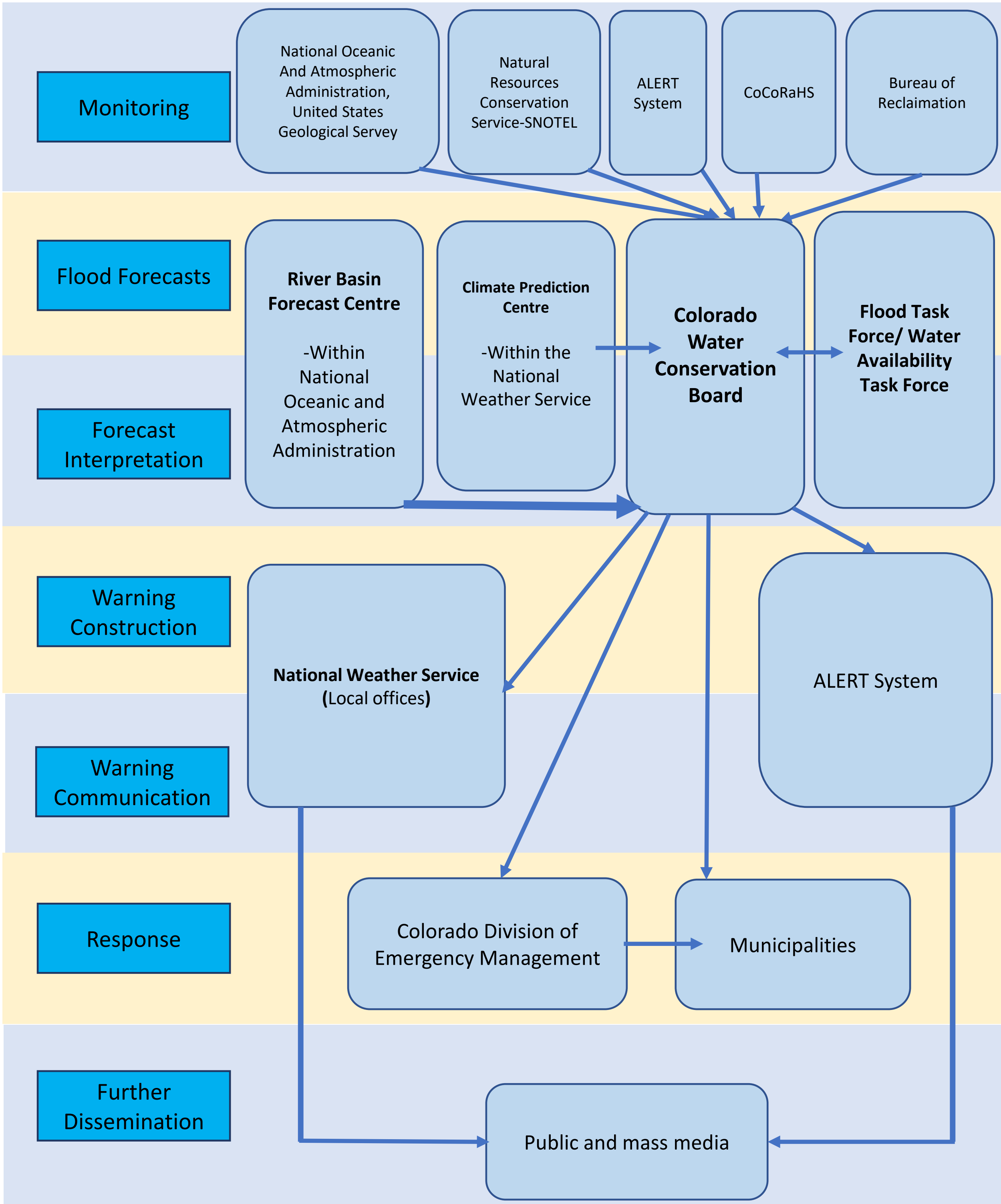

Figure A.6 The Colorado Flood Forecasting Program [5]

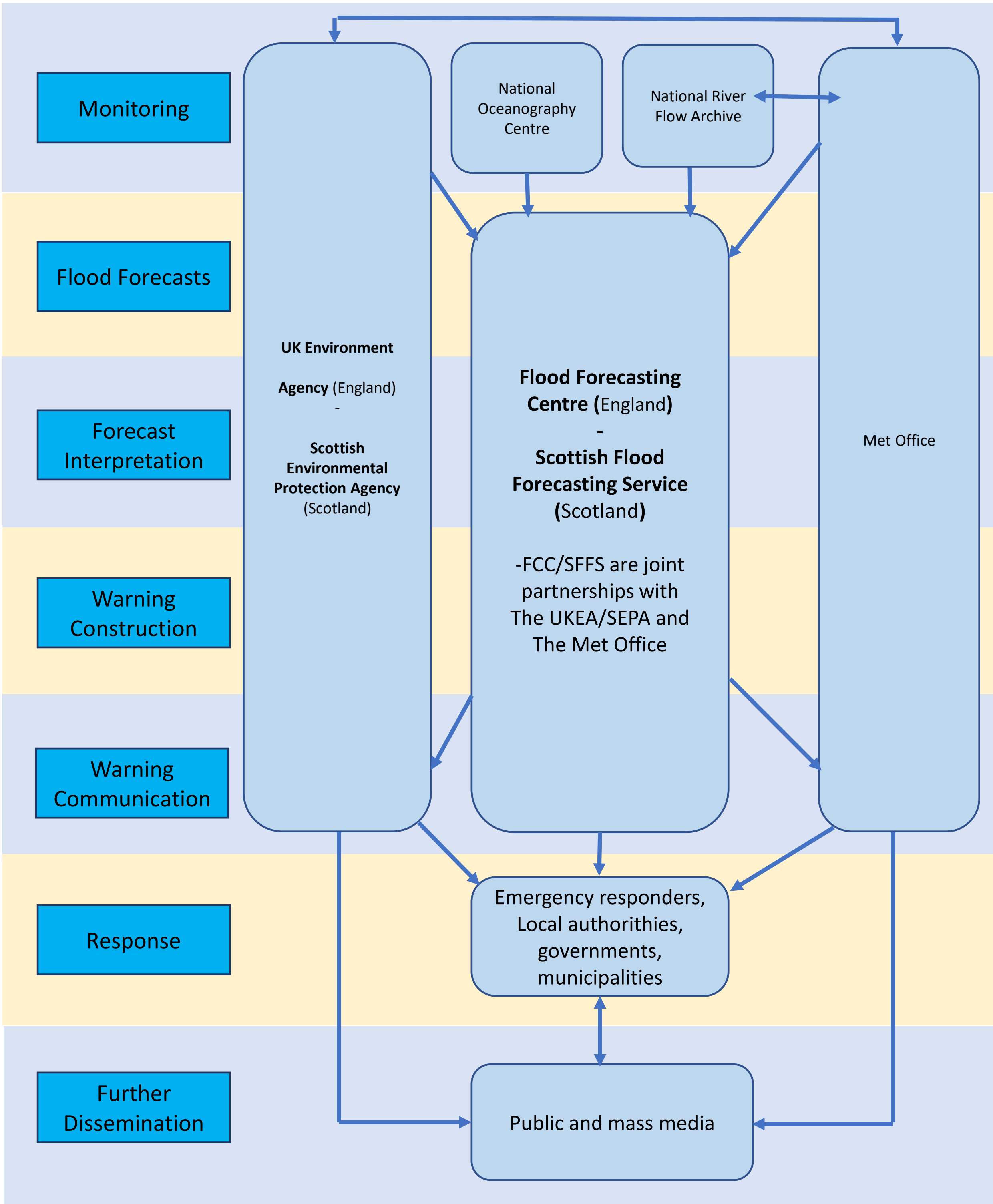

Figure A.7 The England and Scotland Flood Forecasting Program [5]

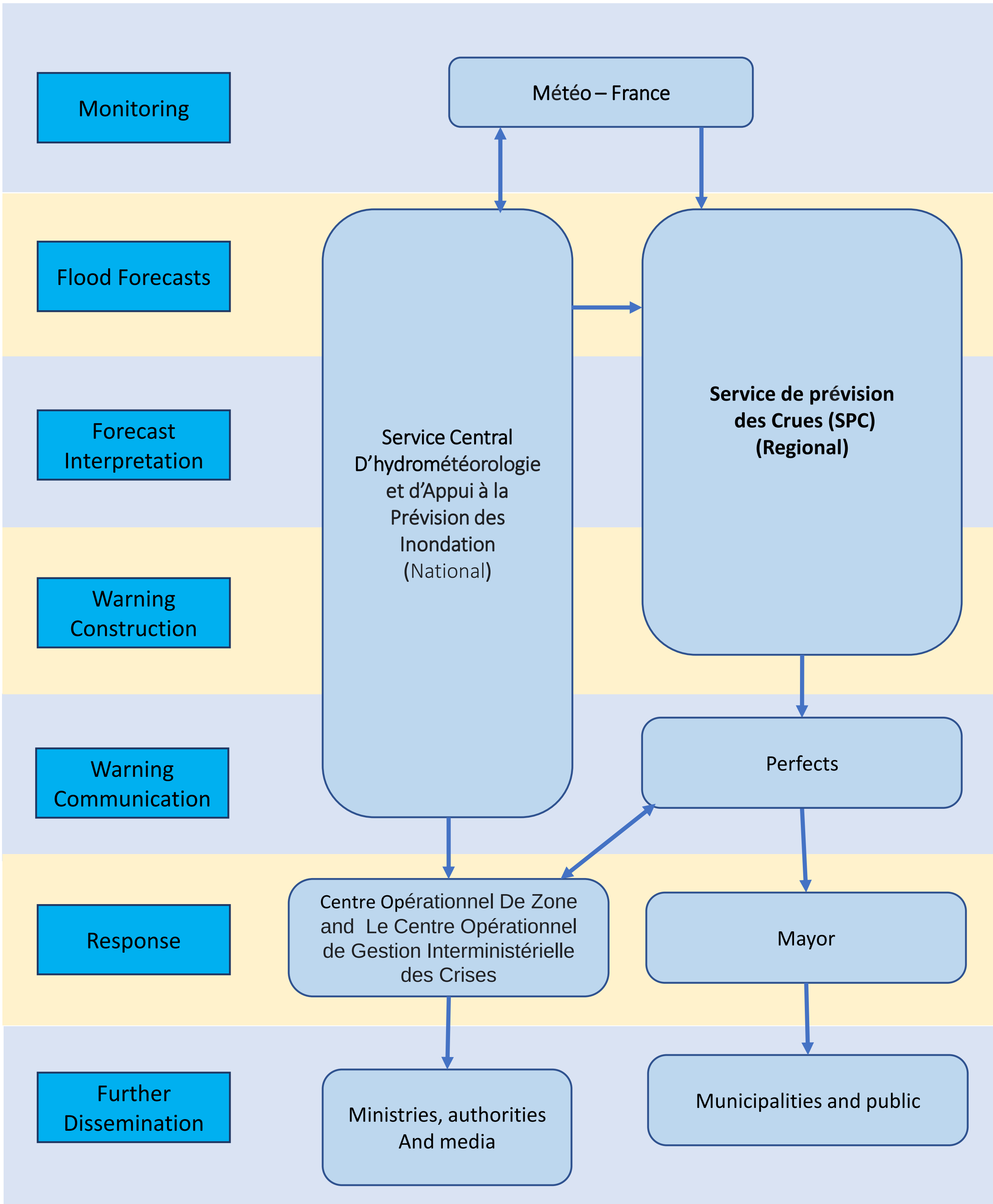

Figure A.8 The France Flood Forecasting Program [5]

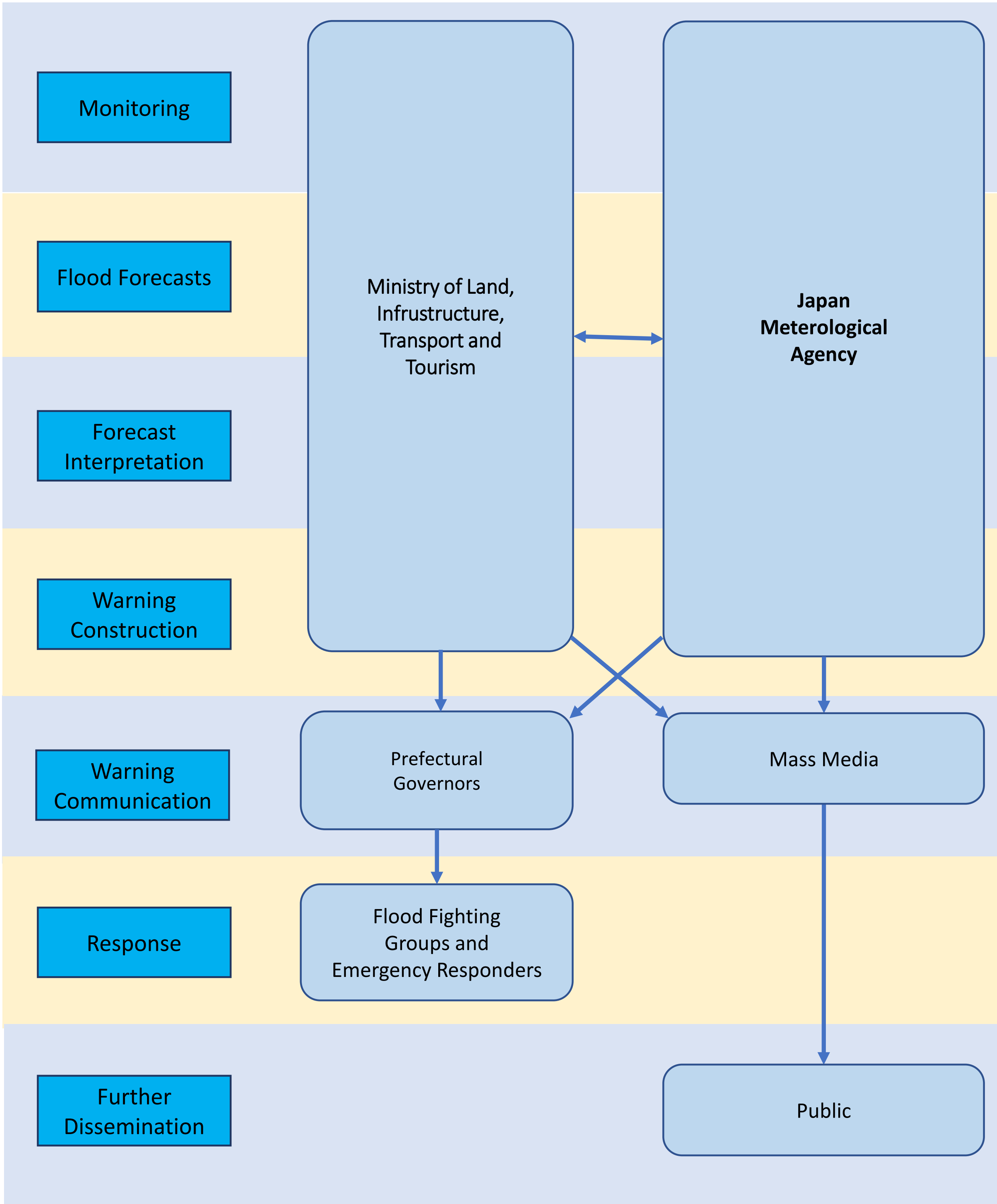

Figure A.9 The Japan Flood Forecasting Program [5]

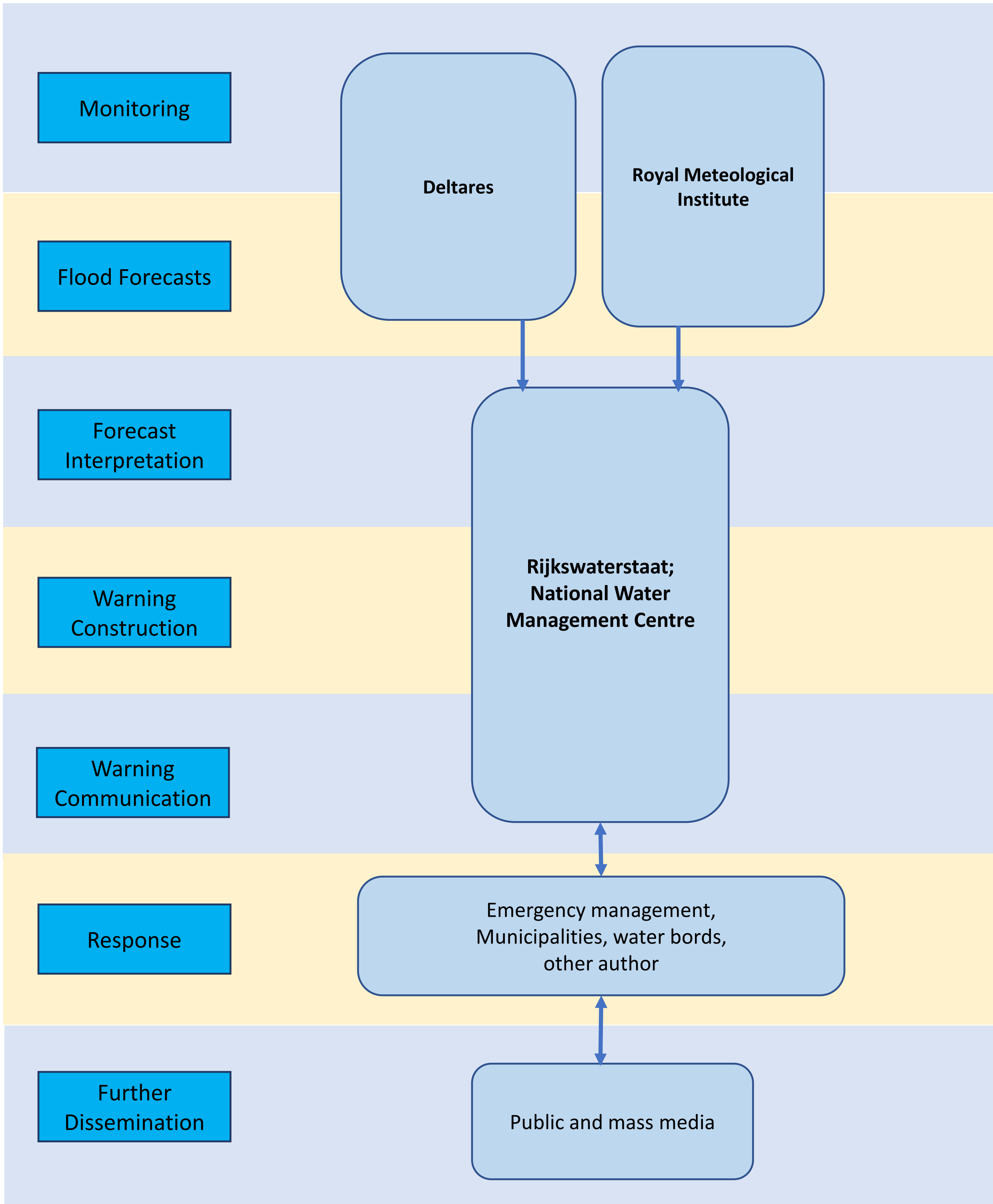

Figure A.10 The Netherland Flood Forecasting Program [5]

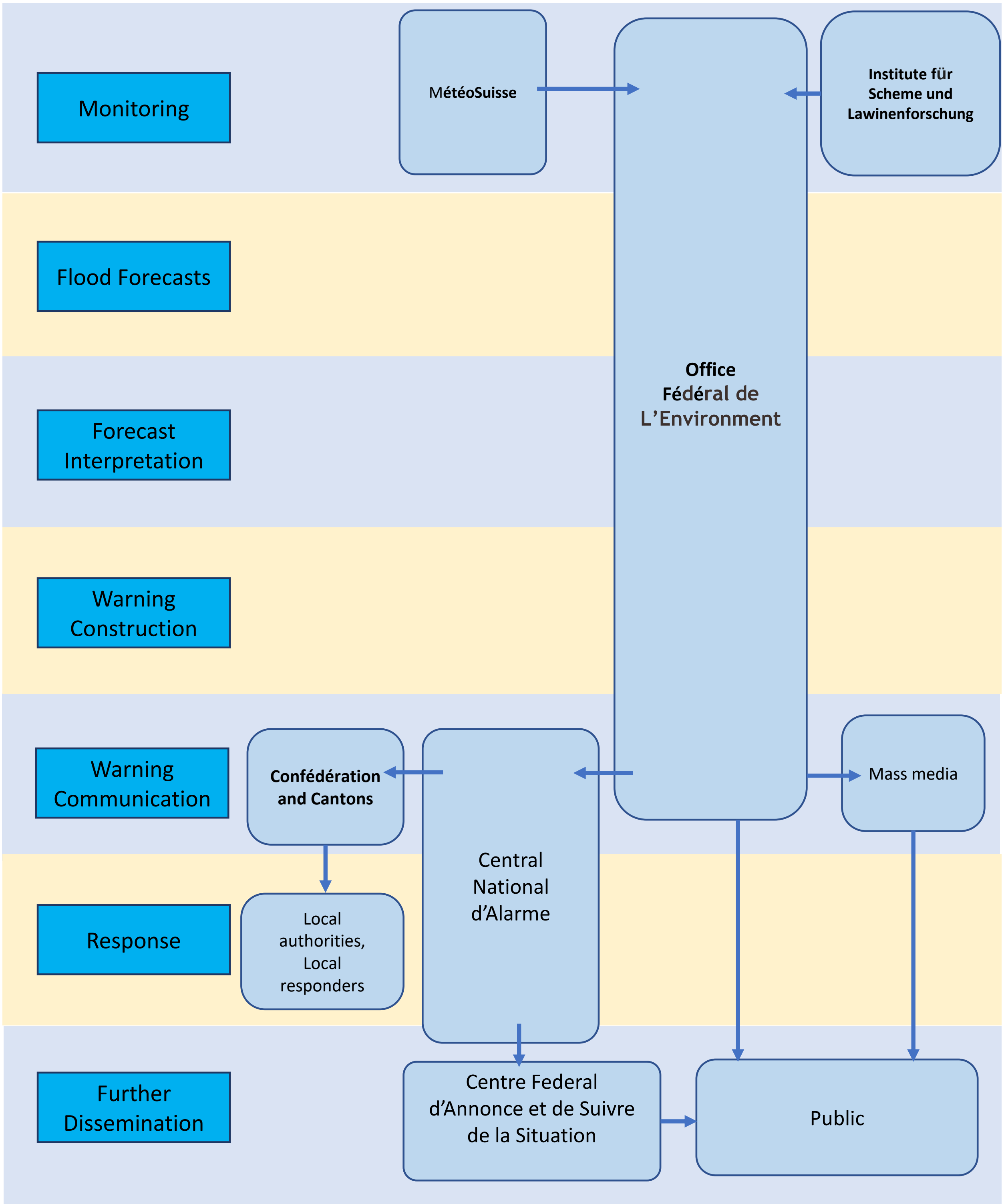

Figure A.11 The Switzerland Flood Forecasting Program [5]

APPENDIX B WATER LEVEL IN THE UPSTREAM OTTAWA RIVER DURING THE 2017 FLOOD EVENT

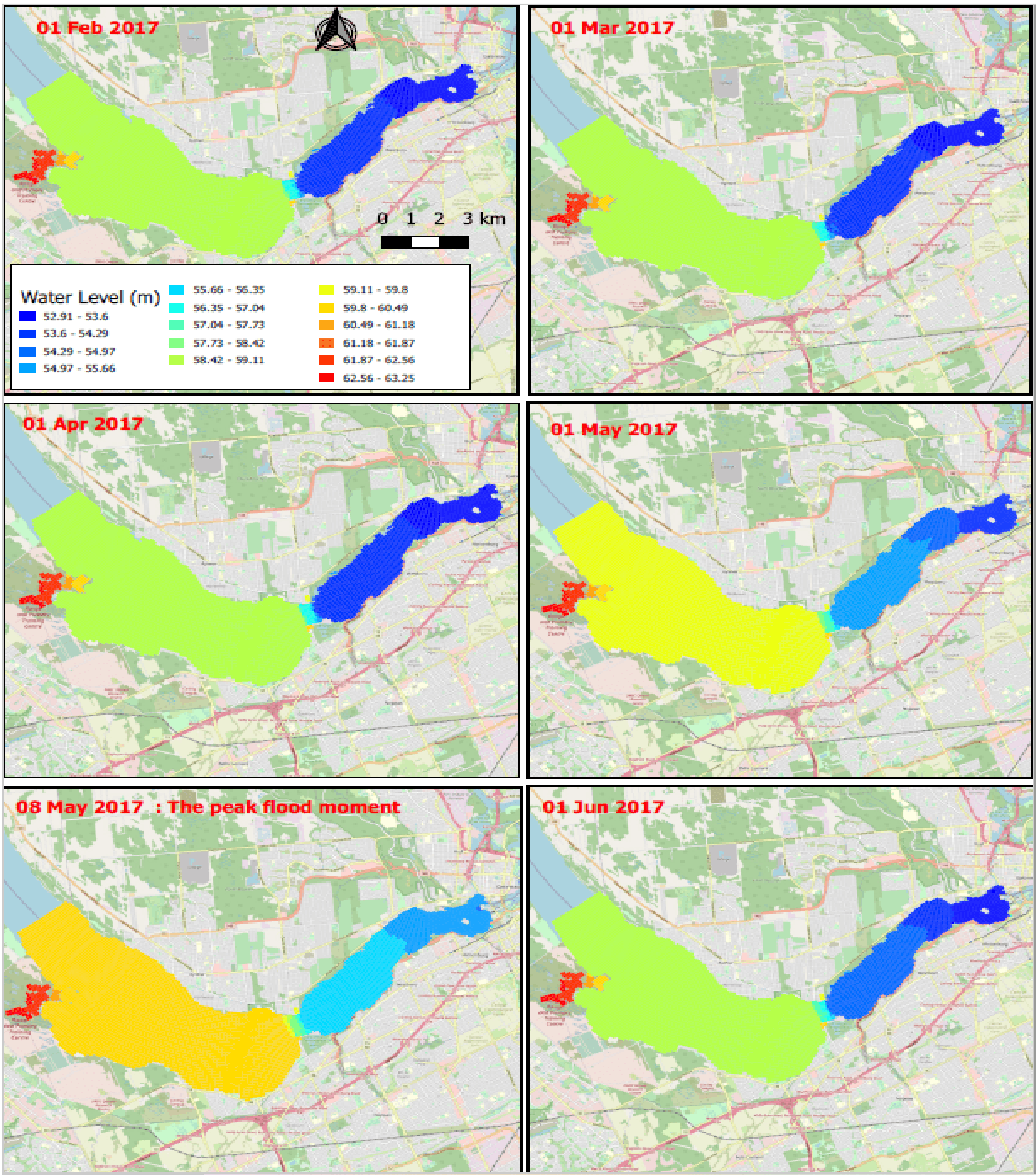

Figure B.1 The evolution of water level in the Upstream Ottawa river from February to June during 2017 flood event

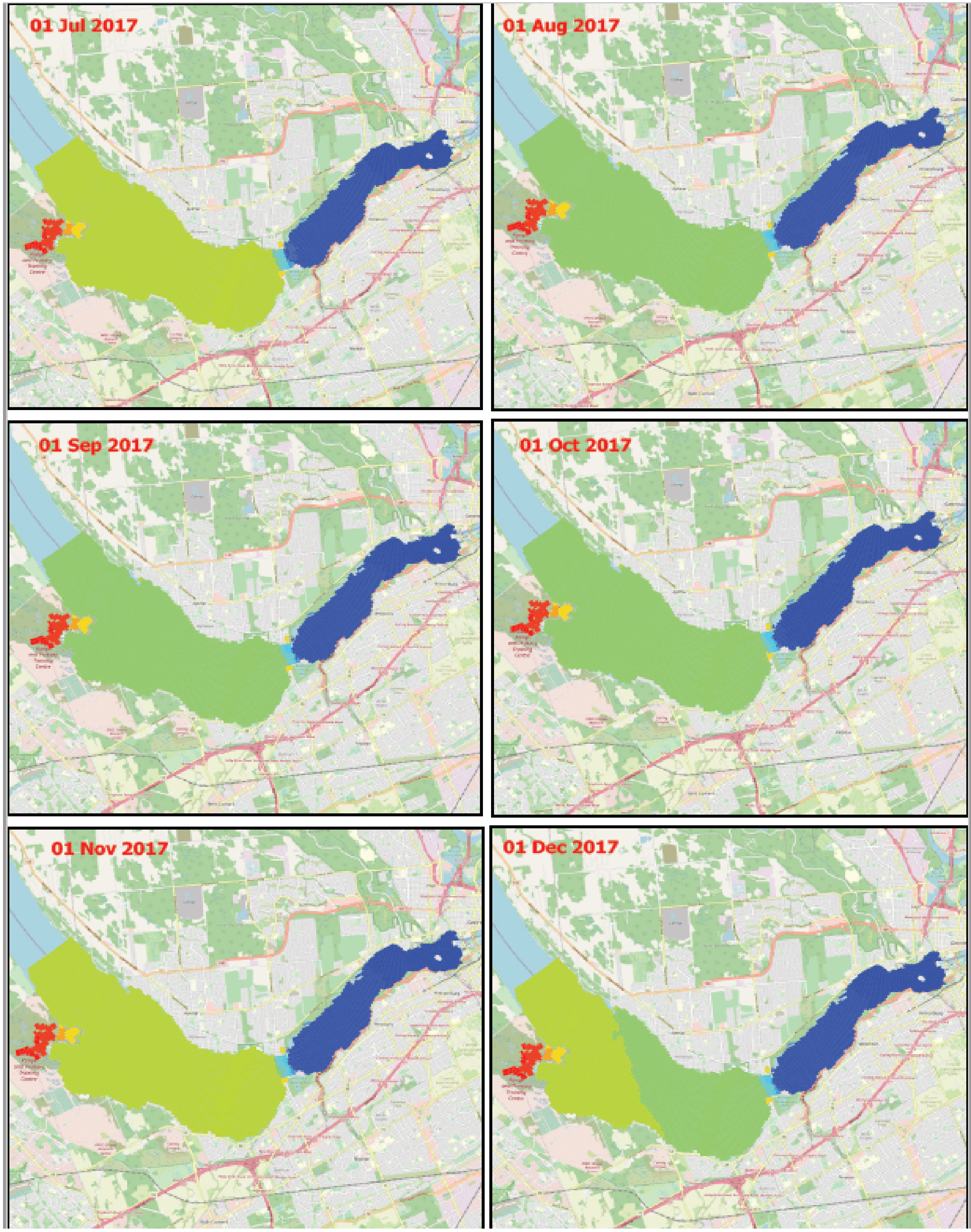

Figure B.2 The evolution of water level in the Upstream Ottawa river from July to December during 2017 flood event

APPENDIX C WATER LEVEL IN THE UPSTREAM OTTAWA RIVER DURING THE 2019 FLOOD EVENT

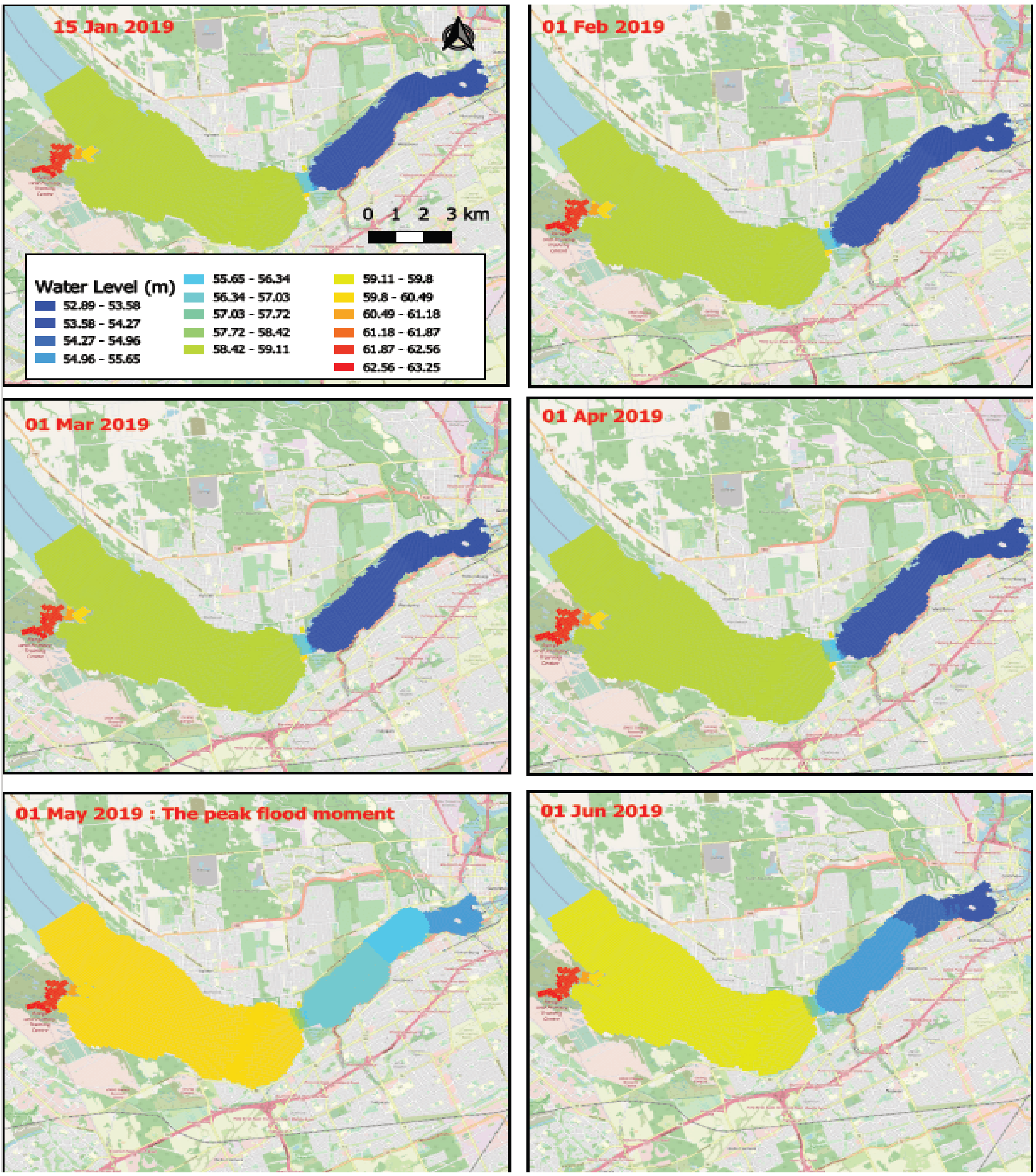

Figure C.1 The evolution of water level in the Upstream Ottawa river from January to June during 2019 flood event

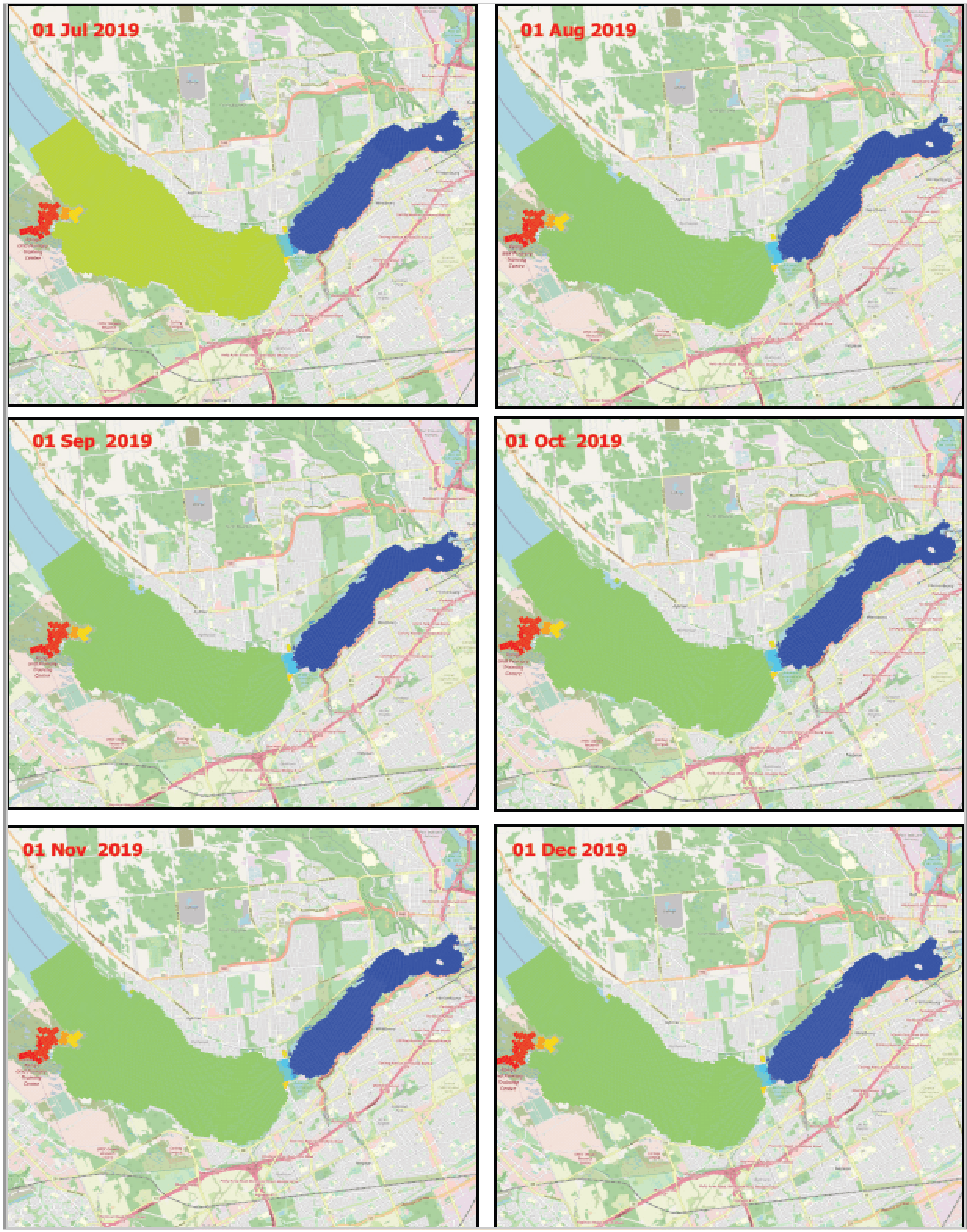

Figure C.2 The evolution of water level in the Upstream Ottawa river from July to December during 2019 flood event

APPENDIX D WATER LEVEL IN THE DOWNSTREAM OTTAWA RIVER DURING THE 2017 FLOOD EVENT

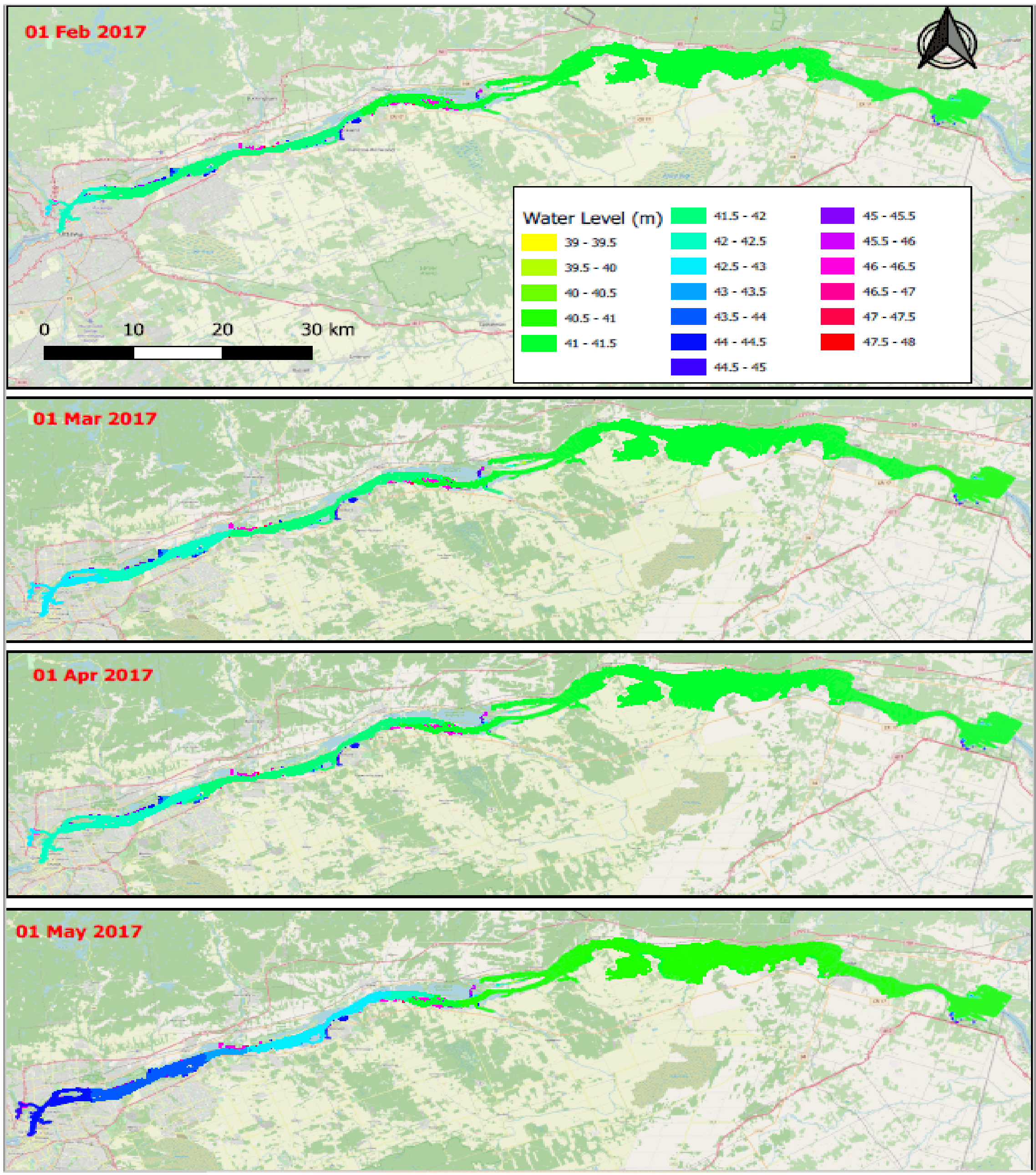

Figure D.1 The evolution of water level in the Downstream Ottawa river from February to May during 2017 flood event

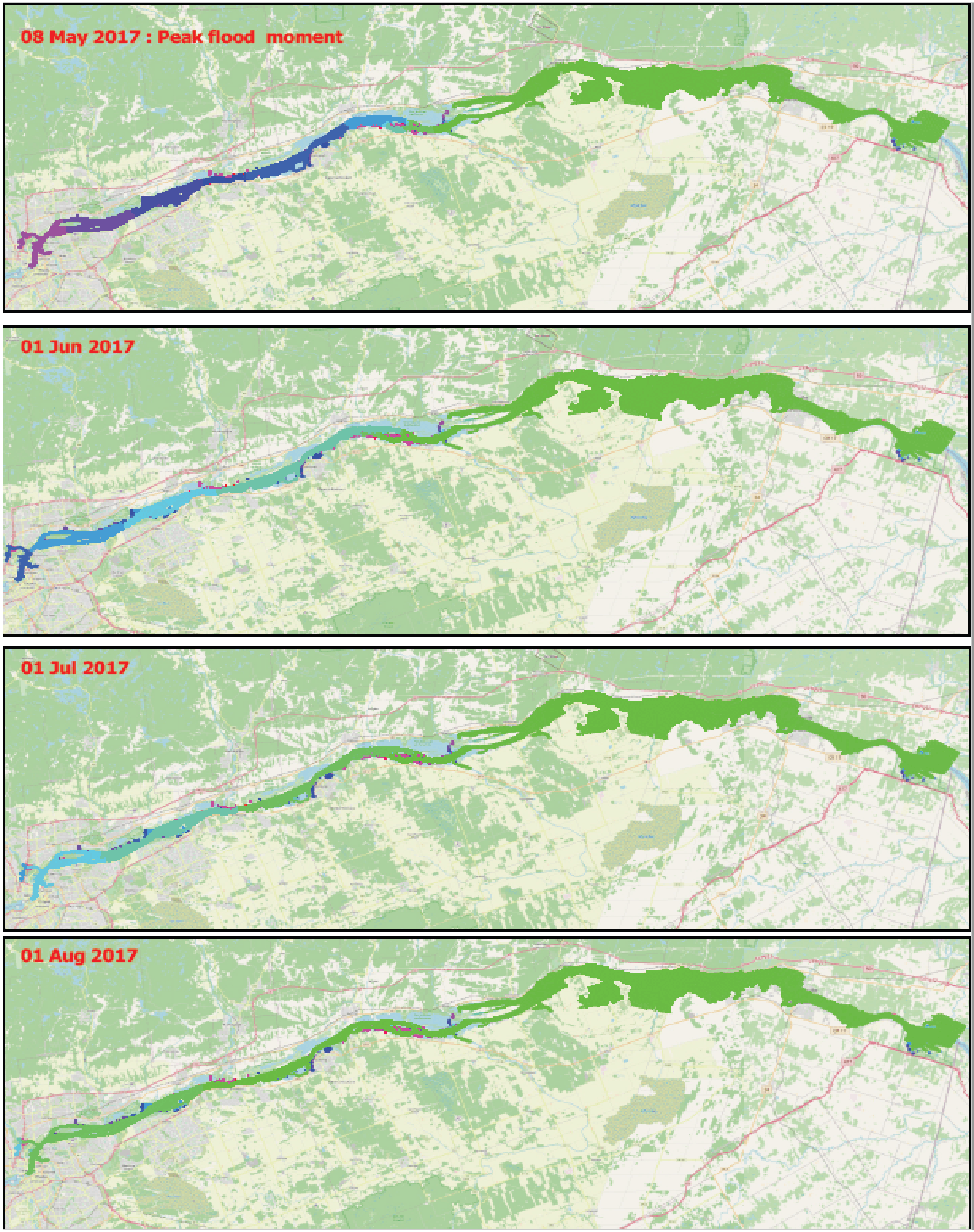

Figure D.2 The evolution of water level in the Downstream Ottawa river from May to August during 2017 flood event

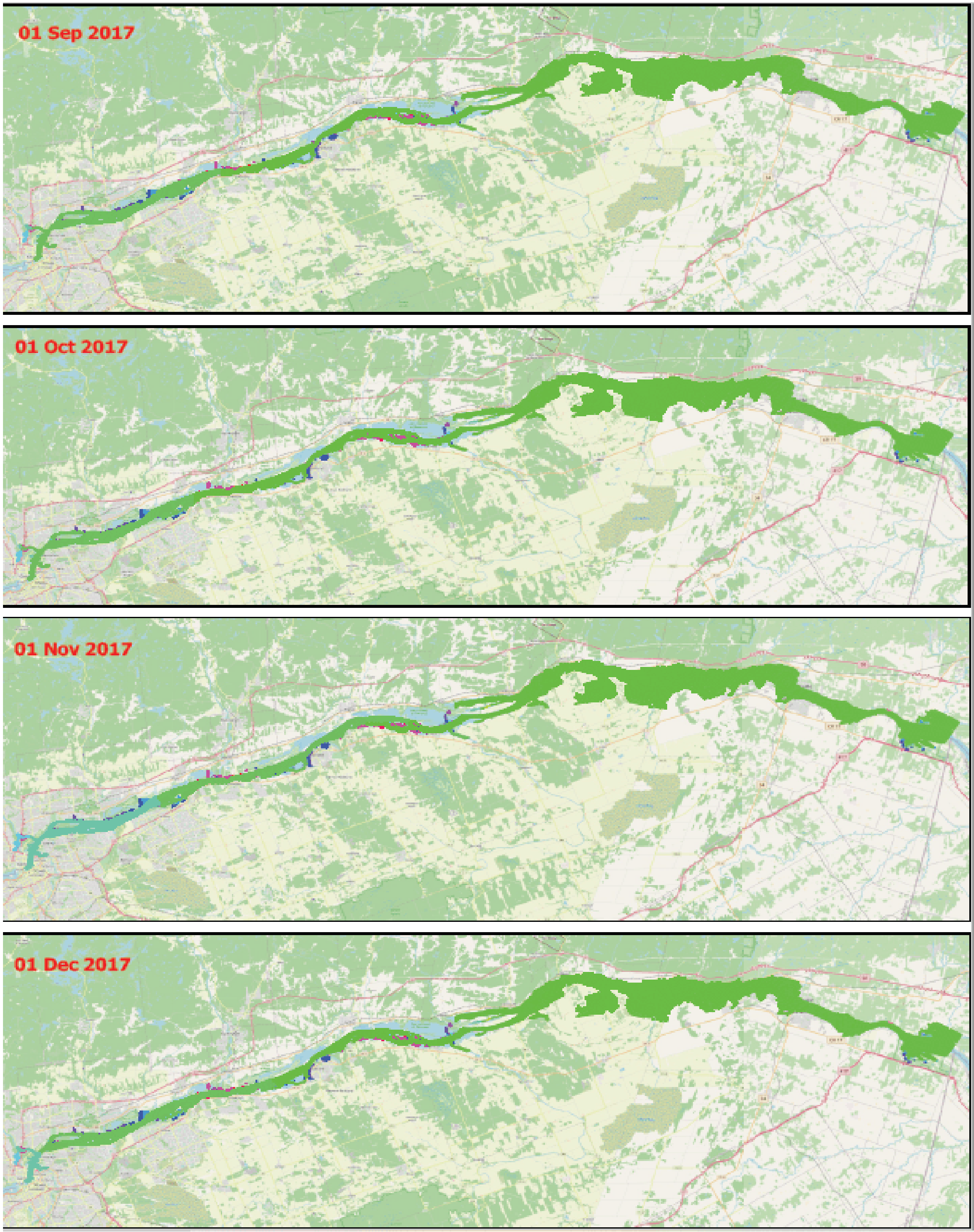

Figure D.3 The evolution of water level in the Downstream Ottawa river from September to December during 2017 flood event

APPENDIX E WATER LEVEL IN THE DOWNSTREAM OTTAWA RIVER DURING THE 2019 FLOOD EVENT

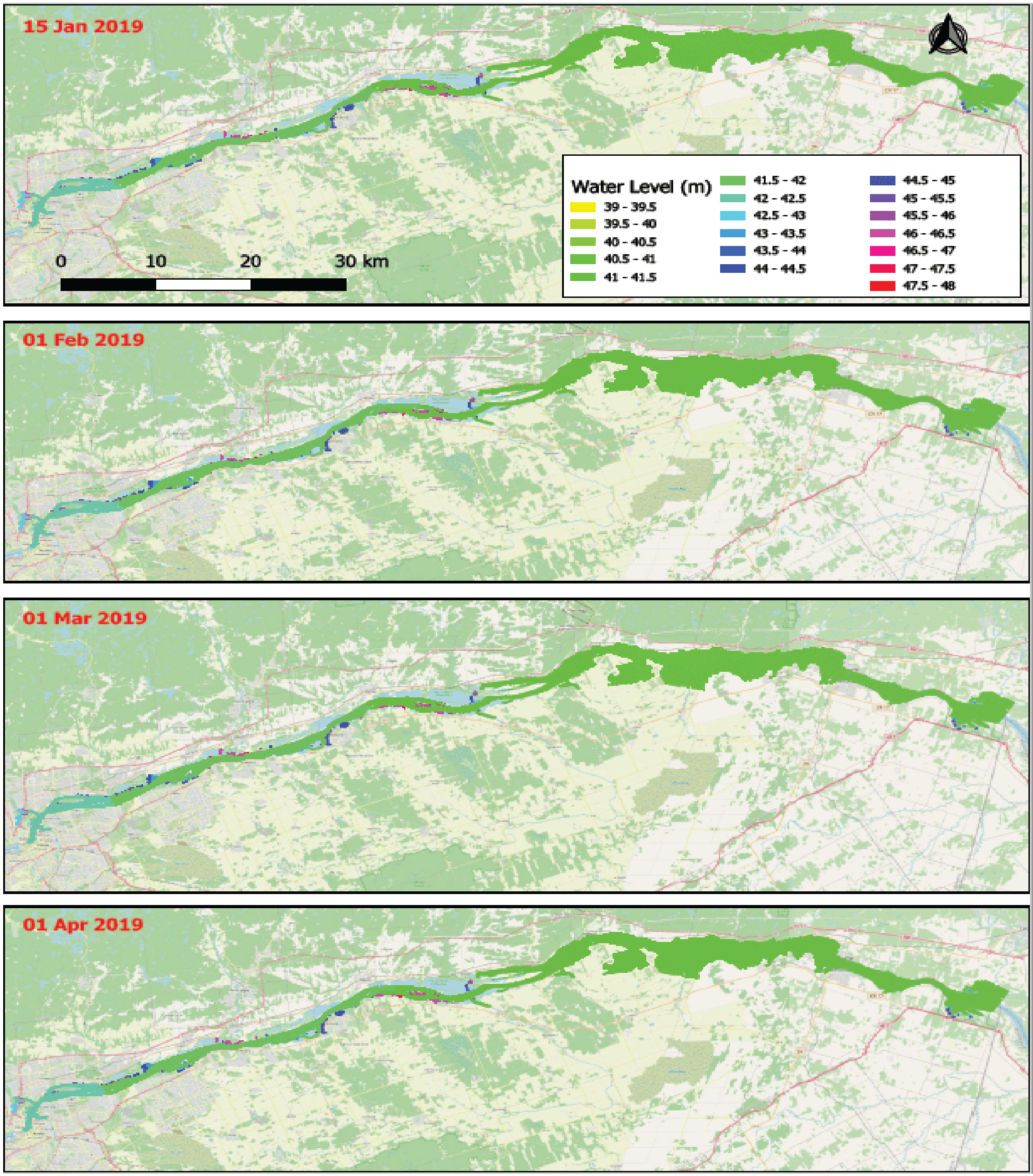

Figure E.1 The evolution of water level in the Downstream Ottawa river from January to April during 2019 flood event

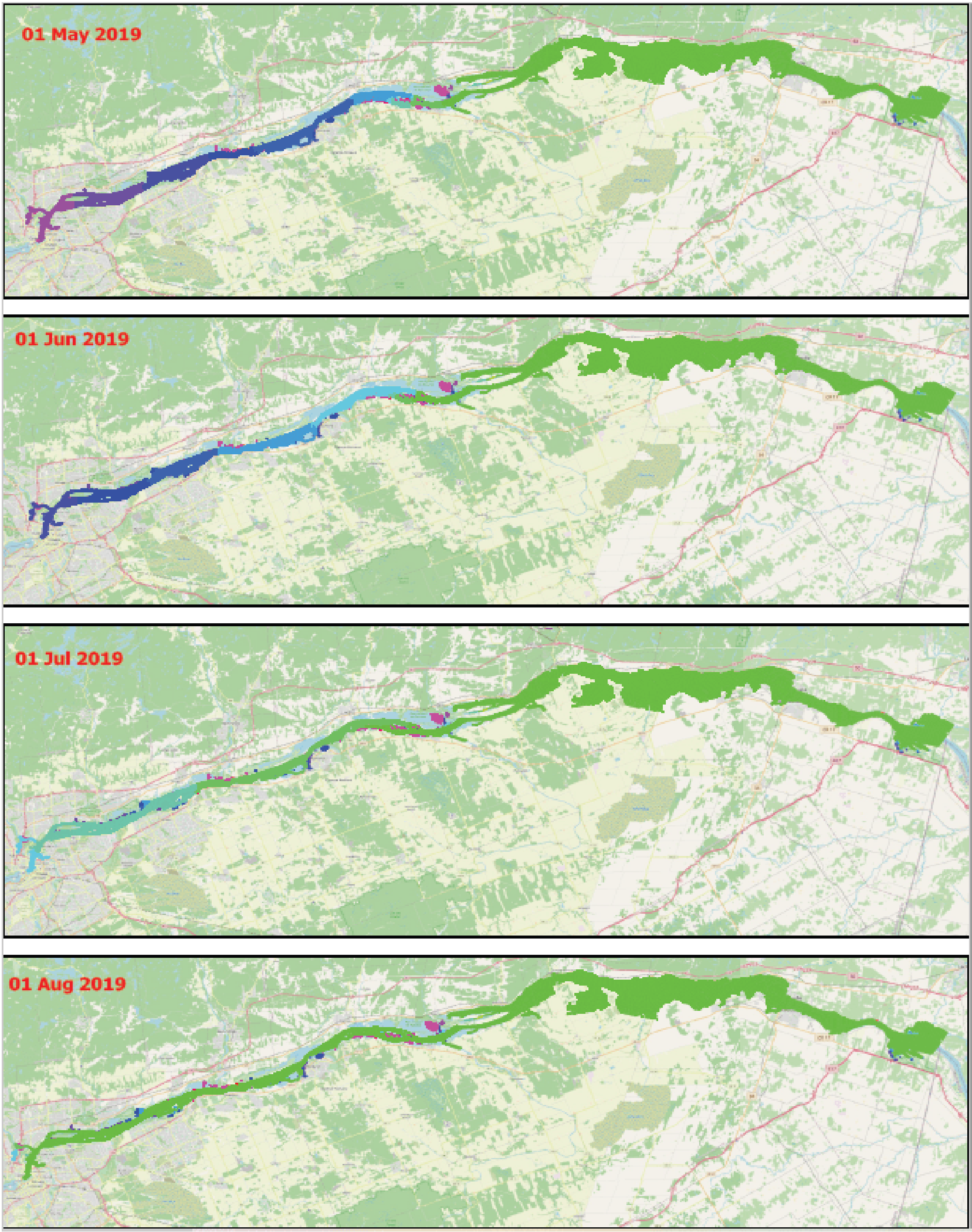

Figure E.2 The evolution of water level in the Downstream Ottawa river from May to August during 2019 flood event

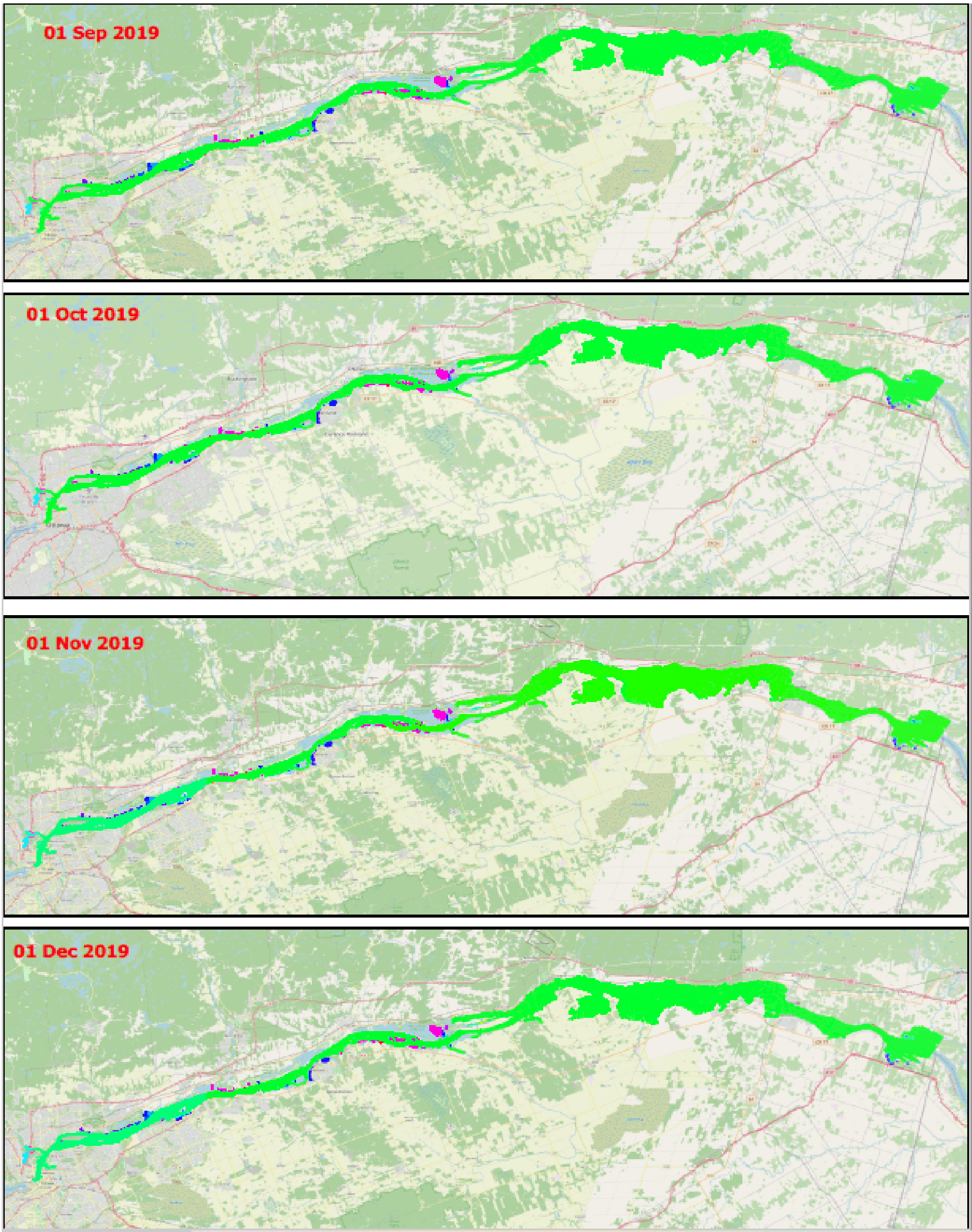

Figure E.3 The evolution of water level in the Downstream Ottawa river from September to December during 2017 flood event