

A Qualitative Approach to Understanding the Role of DEM Error and Climate Change Impact on Long-Term Floodplain Inundation Mapping

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How to cite this paper: Rahman, M.H., Ousmane, S. and Rana, S. (2025) A Qualitative Approach to Understanding the Role of DEM Error and Climate Change Impact on Long-Term Floodplain Inundation Mapping. *International Journal of Geosciences*, 16, 527-539.

<https://doi.org/10.4236/ijg.2025.168025>

Received: July 6, 2025

Accepted: August 12, 2025

Published: August 15, 2025

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Abstract

Watershed management throughout the world has undergone revolutionary changes due to topographic data and the impact of climate change. Research in floodplain inundation mapping reflects these changes. As part of the current research, two aspects are examined: the impact of climate change and the influence of Digital Elevation Model (DEM) error on the Nith River floodplain inundation mapping. The study uses terrain data generated from SWOOP elevation points as well as climate change emissions scenarios regionally assessed by CRCM and MNR (SRES A2 and SR B1). Using Log Pearson Type III, a widely used frequency analysis, floods with a 100-year return period for different climate scenarios and historical storm events were calculated, and a steady-state 1D hydrodynamic HEC-RAS model was applied to simulate extreme event floods. The impacts of DEM errors and climate change on flood simulations were quantified by analyzing the results of the model. A sensitivity analysis of the hydraulic models was performed considering surface roughness and boundary conditions as potential uncertainties. As a result of the impact of climate change, the model indicated a significant increase in flood risk. It is not evident that DEM errors affect model performance, but they should be minimized to produce accurate flood maps. The sensitivity analyses demonstrated that surface roughness influences flood simulations. Geo-processing procedures, HEC-RAS and GeoRAS in ArcGIS, have been used to extract the 100-year flood inundation maps for the current and future conditions and compare them with those for the existing conditions. The 19.8% increase in inundation corresponds specifically to the SRES A2 scenario, representing a high-emission future. The SR B1 scenario (low-emission) was analyzed for comparison, but did not produce the maximum inundation values.

Keywords

DEM, Flood Simulations, Sensitivity Analysis, Surface Roughness, Flood Inundation Maps

1. Introduction

Temperatures will likely rise, precipitation patterns will shift, and extreme weather events will occur more frequently as a result of global climate change brought on by rising greenhouse gas concentrations [1]. Sea level rise and an increase in the frequency of flooding occurrences are two effects of these changes that could have major effects on the planet, such as river deltas. Flooding incidents have the potential to cause fatalities as well as significant environmental, social, and economic harm. This calls for the use of precise flood estimation techniques to give a solid foundation for the creation of flood prevention strategies to deal with upcoming catastrophic occurrences brought on by climate change.

A straightforward statistical method cannot estimate flood inundation without considering the influence of climate change, as extreme value distributions may change in the future. As a result, a more physically orientated strategy that takes hydrological and meteorological data into account is advised. As a result, this method concentrates on correcting DEM flaws and analysing how climate change affects the study basin's hydrology.

The study was initiated with the intent of determining the flood inundation of the Nith River after incorporating the DEM correction process and determining the effects of climate change on the basin's hydrology. Initially, flow estimates for the Nith River were derived through the combined use of the SWAT hydrologic model and statistical analyses of recorded peak flows collected from the Grand River Conservation Authority (GRCA). SWAT was selected because it effectively simulates watershed-scale processes, including precipitation-runoff and land use impacts. It has been widely applied in Canadian watersheds for climate change studies. For this study, SWAT was calibrated using observed stream flow data from the Grand River Conservation Authority (1973-2000) and validated with independent events. Afterward, a hydraulic model was developed for the simulation of flood inundation under various hydrologic conditions.

The study considers extensive terrain data processing and hydraulic modeling using GeoRAS in ArcGIS and HEC-RAS modeling techniques. The terrain processing process involves gathering spatial data and using it for a variety of purposes, such as building terrain surfaces, checking surface elevation, and extracting information for hydraulic model feeds. During the study, bathymetry and hydraulic structures were surveyed for accurate information. The hydraulic model was built and analyzed using HEC-RAS (Version 5.1.0, 2010) in conjunction with GeoRAS.

In order to assess flooding conditions, spatial data analysis, hydraulic modeling, and assessments and evaluations of model results were performed based on the

collected information. The model results were transferred into the GeoRAS process to map the spatial extent of flood hazards.

2. Study Area

In Southern Ontario, the study area is located about 20 kilometers west of Cambridge. The middle reach and the lower reach of the Nith River follow a 25 km course through the villages of Greenfield, Ayr in North Dumfries Township, and Wolverson in Oxford County. As the largest uncontrolled tributary of the Grand River, it has an average slope of 0.12%. **Figure 1** shows the study area as well as the floodplain mapping limits. The river and its floodplain are subject to frequent flooding with significant seasonal variations. As recorded, annual peak flows generally occur during the spring runoff period from February to April.

There are two major settlement areas included in the study reach: Ayr in the Region of Waterloo, and Wolverson in the County of Oxford. In the area, agriculture dominates the landuse. As well as being vegetative in nature, the floodplain area also has dense trees, shrubs, and stunted forest growth. There are eight road bridges that are open to the public, one closed bridge, one private bridge, and two remnant dam structures within the study reach. Currently, the GRCA operates one real-time stream flow gauge and maintains two staff gauges on bridges in the reach.



Figure 1. Study area for the Nith River Hydraulic Model.

3. Methodology

In this study, the major focuses are the accuracy of DEMs, the impacts of climate change on storm events, several uncertainties associated with flood simulations, frequency analysis, and the development of hydraulic models. The integration of HEC-RAS and HEC-GeoRAS tools in ArcGIS enables the development of an innovative technique and is applied in flood mapping and modeling.

The Ministry of Natural Resources' (MNR) climate studies and the North American Regional Climate Change Assessment Program (NARCCAP) provided data for this study. In this study, SWAT was used solely as a hydrologic model to generate streamflow inputs (historical and future climate scenarios). These flows were then routed through a hydraulic model (HEC-RAS), developed using HEC-GeoRAS in ArcGIS, to simulate water surface elevations and inundation extents. SWAT and HEC-RAS served distinct roles and were not integrated into a single model. The model geometry was extracted from corrected and non-corrected DEMs to investigate the influence of errors in DEMs. HEC-GeoRAS [2] tool in ArcGIS was applied to make a 1D HEC-RAS hydrodynamic model based on the available data. Hydraulic models were developed using historical flows as well as climate-viable future flows, and the results were evaluated for the effect of climate change on hydrology and flooding. Floods of 100-year return period were estimated [3] with the most commonly applied frequency analysis, Log Pearson Type III for observed and future periods. In hydraulic research, 100-year return period flows are typically used [4]. The 100-year flood inundations were estimated using the HEC-RAS hydrodynamic model. In 100-year events, the main channel as well as the floodplain are completely submerged, leaving no storage in floodplains. Consequently, a single channel is formed by combining the floodplain and the main channel. In this case, it was assumed that the steady-state approach would be used since such events are typically incorporated into design flows. In order to investigate the influence of DEM error, none of the HEC-RAS parameters or other inflows were changed other than the geometry. A comparative assessment was carried out using model results from historical storm events and future 100-year flooding events. This assumption follows standard design practice for extreme return period events, where the floodplain is considered fully saturated and ineffective for storage due to rapid overbank flow and limited retention capacity. While some localized storage may occur, treating the floodplain as fully submerged provides a conservative estimate of peak water surface elevations, which is consistent with regulatory floodplain mapping approaches. Results of the assessment were presented both in quantified model outputs and in mapping processes. As a result of the model results, flood heights (cm) increased, and the maps corresponded to the extent of flood inundation in the area.

A hydrodynamic model requires many input parameters, such as geometry, flows, boundary conditions, surface roughness, numerical scheme, etc. As only model geometry does not account for model results perturbation, several other conditions, such as roughness and boundary conditions, were also studied for their impact on flood modelling. The whole procedure is shown in **Figure 2**. An-

alyzing uncertainty will enable to understand how different uncertainties affect flood modelling and flood inundation maps. In this study, SWAT was used solely as a hydrologic model to generate streamflow inputs (historical and future climate scenarios). These flows were then routed through a hydraulic model (HEC-RAS), developed using HEC-GeoRAS in ArcGIS, to simulate water surface elevations and inundation extents. SWAT and HEC-RAS served distinct roles and were not integrated into a single model.

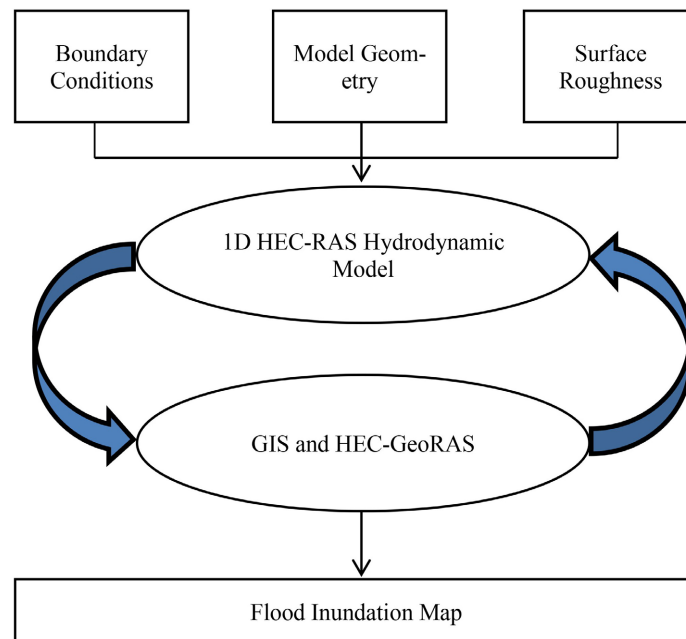


Figure 2. Process of hydrodynamic modelling and flood inundation mapping.

4. Analysis and Development of Hydraulic Model

Flood inundation mapping provides stakeholders with information about flood risk [5]. An in-depth hydraulic analysis of the watercourse is necessary to complete the flood mapping process. A field study and historical flood patterns indicate that the Nith River periodically overflows into the floodplain. Hydraulic model development and calibration were conducted using ArcGIS tools HEC-RAS and HEC-GeoRAS. In the simulation, a steady-state model was used. The river reach extends from Greenfield village upstream to Wolverton downstream of Oxford Bridge in Oxford County.

A hydraulic model was developed based on historical and climate-induced future flows generated by the SWAT hydrologic model. The model geometry was derived from corrected and uncorrected DEMs to assess the impact of DEM errors. In addition, a sensitivity analysis was conducted to examine the effect of different inputs and model parameters.

4.1. HEC-RAS Model

A one-dimensional hydrodynamic flow model, HEC-RAS simulates water flow

through rivers, channels, creeks, etc. It can simulate network channels, dendritic channels, or single-reach channels. Nevertheless, the model needs to be simplified in order to prevent instability. The hydraulic effects of changing cross-section shape, bends, and other two- and three-dimensional aspects of flow are not directly modeled. The flow can be simulated both in a steady and unsteady manner. In a steady flow condition, energy equations are solved through computational procedures that evaluate friction, contraction, and expansion losses. The system solves momentum equations in order to characterize water levels in locations where flows create hydraulic jumps or vary rapidly under conditions of steady and gradually varying flows. Hydraulic jumps, hydraulic bridges, culverts and confluences are included in both methods when solving steady-state flows. By solving the governing equations, flows can be simulated in critical, subcritical, or mixed flow regimes. This is where flows are contracted by bridges, culverts, and weirs.

The roughness values (Manning's n) are used to partition the cross sections into subdivisions in HEC-RAS. Bernoulli's energy equation is applied to calculate basic flood profile.

$$Y_2 + Z_2 + \frac{\alpha_2 V_2^2}{2g} = Y_1 + Z_1 + \frac{\alpha_1 V_1^2}{2g} + h_e \quad (1)$$

where, Y_1, Y_2 = depth of water; V_1, V_2 = average velocities of flow; Z_1, Z_2 = elevation of the main channel; α_1, α_2 = velocity weighting coefficients; g = gravitational force; and h_e = head loss.

In HEC-RAS, the total conveyance is determined by adding up all incremental conveyances computed for each upstream subdivision represented as a cross-section using Manning's Equation (2) and continuity.

$$Q = \frac{1}{n} AR^{2/3} S^{1/2} \quad (2)$$

where, n = Manning's roughness coefficient; A = flow area; S = slope; and R = hydraulic radius.

A high roughness value causes the water surface height to rise under fixed flow rate and slope circumstances. In a similar vein, a change in a channel's overall conveyance represents a change in the water surface height while maintaining a constant roughness and slope. The water surface elevation is affected by the channel bottom elevation in a fixed flow rate and slope situation, as the channel bottom determines Manning's equation slope and Energy equation total head.

The HEC-RAS requires geometric data about floodplains. GeoRAS can digitize and preprocess geometric information for use in HEC-RAS models. Hydraulic model results are post-processed using HEC-GeoRAS to prepare flood inundation maps. By subtracting site topography from water surface topography based on interpolation using the cross-sectional model, a flood inundation map is produced using HEC-GeoRAS. **Figure 3** shows the cross-sections of the channels used as inputs to the hydrodynamic model.

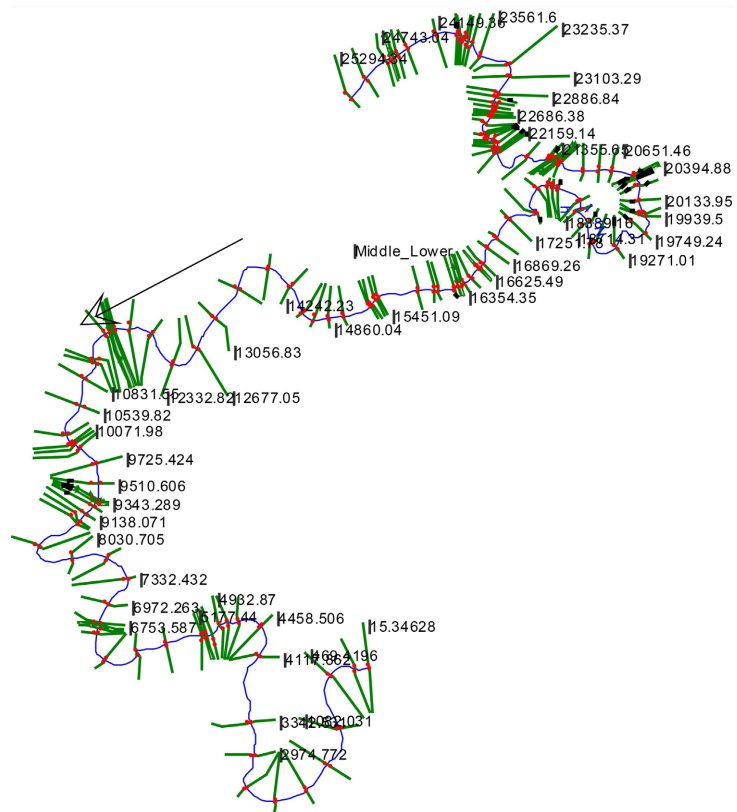


Figure 3. Cross-sectional configuration of the hydrodynamic model extracted from DEM.

4.2. HEC-GeoRAS Model

In combination with HEC-RAS, HEC-GeoRAS is used to process flood maps [6]. A DEM or terrain model is used to extract spatial data and GeoRAS is used to preprocess the data. By using this tool, all geometric information about a hydraulic model can be extracted, such as rivers, structures, catchments, cross-section cut lines, flow paths, and bank lines. In addition, it determines the length of left and right overbanks, flowpaths, and river centerlines, as well as the roughness of the floodplain surface. In HEC-RAS, data exported from GeoRAS are used to develop hydraulic models. Hydraulic structures, bathymetry, or any other information can be incorporated into the model. A calibration process involves tweaking the parameters of the model based on the temporal data. Using GeoRAS, the model simulates water surface elevation, water surface profiles, and velocity, and creates flood inundation maps in GIS by post-processing the results.

4.3. Data Processing

Flood modeling requires geometric data, channel roughness, and boundary conditions. Geometric data processing was one of the major components of this study to investigate the impact of DEM error on flood inundation maps. The DEM was created utilizing elevation point clouds collected by the Southwestern Ontario Orthophotography Project (SWOOP). The filtering process left some voids in the

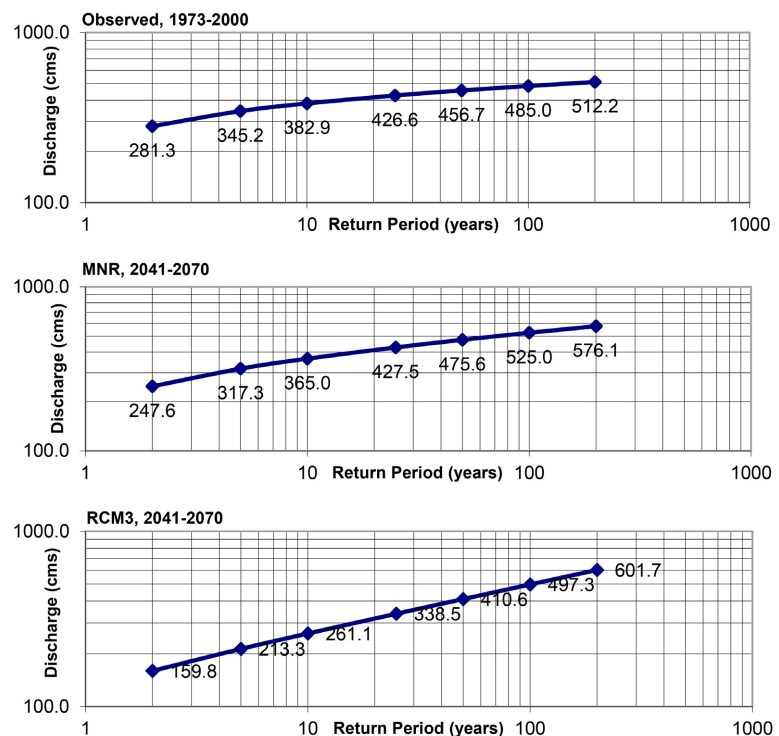
elevation points formed by trees, buildings, and other physical objects. Due to the use of elevation points with voids to prepare DEMs, the shape of the surface shows the errors in the area with voids. The purpose of this study is to correct this error and improve the quality of DEMs.

The boundary conditions define the inflows and outflows at the model boundary. The exchange of mass and momentum occurs in boundary fluxes. Typically, downstream and upstream boundary conditions are specified in a model domain. There are three types of boundary conditions used in flood modeling. Three types of Dirichlet conditions exist: Neumann (specified flow boundary), Cauchy (head-dependent flow boundary), and Dirichlet (specified head boundary). Mixed boundary conditions are commonly referred to as Cauchy boundary conditions. The study evaluated boundary conditions upstream and downstream at normal depths.

4.4. Estimation of Projected Flood Quantities

This study collected and processed hydraulic simulations for the study area. Among the many families of distributions proposed by the statistical genius Pearson, the Log Pearson Type III distribution was used as a random variable analysis model. According to the U.S. federal government, the log Pearson type III distribution as a common distribution [7].

The frequency analysis is illustrated in **Figure 4**. The 100-year return period flows were estimated using data for historical period (1973-2000), processed data from MNR and Canadian Regional Climate Model (CRCM) and Regional Climate Model-3 (RCM3) from NARCCAP with the combination of driving model of Coupled Global Climate Model-3 (CGCM3).



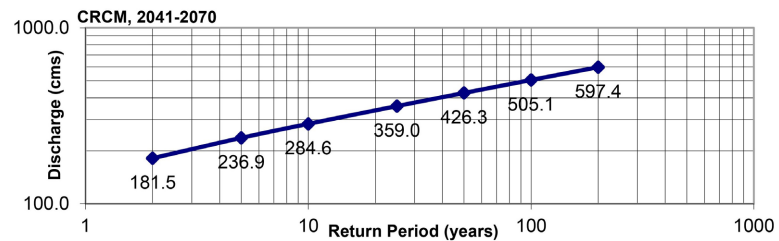


Figure 4. Flood frequency analysis for Nith River at Ayr using Log-Pearson Type III analysis using annual peak streamflow values.

5. Results and Discussion

5.1. Effect of Climate Change on Flood

Recent research statistics and historical events indicate the need for active research. According to IPCC [1], global climate change will likely increase heavy precipitation in most parts of the world under future climate conditions. A primary concern of the study was to investigate possible climate change. It is crucial to understand the impacts of climate change on floods, their occurrence, mechanisms, characteristics, frequencies, and regularities when managing floods and developing water resources systems.

The Nith River flow was significantly affected by climate change between 2041 and 1970. The simulation shows an increase in floodwaters of 39.5 cm in the 100-year flood will inundate the Nith River floodplain by 19.8% more than usual.

5.2. Effect of Uncertainties in Flood Inundation Modelling

There is a need for active research based on recent research statistics and historical events. IPCC [1] predicts heavy precipitation will increase in most parts of the world as a result of global climate change. The study investigated possible climate change as one of its primary concerns. Managing floods and developing water resources systems requires a thorough understanding of the impacts of climate change on floods, their occurrence, mechanisms, characteristics, frequencies, and regularities.

A significant impact of climate change on the Nith River flow was seen between 2041 and 1970. A simulation shows that an increase of 39.5% in floodwaters in a 100-year flood would inundate the Nith River floodplain by 19.8% more.

Fill DEM or Topography: Most models require topography as a main input. According to this study, surface roughness is less important than surface roughness. Topography is often less significant in flood inundation simulations [8]. Flood height increased by 3.2 cm with 1.0% more area inundated due to error correction. Due to the net changes in error, topography did not appear to have a significant impact in this case. In many locations, the DEM correction was negative, resulting in an insignificant residual of the positive correction.

Roughness: The local surface roughness of a channel affects inundation maps significantly [8]. The estimation of surface roughness needs to be accurately calculated based on the local landuse pattern to get a more accurate flood simulation

from a hydraulic model. Since it is not a straightforward task to determine the surface roughness of the site, a sensitivity analysis was conducted with $\pm 20\%$ change in surface roughness to investigate the impact of this uncertainty on flood simulation. Based on the results, flooding simulation was significantly affected by surface roughness, which caused the inundation to be more sensitive. As shown in **Table 1**, a 20% reduction in roughness results in a 12.5 cm reduction in flood height with 6.69% less flooding area. In contrast, with increased roughness of 20%, flood height increased by 13.92 cm by 7.47% of more area of inundation.

Model boundary conditions were also taken into account as input parameters in this study. It is very common for boundary conditions to be quantified as the key input to a model. As input for boundary conditions at its downstream in HEC-RAS 1D modeling with subcritical conditions, the Normal Depth is used. The slope of the river was approximated from 0.01 or 1%, which was the average slope of the river. This assessment indicates that inputs are not just as significant as roughness and DEMs errors in flood modeling. It represents, the flood height decreases by only 0.4 cm because of 2% of normal depth.

Table 1. Impact of uncertainty on flood simulation.

	Changed Manning's "n" by		Error Correction in DEM	Normal Depth
	20% (–)	20% (+)		
Change in Flood Height (cm)	–12.50	13.92	2.40	–0.41
Change in Flow Area (%)	–6.69	7.47	0.25	–0.508

Surface roughness was found to play a determining role in flood simulations in this study.

5.3. Flood Mapping

A floodplain map was prepared for the Nith River based on a return period of 100 years. Maps are based on existing and climate-viable future flow conditions. **Figure 5** shows the inundation maps for both conditions. The differences between the maps indicate extended inundation due to climate change during the 2041–2070 period.

The ultimate goal of this research is to prepare climate-viable floodplain maps. Besides fieldwork, DEMs were prepared and computer models were created as part of the study. A rigorous approach for data collection from the field survey and GRCA data is being used in the process of technical work and floodplain mapping. These data include SWOOP elevation points, topography, landuse, other spatial layers, precipitation, gauge flow records, and water levels for historical storm events. GeoRAS model was used to preprocess all of these spatial data, and model information such as rivers, flowpaths, bank lines, bank stations, cross-section cutlets, hydraulic structures, roughness factors, and obstructions was ex-

tracted to provide the required lengths and elevations of these features. The information, along with flow data and parameters for a 100-year return period, was used in the development of hydraulic models. Water surface elevations and velocity are simulated in the model, which is then post-processed and converted to GIS formats to prepare a 100-year flood map. A comparison of the observed and climate viable flood maps showed that inundation was extended as a result of the combination of climate change impact and DEM error correction.

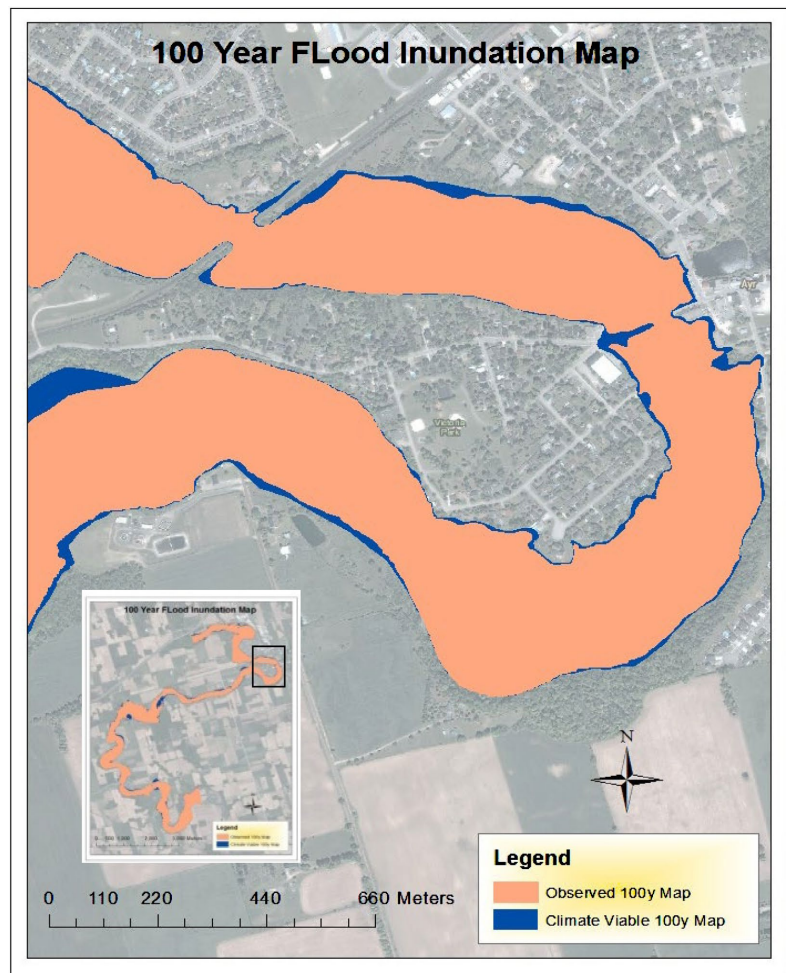


Figure 5. Observed and climate viable flood inundation maps of the Nith River for a 100-year return period.

6. Conclusions

In this study, the influence of climate change on floodplain mapping and the impact of DEM errors are demonstrated. Flood inundation mapping processes are conducted using HEC-GeoRAS, GIS, and HEC-RAS hydraulic models. In particular, it emphasizes extreme storm events and the topography of watersheds. The output of this approach is highly dependent on the characteristics of the watershed and the climate scenarios used in the hydrologic simulations.

The results showed a noticeable increase in flood height by 39.5 cm during the

2070 time horizon, which may cause floodplain inundation to increase by 19.8%. Other emission scenarios or combinations of climate change results may affect the results.

The DEM error correction increases flood height by 3.2 cm, resulting in approximately 1.0% more inundation in the floodplain. Increased flood height is caused by a net change in DEM error correction. It is therefore recommended to minimize the DEM errors before using them to model and map floodplains.

In flood simulation, uncertainties require the fulfillment of the research objectives to be evaluated. In flood simulations, roughness factor consideration plays a governing role in model development. As determining the roughness factor throughout the study area is not a straightforward task, this study investigated a $\pm 20\%$ change in roughness to calculate the influence on flood simulation. It was found that a $\pm 20\%$ change in surface roughness can change about 13 cm of flood height and about 7% changes in inundation area.

The purpose of this study was to limit the potential of explanatory variables that influence floods such as snow water equivalent studies, seasonal floods, river morphology, etc. In the future, the flood maps may change as the river may bifurcate or shift as a result of morphological changes. Future research may be able to benefit from it.

The research integrated all available information related to the study area into the updated floodplain mapping process. The technology and mapping process will provide the users a comprehensive understanding of climate change impact, influence of DEM error and floodplain mapping information. This study will provide better understanding and guidelines for floodplain and watershed development for users and decision makers. It will be useful in guidance of minimizing the risk of flood damages and any other public safety risk associated with future flooding. The research outcome will increase the reliability of flood forecasting and warning activities, emergency preparedness and existing stakeholders retaining in the floodplain.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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