ICFM 10
Adapting to Global Change:
Innovative Approaches to Flood Management and Resilience
May 20-22, 2026 | Western University, London, Ontario, Canada

Hydrologic Modelling to Investigate Flood Mitigation Measures in the Muskoka River Watershed using SWAT+

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ABSTRACT

Recent significant flooding events in the Muskoka River Watershed in Ontario, Canada prompted the provincial government to provide funding for research to help reduce the impact of flooding and improve the watershed's health while considering implications of social, environmental, and economic factors in decision-making processes. This study comprises the development, calibration, and validation of a hydrologic model of the 5,100 square kilometres watershed using the Soil and Water Assessment Tool (SWAT+) to better understand the sensitivity of watershed response to changes in climate and land-use.

The model was calibrated at a daily timestep over five years and further validated using a separate five-year period. It was then run for 30-years under changing climate, land-use, and potential flood mitigation measure scenarios. Scenarios included varying levels of wetland enhancement, forest reduction, and online reservoirs, to evaluate their role in the Muskoka River watershed response and to test local response to increased storage.

The results showed that the additional reservoirs effectively reduce peak flows in the area local to the reservoir, but they did not have a significant impact on reducing flood risk downstream in the main system. At a local level, increasing wetland cover reduced peak flows in tributary channels, particularly in summer months. Similarly, a reduction in forest cover was associated with an increase in summer runoff and a faster hydrologic response, impacting local peak flows. The study also identified an existing park that likely provides flow attenuation in the early spring, which may be a key area to protect from future development.

The results demonstrate the importance of protecting natural wetlands and forests to manage local riverine flooding in the Muskoka River Watershed. The developed hydrologic model and scenario analysis results can inform future planning and watershed management and can be used to evaluate potential local flood mitigation measures.

KEYWORDS: Flood mitigation, Hydrologic modelling, watershed response, scenario analysis

1 INTRODUCTION AND BACKGROUND

The Muskoka River Watershed has experienced several major flooding events in recent years, most notably in 2019, 2016, 2013, and 2008. These events affected multiple parts of the system, including the Big East River north of Huntsville, the North Branch of the Muskoka River between Huntsville and Bracebridge, the South Branch of the Muskoka River near Purbrook, the Lake Rosseau–Lake Joseph system, and Lake Muskoka. Across the District, road washouts and widespread damage to public and private infrastructure highlighted the need for a clearer understanding of the watershed's flood dynamics.

The Muskoka River Watershed Hydrologic Modelling Study was undertaken to develop a hydrologic model of the Muskoka River Watershed capable of identifying the drivers of flooding in the system with a focus on the main river branches. The modelling was performed using the SWAT+ software. A calibrated baseline model was first established to represent existing hydrologic conditions. Building on this foundation, a scenario analysis was completed to evaluate how three major categories of change could alter flood behaviour across the watershed, including climate change, land use change, and reservoir storage. Although this paper focuses on the reservoir storage category, brief summaries of the climate and land-use results are included to provide context for interpreting the reservoir findings and to support a discussion in the conclusion of this paper.

The baseline modelling confirmed that flooding in the Muskoka River system is primarily driven by snowmelt and multi-day rainfall events in the spring season. Climate change scenarios significantly alter the watershed's flow regime. Higher winter temperatures reduced snowfall and increased the frequency of mid-winter melt events, leading to a smaller snowpack and lower spring peak flows across much of the system. The freshet shifted earlier in the year. Summer peak flows increased modestly due to more frequent high-intensity short-duration storms, which the watershed generally absorbs more effectively than freshet flows. Overall, climate change produced a redistribution of peak flows rather than a consistent increase in the maximum annual flood magnitude. Land use change scenarios resulted in small changes in peak flows relative to baseline conditions. Population growth, deforestation, and wetland enhancement scenarios produced small but measurable changes in flow in summer months, generally proportional to the extent of land cover alteration, and had a negligible impact on larger spring flood flows.

This paper focuses on reservoir storage as it remains the most operationally relevant aspect of flood behaviour in the Muskoka River system. The scenarios presented here are strictly exploratory: they are not intended to recommend new reservoir construction, which would require extensive environmental, cultural, and infrastructure assessment. Instead, the analysis is meant to improve the understanding of how additional storage, whether hypothetical or through adjustments to existing reservoir operations, could influence flood attenuation.

The objective of this paper is therefore to present the methodology and results of the reservoir storage scenarios and to assess their potential effectiveness as a flood mitigation strategy within the Muskoka River Watershed.

2 STUDY AREA

The Muskoka River Watershed covers approximately 5,100 km² on the Canadian Shield in central Ontario. The watershed is divided into three major subbasins: the North Branch Muskoka River (including the towns of Huntsville and Bracebridge), the South Branch Muskoka River (including the town of Gravenhurst), and the Lower Muskoka River (extending toward the villages of Port Carling and Bala). The landscape is predominantly forested outside of the urban centres, with thin soils, exposed bedrock, and a dense network of lakes and wetlands typical of the Shield.

The watershed contains more than 2,000 lakes, including 650 lakes larger than eight hectares, and 38 provincially significant wetlands. Water levels and flows are influenced by an extensive system of water control structures: 65 dams operate throughout the watershed, including 23 major control structures. Although none of these dams were originally constructed for flood control – most were built to support log driving and commercial navigation – their roles have evolved to include recreation, fisheries management, and, to some extent, flood moderation.

Hydrologic response in the watershed is shaped by the interaction of rainfall, snow accumulation and melt, lake storage, and operational decisions at the control structures (which are driven by the Muskoka River Water Management Plan). The combination of large lake storage volumes, complex channel networks, and variable winter conditions makes the Muskoka River system particularly sensitive to changes in climate, land use, and control structure operations, underscoring the need for a comprehensive modelling approach.

3 MODEL DEVELOPMENT

A hydrologic model of the Muskoka River Watershed was built, calibrated, and validated using SWAT+. The continuous model runs on a daily timestep for 32 years, including 2 warm-up years.

3.1 Model Setup

Provincial datasets for soil (Gao et al. 2007), watercourses and elevation were used along with District LiDAR (Hatch, 2023), and land cover mapping (Dougan & Associates, 2022) to set up the physical parameters in the model. These parameters were not subjected to calibration, as they are physical characteristics of the watershed, assigned using measured data. This is a common approach, especially considering detailed models with over 100 parameters, such as SWAT+ (e.g., Kumarasamy and Belmont, 2018). Climate data was input as daily maximum and minimum temperature and daily precipitation, using five Environment and Climate Change Canada (ECCC) stations. Future projected climate data for climate change scenario analysis was downloaded from ClimateData.ca (Web-1).

Major lakes were modelled as reservoirs that are online to the channel network. The Ministry of Natural Resources and Foresty (MNRF) Operations Manual (2007), dam geometry files, and dam safety assessments were used to characterize the reservoirs. The manual includes details for each reservoir such as operating level curves based on the watershed management plan, and stage-storage curves. The reservoirs typically have seasonal operating rules according to the watershed management plan, to manage water levels in the lakes throughout the year. The principal spillway of the reservoir is the level at which water begins to flow out of the reservoir in a controlled manner, which is adjusted seasonally to maintain target lake levels. The emergency spillway is the level at which water overflows the outlet – and is considered the maximum lake level.

In the model, reservoirs are characterized by the surface area and volume required to fill them up to the principal spillway and the emergency spillway elevations. The volume at the principal spillway elevation is equivalent to the normal reservoir storage volume, and the volume at the emergency spillway elevation is equivalent to the maximum reservoir storage volume. These measurements define the stage storage relationship for each reservoir, which is used to calculate reservoir storage based on the change in inflow and outflow volumes at each timestep.

The outflow volumes are calculated by a set of rules defined in the reservoir release decision tables that are based on the volume of water relative to the defined principal and emergency spillway volumes at each timestep. The decision tables can be coded to release varying outflow rates depending on the time of year to simulate seasonal operational rules at the dam control structures. The reservoir geometries and release decision tables were characterized using the most recent Water Level Operating Zone Limits graphs for the corresponding dam structure, provided by the MNRF through the Muskoka River Water Management Plan.

The principal and emergency spillway elevations were set equal to the minimum and maximum water surface elevations of the target operating level curve. The surface areas and volumes were determined from the corresponding lake storage table, provided by the MNRF. Twelve reservoir release equations were developed (one for each month of the year) to simulate the seasonal operating rules at the dam. The equations relate the average volume of the normal operating zone and target release rate in the form of a rating curve, represented by the number of drawdown days that would be required to lower the average storage volume over the spillway elevation (or top of stop log elevation). The drawdown days are calculated as half the maximum storage volume (*evol*) minus the storage volume at the specified spillway elevation (*vol*), divided by the target release rate for that month, as shown in Equation 1.

$$drawdown\ days = \frac{0.5 \times (evol - vol)}{target\ release\ rate} \tag{1}$$

The target release rates were obtained from the Downstream River Flow Operating Zone Limits graphs provided by the MNRF for each dam. A thirteenth equation was included to calculate the release rate when the reservoir storage volume exceeds the emergency storage volume, which results in a faster release. The drawdown days of the reservoir volume over the emergency storage volume is included as a calibration parameter.

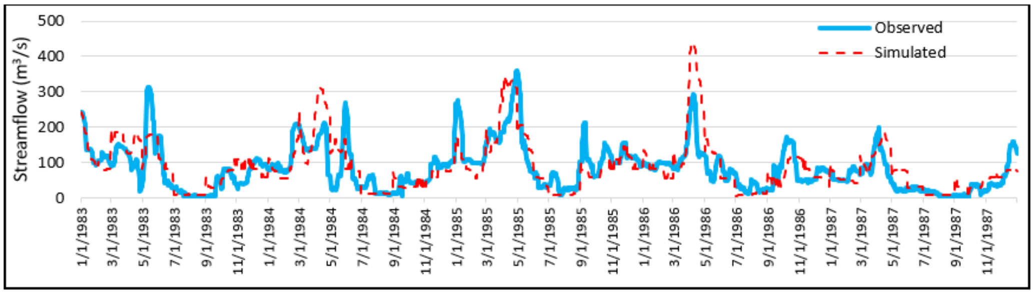
3.2 Calibration and Validation

To evaluate model performance over a variety of conditions, it is considered best practice to select calibration and validation periods that include wet, dry, and average years (Arnold, J.G., et. al., 2012). The calibration and validation periods were each selected to be 5 years in length to include variation in precipitation.

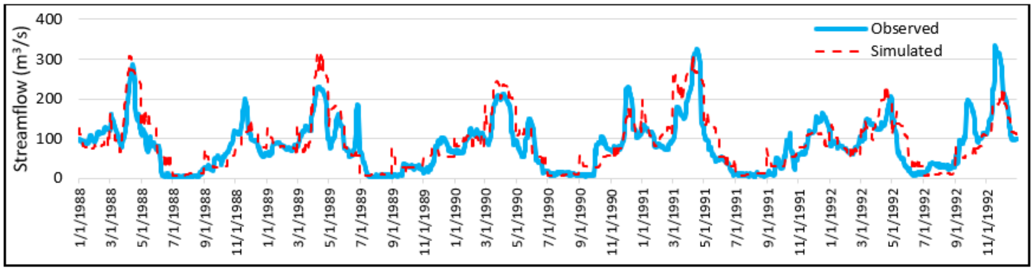
The model was calibrated using a split sample technique, both spatially and temporally. Spatially, the model was divided into five basins, and each basin was calibrated and validated separately, beginning upstream, and working downstream to the model outlet. The basins were delineated based on five Water Survey of Canada (WSC) gauges with available flow data during the calibration and validation period. Temporally, the calibration and validation periods were separated as described above.

A sensitivity analysis was performed on over 20 model parameters (2 were reservoir based) to determine the parameters of the hydrological processes that impact streamflow from which 11 were selected. Hydrological parameters that could be measured and assigned with a higher level of certainty were excluded from the calibration process – this included many of the reservoir parameters. Of the 11 parameters chosen to calibrate the model, five control snow accumulation and melt, four are related to infiltration and baseflow processes, and two are related to reservoir release. The model was highly sensitive to the reservoir release parameters.

Once the model was calibrated, each basin was validated. The results of the calibration and validation procedures were evaluated using both graphical and statistical methods, including percent bias (PBIAS), Nash Sutcliffe Efficiency (NSE), and the Coefficient of Determination (R^2). Results for basin 5, which is located at the downstream southwestern end of the watershed, with an outlet downstream of Bala Dams, are shown in Figure 1. Basin 5 shows how well the model followed the Bala Lake (reservoir) rules as it achieved good calibration results across all seasons.



Basin 5 Observed and Modelled Streamflow During Calibration Period



Basin 5 Observed and Modelled Streamflow During Validation Period

Figure 1: Calibration and validation results for basin 5

4 RESERVOIR SCENARIO ANALYSIS

A scenario analysis was performed to assess the ability of the reservoir storage to attenuate peak flow rates and reduce flood risk in the system. To assess the potential for reservoir storage to reduce peak flows in the Muskoka River system, a targeted analysis was conducted focusing on the hydrologic response to hypothetical reservoirs. This section outlines the approach used for site selection and reservoir routing of the hypothetical reservoirs to evaluate their influence on flood attenuation.

4.1 Site Selection

Potential reservoir sites were identified through a spatial analysis of high-resolution LiDAR data. The objective was to locate suitable locations where a dam could theoretically be constructed at a natural constriction in the river, with sufficient upstream width to provide meaningful storage. Sites were selected to ensure that impounded water would not propagate excessively far upstream, thereby avoiding large-scale alterations to the flow regime or inundation of long river reaches. As part of this screening, efforts were made to minimize potential impacts to existing infrastructure such as roads, bridges, and developed areas.

For each candidate site, LiDAR-derived elevation data were used to delineate the potential reservoir footprint and to develop a stage–storage relationship up to a maximum containing elevation. This provided a realistic estimate of the storage volume available at each site and formed the basis for subsequent reservoir-routing simulations. Figure 2 shows the hypothetical reservoir locations and Table 1 describes their location and purpose in terms of flood mitigation.

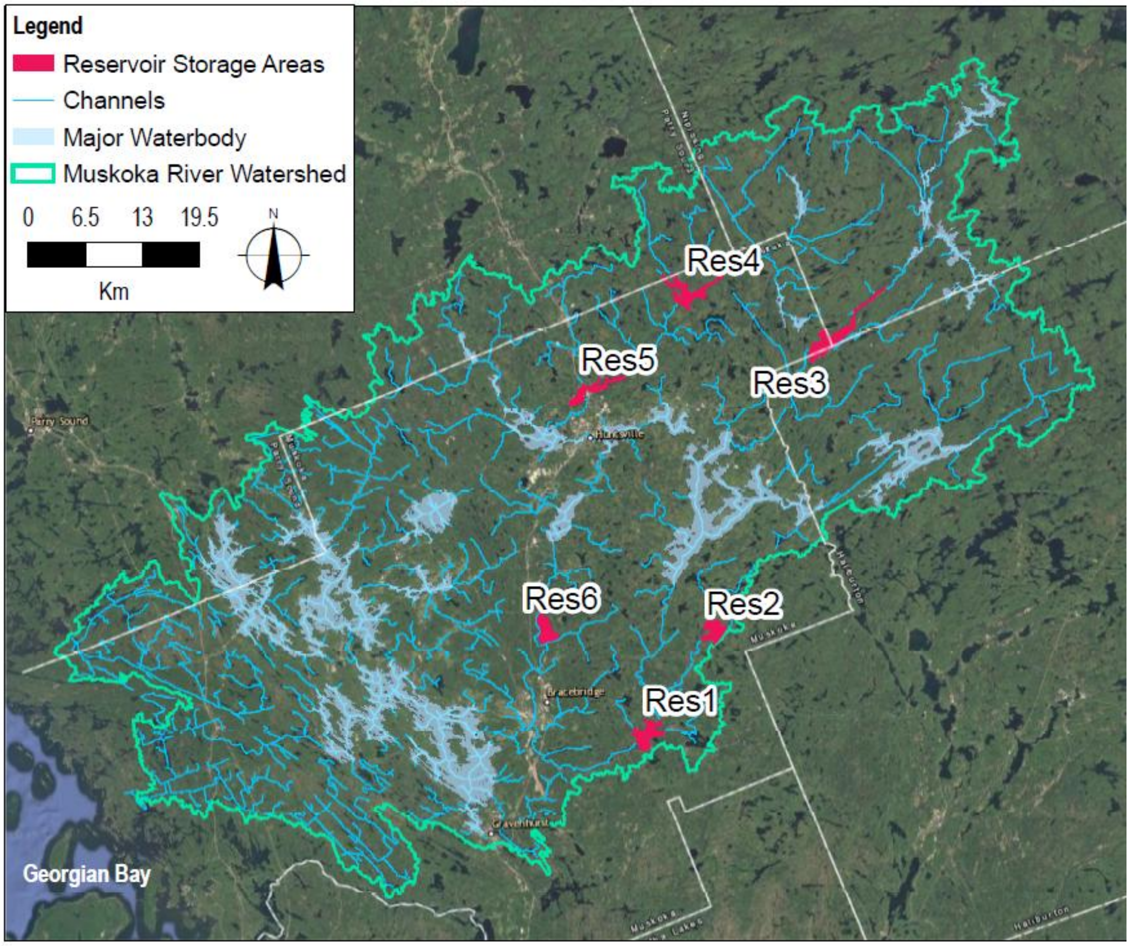


Figure 2: Hypothetical reservoir locations

Table 1 Site Selection of Hypothetical Reservoirs for Analysis

Reservoir	Location	Description
Res1	South Branch Muskoka River near Purbrook	Intended to mitigate flood risk on the South Branch Muskoka River near the Purbrook community, an area identified as high risk (DMM Floodline and LiDAR Mapping 2.0 (Web-2))
Res2	Tributary of the South Branch Muskoka River upstream of Purbrook	Located further upstream than Res1, with a larger storage volume. Intended to reduce flood risk on the South Branch Muskoka River near Purbook.
Res3	Oxtongue River upstream of the community of Dwight and Lake of Bays	Located further upstream in the watershed, with a larger storage volume. Intended to reduce downstream flood risk on the South Branch Muskoka River near Purbook.
Res4	Big East River at the site of the historic Distress Dam	Reinstatement of the historic Distress Dam on the Big East River, which currently functions as a low-capacity weir. Intended to mitigate existing flood risk on the Big East River near Highway 11 and downstream on the North Branch Muskoka River.
Res5	Big East River near Highway 11	Intended to mitigate existing flood risk on the Big East River near Highway 11 and downstream in the North Branch Muskoka River.
Res6	North Branch Muskoka River between Port Sydney and Springdale Park	Use of an existing quarry pit as flood storage to reduce downstream flood risk on the North Branch Muskoka River, particularly for the Town of Bracebridge. The quarry is currently active, so the scenario reflects a theoretical closure plan with storage maximized within property, topographic, and infrastructure constraints.

4.2 Reservoir Routing

For each hypothetical site, reservoir routing was performed using a historical flood event and the stage-storage relationship derived from the LiDAR-based topography. Simple weir and gated weir outlet structures were used to control the release flow.

Historical flood events were selected based on their relevance to different parts of the watershed. The 2019 and 2013 events represent the largest observed floods on the main river branches, with the dominant event varying by subbasin. For each candidate reservoir site, the flood hydrograph corresponding to the most representative event was used as the inflow condition for routing. The 2013 flood event was applied to assess flood impacts and mitigation measures on the Big East River and Oxtongue River, and the 2019 flood event was applied on the north and south branches of the Muskoka River. The 2013 and 2019 floods were classified as milti-day rain-on-snow events, which produced peak flow rates in April and May of these years. The design flood events were obtained from the nearest Water Survey Canada hydrometric station and prorated to the reservoir locations.

Routing simulations were performed using SWMM-based software to estimate the maximum potential reduction in peak flow at the reservoir outlet. Reservoirs that demonstrated meaningful peak flow reduction at the local scale were retained for the scenario analysis. SWMM was used for the initial reservoir routing because of its functionality and ease-of-use, which allowed for multiple reservoir locations to be tested quickly to identify the best options for inclusion in the SWAT+ model and scenario analysis. Table 2 summarizes the available storage and performance in peak flow reduction.

The results show that the peak inflow rate at Res5 on the Big East River is higher than at Res6 on the North Branch Muskoka River, even though Res6 is located much further downstream on the same system where the contributing catchment area is larger. While the peak flow rate at Res6 is lower, the total flood volume is substantially greater, meaning far more storage would be required to meaningfully reduce the peak. This pattern of lower peak flows but larger flood volumes downstream is driven by the attenuating influence of the Huntsville Lakes and Mary Lake, which lie between Res5 and Res6 and moderate flows as water moves through the system.

Table 2 Reservoir Capacity and Performance in Peak Flow Reduction

Reservoir	**Maximum Storage Volume Available (1000 m^3)**	**Maximum Available Depth (m)**	**Design Flood Peak Inflow Rate (m^3/s)**	**Effective Design Flood Peak Flow Reduction**
Res1	14,900	4	192.8	Less than 1 m^3/s
Res2	6,400	4	15.1	Approximately 10 m^3/s
Res3	11,000	8	107.1	Approximately 25 m^3/s
Res4	10,000	11	176.4	Approximately 120 m^3/s
Res5	2,800	4	277.4	Less than 10 m^3/s
Res6	22,800	6	247.9	Approximately 5 m^3/s

Figure 3 compares the inflow (Quarry Lake) and outflow (Outlet) hydrograph immediately downstream of Res6, the hypothetical quarry reservoir on the North Branch Muskoka River from the reservoir-routing exercise performed using the SWMM model. The design flood hydrograph spans roughly one month, illustrating the challenge of attenuating such a long-duration event. Any reservoir storage located on the main river system – particularly downstream of the Huntsville Lakes on the North Branch or Lake of Bays on the South Branch – would require very large storage volumes to achieve meaningful peak flow reduction.

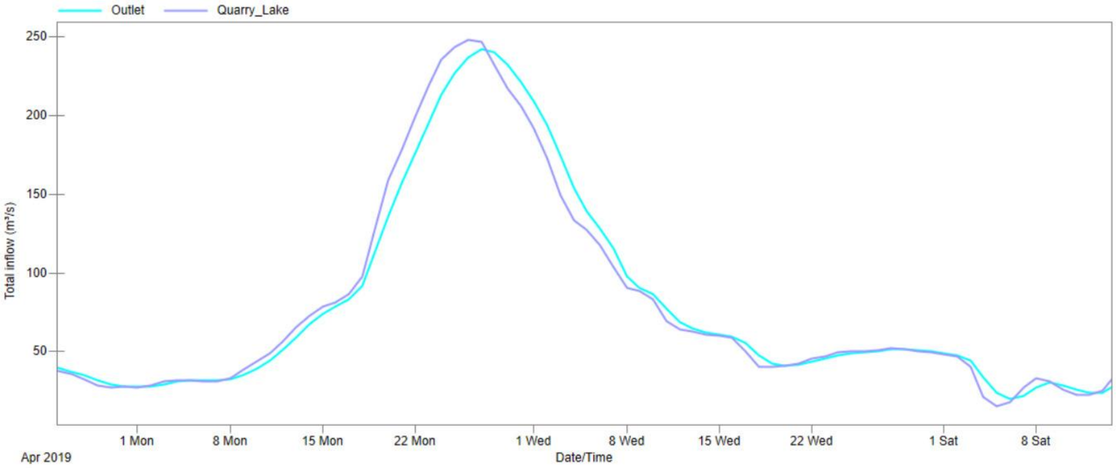


Figure 3 – Res 6 (Quarry Lake) Design Flood Peak Flow Rate Reduction

Among the sites assessed, Res2, Res3, and Res4 provided the greatest peak flow reduction and were carried forward into the SWAT+ scenario analysis. Res5 was not included because it is located close to Res4 (the Distress Dam reinstatement scenario) but offers significantly less attenuation and is therefore considered redundant.

4.3 Scenario Analysis

The reservoirs selected for the scenario analysis were incorporated into the SWAT+ model to evaluate their system wide effects. This step allowed assessment of how attenuation at individual sites propagates downstream, interacts with other branches, and influences peak flows at key locations throughout the Muskoka River system. The impacts of reservoir storage on peak flow rates through the Muskoka River system are summarized in Table 3.

Table 3 Reservoir Performance in Peak Flow Reduction on Muskoka River System

Location	Associated WSC Station ID	Peak Flow % Change from Existing Conditions		
		Res2	Res3	Res4
Big East River near Huntsville	02EB013	0%	0%	**-6%**
North Branch Muskoka River at Port Sydney	02EB004	0%	0%	**-1%**
South Branch Muskoka River at Baysville	02EB008	0%	0%	0%
Indian River (Port Carling)	02EB020	0%	0%	0%
Muskoka River below Bala	02EB006	0%	0%	0%
Oxtongue River near Dwight	02EB014	0%	**-11%**	0%
South Branch Muskoka River near Purbrook	n/a	0%	0%	0%
Big East River near Williamsport Road	n/a	0%	**-31%**	0%

5 DISCUSSION

The results demonstrate that larger reservoirs can reduce peak flow rates locally; however, their ability to reduce peak flow rates is diminished further downstream in the system as the river receives runoff from larger contributing drainage areas and flows through the operated major lakes. This is most evident in the results for Res3 and the Res4. Res3 provides an 11% reduction in peak flow rate on the Oxtongue River near the village of Dwight, and no change on the South Branch Muskoka River at Baysville. Res4 provides a 31% reduction in peak flow rate in the Big East River near Williamsport Road; however, as the river gains more runoff from the downstream contributing drainage areas, and meanders through wetlands and under roads toward Lake Vernon, the flow reduction is diminished to 6%, and reduces to 1% downstream of the Huntsville Lakes and Mary Lake at Port Sydney.

Res2 has the capacity to significantly attenuate the peak flow rate on the tributary where it is located as shown in Table 2; however, it provides negligible impact on the main branches of the Muskoka River system as shown in Table 3 due to the relatively high flow rates in the main branch compared to the volume of the reservoir. Res2 and Res3 demonstrate how online storage can be an effective way of reducing peak flow rates on the tributaries and upper reaches of the river system. It is important to note that there may be other locations within the watershed where online storage could effectively mitigate flooding at a local level. To mitigate flooding on the main branches of the Muskoka River, very large reservoirs would be required, or many relatively smaller reservoirs would need to be constructed on the tributaries and upper reaches of the river system to reduce the peak flow rates contributing to the main stems.

6 CONCLUSIONS

The study assessed the potential for flood storage to reduce peak flow rates in the Muskoka River system by evaluating the performance of six hypothetical reservoirs. Reservoir sites were selected based on conceptual feasibility, considering topographic constraints and the need to avoid major impacts to existing infrastructure. Reservoirs located on the Big East River (upstream of the Huntsville Lakes) and on the Oxtongue River (upstream of Lake of Bays) provided the greatest local peak flow reduction. However, their effectiveness diminished downstream due to the large volume and long duration of the flood hydrographs moving through the system.

The broader study's climate change analysis showed that flood flows in the watershed are highly sensitive to warming temperatures and shifting precipitation patterns. For this reason, any future assessment of reservoir storage should be paired with a range of climate change scenarios. Given the required storage volumes, it may not be feasible to add new reservoirs to the system for the purpose of flood control on the main branches of the Muskoka River. Therefore, there may also be value in examining adjustments to existing structures and operating rules on existing reservoirs and dams. Their performance under changing climate conditions and ability for flood control warrants further evaluation.

Overall, the results suggest that reservoir storage could provide meaningful peak flow reduction and flood mitigation in the upper parts of the watershed, particularly on the Big East River near Highway 11 where hydrographs are shorter and less attenuated. Any further consideration of reservoir storage would need to weigh these potential benefits against significant environmental, cultural, infrastructure, and cost implications, and may not be feasible in the downstream reaches.

ACKNOWLEDGEMENTS

This work was made possible through funding from the District Municipality of Muskoka and the Government of Ontario. The authors would like to thank ClimateData.ca for providing the climate information used in this study. ClimateData.ca was created through a collaboration between the Pacific Climate Impacts Consortium (PCIC), Ouranos Inc., the Prairie Climate Centre (PCC), Environment and Climate Change Canada (ECCC), Centre de Recherche -20.0 Informatique de Montréal (CRIM) and Habitat7.

REFERENCES

Arnold, J.G., Moriasi, D.N., Gassman, P.W., Abbaspour, K.C., White, M.J., Srinivasan, R. Santhi, C., Harmel, R.D., van Griensven, A., Van Liew, M.W., Kannan, N., Jha, M. K. (2012). SWAT: Model Use, Calibration and Validation. American Society of Agricultural and Biological Engineers, 55(4), 1491 1508.

Dougan & Associates Ecological Consulting & Design (2022). Muskoka River Watershed IWM Natural Capital Inventory: Phase 2 Final Report: Data Enhancements, New Data & Verification.

Gao, Cunhai & Shirota, Jiro & Kelly, Ross & Brunton, Frank & Haaften, Steve. (2007). Bedrock Topography And Overburden Thickness Mapping, Southern Ontario. Diamond Jubilee Proceedings of the 60th Canadian Geotechnical Conference and the 8th Joint CGS/IAH CNC Groundwater Conference: Ottawa, Ontario, Canada.

Hatch (2023). Floodplain Mapping Technical Report for Floodplain Mapping Study (H366496-0000-200-230-0002).

Kumarasamy, K, and Belmont, P. (2018). Calibration Parameter Selection and Watershed Hydrology Model Evaluation in Time and Frequency Domains. Water, 10(6), 710.

Ministry of Natural Resources and Forestry, MNRF (2007). Muskoka River Dam Operation Manual.

Web sites:

Web-1: https://climatedata.ca, consulted 20 July 2023.

Web-2: https://experience.arcgis.com/experience/4aefea73e8684812a2e3d0bf8006ca50/page/2D, consulted 5 December 2025.