Preliminary Flood Hazard Assessment at South Bruce Study Area

NWMO-TR-2022-16

December 2022

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AECOM Canada Ltd.

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This report has been prepared under contract to NWMO. The report has been reviewed by NWMO, but the views and conclusions are those of the authors and do not necessarily represent those of the NWMO.

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EXECUTIVE SUMMARY

Title: **Preliminary Flood Hazard Assessment for South Bruce Study Area**

Report No.: **NWMO-TR-2022-16**
Author(s): Andres Rodriguez, Rikke Brown
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Abstract

A nuclear waste management facility is being considered in the Saugeen Ojibway Nation-South Bruce area in Ontario, for the long-term containment and isolation of used nuclear fuel. The proposed concept of the facility is comprised by an underground deep geological repository (DGR) and includes access roads and various surface support facilities.

The NWMO owned and optioned land, within or near the Municipality of South Bruce, is approximately 5 km northwest of the Town of Teeswater. The land is mostly located within a catchment that drains north into the Teeswater River. The Teeswater River drains into the Saugeen River, which makes its way to Lake Huron at Southampton, Ontario. Lake Huron is approximately 30 km west of the study site.

The South Bruce Site and surrounding area are within the Teeswater River watershed. Catchment delineations were completed using the Ontario Flow Assessment Tool (OFAT) and then refined using GIS software with the available SWOOP 2015 digital terrain data from MNRF available through Ontario GeoHub. The topography of the site is levelled uniform, with consistent gentle slopes and topographical features. Sheet flow directions are towards the Teeswater River or its tributaries, however these drainage patterns are not visually discernible.

The predominant soil type within the South Bruce study site is reported as loam soil which is a mineral material made up of sand, silt and clay with other coarse materials present and with organic matter content of less than 30%. Furthermore, the predominant bedrock geology near Teeswater and the study site is defined as till and glacial fluvial outwash deposits formed by limestone, dolostone and shale from the middle Devonian period.

A qualitative assessment was first completed as part of the preliminary assessment of flooding hazards for the South Bruce Site. This qualitative assessment is based on the guidelines provided in the IAEA Safety Standards document entitled *Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations* (IAEA 2011). Of a particular note, all assessment work presented in this report is based on current existing conditions, e.g., without the assumption of any future development or landscape grading.

The qualitative analysis indicated that hydrological hazards such as storm surges, wind generated waves, tsunamis, seiches, bores and mechanically induced waves have no effects with respect to surface flooding within the site. There is no specific indication that local high ground water levels are an issue at this site and are beyond the scope of this surface water study. However, for areas within the catchments where potential high ground water may be found, the selection of the hydrologic soil infiltration parameters accounts for them. It was also determined during the qualitative assessment that the risk of flooding hazards due to extreme precipitation events requires further consideration.

Flooding hazards have been quantitatively assessed for two conditions: direct rainfall on site, and rainfall on the upstream catchments. The qualitative analysis noted that, due to the site topography and proposed layout with respect to the catchments, extreme precipitation events should be applied without reduction factors, and the catchment response to precipitation is expected to be long due to the runoff conveyed from the large upstream catchments via the Teeswater River to the study site.

A hydrologic model of the study site was developed for this assessment with the software HEC-HMS version 4.8. The results of the hydrologic model indicated that the SCS-Type II rainfall distribution creates the highest peak flows for all catchments. The SCS Type II distribution with a duration of 24 hours was therefore applied to the probable maximum precipitation (PMP) value reported by Ontario Ministry of Natural Resources (OMNR 2006) since this is the highest precipitation value (462 mm) for the study site, as reported in *Climate Change Impacts on Climate Variables for a Deep Geological Repository* (South Bruce Study Area) by Golder (2020).

A total of 14 scenarios were included in this preliminary flood hazard assessment. These scenarios are divided by period (current, mid-century, and end-of-century), climate change scenario (three PMP risk projections) and by type of flood (direct rainfall on-site and rainfall on upstream catchments). Two additional scenarios were also undertaken to evaluate the preliminary flood hazard assessment for the 500-year storm event.

A hydraulic model was then created with the software HEC-RAS (version 5.0.7) to transform the calculated extreme precipitation amounts into surface runoff depths at the study site. The results of the model for all 16 scenarios show areas where surface ponding occurs as well as the floodplain boundaries of the Teeswater River and its tributaries within the study site. This ponding is based on the topography developed from the SWOOP 2015 data.

The proposed site is located at the downstream end of three delineated catchments within the Teeswater River with a total area of 220 km^2. It is therefore sensitive to precipitation and runoff from upstream areas. These results show the consequences of an extreme precipitation event affecting the entire catchment. Additionally, the site could be vulnerable to further modifications to upstream catchment areas such as land use changes (i.e. increase in urban development which in turn increases impervious areas) and other events such as the release of impounding water from hydraulic structures (i.e. culvert, bridge and dam failures). A sensitivity analysis was undertaken to assess the impact of release of impounded water from two dams located on the Teeswater River upstream of the site. The flood hazard potential due to the release of impounded water, undertaken with a PMP with 95% percentile climate change risk, indicated that the release of impounded water at both dam structures produce minimal increases in floodplain boundaries when compared to the base scenario without a sudden release of impounded water. The increases in floodplain boundaries are minimal and not clearly visible at the scale presented in this report.

These preliminary results consider only existing conditions and do not consider any grading or ditch configurations which would form part of the civil design within the proposed study site. That is, these results show the effects of an extreme storm on the site as it exists now, before any design. As the detailed design progresses for the proposed facilities at the South Bruce study site, it is expected that site grading will modify some of the current floodplain delineations. In addition, it is also expected that site stormwater management measures such as ditches will further mitigate surface flooding impacts within the site.

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1. INTRODUCTION

The Nuclear Waste Management Organization (NWMO) has retained AECOM Canada Ltd. (AECOM) to carry out preliminary flood hazard assessments at two study sites located in the Wabigoon Lake Ojibway Nation (WLON)-Ignace area and the Saugeen Ojibway Nation (SON)-South Bruce area, respectively. Both locations are within the province of Ontario.

This report presents our results for the South Bruce Site. A separate report addresses the Revell site within the WLON-Ignace study area (AECOM 2021, NWMO-TR-2021-26). Given the nature of the assessment, AECOM carried out the same scope of work for both sites which are included in these reports. Therefore, the reports contain similar sections which are specific to the findings of each site.

These sites are being considered for the development of a deep geological repository (DGR) for the long-term containment and isolation of used nuclear fuel in Canada. The DGR facility would consist of various surface support facilities and an underground repository. The repository would be located at an approximate depth of 650 m in the host rock formation.

The intent of this assignment is to carry out a preliminary flood hazard assessment at each study site to determine surface flood hazards around and within the land parcels that are being considered for this facility.

As per the objectives of this project, a qualitative flood hazard assessment was completed first. This qualitative assessment was based on the guidelines provided in the IAEA Safety Standards entitled *Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations* (IAEA 2011).

Flooding was then quantitatively assessed for two conditions: direct rainfall on-site and upstream watershed flooding.

To support the preliminary flood hazard assessments, NWMO has previously commissioned independent studies to determine the probable maximum precipitation (PMP), intensity-duration-frequency (IDF) curves, and snowpack accumulation projections for both sites considering current and future climate conditions. Results for the South Bruce study area are presented in the report entitled *Climate Change Impacts on Climate Variables for a Deep Geological Repository (South Bruce Study Area)* by Golder (2020).

The Golder (2020) report is a case study for the South Bruce Site for the Deep Geological Repository (DGR) where a preferred method was applied to assess the climate change impacts on the PMP and Intensity-Duration-Frequency (IDF) amounts during the currently planned DGR implementation timeline.

The results of the Golder (2020) analysis were presented for a range of global climate models and expressed in terms of percentiles. This allows that an acceptable level of risk can be selected by using the desired percentile. The results of the Golder (2020) study indicate that climate extreme projections for the 2050s and 2080s are likely to be wetter, which is consistent with the current and future climate projections.

The preliminary flood hazard assessment presented in this report relies on the values for precipitation and climate change projections presented in the Golder (2020) report. This is the basis of the hydrologic modeling supporting the preliminary flood hazard assessment for the South Bruce Site.

The design of the DGR stormwater management system and the placement of the DGR surface facilities and shafts within potential siting areas must consider the range of credible storms for the watershed. The assessment will use the estimated PMP, IDF, and snowpack accumulation values provided by the independent case studies and will be completed in two phases.

Note that the present preliminary analysis is based on the existing topography represented by the Southwestern Ontario Orthophotography Project (SWOOP 2015) digital terrain dataset. It does not include the repository surface facilities, drainage ditches, excavated rock management area, or other features of the project that would affect the flood response. It provides information on the response of the natural site, as input to the design of the surface facilities and their surface water management system.

1.1 Overview of Analysis Approach

The steps that were carried out to complete this preliminary flood hazard assessment at the South Bruce Site are summarized in Figure 1. A total of 12 steps were defined and they include, in logical order, the tasks to be completed to obtain preliminary floodplain boundaries for the proposed assessment scenarios.

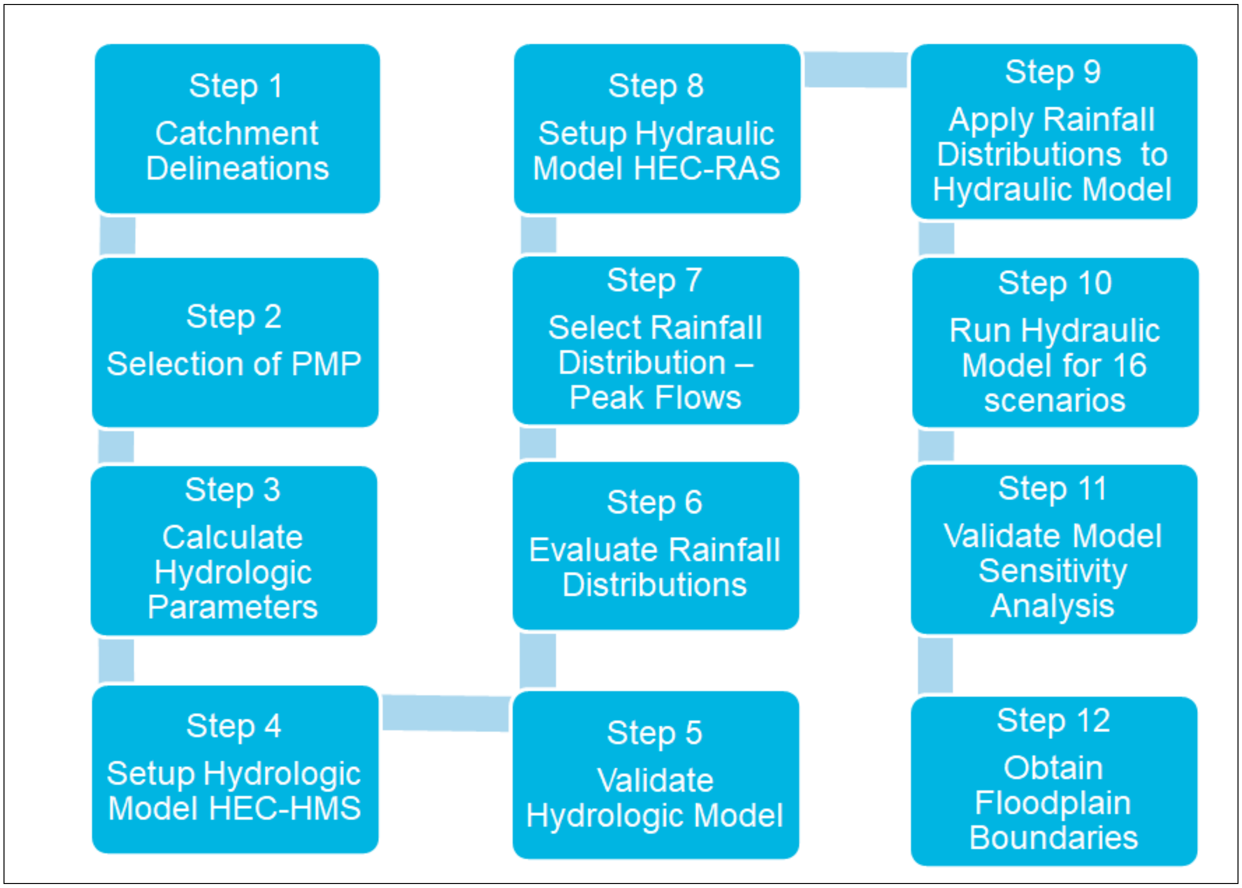

Figure 1: Steps for Flood Hazard Assessment

A brief explanation of each step is provided below, while further details for each step are provided in other sections of this report.

Step 1: Catchment Delineations

Catchment areas are defined by surface topography. Catchment delineations for the South Bruce Site will define the boundaries where rainfall is collected and is conveyed as surface runoff towards each catchment outlet. This is the initial step to calculate peak flows which are needed to define floodplain boundaries.

Step 2: Selection of PMP and 500-Year Storm Event

The selection of the Probable Maximum Precipitation (PMP) and 500-year storm event will be based on the results provided by Golder (2020) for the South Bruce Site. The PMP defines the assumed maximum rainfall input that is possible to occur at the site for a given rainfall duration, that is the largest storm that has been observed or that is expected to occur in the catchment due to a sudden shift of the storm track with a correction to maximize for air moisture. At the present time, there is no defined annual exceedance probability for the PMP and the probability differs between sources.

A rainfall volume can be calculated for each catchment, where the PMP is defined as a total precipitation amount in mm for a given duration and each catchment has a surface area in square metres.

The distribution of rainfall over time is also important. The selection of the PMP is an iterative process where different rainfall distributions are applied to a hydrologic model, and the highest peak flow calculated by the model defines the most critical rainfall distribution.

Step 3: Calculate Hydrologic Parameters

A hydrologic model using the software HEC-HMS was used to calculate peak flow runoff values for each catchment for the selected PMP and 500-year storm values. The hydrologic model requires the input of hydrologic parameters such as time of concentration, surface infiltration coefficients, and impervious areas, to calculate excess precipitation that is transformed into surface runoff.

Step 4: Setup the Hydrologic Model in HEC-HMS

The hydrologic model was developed based on the previous steps. The results of the hydrologic model will be used in subsequent steps to define floodplain boundaries.

Step 5: Validate Hydrologic Model

Validation of the model for downstream sections was completed by comparing the results with the Modified Index Flood Method (MIFM) and the Unified Ontario Flood Method (UOFM). The MIFM relies on a regional frequency analysis of annually recorded maximum peak flow rates and provides values for a series of annual exceedance probabilities (i.e., peak flows for different return periods). The UOFM is based on a regression analysis method based on historical stream flow data from 118 stations from the Water Survey of Canada with data collected until December 31, 2014 and considers catchment area, lake attenuation, and mean annual precipitation within two of Ontario’s three identified ecosystems.

Step 6: Evaluate Rainfall Distributions

Once it was considered that the hydrologic model was representative of site conditions, the PMP values (which define an amount of rainfall for a given duration) were applied to the hydrologic model using different rainfall distributions (which define how rainfall amounts are distributed over time).

Step 7: Select Rainfall Distribution – Peak Flows

The results of Step 6 were analyzed to select the rainfall distribution that creates the highest peak flow for each catchment. This selected rainfall distribution was carried forward for hydraulic analysis at the South Bruce Site.

Step 8: Setup Hydraulic Model in HEC-RAS

Once the selection of the critical rainfall distribution is completed, a hydraulic model of all catchments was developed with the software HEC-RAS. The model requires parameters to represent the characteristics of each catchment to create a geometry file that is used for hydraulic routing, as well as boundary conditions and control specifications that define each scenario.

Step 9: Apply Rainfall Distributions to Hydraulic Model

Once the hydraulic model setup was completed, the selected rainfall distributions from Step 7 were added to the hydraulic model. The excess rainfall amounts were also applied to the HEC-RAS model which in turn calculates the runoff conveyance and flow accumulation for each catchment. The hydraulic model also calculates the floodplain boundaries for both rainfall on-site and rainfall on upstream areas.

Step 10: Run Hydraulic Model for 16 Scenarios

The hydraulic model was used to analyze the 16 scenarios defined for this preliminary flood hazard assessment.

Step 11: Validate Model and Sensitivity Analysis

The hydrologic and hydraulic models were further reviewed to determine the sensitivity of main parameters and the impact of changing them in the results. This task was completed to understand the numerical properties of the models and how reasonable ranges of different uncertain parameters may affect model results.

Step 12: Obtain Floodplain Boundaries

The last step was to export the results that show the floodplain boundaries from the hydraulic model for all 16 scenarios. The model boundaries were mapped and presented in this report.

2. PHYSICAL SETTING

The physical setting of the South Bruce Site includes relevant characteristics that can affect regional and local drainage. In turn, these characteristics can influence the hydrologic cycle and processes which define the amount and distribution of excess runoff over time, and therefore have an impact on the resultant overland flood events. Further details of the physical setting of the site and the watershed where it is located are presented in the following sections.

2.1 Site Location and Features

The land parcels owned or optioned by NWMO are shown in Figure 2. The location of this land within the Province of Ontario is also presented on this figure.

These parcels are within or near the Municipality of South Bruce, approximately 5 km northwest of the Town of Teeswater. The land is located within a catchment that drains north into the Teeswater River that drains into the Saugeen River, which makes its way to Lake Huron at Southampton, Ontario.

This preliminary assessment was focused on these parcels of land referred to subsequently as the “study site”. The floodplain boundaries within the Teeswater River and nearby tributaries were therefore analyzed within the study site for direct rainfall and rainfall from upstream catchments.

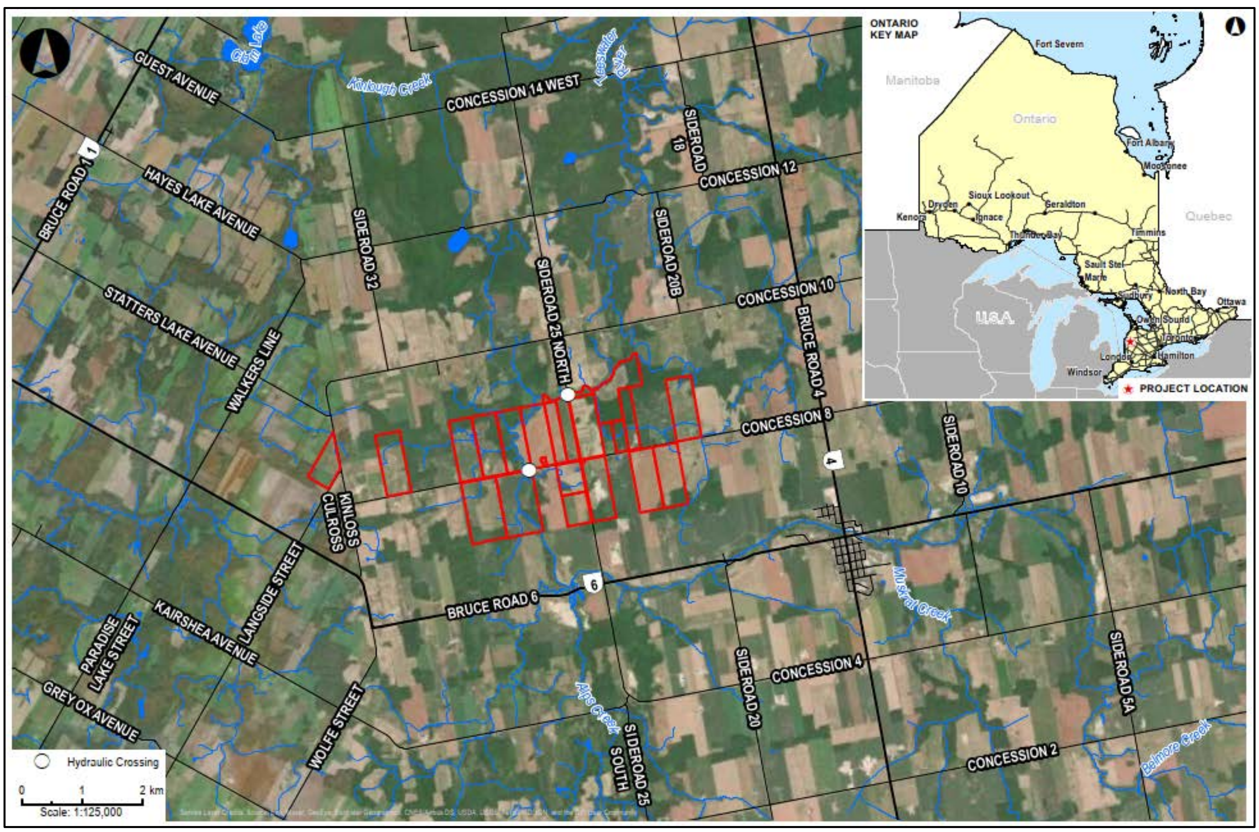

Figure 2: South Bruce area showing all NWMO owned/optioned land parcels in red

Available aerial imagery (ESRI 2022) shows that the predominant land cover within the study site includes agricultural land with patches of forested land. No major development or infrastructure has been identified in this assessment with the exception of roadways and stream crossings. This includes any above ground or buried utilities which were not reviewed or identified in this assessment.

2.2 Catchment Areas

Preliminary catchment delineations were completed using the Ontario Flow Assessment Tool (OFAT). OFAT provides an online automated portal which is based on the Ontario Hydro Network geospatial layer and the Ontario provincial Digital Elevation Model (DEM) to delineate catchments with a horizontal resolution of 30 m by 30 m. OFAT can also calculate catchment parameters including land cover percentages from the Ontario Land Cover Compilation (OLCC ver. 2.0) layer as well as surface area, catchment and channel average slopes, terrain elevations, and mean temperature and precipitation amounts.

The preliminary catchment delineations from OFAT were exported to GIS software and refined with the available DEM from the Southwestern Ontario Orthophotography Project (SWOOP 2015) mission which is provided by the Ministry of Natural Resources and Forestry (MNRF) and is available through Ontario GeoHub.

Orthophotography images show water surfaces, therefore, any waterbodies (lakes, watercourses, etc.) are reflected in the DEM showing the water elevation the day the imagery was flown and is not necessarily the bottom or invert of the waterbody. For the purposes of this assessment, the DEM was used as obtained and no modifications were undertaken to reflect a waterbody invert or bottom.

As mentioned previously, the study site is located within the Teeswater River watershed. For hydrologic analysis, the total watershed downstream of the study site was delineated into three catchments. These catchments are labeled CA1 to CA3 and arranged by upstream to downstream runoff contribution to the river. The study site is located within the most downstream watershed catchment, CA3. The total area of these catchments and other relevant parameters are included in Table 1**,** while the catchment boundaries are shown in Figure 3.

Although the study site footprint is located within catchment CA3, catchments CA1 and CA2 were also included in the hydrologic analysis because they contribute flow to the Teeswater River and have an effect on flooding from upstream areas at the study site. However, for the purposes of this preliminary assessment, the focus was on catchment CA3 during hydraulic simulations and result presentation.

Table 1: Delineated Catchment Areas

Catchment ID	Surface Area (ha)	Drainage Direction	Max/Min Elevation* (m)	Receiving Stream
CA1	12473	East to West	391/288	Teeswater River
CA2	5892	South to North	343/275	Teeswater River
CA3**	3599	East to North	334/272	Teeswater River

* Indicated in metres above sea level
** Study Site is located within this catchment

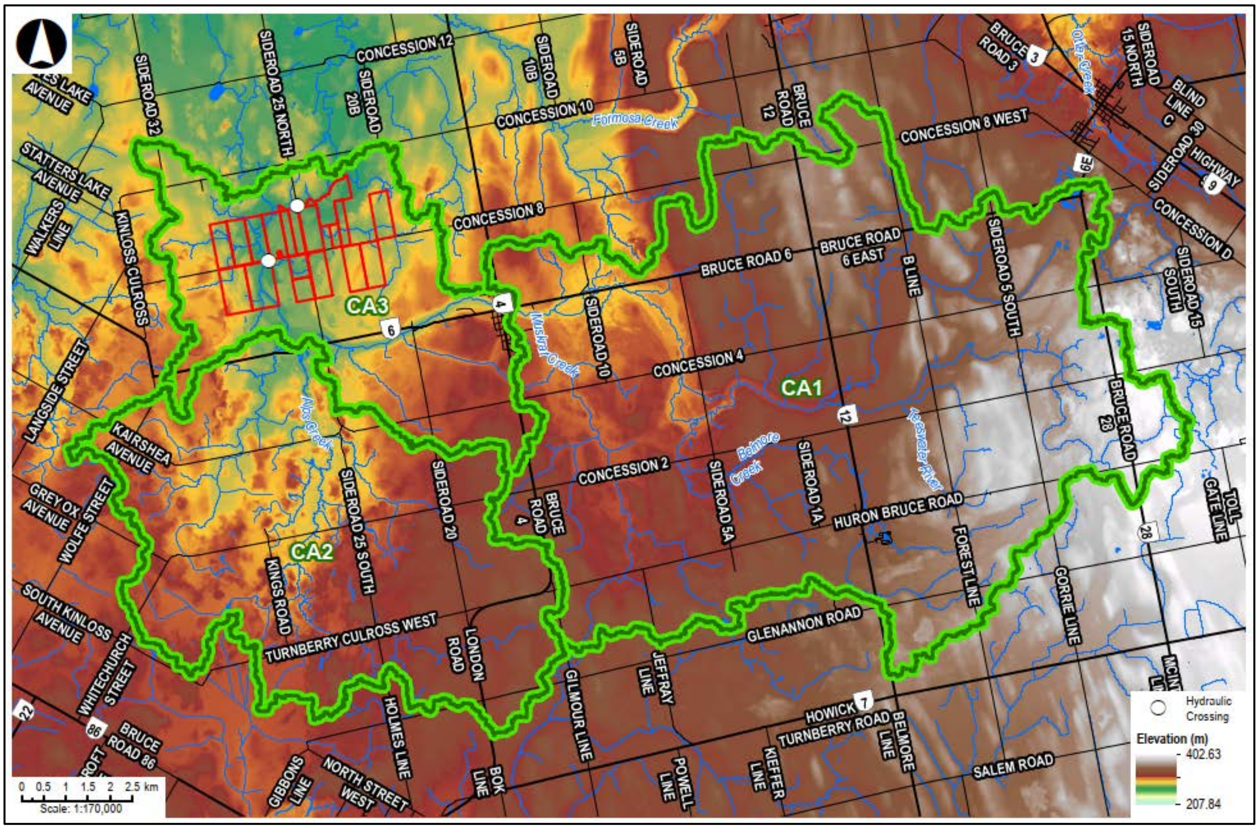

Figure 3: Catchment Areas and DEM around the South Bruce portion of the NWMO owned/optioned land (study site) considered in present assessment (red outline)

2.3 Topography

A digital elevation model (DEM) which covers all catchments was generated with the available SWOOP 2015 data. The DEM has a spatial resolution of 2 m by 2 m and is georeferenced using the plane coordinate grid projection Universal Transverse Mercator NAD1983 – Zone 17 North. The vertical datum is Canadian Geodetic Vertical Datum (CGVD) 1928. The DEM is presented in Figure 3 and was used as the base terrain raster for this assessment.

The topography of the site is a levelled uniform, consistent slope with no topographical features and no well-defined sheet flow direction. These features are typical for this area of the province. Terrain elevations within the study site range between 280 m above sea level to 380 m above sea level, and the lowest point is on the north portion of the site.

The topographic conditions also define the drainage characteristics of the catchments, where sheet flow accumulation becomes concentrated into drainage swales which eventually form watercourses. From the point of view of potential surface flooding, the location of watercourses, lakes, wetlands, and surface depressions provide the baseline condition where flood hazards are most likely to be identified.

2.4 Drainage Patterns

Overall drainage patterns for all catchments were inferred based on the topography and location in relation to the Teeswater River. A drainage mosaic has been developed and is shown in Figure 4, with all three catchments draining into Teeswater River (CA1, CA2, CA3).

Furthermore, each catchment area contains a series of mapped streams and lakes with hydrological stream orders that range from 1 to 5. The hydrological stream order is used as an indicator to describe the density of a stream network by increasing the order at confluence points. The simplest stream network is therefore a single stream with order 1; however, its confluence with another tributary stream of order 1 means an increase to order 2. This process is repeated until the outlet is reached. The most complex stream network is found in CA1 and CA2; the least complex is in CA3, which contains the downstream section of the Teeswater River. Since CA1 and CA2 contribute to the Teeswater River through CA3, the stream order is maintained with a value of 3.

The available data shows that catchments CA1, CA2 and CA3 have natural flow regimes with hydraulic structures (i.e., road crossings), but no other natural obstructions are evident. This condition will not likely change with the construction of an access road to the site within catchment CA3. Through the site, there are two hydraulic structures at Concession 10 and Concession 8 (indicated on Figure 2 and Figure 3). Downstream of Catchment CA3, where the Teeswater River continues until its confluence with the Saugeen River, there are other hydraulic crossings which may affect the Teeswater River flow regime. Stream obstructions can cause backwater effects which can extend inside the study area and are not analyzed as part of this assessment.

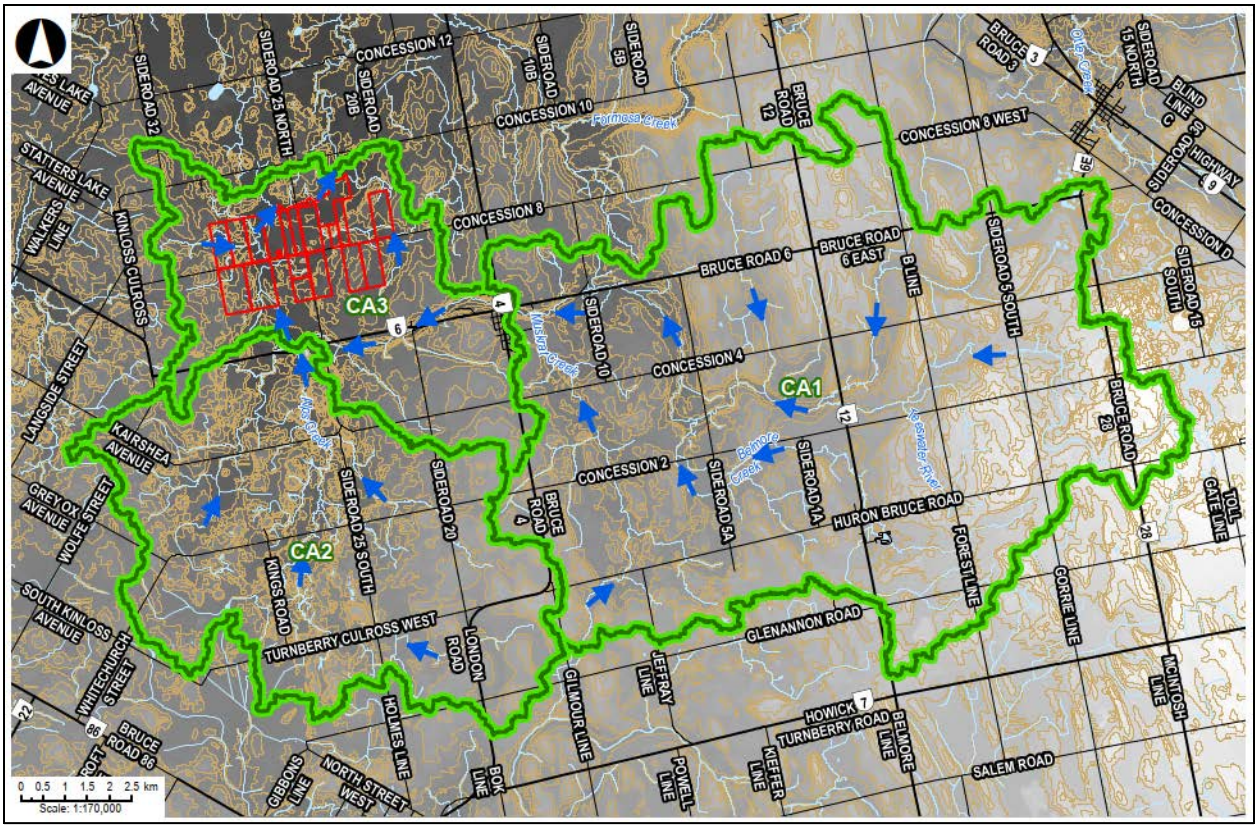

Figure 4: Drainage Mosaic for the Study Site

2.5 Land Cover

Land cover classifications for all catchments were obtained from the Ontario Land Cover Compilation layer (OLCC version 2) from the Ministry of Northern Development, Natural Resources and Forestry and are shown in Table 2 as percentages of total area.

The predominant land cover type in all catchment areas is agriculture and undifferentiated rural land use. All three catchments also present smaller percentages of wetlands (swamp and marsh). Land cover types are shown in Figure 5.

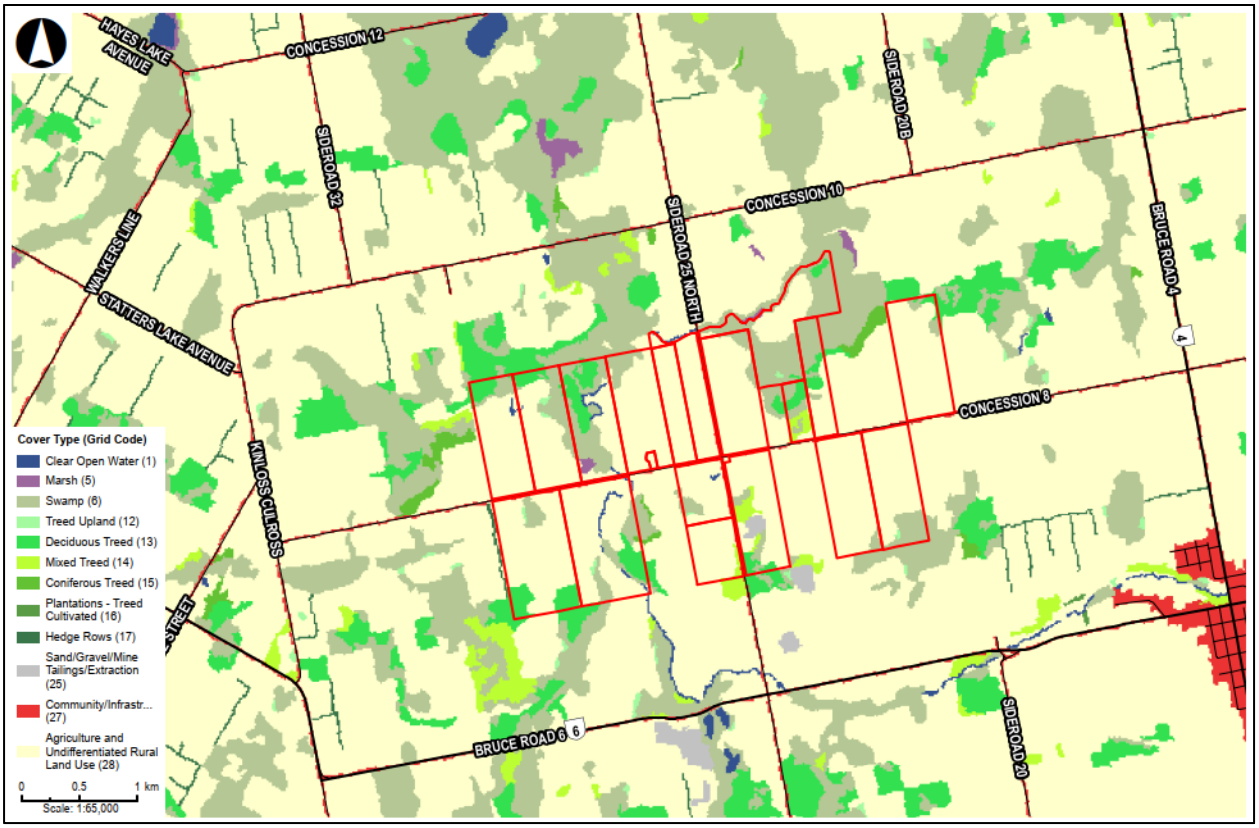

Figure 5: Land Cover Types

The calculated land cover percentages in Table 2 were reviewed based on the most recent aerial imagery that is available to reflect recent changes in land cover (if any).

Table 2: Land Cover Percentages for Each Catchment

Land Cover Type	CA1 (%)	CA2 (%)	CA3 (%)
Open water	0.22	0.24	0.41
Marsh	0.08	0.15	0.12
Swamp	12.99	22.55	13.32
Treed upland	0.22	0.26	0.19
Deciduous treed	3.44	4.21	5.71
Mixed treed	2.18	2.19	1.72
Coniferous treed	0.52	0.62	0.52
Plantations - Treed Cultivated	0.09	1.63	0.03
Hedge Rows	0.22	0.20	0.25
Sand/Gravel/Mine Tailings/Extraction	0.16	0.28	0.26
Community/Infrastructure	2.47	1.81	3.82
Agriculture and Undifferentiated Rural Land Use	77.41	65.85	73.64
Total	100.00	100.00	100.00

2.6 Surficial Soils

The available information regarding surficial soils was obtained from the Soil Survey Complex layer (Ontario GeoHub) published by the Ontario Ministry of Agriculture, Food, and Rural Affairs; Agriculture and Agri-Food Canada and Ontario Ministry of Natural Resources. This layer shows soil attributes such as drainage condition, parent material, soil classification, soil order code, soil group and organic group.

Furthermore, the layer shows that the catchment that contains the study site (Catchment CA3) is contained within the same soil order code as shown in Table 3. A description of each soil attribute was obtained from the *Land Information Ontario Data Description Soil Survey Complex* (Ontario 2019) document that is provided with the geospatial layer and from The Canadian System of Soil Classification (AAFC 1998).

Table 3: Surficial Soil Characteristics

Attribute	Value	Description
Soil Drainage	W – Well Drained	Water is removed from the soil readily but not rapidly. Excess water flows downward readily into underlying pervious material or laterally as subsurface flow. Soils have intermediate available water storage capacity (4-5 cm) within the control section. Water source is precipitation. On slopes subsurface flow may occur for short durations, but additions are equalled by losses. (AAFC 1998)
Kind of Material	L - Loam	Mineral materials contain sand, silt and clay as well as coarse fragments in variable proportions, but percent organic matter is less than 30%. (AAFC 1998)
Local Surface	M - Rolling	A regular sequence of moderate slopes extending from rounded and, in some places, confined concave depressions to broad, rounded convexities producing a wavelike pattern of moderate relief. Slope gradients are generally >5% but may be less. This surface form is usually controlled by the underlying bedrock. (AAFC 1998)
Soil Order Code	Luvisolic	Soils of the Luvisolic order typically have a light-coloured, eluvial layer (Ae horizon) near the surface overlying a layer where silicate clay has accumulated (Bt horizon). Generally, these soils develop in medium textured, base-saturated parent materials, under forest vegetation in subhumid to humid, mild to very cold climates. Luvisolic soils occur everywhere in Canada, from southern Ontario to the zone of permafrost, and from the West to East Coast. (AAFC 1998)
Soil Great Group Code	Gray Brown Luvisol	Soils of this great group have a forest mull surface horizon (Ah horizon in which the leaf litter is usually quickly incorporated into the soil and humified as a result of high biological activity and the abundance of earthworms). Gray Brown Luvisols occur typically under deciduous or mixed forest vegetation in the St. Lawrence Lowland. (AAFC 1998)
Organic Group	Humisol	Organic soils that are formed in organic materials that are in an advanced stage of decomposition and are typically saturated with water. (AAFC 1998)

2.7 Quaternary and Bedrock Geology

At the South Bruce Site, a relatively undeformed succession of marine sedimentary rocks overlies the Grenvillian (Precambrian) basement of southern Ontario. In general, the stratigraphy in South Bruce are predominantly carbonates (limestone, dolostone) with some beds of anhydrite/gypsum and shale layers.

Quaternary geology information for the study site was obtained from Map 2556 – Quaternary Geology of Ontario (Southern Sheet) published by the Ontario Ministry of Northern Development and Mines (Barnett et al. 1991). The available layer presents details regarding quaternary geology including geologic value, unit name and description. For the purposes of this qualitative assessment, all parcels that form the study site at South Bruce are located within two geologic codes as shown in Table 4. The parcels contain geologic codes 11, 22 and 23 (described below), at 20%, 40% and 40%, respectively.

Table 4: Quaternary Geology Classification

Geologic Code	Unit Name	Description
11	Rannoch Till (Huron-Georgian Bay lobe)	Silt to clayey silt matrix becoming finer grained southward and highly calcareous.
22	Glaciofluvial ice-contact deposits	Gravel and sand with minor till, includes esker, kame, end moraine and ice-marginal delta.
23	Glaciofluvial outwash deposits	Gravel and sand, includes proglacial river and deltaic deposits.

3. METEOROLOGICAL CONDITIONS

3.1 Baseline Climate Variables

Climate variables for the South Bruce study area are provided in Golder (2020) to enhance the understanding of extreme rainfall projections by providing more context with respect to baseline conditions.

These variables were calculated for the period of 1979 to 2019 to maintain consistency with the period that was applied to calculate PMP and IDF values. The data includes mean monthly and yearly values for precipitation and temperature, as well as relevant WMO indices such as rain and snow, snow depth, potential evapotranspiration, drought index, wind speed and relative humidity. A summary of relevant information is provided in Table 5.

The data shows that the annual total average rainfall amount at the South Bruce Site is 988.6 mm, and the wettest months of the year are May to October with monthly precipitation amounts ranging between 84.6 mm to 95.3 mm. The maximum hourly wind speed and instantaneous gust wind speed was documented in Golder (2020) (Table 28) from climate normals measured at Wiarton A (Environment Canada Station 6119500). Wind speed is used to assess the wave generation potential in nearby lakes. The maximum hourly wind speed was recorded in March at 84 km/h and the instantaneous gust wind speed was recorded in the month of April at 126 km/h. For these maximum wind speeds there was no wind direction noted by Golder (2020).

Table 5: Monthly Baseline Climate Parameters

Parameter	Jan	Feb	Mar	Apr	May	Jun
Mean Temperature ºC*	-6.1	-5.7	-0.6	6.3	12.9	17.6
Min. Temperature ºC*	-12.5	-13.7	-6.0	1.9	8.1	14.4
Max. Temperature ºC*	-0.8	-0.7	6.7	9.9	16.3	21.5
Mean Precipitation (mm)**	83.1	63.1	61.7	75.7	84.6	86.9
Min. Precipitation (mm)**	39.9	17.2	14.6	16.4	14.4	24.3
Max. Precipitation (mm)**	159.4	140.5	178.3	169.2	205.2	206.4
Parameter	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Mean Temperature ºC*	20.0	19.0	15.1	8.7	2.7	-2.7
Min. Temperature ºC*	16.8	16.6	12.4	5.8	-0.7	-10.2
Max. Temperature ºC*	22.2	21.5	18.0	12.9	6.2	3.2
Mean Precipitation (mm)**	85.0	86.3	95.3	87.7	90.8	88.4
Min. Precipitation (mm)**	2.0	35.2	24.8	25.4	26.6	29.4
Max. Precipitation (mm)**	213.4	192.2	251.7	213.2	170.5	163.3

*Table 22 of Golder (2020)
**Table 21 of Golder (2020)

3.2 Extreme Rainfall Events

This assessment requires the determination of flooding hazard standards that will define the hydrologic input in the form of extreme rainfall events. In Ontario, these flood standards are defined in the *River & Stream Systems: Flooding Hazard Limit Technical Guide* by the Ontario Ministry of Northern Development, Mines, Natural Resources and Forestry, formerly the Ministry of Natural Resources (2002).

The Technical Guide defines three types of flood events that can be used as flood standards; these are synthetic storms derived from Hurricane Hazel (1954) and the Timmins storm (1961), statistically derived flood events with an annual exceedance probability (AEP) of 1/100 (100 year return period event), and observed historical events that exceed this flood event.

The Technical Guide also notes that the magnitude of each storm depends on other factors, and therefore Ontario has been divided in three zones each with their own flood hazard criteria. The study site is located within Zone I, where the flood hazard criteria are defined by the flood produced by the Hurricane Hazel storm or the 0.01 AEP flood event, whichever is greater.

Other extreme events can include larger storms where a lower AEP is assigned such as 0.001 or 0.0001 (the 1,000- and 10,000-year return period events, respectively) and the probable maximum precipitation event. Moreover, this preliminary assessment will rely on the independent study undertaken by Golder (2020) to select the range of extreme rainfall events which may be different than the ones described in the Technical Guide; however, the description of flood standards is presented as a reference for the purposes of this qualitative assessment.

Further information regarding the development of the probable maximum precipitation (PMP) for different conditions is included in the Golder report. The analysis included the development of a consolidated baseline for PMP calculations from data derived from historical weather records. One main station (Wroxeter) was used for the analysis, while nine more weather stations were screened for larger storms and one weather station provided sub-daily intensity-duration-frequency (IDF). Further details of this analysis are included in Chapter 3 of the Golder report.

3.2.1 Probable Maximum Precipitation

The definition of the PMP event can be different between jurisdictions; however, for the purposes of this qualitative assessment the definition has been obtained from the Dam Safety Guidelines published by the Canadian Dam Association (CDA 2007).

The Dam Safety Guidelines define the probable maximum flood generated by the PMP as the “most severe flood that may be expected to occur at a particular location”. Therefore, the PMP is defined as the largest storm that has been observed or that is expected to occur in the catchment due to a sudden shift of the storm track with a correction to maximize for air moisture. The ratio for air moisture is calculated with the maximum expected air moisture and the actual air moisture that occurred during the passage of the storm.

Furthermore, the World Meteorological Organization (WMO) defines the PMP as the “greatest depth of precipitation for a given duration meteorologically possible for a design watershed or a given storm area at a particular location at a particular time of year, with no allowance made for long-term climatic trends” (WMO 2009).

Even when the definition of the PMP is straightforward, most times its calculation is not because of lack of reliable data or potential differences that may arise from its interpretation.

The NWMO commissioned an independent study to determine the probable maximum precipitation (PMP), IDF curves, and snowpack accumulation data for both Revell and South Bruce Sites considering current and future climate conditions (Golder 2020). Those results are used as-is as input parameters for this study. Further details related to the review of and recommended PMP value for use in this assessment is provided in Section 5.3 and Table 13 and Section 5.6 and Table 18. AECOM review of these parameters was out of the scope of work of this preliminary flood hazard assessment.

3.2.2 Historical Storm

The Hurricane Hazel storm was a summer storm that occurred over Southern Ontario on October 15, 1954 and generated severe damage and loss of life. The path of Hurricane Hazel was west of Toronto; however, it has been adopted by the MNRF as the flood hazard storm for Zone I. Following the analysis of this storm, MNRF adopted its formal definition as a 48-hour event with a total rainfall depth of 285 mm. This storm is applicable to catchments smaller than 25 km^2 within Zone I. For larger basins, the MNRF provided rainfall amounts to be modified by a reduction factor percentage for different drainage areas (MNR 2002).

The Golder Report (2020) also mentions one major precipitation event that occurred in 1986 with the highest average precipitation across the stations reviewed. The total 1-day precipitation registered at Wroxeter for the 1986 storm was 120.6 mm over two days (September 10^{th} and 11^{th}).

3.2.3 Annual Exceedance Probability Storms

These storms are produced with maximum precipitation that is defined by statistical methods, where historical precipitation records are fitted into a given statistical distribution. The results are provided as intensity-duration-frequency (IDF) curves where maximum precipitation for different AEP and storm durations are provided.

As an example, the Ontario Ministry of Transportation provides an online tool to calculate IDF values within the province (MTO 2016). A search with this tool indicated that the maximum rainfall depth at the site that corresponds to a 24-hour storm with an AEP of 1% is 130.7 mm (100-year return period).

A detailed analysis of IDF statistics was completed by Golder (2020) in Section 3.2.3 of the report. The analysis included sub-daily, daily, and multi-day IDF curves for the South Bruce Site based on nearby stations. As an example, the spatially interpolated IDF curves for the study area indicate that the 24-hour event with a 100-year return period is 142.2 mm and is higher, but in general in agreement with the MTO IDF online IDF Curve Lookup tool.

4. QUALITATIVE ASSESSMENT OF HYDROLOGICAL HAZARDS

The qualitative assessment of flood hazards includes a preliminary evaluation based on the supporting information that was gathered for this report. The factors considered are based on the Specific Safety Guide SSG-18 by the International Atomic Energy Agency (IAEA 2011), specifically the items included in Section 5 of that document which provides recommendations regarding the analysis of hydrological hazards.

4.1 Storm Surges

Storm surges are created by a combination of factors such as strong winds, wind direction, fetch, atmospheric pressure, and terrain bathymetry (USACE 1984). The study site and catchments do not contain any major waterbodies where these effects can be of significance.

Furthermore, the Atlas of Canada 6th Edition (NRCan 2009) includes a map reproduced as Figure 6 with locations with different levels of frequency and severity of storm surges in coastal regions. As shown in the map, there is one identified location along the Lake Huron coast at Goderich, Ontario with a low severity medium frequency for storm surges. Goderich is located on Lake Huron in the general region of the study site.

The study site is approximately 30 km due east from Lake Huron. Lake Huron is considered an enclosed body of water. At Lake Huron, the elevation of the coast is +/- 210 m above sea level. The study site average elevation is 280 m above sea level. The vertical distance between the two areas is +/- 70 m. The existing topography difference, distances, and historical wind speeds in the area make the site out of reach of any possible surges or seiches from Lake Huron.

The Teeswater River is a waterbody located near the study site at less than 1 km away, however, the channel width is 30 m and protected by forested areas and therefore there is no significant open water distances (i.e., fetch) for storm surges to develop.

Therefore, for the reasons noted above any flooding hazards due to storm surge are not considered to be significant for the study site. Additionally, the location, topography and distance to Lake Huron (30 km) also support this conclusion.

4.2 Wind Generated Waves

Like storm surges, wind generated waves are dependent on physical parameters such as wind velocity, fetch, wind direction, and water depth. It was indicated in Section 3.1 that the maximum wind speed recorded within the record of climate normals was 84 km/h. The site is near a watercourse with a channel width of approximately 30 m and protected by forested areas. Therefore, there is no significant open water distances (i.e., fetch) for wind generated waves to develop.

For other waterbodies the distance increases even further adding topographic features and obstacles that will prevent any effects at the study site. As an example, the distance between Lake Huron and the study site is 30 km with a vertical difference in terrain of +/- 70 m. Therefore, flooding hazards due to wind generated waves are not considered to be significant.

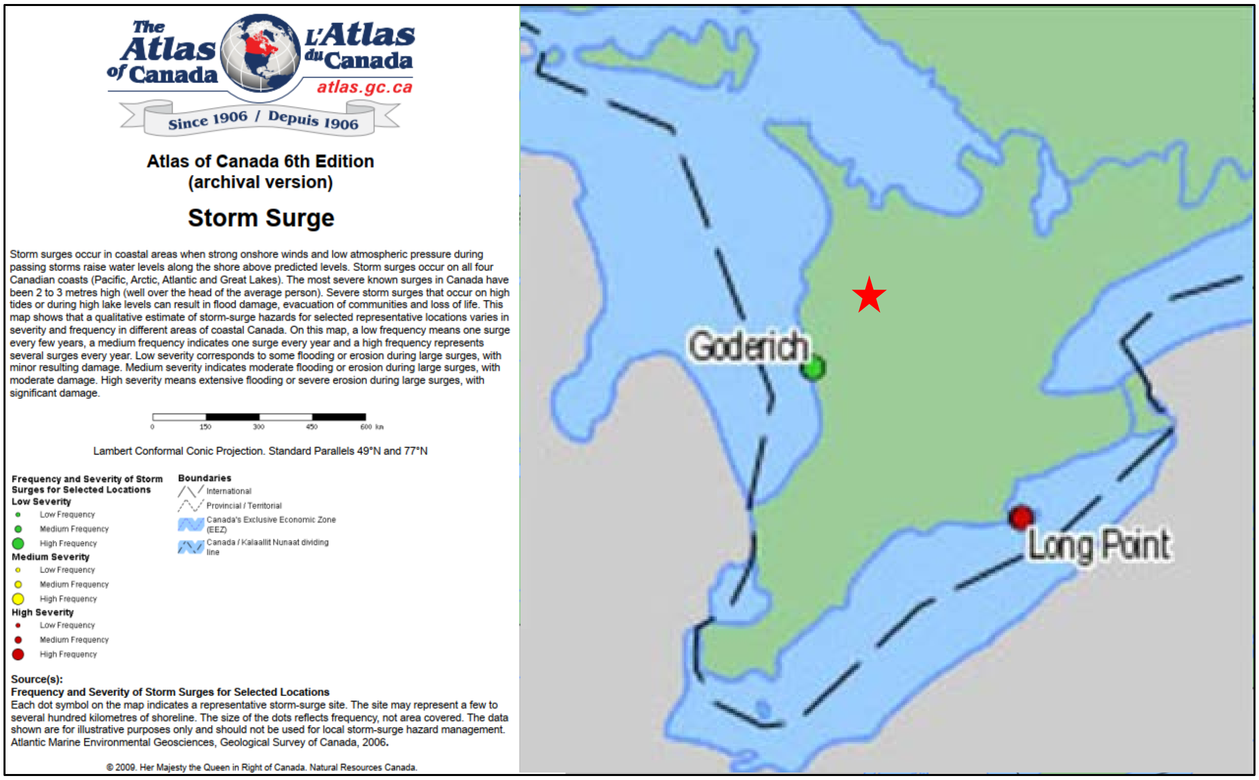

Figure 6: Potential Location of Storm Surges in Southern Ontario (modified map)

4.3 Tsunamis

Given the location and characteristics of the study site (30 km from Lake Huron and +/- 70 m higher in elevation), flooding hazards caused by tsunamis are not considered to be significant. A landslide created near a lake shore may create a large displacement of a volume of water creating a tsunami like event; however, the study site is not located near a large body of water needed to cause such event.

As indicated previously, Lake Huron is too far away to generate any realistic hazards due to tsunamis on the study site.

4.4 Seiches

Seiches are long period standing waves that remain after the forces that created them have ceased to act (USACE 1984). Like the previous factors, seiches are not considered to be significant for this study site with regards to flood hazards. The existing topography, site orientation, distances, and historical wind speeds in the area make the site out of reach of any possible seiches from Lake Huron.

4.5 Extreme Precipitation Events

If large enough, rainfall events have the potential to generate localized flooding on the study site as well as flooding from upstream areas. Extreme storms such as Hurricane Hazel or the PMP have been identified as large rainfall events that can occur within the site and within the upstream watershed.

Flooding hazards on-site or in the upstream watershed can also be intensified by other factors including but not limited to antecedent soil moisture conditions, snowmelt rates, drastic changes in land cover caused by external factors (i.e., urban development), the distribution of rainfall over time, climatic conditions and temporary blockages caused by rainfall events (i.e., debris flows). For these reasons flood hazards from extreme rainfall events are considered a significant factor, and the risk should be evaluated.

As part of this qualitative assessment, Figure 7 shows locations of watercourses and waterbodies that have the potential to create flooding which can expand laterally and reach proposed infrastructure (i.e. site access roads, rock waste management area, proposed site). Additionally, terrain features such as surface depressions or wide gentle slopes can generate localized flooding or sheet flow within the study site.

Both types of flooding from rivers and local features were included in this assessment as flooding from upstream areas and rainfall on-site.

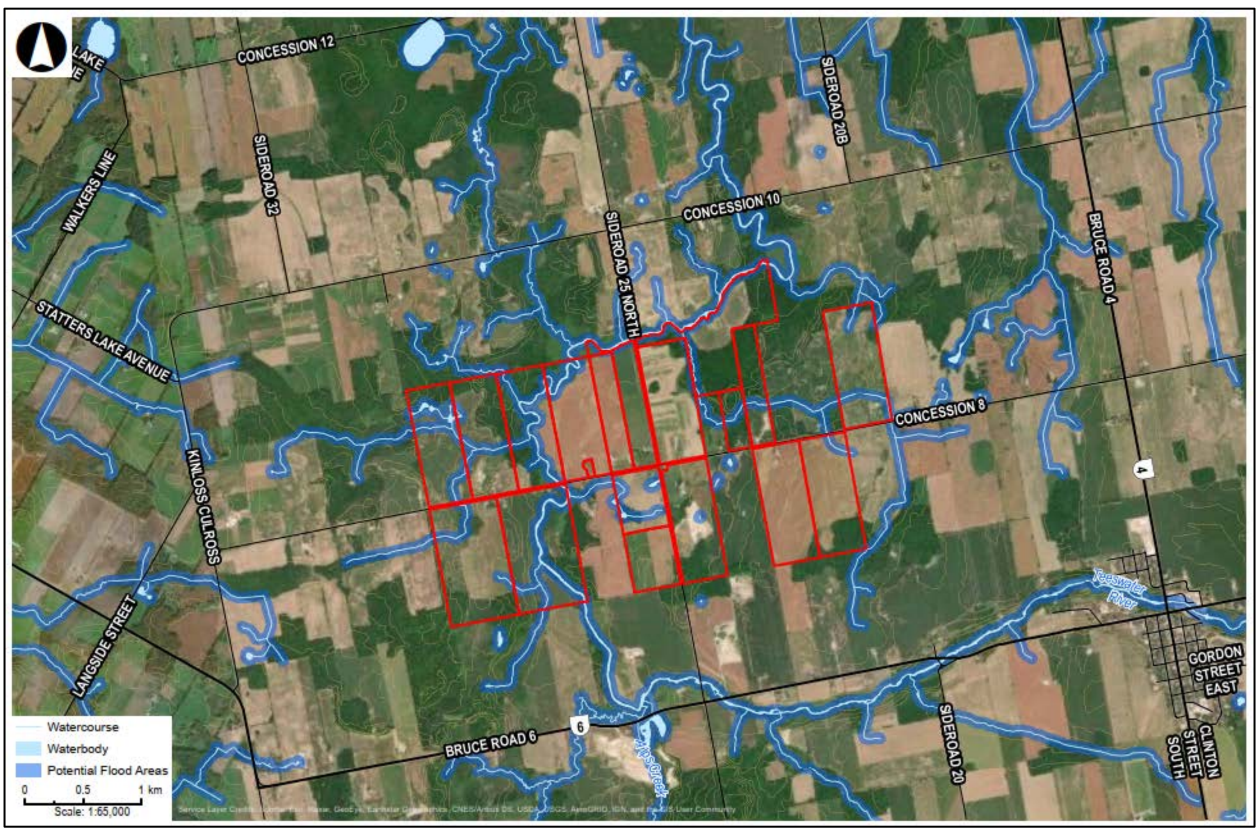

Figure 7: Potential Location of Flood Hazards

4.6 Floods Due to the Sudden Release of Impounded Water

A review of available spatial layers from the MNRF indicated that there are two mapped dams or man-made structures on the Teeswater River upstream of the study site within catchments CA1 and CA3. This evaluation is based on a desktop review of mapped structures in Ontario presented in a digital spatial layer from Ontario GeoHub: Ontario Dam Inventory. Field verification work related to these structures was not part of this analysis. The location of the two mapped structures on the Teeswater River are illustrated in Figure 8.

Furthermore, the identified hydraulic structures at every local and provincial road crossing as the Teeswater River approaches the site plus those road crossing structures that are located downstream of the study site do not include any water impoundment works.

It is possible, however, that natural obstructions such as beaver dams, ice jams, or debris may cause a sudden release of impounded water. If this occurs, the waterbodies and wetlands will act as buffer zones that can attenuate the effects of the generated transient waves. The location of the study site in the downstream areas of the catchments also minimize the flooding potential due to a release of impounded water.

Therefore, flooding hazards due to a sudden release of impounded water are considered a potential risk to the study site; evaluation of this hazard has been undertaken as a sensitivity analysis and is reported in Section 6.

Figure 8: Mapped Dams or Man-Made Structures on the Teeswater River

4.7 Bore and Mechanically Induced Waves

Following the same rationale that was applied to storm surges and wind induced waves, bores induced by tides or any other factor and mechanically induced waves are not considered a significant factor for the site with regards to flood hazards.

4.8 High Groundwater Levels

Shallow or near surface groundwater levels have the potential to reduce soil infiltration and storage capacities, therefore, increasing the amount of overland runoff. Wetlands, fens and bogs are general indicators of local high groundwater levels, and they can also be created by the interception of groundwater.

While there is no specific indication of local high ground water levels, an assessment of the potential for groundwater to penetrate below ground components of the facility is beyond the scope of this surface water study. However, consideration for areas that have potential high groundwater within the catchment and contributing areas upstream will be accounted for in the surface flow hydrological assessment through the selection of soil infiltration parameters for those areas.

4.9 Summary and Conclusions

A qualitative assessment has been completed as part of the preliminary assessment of potential flooding hazards for the South Bruce Site. This qualitative assessment was based on the guidelines provided in the IAEA Safety Standards entitled Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations (IAEA 2011).

The IAEA Safety Standards document includes seven hydrological hazards which are storm surges, wind generated waves, tsunamis, seiches, extreme precipitation events, floods due to the sudden release of impounded water, bores and mechanically induced waves, and high groundwater levels.

The results of the qualitative analysis show that based on the available information and site conditions, flooding hazards due to extreme precipitation events and flooding due to the sudden release of impounded water require further consideration. A full quantitative analysis of extreme precipitation events has been conducted as part of this study along with a sensitivity analysis of flooding resulting from the release of impounded water from the two identified dams. This sensitivity analysis is presented in Section 6.2. Other hydrological hazards are determined to be of no significance.

For flood hazards due to extreme precipitation, a preliminary determination of areas where flood hazards may be of concern are shown in Figure 7. It is also recognized that effects of extreme precipitation events can be compounded by other factors such as urban development, natural obstructions, ice jams, and antecedent soil conditions.

Given the large catchment size upstream of the Teeswater River in relation to the study site location, the general low slope of the local terrain, and general soil conditions, any reductions in surface flows due to infiltration or evapotranspiration were considered to be negligible for short storm durations. Flooding from upstream areas entering the site are likely to have the larger impact when compared to rainfall on any existing or proposed surface infrastructure. However, the proposed site infrastructure may have a localized impact on site surface water hazards.

Finally, a set of extreme PMP rainfall events were selected from Golder (2020) based on different parameters and time projections. The input of these PMP storms to a hydrologic model that calculates excess runoff and then a hydraulic model that translates excess runoff into water depths is the next step of this preliminary flood hazard assessment.

4.10 Other Considerations

Other factors to consider for future potential impacts due to flooding include the following, however, these were not part of the scope of work for this preliminary flooding assessment:

- The effects of land cover changes due to agricultural practices, land development, changes to vegetation due to drought and/or climate change patterns and ice jams at hydraulic crossings.

5. SURFACE FLOOD HAZARD ASSESSMENT

From the overall analysis approach to this flood hazard assessment as outlined in Section 1.1, the following section outlines Steps 2 to 7 based on the findings presented in previous sections as well as the scope and objectives of this project. A total of 16 scenarios were evaluated to define the extent of surface flooding at the South Bruce study area, focusing on catchment CA3.

A summary of the steps that were completed for this assessment and details regarding the development of hydrologic and hydraulic models for the catchments is included below.

5.1 Proposed Assessment Scenarios

As defined in the scope of work, 16 scenarios were included in this preliminary flood hazard assessment. These scenarios are divided by period (current, mid-century, and end-of-century), climate change scenario (three PMP risk projections) and 500-year event (current climate change scenario) and by type of flood (direct rainfall on-site and flooding from upstream catchments).

The distinction between types of floods recognizes that the site receives direct rainfall amounts that can create local water accumulation and ponding, while flooding from upstream catchments is defined as rainfall that generates streams to exceed their normal conveyance capacity, which in turn increases floodplain extents and therefore has the potential to impact proposed project components such as roads, hydraulic structures, buildings and related infrastructure.

The assessment of both flood types required the development of a hydrologic model for all catchments (CA1 to CA3) by using the hydrologic software HEC-HMS (version 4.8), as per the approved software plan. HEC-HMS was used to simulate rainfall processes and calculate excess runoff that is conveyed towards each catchment outlet.

The excess rainfall was then applied to a two dimensional (2D) hydraulic model of catchment CA3 developed in the software HEC-RAS (version 5.0.7), as per the approved software plan. HEC-RAS calculates the water elevation and velocities based on the inputs provided by HEC-HMS as well as the selected parameters which are specific to each catchment (i.e., Manning's roughness coefficients, boundary conditions, terrain characteristics). Further details regarding the flood hazard assessment are provided below.

5.2 Hydrologic Model Development (HEC-HMS)

The hydrologic software HEC-HMS was developed and is maintained by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers and is specifically designed to simulate hydrologic processes in rural dendritic watersheds. The software includes sub-routines for hydrologic simulations such as infiltration, application of unit hydrographs, and hydrologic routing. HEC-HMS also includes procedures necessary for continuous simulation including evapotranspiration, snowmelt, and soil moisture accounting, however, these processes were not applied since all flood events that were applied during this assessment have a short duration (i.e., 24 hours or less). For reasons explained further in this report, rain on snow projection events are not considered critical when compared to PMP events with shorter durations and thus were not analyzed.

HEC-HMS was used to calculate the resultant hydrographs and peak flows for all catchments (CA1 to CA3) to define the critical rainfall distribution to be used for hydraulic modelling. Additionally, the model was expanded to include all 16 scenarios that were part of the analysis.

5.2.1 Model Setup

The HEC-HMS hydrologic model was setup to simulate catchments CA1, CA2 and CA3 as individual elements. These elements are connected with junctions that maintain the flow order from CA1 and CA2 as they discharge into CA3 with the total resulting flow directed to the outlet of catchment CA3. Each catchment element must have a surface area where precipitation occurs, the selection of which hydrologic processes are simulated by the model was made based on the characteristics of the rainfall distributions of interest and the scope of this project.

Given that the extreme PMP distributions used in this preliminary assessment are mainly single events with short durations of 3, 6, 12 and 24 hours (with the exception of the rainfall on snow event), the hydrologic model was adjusted to include routing and infiltration parameters with the SCS curve number and SCS unit hydrograph methods, while other parameters such as baseflow, evapotranspiration and canopy storage were not applied because the rainfall distributions are too short for these processes to have any influence in the resultant hydrographs.

The total surface area of each catchment was applied to the hydrologic model, which in turn calculates total rainfall volumes by multiplying the surface area by the rainfall depth at each timestep. The hydrologic model applies the rainfall amounts following the defined rainfall distributions and calculates reductions to account for infiltration loses.

5.2.2 Delineation of Catchment Areas

Catchment areas were delineated with the SWOOP 2015 Digital Elevation Model (DEM) during the qualitative assessment as shown in Figure 3. Further details about each catchment are also included in Table 6. The largest catchment area is CA1.

Catchments CA1 and CA2 were included in the analysis due to their contributions of upstream watershed flows to CA3, however, they are not considered to be relevant with respect to the general site area.

5.2.3 Other Modelling Parameters

Based on the selection of the SCS curve number and SCS unit hydrograph methods the hydrologic model required four parameters: three are related to the calculation of infiltration loses for each catchment, and one is related to the hydrologic routing.

The SCS curve number method requires the calculation of initial abstraction, percentage of directly connected impervious area within the catchment, and the composite CN for each catchment. The parameters related to the SCS curve number for all catchments are shown in Table 6.

Table 6: SCS Curve Number Parameter Calculation

Catchment	Area (ha)	Basin Type	Soil Type (%) CN= 46	CN= 53	CN= 60	CN= 61	CN= 69	CN= 73	CN= 77	Composite CN (rounded)	Initial Abstraction (mm)
CA1	12473	Southern	1.0	3.0	4.0	9.0	29.0	54.0	0.0	70	10.9
CA2	5892	Southern	5.0	2.0	3.0	25.0	24.0	40.0	1.0	67	12.5
CA3	3599	Southern	6.0	2.0	4.0	30.0	21.0	37.0	0.0	67	12.5

The selected SCS curve number values are based on the predominant soil types within the study area, these are shown in Table 2 and were assigned SCS CN values between 46 and 77 for a mixture of well drainage and poorly drained loams with a predominate crop land use with some forested land cover.

A composite CN was then obtained by multiplying the product of each percentage area by its corresponding CN value. As an example, the composite CN for catchment CA1 is calculated by adding the product of each individual CN value by the percentage of soil type area (i.e., 46*0.01 + 53*0.03 + 60*0.04 + 61*0.09 + 69*0.29 + 73*0.54 + 77*0.0 = 70).

The initial abstraction accounts for precipitation that is kept by the catchments near the beginning of a rainfall event and is therefore not made available as excess runoff during such event. The initial abstraction therefore simulates the capacity of a catchment to store rainfall mainly by interception and depression storage.

The initial abstraction must be taken from the total precipitation before any runoff can occur in the hydrologic model. The initial abstraction for each catchment was calculated as a function of the CN value as per the MTO Design Manual (1997).

The time of concentration (Tc) which is related to the hydrologic routing was calculated with the Uplands overland flow method. The length and slope for both the overland flow and channel paths were calculated with the available 2015 SWOOP data.

The overland velocities were estimated with the Uplands Method, based on the terrain slopes and land cover types. The time of concentration for each catchment was then calculated by dividing the channel length with the velocity for the overland flow and channel flow components separately, and then adding both components into a single time of concentration.

The hydrologic model requires the input of the lag time, which is approximated as 0.6 times Tc, this is recommended in the HEC-HMS User’s Manual. The parameters that were used for the calculation of Tc are included in Table 7.

Table 7: Parameters for the Calculation of Tc (Uplands Method)

Catchment	Area (ha)	Overland Flow Length (m)	Overland Flow Slope (%)	Overland Flow Velocity (m/s)	Channel Flow Length (m)	Channel Flow Slope (%)	Channel Flow Velocity (m/s)	Tc (min)	Lag Time (min)
CA1	12473	800	1.3	0.10	28175	0.32	0.68	822	493
CA2	5892	950	0.8	0.09	14375	0.03	0.23	1227	736
CA3	3599	1100	1.2	0.10	13225	0.30	0.66	521	313

5.2.4 Validation of the Hydrologic Model

The hydrologic model provides calculations of peak flows and volumes for each considered scenario by using input parameters such as catchment area, precipitation amounts, and the equations that define other hydrologic processes (i.e., SCS curve number and SCS unit hydrograph).

An important step for hydrologic modelling is to check that the results are consistent with observed data when feasible, which means to calibrate the model, or at least to review whether other methods provide similar results.

For a hydrologic model, a calibration procedure requires long term flow records at the site or at nearby catchments that can be transposed to the site. In this regard, a detailed model calibration procedure is feasible for catchment CA1, upstream of the South Bruce Site. A Water Survey of Canada Station (02FC020) is located on the Teeswater River at Teeswater which has long term flow and water level data. To use this station for calibration, precipitation data are needed at 15-minute or 1-hour intervals from a local Environment Canada weather station. However, a review of available data indicated that there are no Environment Canada stations within the area that have precipitation records with the required time interval. Without the precipitation data recorded at these intervals, a calibration exercise using the Water Survey of Canada Station was not feasible.

Since model calibration is not feasible, a validation of the model was instead completed by checking the results of the 100-year event from the hydrologic model with the Modified Index Flood Method (MIFM) and the Unified Ontario Flood Method (UOFM).

The MIFM method relies on a regional frequency analysis of annually recorded maximum peak flow rates to produce a statistical regression for the 25-year runoff event for an equivalent catchment area of 25 km^2, with factors applied for other flood events. Details of the MIFM and its application are included in Chapter 8 of the MTO *Drainage Management Manual* (1997). The parameters that were applied to the method for the South Bruce Site and results of the MIFM are presented in Table 8.

Table 8: Calculation of the Modified Index Flood Method

Catchment	Area (km^2)	Basin Type	Lag Time (min)	Q_{25} Base (m^3/s)	Peak Factor	Q_{100} MIFM (m^3/s)	Q_{100} HEC-HMS (m^3/s)
CA1	124.73	Southern	493	49.3	1.0	61.7	137.5
CA2	58.92	Southern	736	14.7	1.1	20.2	47.5

The UOFM is a regression analysis method based on historical stream flow data from 118 stations from the Water Survey of Canada, with data collected until December 31, 2014. This method considers catchment area, lake attenuation, and mean annual precipitation within two of Ontario's three identified ecosystems. The UOFM uses empirically derived constants to infer regional flow intensities for a particular catchment area. The full details of the method and the associated analysis and background information are provided in the research report titled *Unified Ontario Flood Method (UOFM), Regional Flood Frequency Analysis of Ontario Stream Using Multiple Regression* (Sehgal 2015). The parameters that were applied to the method for the South Bruce Site and results of the UOFM are presented in Table 9.

Table 9: Calculation of the Unified Ontario Flood Method

Catchment	Area (km^2)	Lake Area (km^2)	Lake Attenuation Index	Ecosystem	Q_{100} UOFM* (m^3/s)	Q_{100} HEC-HMS (m^3/s)
CA1	124.73	16.8	1.14	Mixed Wood Plains	120.1	137.5
CA2	58.92	13.5	1.23	Mixed Wood Plains	49.7	47.5

* Upper Flow Limit

The HEC-HMS model results were more consistent with the results from UOFM versus the MIFM. Upon review of the MIFM methodology, the lag time for CA1 and CA2 are too long for the calculation to be applicable, and the results from the MIFM were dismissed for comparison to the hydrologic model results. Therefore, of the two regional methods, the UOFM is better aligned to the modeling of the site.

The results of the UOFM show the calculated peak flows for the 100-year flood event for catchments CA1 to CA2 in Table 9. Additionally, the HEC-HMS model was used to calculate the same peak flows corresponding to the 100-year event with IDF values from Golder (2020).

The results show differences of 13% less peak flow from the UOFM compared to HEC-HMS for catchment CA1. For catchment CA2, the peak flow from the UOFM was 4% greater than HEC-HMS. The HEC-HMS results are both higher and lower than UOFM for both catchments suggesting the results of this analysis will not result in an underprediction of flood hazards.

Given that the results of the hydrologic model and UOFM are close for CA1, the largest catchment, and produced higher peak flows for CA2, it was concluded that the hydrologic model is able to simulate flood events within the South Bruce study area for the purposes of this preliminary flood hazard assessment.

5.3 Selection of PMP and Snowpack Accumulation Values

The preliminary flood hazard assessment requires the determination of extreme runoff amounts for current and future conditions at the South Bruce study area. Runoff is generated by rainfall and/or snowmelt, which forms the hydrological input to the catchments of interest. Extreme hydrologic inputs, such as the probable maximum precipitation (PMP) and rainfall on snow projections, were selected from the parameters included in the Golder (2020) report.

The Golder (2020) report provides a detailed assessment of baseline climate conditions and climate projections that extend to the year 2100 at the South Bruce study area. Further projections beyond the year 2100 are provided by Golder (2020) in a qualitative basis only since current climate change models do not extend further. Furthermore, for the purposes of this preliminary flood hazard assessment, projections beyond the year 2100 were not part of the scope of work and therefore are not included in the analysis.

The selection of extreme hydrologic inputs is required to calculate excess runoff at the South Bruce study area. The HEC-HMS hydrologic model includes two defined catchments upstream (CA1 and CA2) and one containing the site (CA3); hydrologic parameters are provided for each catchment, and the model determines the resultant flow hydrographs and peak flows for each catchment.

Additionally, an assessment was completed to estimate which rainfall distributions should be considered when determining potential highest peak flows for each catchment. The durations selected were based on the analysis carried out by AMEC and presented in the report *OPG's Deep Geologic Repository for Low & Intermediate Level Waste Maximum Flood Hazard Assessment* (2011).

The rainfall distributions that were considered include the 6-hr and 12-hr LRIA (OMNR 2004), the SCS Type II 24-hr distribution and the Chicago 3-hr distribution. These are normalized and given in hourly percentages of total precipitation as shown in Table 5.10 of AMEC (2011) to create the rainfall distributions.

Additionally, based on the characteristics of the South Bruce study area, the Chicago rainfall distribution was added to represent a short event with a high and concentrated rainfall intensity, even when it is recognized that this distribution is more suited to catchments where urban land cover is predominant. The considered rainfall distributions are included in Table 10.

The hydrologic modelling of the South Bruce study area was completed to determine which distribution generated the highest peak flows, which was carried forward for hydraulic simulations.

Table 10: PMP Rainfall Distributions* (AMEC 2011)

Duration (hr)	SCS Type II – 24 hr**	LRIA – 12 hr**	LRIA – 6 hr**	Chicago – 3hr
0	0.0	0.0	0.0	10.0
1	1.1	2.0	8.0	75.0
2	1.2	3.0	9.0	15.0
3	1.2	3.0	11.0	
4	1.4	4.0	49.0	
5	1.5	6.0	15.0	
6	1.7	51.0	8.0	
7	1.9	15.0		
8	2.2	4.0		
9	2.6	4.0		
10	3.4	3.0		
11	5.4	3.0		
12	42.8	2.0		
13	10.9			
14	4.6			
15	3.6			
16	2.6			
17	2.2			
18	1.9			
19	1.6			
20	1.5			
21	1.3			
22	1.2			
23	1.2			
24	1.1			

*Values are indicated as percentages of total rainfall
**From Table 5.10 in AMEC (2011)

5.3.1 Determination of Extreme Hydrologic Inputs

The Golder (2020) report presents the procedures applied to develop baseline climatic datasets based on an analysis of historical weather records near the South Bruce study area. Eleven weather stations were evaluated and screened for large storms. For the development of a consolidated climate baseline (periods between years 1966 to 2020), PMP estimates and daily/multi-day IDF curves, the Wroxeter 6129660 station was used. For sub-daily IDF, the Mount Forest 6145504 station was used.

The analysis of future climate scenarios was completed by Golder (2020) with two distinct data ensemble sources that provide 136 bias-corrected climate projections, namely the BCCAQ (version 2) and LOCA. The BCCAQ version 2 is the Pacific Impact Consortium data ensemble which uses bias correction/constructed analogues with quantile mapping reordering. This dataset consists of an ensemble of 24 models with 72 projections that consider three representative concentration pathways (RCP 2.6, RCP 4.5 and RCP 8.5), where RCP 2.6 has the most favourable outcome and RCP 8.5 is the most extreme.

The LOCA data ensemble consists of 32 models with 64 projections including RCP 4.5 and RCP 8.5. Additional details of each model are included in Section A.3 of Golder (2020). It is also mentioned that the BCCAQv2 dataset contains drawbacks with regards to data interpretation and for this reason the LOCA approach was selected for further analysis.

The projections were developed for three distinct periods and are defined as current period (present to 2040), mid-century period (2041-2070) and end-of-century period (2071-2100).

It is also noted that different phases of the proposed deep geological repository overlap the future climate projection periods. As such, for the purposes of this preliminary assessment, the site characterization, preparation, and construction are assumed to occur between 2023 to 2043, the operational phase from 2043 to 2083, and the extended monitoring phase from 2083 and beyond 2100. Furthermore, as stated by Golder (2020), the overlap between climate projections and proposed project phases means that different levels of risk may be adapted over time as the project phases are progressing.

The projected changes in the probable maximum precipitation (PMP) estimates were divided in percentiles and provided for timespans that extend to the 2050s (mid-century) and 2080s (end-of-century). These percentiles define the level of uncertainty and show how the PMP projections are distributed, where higher percentiles are associated with higher risk. The projected percent changes in PMP estimates are reproduced in Table 11.

Table 11: Projected Percent Changes in PMP Estimates

Percentiles	**2050s (%)***			**2080s (%)****		
	1-Day	**2-Day**	**3-Day**	**1-Day**	**2-Day**	**3-Day**
Minimum	-28.9	-27.9	-25.0	-25.7	-36.9	-36.8
5%	-15.3	-11.1	-11.1	-8.7	-12.0	-11.0
25%	3.5	4.9	5.2	6.5	8.2	8.8
50%	***10.6***	11.4	12.7	***20.1***	22.6	24.5
75%	***20.2***	21.2	22.3	***41.7***	44.6	45.4
95%	***38.6***	47.3	49.2	***66.5***	70.0	72.8
Maximum	102.7	101.7	115.9	95.3	100.6	96.0

* Table 34 (Golder 2020)
** Table 35 (Golder 2020)
Values in bold and italic used to increase the PMP for the climate change projection scenarios outlined in Table 17.

The determination of a projected PMP value is carried out by multiplying the corresponding percentage to the selected current value. For instance, to obtain the 1-Day PMP value projected to the 2050s, the present 1-Day PMP value must be multiplied by 1.106 to obtain the projection associated with the 50th percentile. Other projections are obtained in the same manner.

The analysis completed by Golder (2020) also included the calculation of IDF curves for the South Bruce Site. These curves are included for return periods ranging from 2 years to 200 years, where the probability of occurrence is the inverse of the return period; as an example, the 100-year return period event has a 1% probability of occurrence at any given time. The analysis included the GEV distribution of the IDF curves from the Mount Forest (6145504) Station as shown in Table 12.

Table 12: GEV Distribution of IDF Curves for Mount Forest – South Bruce Study Area (mm)*

Return Period (years)	Duration								
	5 min	10 min	15 min	30 min	1 h	2 h	6 h	12 h	24 h
2	8.8	12.9	15.3	20.1	24.7	30.6	38.1	43.7	49.4
5	10.8	15.5	18.6	25.5	32.6	39.8	48.6	55.5	63.4
10	12.1	16.7	20.3	28.9	38.1	45.4	56.4	63.3	72.6
20	13.2	17.7	21.6	32.2	43.4	50.6	64.5	70.6	81.4
50	14.6	18.6	23.0	36.4	50.6	56.9	75.9	80.0	92.7
100	15.5	19.1	23.8	39.5	56.1	61.4	85.3	86.9	101.2
200	16.4	19.5	24.5	42.5	61.7	65.7	95.4	93.8	109.7
500	17.4	20.0	25.2	46.4	69.4	71.0	110.0	102.7	120.7
1000	18.2	20.2	25.6	49.4	75.3	74.7	122.1	109.4	129.1
2000	18.9	20.4	26.0	52.2	81.4	78.3	135.1	116.0	137.4

* Table 6 (Golder 2020)

5.3.2 Selection of PMP Values

Values for the base PMP event were calculated at the South Bruce study area by Golder (2020) with the Hershfield method and further validated with the transposition method as well as data reported in a separate study conducted by the Ontario Ministry of Natural Resources (OMNR 2006). As indicated by Golder, the direct calculation of sub-daily PMP values was not completed because the available data were provided with a daily resolution. Instead, an estimation of sub-daily PMP values was undertaken using proration methods from available IDF curves. Relevant PMP values reported by Golder (2020) are reproduced in Table 13.

Table 13: PMP Summary Statistics and Comparison Values (Golder 2020)

Method/Source	6-Hour (mm)	12-Hour (mm)	1-Day (mm)	24-Hour (mm)	2-Day (mm)	3-Day (mm)
Hershfield/Golder	385.9	393.3	405.2	457.9**	425.1	417.4
Transposition*/Golder	348.8	355.5	366.3	413.9**	445.9	472.8
OMNR (2006)				462.0	---	---

*For watershed areal extent of 25 km^2
**Converted to 24-hour duration using a multiplier of 1.13 as recommended by WMO (2009).

The factor of 1.13 that is applied to convert from 1-day to 24-hr PMP is based on WMO guidance to approximate results from statistical analysis such as the Hershfield method. For the South Bruce study area, the method was applied to precipitation data with a resolution of one day, and therefore, the factor is recommended to estimate values towards the true maxima. This is based on the analysis of rainfall data as indicated by Hershfield (1961).

Another way to explain this is to mention that the 1-day PMP is based on the analysis of one day precipitation records which include the average rainfall for each day, instead of its maximum, and therefore the factor is used to bring the daily averages to a maximum for the day such as the 24-hr PMP.

As shown in Table 13, the corresponding PMP values corresponding to each duration are similar and within the same order of magnitude for all methods. Based on the analysis, the Hershfield method provides PMP values calculated at the South Bruce Site and are therefore considered to have the highest accuracy.

The Golder (2020) report notes that the determination of PMP via the transposition method varies with the area. The bounding circle enclosing the stations from which major storms were identified to undertake the transposition method is approximately 4,111 km^2. The PMP values for this size of area correspond to values 186 to 200 mm less during the 24-hour and 1-day durations compared the Hershfield method results. Therefore, the more conservative transposition method values for PMP from the lowest areal extent (25 km^2) are proposed and reported by Golder (2020) since they were the closest to the Hershfield method.

It is also recognized that the 2-day and 3-day PMP values are less than the 1-day and 24-hour duration for both Hershfield method. The Golder (2020) report recommended using the 24-hour PMP value to represent the 2-day and 3-day PMP values. For the transposition methods, the 2-day and 3-day PMP values are only 7% to 12% higher than the 24-hr value. This higher time of concentration combined with the marginal increases in total rainfall over a much longer time span would result in significantly lower hourly intensities when compared to the 24-hour rainfall which will result in significantly lower flow rates through the study site. Therefore, longer rainfall events such as 2-day and 3-day were not considered for further assessment.

Rainfall on snow projections are also provided in the Golder (2020) report to define potential scenarios where peak flooding events may be driven by a combination of rain and snowmelt rather than events driven exclusively by precipitation (i.e., PMP and IDF statistics). Table 19 of Golder (2020) includes the rainfall on snow projections for the South Bruce study area; these values are included in Table 14.

Table 14: Rainfall on Snow Projections for the South Bruce Study Area (Golder 2020) in mm

Return Period (years)	Duration						
	1-Day	2-Day	3-Day	4-Day	5-Day	6-Day	7-Day
2	43.3	59.2	71.5	80.7	91.0	99.0	106.3
5	54.5	73.1	90.2	103.3	118.0	129.4	138.9
10	62.0	82.3	102.6	118.3	135.8	149.5	160.5
20	69.1	91.2	114.5	132.7	152.9	168.8	181.2
50	78.3	102.6	129.9	151.4	175.0	193.8	207.9
100	85.3	111.2	141.4	165.3	191.6	212.5	228.0
200	92.2	119.7	152.9	179.2	208.1	231.2	248.0
500	101.2	131.0	168.0	197.6	229.9	255.8	274.4
1000	108.1	139.5	179.5	211.5	246.4	274.4	294.3
2000	115.0	148.0	190.9	225.3	262.9	293.0	314.3
Return Period (years)	**10-Day**	**20-Day**	**30-Day**	**50-Day**	**75-Day**	**90-Day**	**120-Day**
2	126.5	167.0	201.9	264.4	333.7	372.0	436.6
5	168.1	219.1	261.0	324.3	398.0	434.4	507.4
10	195.7	253.6	300.2	363.9	440.6	475.7	554.2
20	222.1	286.8	337.7	401.9	481.4	515.3	599.2
50	256.4	329.6	386.3	451.1	534.3	566.6	657.4
100	282.0	361.7	422.7	487.9	573.9	605.1	700.9
200	307.6	393.7	459.0	524.7	613.4	643.4	744.4
500	341.3	435.9	506.9	573.1	665.5	693.9	801.7
1000	366.8	467.9	543.0	609.7	704.9	732.1	845.0
2000	392.3	499.7	579.2	646.3	744.2	770.3	888.3

Since snowmelt processes are dominated by climatic variability, where temperature is the most important parameter, the definition of a significant rainfall on snow event requires the analysis of how rainfall on snow projections are transformed into runoff.

The daily snowmelt amount was therefore calculated with the Eastern Canada Forested Basin Equation (Pysklywec et al. 1968) included in Section A.2.4 of Golder (2020) and labeled Equation 38, where a degree-day method was applied. The equation defines snowmelt depleted from the snowpack as a function of mean daily air temperature.

The rationale for the evaluation of PMP values with different rainfall distributions is explained below.

- The SCS Type II distribution with a duration of 24 hours was applied to the PMP value reported by OMNR (2006) since this is the highest value (462 mm) for the South Bruce study area.

- The LRIA distributions with durations of 6 hours and 12 hours were applied to the corresponding PMP values provided in the Hershfield method (385.9 mm and 393.3 mm, respectively). The transposition method provides lower PMP values and for areal distribution of 25 km^2 which makes this method less accurate for the South Bruce study area.

- The Chicago distribution with a duration of 3 hours was applied to the interpolated PMP value from Table 17 of Golder (2020), which provides sub-daily PMP values for the South Bruce study area using the Hershfield method.

- The 20 day-100 year rainfall on snow projection event was evaluated by using the snowmelt function provided in the Golder (2020) report (Section A.2.4), where the relationship between temperature and runoff from melting is defined with a linear function.

The results of the hydrologic modelling that was completed to determine which distributions produce the highest peak flows at each catchment area are presented in Table 15.

As shown in Table 15, the highest peak discharge values are generated by the SCS Type II (24-hr) and the LRIA (6-hr) distributions. The results from both distributions have also similar magnitudes. The SCS Type II (24-hr) resulted in the greatest peak flows for CA1 and CA2. For CA3 the highest peak flow was generated with LRIA (6-hr), however, the difference in peak flows with the SCS Type II (24-hr) is negligible (2% difference). Therefore, to maintain consistency for hydrologic and hydraulic simulations, the SCS Type II (24-hr) was selected as the critical rainfall distribution. The SCS Type II (24-hr) was applied to all catchments.

Furthermore, the LRIA (12-hr), LRIA (6-hr) and the Chicago (3-hr) distributions were not carried forward for floodplain delineation. Additionally, the rain on snow 20 day-100 year event does not generate high peak flows because the resultant runoff is distributed over a long period of time which in turn decreases its intensity. For the same reason, rain on snow projection events are not considered critical when compared to PMP events with shorter durations; this is in agreement with Section 3.4 of Golder (2020), where it is indicated that for shorter durations extreme rainfall events take prominence over rain on snow events.

Table 15: Selection of Critical Rainfall Distributions at the South Bruce Study Area

Catchment	Duration	Distribution	Peak Discharge (m^3/s)
CA1	24 hr	SCS Type II	967
	12 hr	LRIA	897
	6 hr	LRIA	935
	3 hr	Chicago	766
	20 days	Rain on Snow	51
CA2	24 hr	SCS Type II	331
	12 hr	LRIA	296
	6 hr	LRIA	301
	3 hr	Chicago	244
	20 days	Rain on Snow	24
CA3	24 hr	SCS Type II	387
	12 hr	LRIA	367
	6 hr	LRIA	397
	3 hr	Chicago	333
	20 days	Rain on Snow	14

For longer rain on snow events, the volumetric capacity becomes significant; however, for floodplain assessments the capacity to generate high peak flows is the dominant variable.

5.4 500-Year Storm Event

The preliminary flood assessment in the previous sections has focussed on the PMP and the application of climate change projections to assess the potential impacts to the site. An additional preliminary flood assessment was requested by NWMO for the 500-year storm event for information to support future planning of the site, even though detailed design and grading were not the subject of this report.

The assessment for the 500-year storm event used the same parameters for the development of the hydrologic model as described in Sections 5.1 and 5.2. The hydrologic evaluation of the 500-year storm event differs only from the PMP analysis by requiring the total precipitation and applying it to a storm distribution. For consistency with the PMP analysis, the distribution applied was the 24-hour SCS Type II distribution. The 500-year total precipitation for 24 hours was obtained from Golder (2020) and is 174.4 mm. Table 16 summarizes the total 24-hour precipitation from Golder (2020) from which the 500-year precipitation was obtained and is indicated in bold in Table 16.

Table 16: 24-Hour IDF Curve for the South Bruce Study Area

Return Period (years)*	24-Hours** (mm)
2	57.7
5	80.3
10	95.3
25	109.7
50	128.3
100	142.2
200	156.1
500	**174.4**
1000	188.2
2000	202.0

*From Table 9 (Golder 2020)
**Converted to 24-hour duration using a multiplier of 1.13 as recommended by WMO (2009).

The application of the 500-year precipitation amount to the 24-hour SCS Type II distribution results in a rainfall hyetograph. The rainfall hyetograph was applied to HEC-HMS for evaluation and extraction of flow hydrographs to input into the hydraulic model for the preliminary flood hazard assessment.

5.5 Flood Assessment Scenarios

Based on the available information, 16 scenarios are proposed to carry out this preliminary flooding assessment as shown in Table 17. The scenarios consider a combination of percentiles applied to the selected critical rainfall distribution (SCS Type II with a 24-hour duration). Also included in the scenarios is the 500-year storm event evaluation. These scenarios were applied to all catchments during the hydraulic simulations.

Based on the selected risk profile, NWMO can select the appropriate level of risk as defined in Golder (2020) and apply them to each project phase. Further details regarding the hydrologic model, and how the hydraulic simulations were carried out to determine floodplain boundaries, are provided in the following sections.

Table 17: Selected Scenarios - Preliminary Flooding Hazard Assessment

Time Period	Hydrologic Condition	
	Direct Rainfall on Site	**Rainfall on Upstream Catchments**
Current (present-2040)	Scenario 1: SCS Type II - 24 hr PMP	Scenario 2: SCS Type II - 24 hr PMP
Mid-century (2041-2070)	Scenario 3: SCS Type II - 24 hr PMP 50th percentile	Scenario 4: SCS Type II - 24 hr PMP 50th percentile
	Scenario 5: SCS Type II - 24 hr PMP 75th percentile	Scenario 6: SCS Type II - 24 hr PMP 75th percentile
	Scenario 7: SCS Type II - 24 hr PMP 95th percentile	Scenario 8: SCS Type II - 24 hr PMP 95th percentile
End-of-century (2071-2100)	Scenario 9: SCS Type II - 24 hr PMP 50th percentile	Scenario 10: SCS Type II - 24 hr PMP 50th percentile
	Scenario 11: SCS Type II - 24 hr PMP 75th percentile	Scenario 12: SCS Type II - 24 hr PMP 75th percentile
	Scenario 13: SCS Type II - 24 hr PMP 95th percentile	Scenario 14: SCS Type II - 24 hr PMP 95th percentile
Current (present-2040)	Scenario 15: SCS Type II - 24 hr 500-year	Scenario 16: SCS Type II - 24 hr 500-year

5.6 Hydraulic Model Development (HEC-RAS)

Details of the 2D hydraulic model that was developed for this project are included in the following sections.

5.6.1 Model Setup

A two dimensional (2D) hydraulic model of the study site was created using HEC-RAS version 5.0.7, which is developed by the U.S. Army Corps of Engineers and is widely used and accepted in Ontario to simulate open channel hydraulics and delineate floodplain boundaries.

The program can calculate water surface elevations and other parameters, such as velocity and shear stress along stream networks. It can also model hydraulic structures such as bridges, culverts, and weirs. Given that this project included a preliminary assessment and the terrain that was applied to the model is based on the SWOOP 2015 dataset, assumptions were made for identified stream crossings such as type of structure, invert elevation, width and shape.

5.6.2 Model Domain

The domain of the hydraulic model includes only catchment CA3 as shown in Figure 9. The model domain defines the area where the 2D hydraulic calculations are completed and is formed by a mesh with computational cells with a resolution of 25 m by 25 m.

The use of a 2D model allows for the direct calculation of water elevations and velocities in both horizontal directions (i.e., in the direction of the channel as well as laterally towards the floodplain areas), where average water velocities over the water column are assumed by the model.

The 2D model was also used to input the excess precipitation calculated by HEC-HMS directly into the mesh at catchment CA3, hence simulating the transformation of rainfall into runoff with a method known as “rain-on-grid”. This method provides a more realistic approach to surface runoff routing because the precipitation input is transformed into runoff following terrain characteristics and using the assigned Manning’s coefficients to represent friction forces exerted by the terrain on the flow.

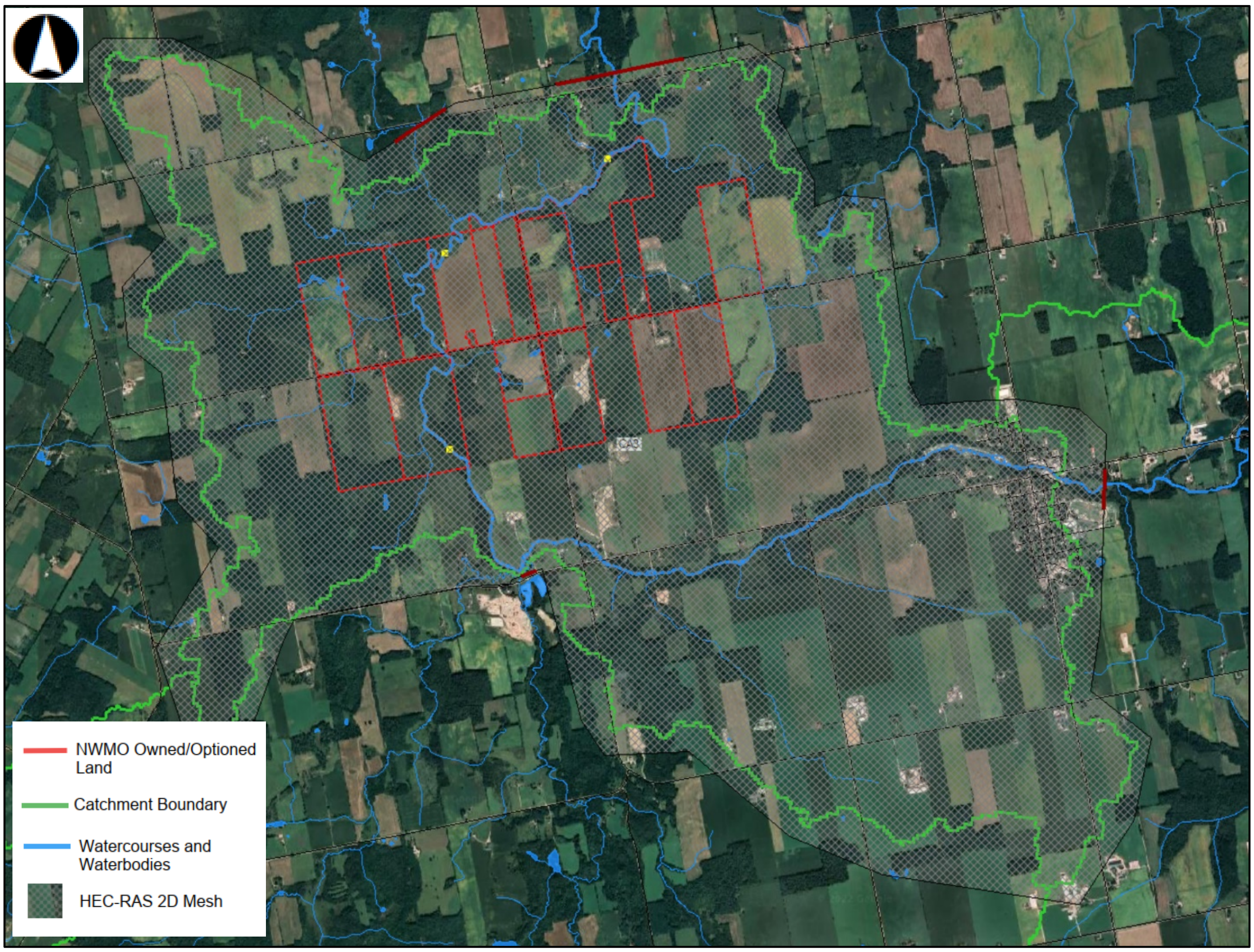

Figure 9: HEC-RAS Model Domain

Additionally, the rain-on-grid method requires the hydrologic model (in this case HEC-HMS) to remove precipitation losses because the terrain in HEC-RAS is represented as fully impermeable, and therefore, the use of total precipitation amounts would be unrealistic. The hydrologic model calculates the excess precipitation (i.e., runoff) for the selected critical rainfall distribution (i.e., 24-hr SCS Type II). Further details are provided in the next section.

5.6.3 Boundary Conditions

The main boundary conditions assigned to the model are excess precipitation for catchment CA3 and inflow hydrographs from catchments CA1 and CA2 into the model domain. These boundary conditions were applied for the 16 scenarios as shown in Table 18.

It is also recognized that each scenario type is distinguished by the flooding hazard (i.e., rainfall on-site and flooding from upstream areas).

Therefore, recognizing that is not feasible to separate one scenario type from the other (i.e., the rainfall event that can create flooding on-site is likely happening on upstream catchments simultaneously), it was decided to design the hydraulic model to pair scenarios and present them together as the combined effect of rainfall on-site and flooding from upstream areas.

For the Teeswater River outlet, a normal channel slope of 1% was assigned downstream of Concession Road 10. This location was chosen to account for the hydraulic effects of the road which could act as a weir if water overtopping occurs. This road is a horizontal restriction in the topography and therefore it was included in the 2D model domain to estimate the downstream water levels for catchment CA3. The normal slope value of 1% was calculated from SWOOP 2015 terrain downstream of catchment CA3; however, this boundary condition is not considered to be critical due to its location and the hydraulic control provided by the Concession Road 10 crossing.

Table 18: PMP and 500-year Precipitation and Flow Inputs applied to the HEC-RAS Model

Scenario*	Period	Total Precipitation (mm)	Peak Flow (m^3/s)		Excess Precipitation (mm)
			CA1	CA2	CA3
Current (Scenarios 1-2)	Current	462	967	331	371
Scenarios 3-4 +10.6%	Mid-Century	511	1088	372	418
Scenarios 5-6 +20.2%		555	1198	410	461
Scenarios 7-8 +38.6%		640	1409	482	544
Scenarios 9-10 +20.1%	End-of-Century	555	1197	410	461
Scenarios 11-12 +41.7%		654	1445	495	558
Scenarios 13-14 +66.5%		769	1730	593	670
Scenarios 15-16 500-year	500-year	174	279	97	106

*PMP Climate Change percentages based on Golder (2020) projections included in Table 11

5.6.4 Manning's Roughness Coefficient

The Manning's roughness coefficients simulate the friction forces that are exerted by land surfaces on the water flow. For all catchment areas land cover types were defined from the Ontario Land Cover Compilation Layer V.2 (MNRF 2014) shown in Table 2 and Figure 5.

Each land cover type was assigned a corresponding Manning's coefficient based on accepted engineering methodologies and guidelines. The selected Manning's coefficients included in the model are summarized in Table 19.

Table 19: Selected Manning's Roughness Coefficients

Land Cover Code	Description	Manning's Coefficient
1	Clear Open Water	0.001
5	Marsh	0.06
6	Swamp	0.06
12	Treed Upland	0.04
13	Forest – Dense deciduous	0.1
14	Mixed Treed	0.1
15	Coniferous Treed	0.1
16	Plantations – Treed Cultivated	0.04
17	Hedge Rows	0.06
25	Sand / Gravel	0.04
27	Community / Infrastructure	0.05
28	Agriculture and Rural Land Use	0.035

5.6.5 Derivation of Probable Maximum Flood Levels

The HEC-RAS model simulations that were completed for catchment CA3 area based on the defined boundary conditions and hydraulic input parameters that are shown in Table 18. The floodplain boundaries calculated for each scenario are presented in Figures 10 to 17.

The results include flooding from upstream areas as well as flooding on-site on the same figure, as explained previously. The results show floodplain boundaries for each scenario for maximum depth water within the study site.

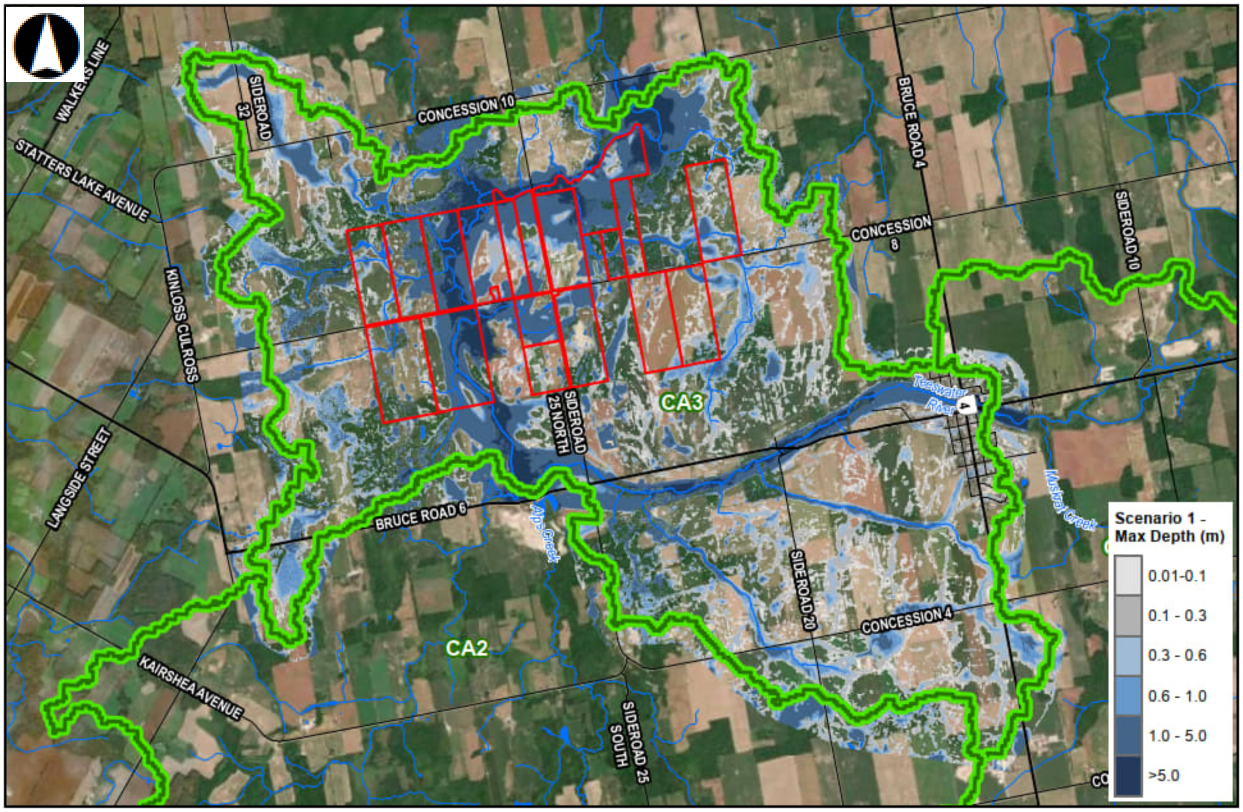

Figure 10: Scenarios 1 and 2 – Floodplain Boundaries for Current Condition Showing Maximum Depth of Water

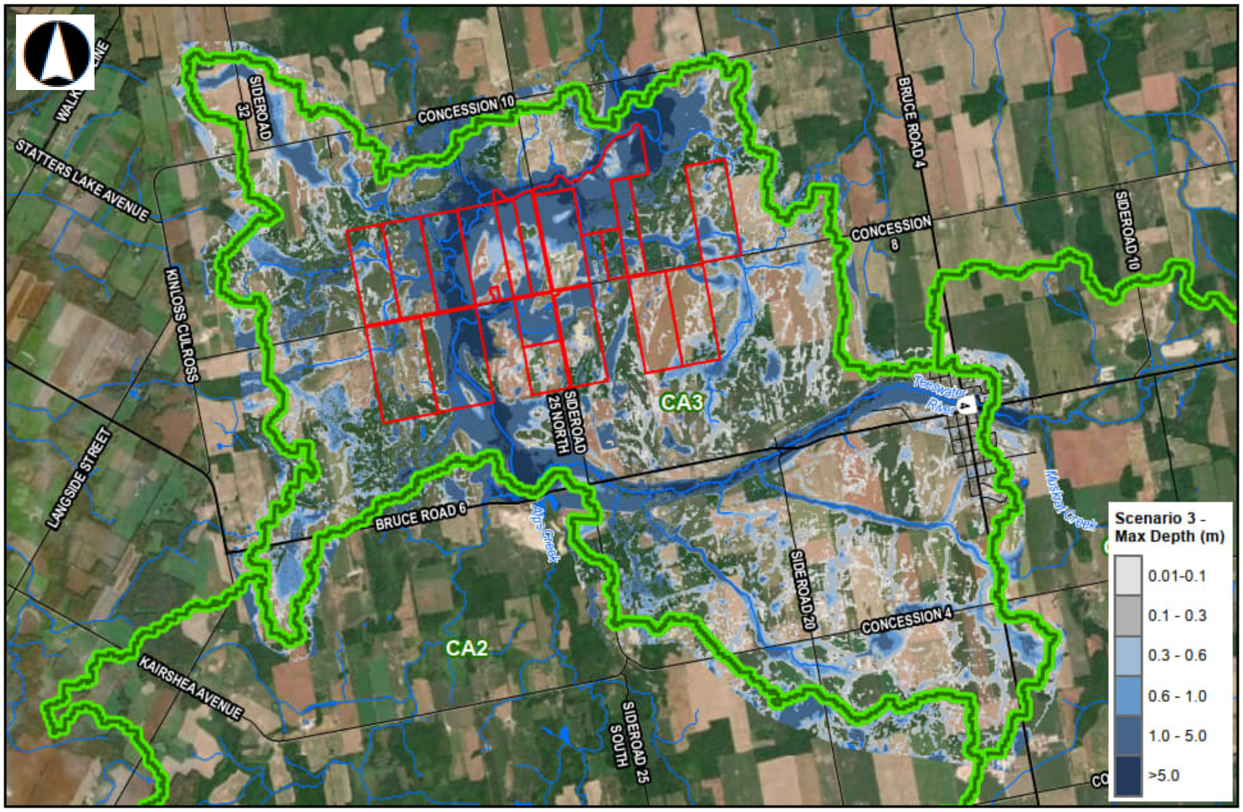

Figure 11: Scenarios 3 and 4 – Floodplain Boundaries for Mid-Century (50%) Showing Maximum Depth of Water

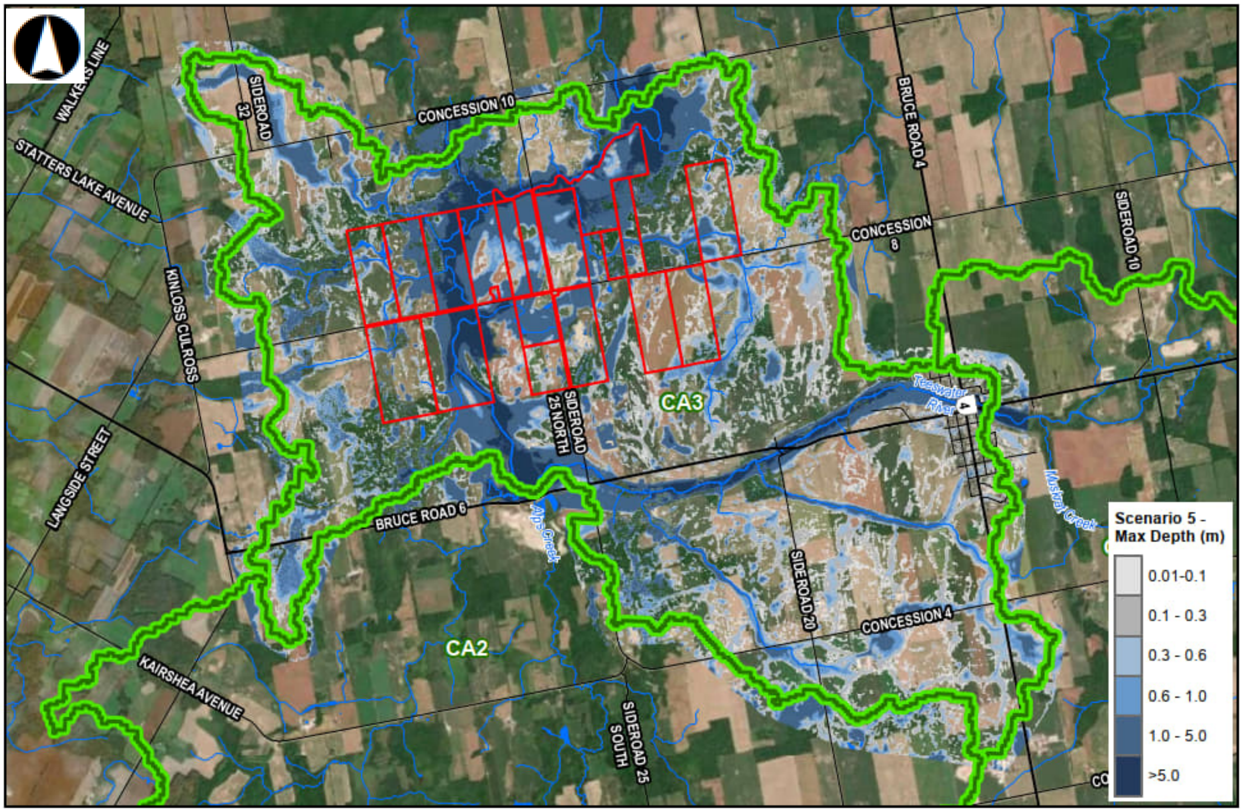

Figure 12: Scenarios 5 and 6 – Floodplain Boundaries for Mid-Century (75%) Showing Maximum Depth of Water

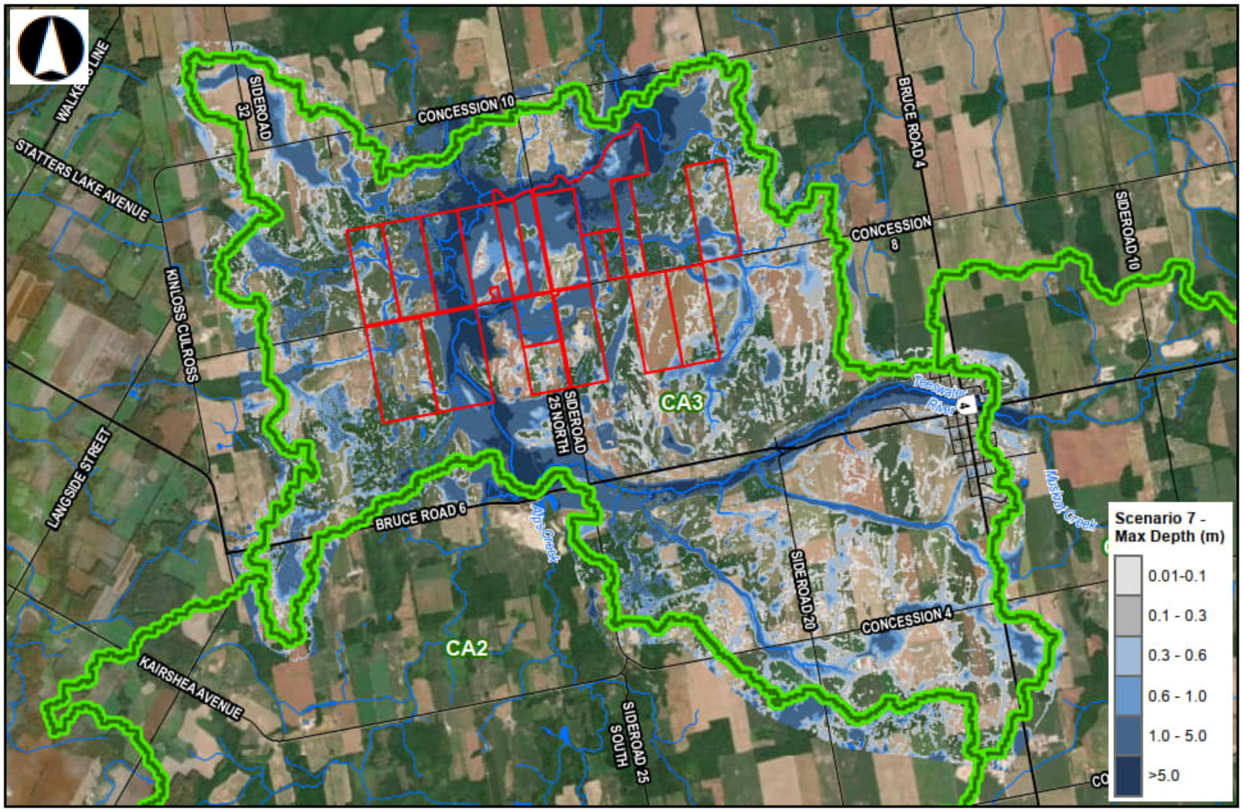

Figure 13: Scenarios 7 and 8 – Floodplain Boundaries for Mid-Century (95%) Showing Maximum Depth of Water

For the mid-century scenarios, the model results show that increasing precipitation amounts have an impact on floodplain boundaries. This is because the proposed South Bruce study area is located downstream of catchments CA1 and CA2, and therefore there is significant surface area within these catchments (including the Town of Teeswater) where precipitation can accumulate and be transformed into surface runoff as it is routed downstream. The same effect can be observed in the end-of century scenarios.

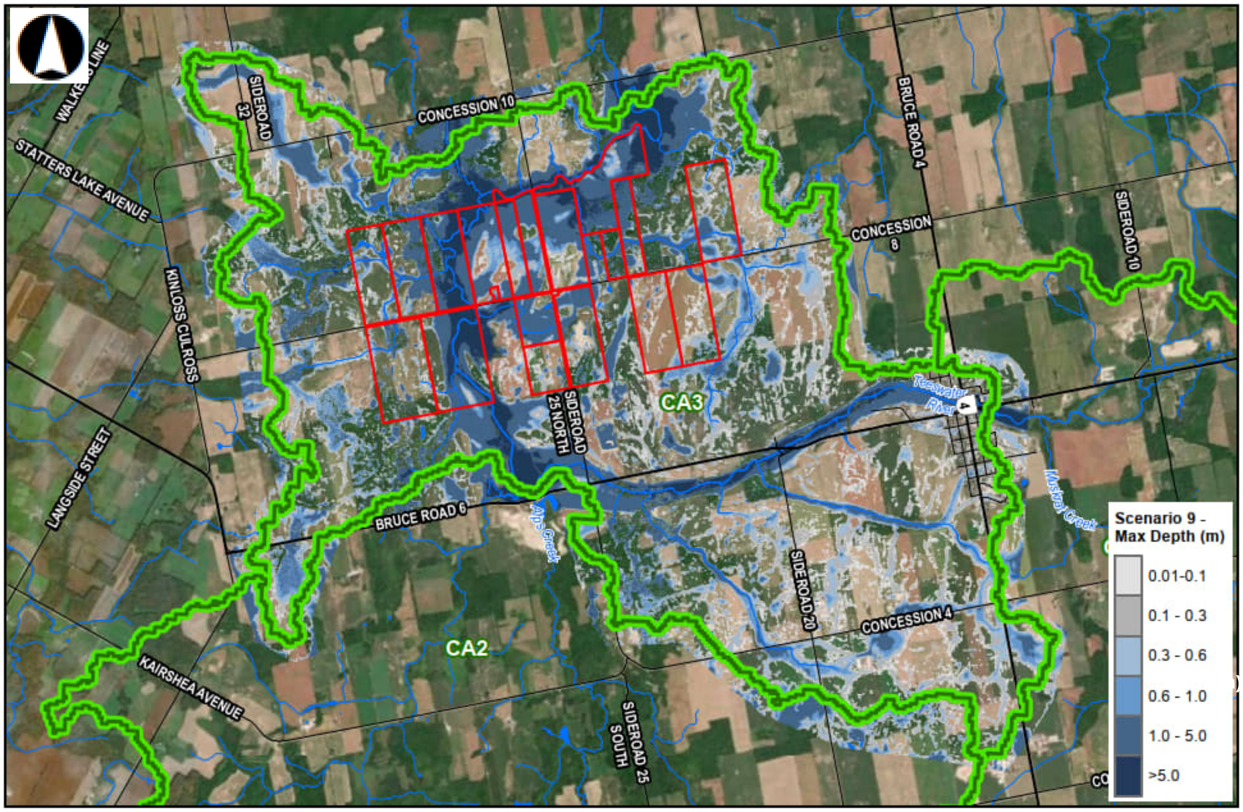

Figure 14: Scenarios 9 and 10 – Floodplain Boundaries for End-of-Century (50%) Showing Maximum Depth of Water

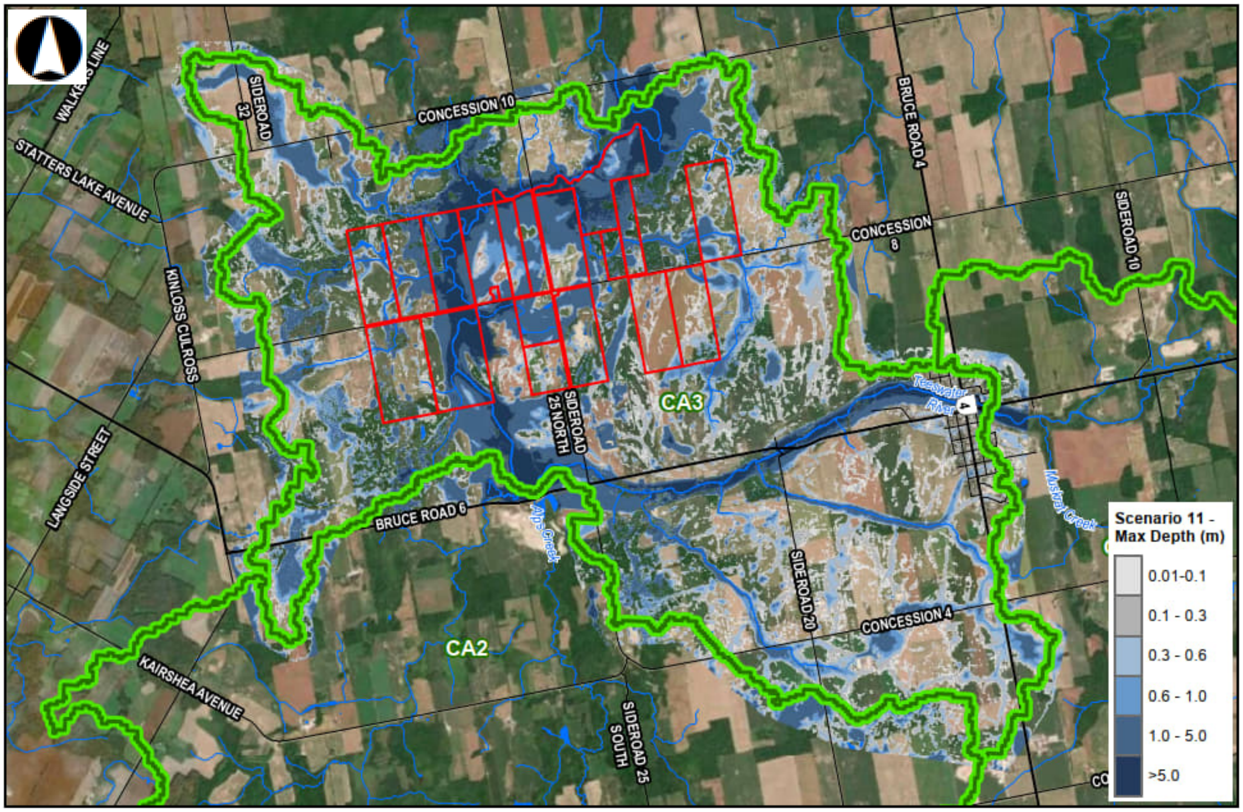

Figure 15: Scenarios 11 and 12 – Floodplain Boundaries for End-of-Century (75%) Showing Maximum Depth of Water

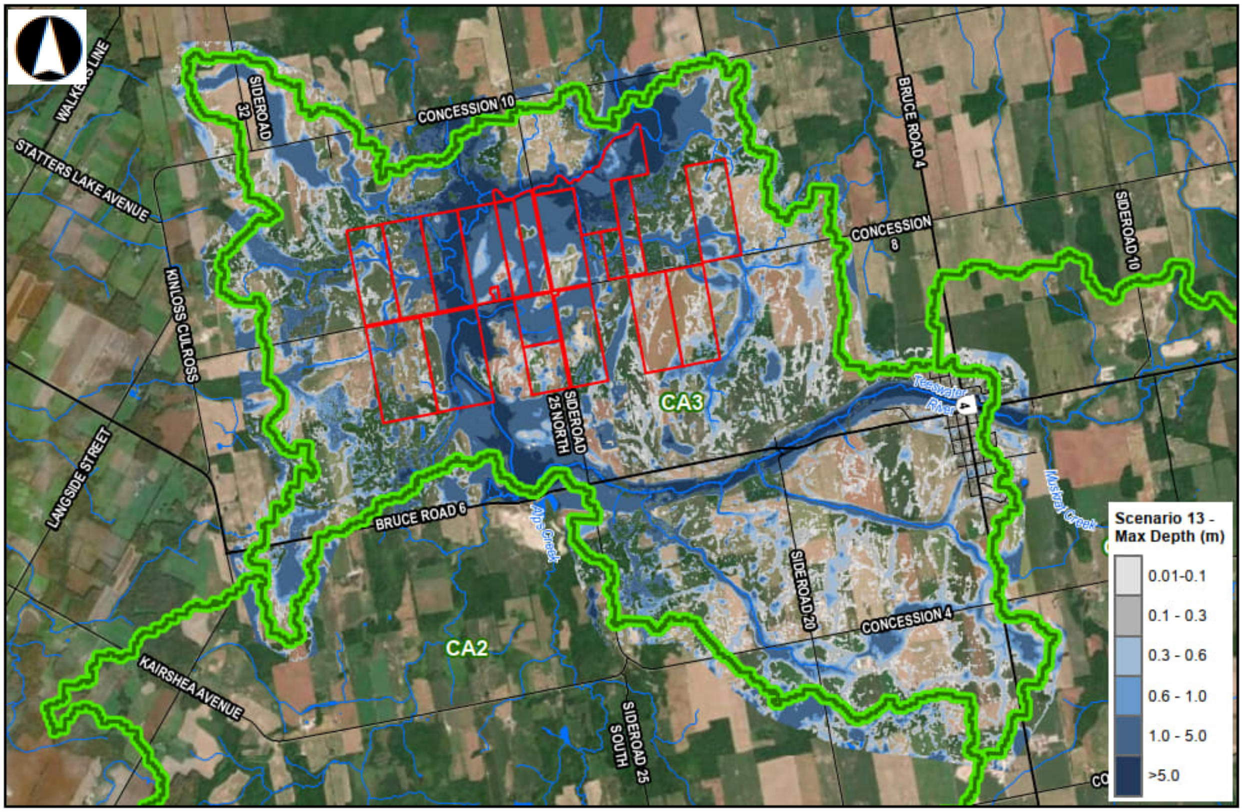

Figure 16: Scenarios 13 and 14 – Floodplain Boundaries for End-of-Century (95%) Showing Maximum Depth of Water

The results from Scenarios 15 and 16 (the 500-year preliminary flood hazard assessment) are presented in Figure 17 below.

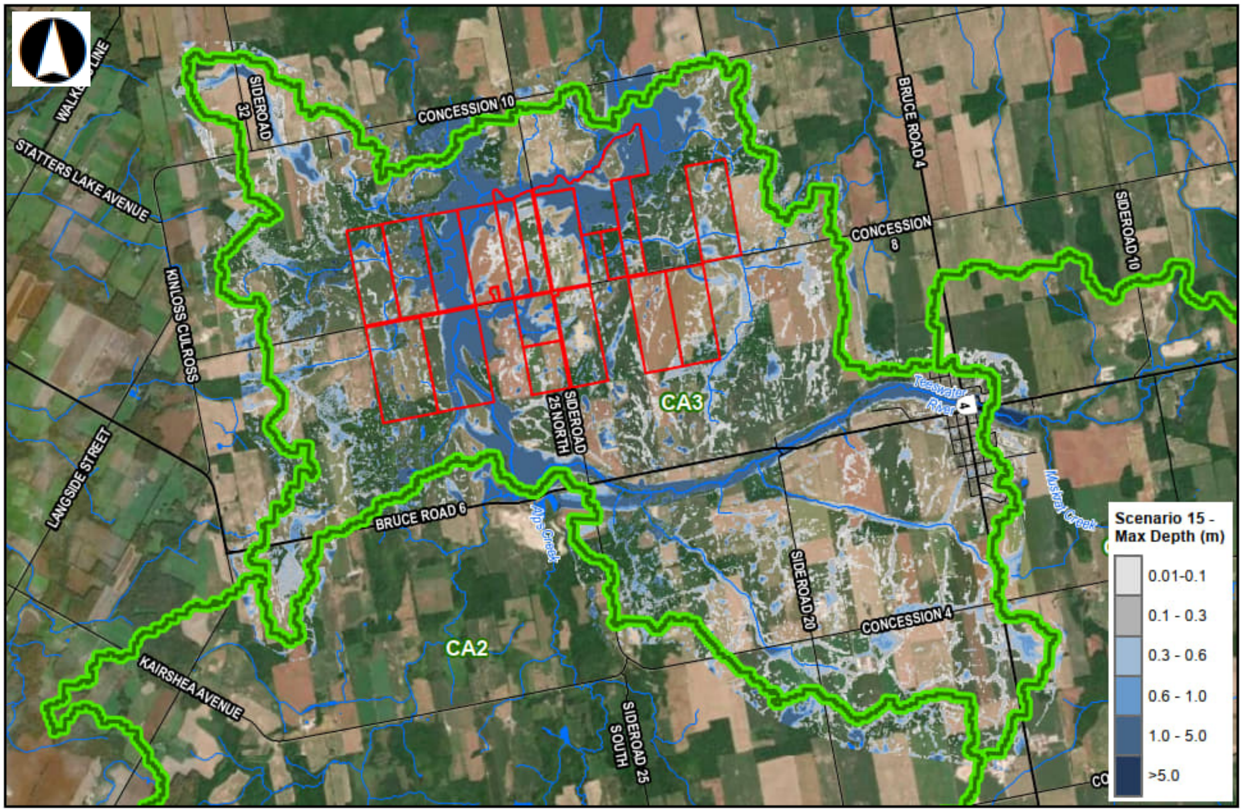

Figure 17: Scenarios 15 and 16 – Floodplain Boundaries for 500 Year Storm Showing Maximum Depth of Water

As shown in Figures 10 to 17, surface flooding is present across different areas within the site for all scenarios, where all property parcels have flooding impacts. However, even when the model results show areas where surface ponding occurs, a more detailed analysis of impacts is warranted to determine areas of concern based on the proposed site grading for surface facilities.

6. SENSITIVITY ANALYSIS

To assess the impact of variations in input parameters on peak flows (hydrologic model) and water levels (hydraulic model) a sensitivity analysis was completed. An additional sensitivity analysis was completed to assess the impact of the release of impounded water from two dams upstream of the site on the Teeswater River on the South Bruce study area.

6.1 Input Parameters

Two input parameters from the hydrologic model and one parameter from the hydraulic model were selected; these are the SCS curve number (CN), the time of concentration (Tc) and the Manning's roughness coefficient.

As part of the sensitivity analysis, the base input parameters for each of the hydrologic and hydraulic models were increased by 20%. For the hydrologic parameters, each drainage area has its own CN values assigned as shown in Table 6, therefore for each drainage area the CN was increased by 20% to carry out hydrologic simulations for scenarios 1-2, 7-8 and 13-14, which present the highest impacts.

Similarly, the time of concentration for each drainage area (Table 7) were increased by 20% to carry out the hydrologic simulations. For the sensitivity analysis for the hydrologic model parameters, the simulations with modified SCS curve numbers and times of concentration were completed separately. The results of the sensitivity analysis for the hydrologic modeling are summarized in Table 20 and Table 21

Table 20: Percent Change in Peak Flow - CN increased 20% vs. Base Model

Catchment Area ID	Scenarios		
	1-2	7-8	13-14
CA1	9.9	7	5.7
CA2	8.7	6.4	5.3
CA3	9.7	6.8	5.5

Table 21: Percent Change in Peak Flow – Tc increased 20% vs. Base Model

Catchment Area ID	Scenarios		
	1-2	7-8	13-14
CA1	-13.4	-13.4	-13.4
CA2	-13.8	-13.8	-13.8
CA3	-13	-13	-13

The sensitivity analysis for hydrologic parameters shows that the increased CN values resulted in increased peak flows for all catchment areas for the scenarios presented, it was also observed that the increases were consistent between the evaluated scenarios for each catchment area, where the highest values correspond to the current condition (scenarios 1-2) while the lowest changes occurred for scenarios 13-14. These results suggest that the hydrologic model is not extremely sensitive to changes of the SCS curve number.

An increase by 20% of the time of concentration (Tc) resulted in peak flow decreases for all catchment areas under the scenarios evaluated. The percent difference in peak flows versus the base model is consistent between the scenarios evaluated for all catchment areas.

The Manning's roughness coefficient was selected as the hydraulic parameter for the sensitivity analysis to assess the impact on the resulting water levels. The Manning's n is based on land cover characteristics with the base parameters included in Table 19.

The selected Manning's coefficients were increased by 20% for all land cover types within the drainage areas except for clear open water which has a Manning's roughness of 0.001 and is not expected to change. To assess the impact on the water levels, three comparison points were chosen as shown in Figure 18.

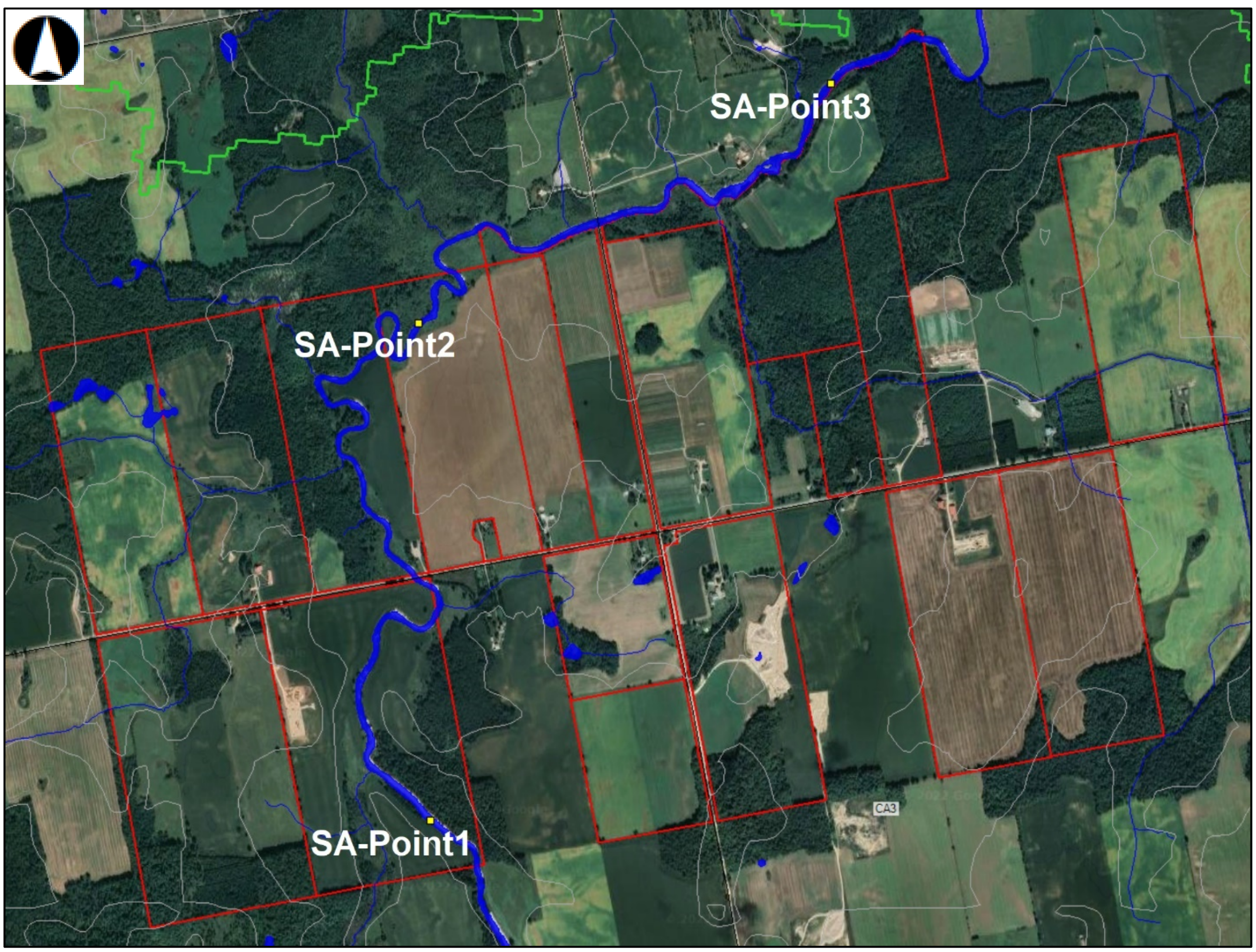

Figure 18: Location of Points for Water Level Changes - Sensitivity Analysis

The results of the sensitivity analysis from the hydraulic model are summarized in Table 22.

Table 22: Change in Water Elevations between Modified and Base Model

Location	Water Elevations (m) / Scenarios		
	1-2	7-8	13-14
SA-Point1	281.3/281.1	282.0/281.8	282.5/282.2
SA-Point2	280.6/280.5	281.3/281.1	281.6/281.4
SA-Point3	279.7/279.5	280.2/280.0	280.5/280.3

The results of the sensitivity analysis on water elevations indicate that the increase in Manning's roughness coefficient has a limited impact with increases ranging from 0.1 m to 0.3 m.

Overall, the sensitivity analysis for peak flows (hydrologic model) and water elevations (hydraulic model) at the sampled points show that a change in model parameters have a limited impact on the model results, suggesting that the hydrologic and hydraulic models simulate all scenarios and maintain a narrow range of results even with changes in parameters.

This condition is favourable with respect to the requirements of this preliminary flood hazard assessment because the model results are consistent without large variations when certain parameters are modified.

6.2 Release of Impounded Water

Two dams were identified in the Teeswater River upstream of the study site and discussed in the qualitative assessment in Section 4.6, Their locations are indicated on Figure 8. The NWMO requested a sensitivity analysis be undertaken to determine the impact of the release of impounded water from the two dams on the South Bruce Site. NWMO requested that this assessment be completed assuming the PMP with the 95% percentile for climate change risk projections to 2080. This is the storm event associated with Scenarios 13 and 14 (see Table 17 and Table 18 for the scenarios and total precipitation for each) and is the highest total precipitation used for the preliminary flood hazard evaluation.

The following sections outline the steps and parameters used to modify the 2D hydraulic model that was created and used for the preliminary flood hazard assessment to include the identified dams and undertake dam breach simulations that include the sudden release of impounded water from both structures. The resulting depth of water and water elevations on the study site are also presented in this section.

6.2.1 Expansion of the Hydraulic Model

As noted above, the 2D hydraulic model created for the preliminary flood hazard assessment was expanded to include the two dams and to undertake the dam breach analysis. The expansion of the model is explained in the sections below.

6.2.1.1 Model Domain

The model domain base is the one developed for the preliminary flood hazard assessment and described in Section 5.6.2. The model domain defines the area where the 2D hydraulic calculations are completed for this sensitivity analysis and is formed by a mesh with computational cells with a resolution of 25 m by 25 m.

The base domain of the model only included CA3 as presented in Figure 9. For this sensitivity assessment, the terrain has been expanded to include the most upstream dam located in catchment CA1 and just upstream of Belmore Creek. The downstream dam location was already within the 2D terrain within catchment CA3 near Andrew Street in Teeswater. The updated model domain is presented in Figure 19.

As per the preliminary flood hazard assessment undertaken and described in previous sections of this report, the 2D model was similarly used to input the excess precipitation calculated by HEC-HMS directly into the mesh at catchment CA3, hence simulating the transformation of rainfall into runoff with a method known as “rain-on-grid”.

The expanded model domain encroaches into CA1, but it is only for the simulation of the dam breaks. The peak flow input into the hydraulic model is a hydrograph representing flow generated by the area (catchment CA1). A consequence of the expansion of the model domain is the requirement to distribute flow inputs from CA1 into the main branch (Teeswater River) and two tributaries (Muskrat Creek and Belmore Creek). The main flow hydrograph was adjusted by catchment area to maintain the same flow input that was applied to preliminary flood hazard assessment.

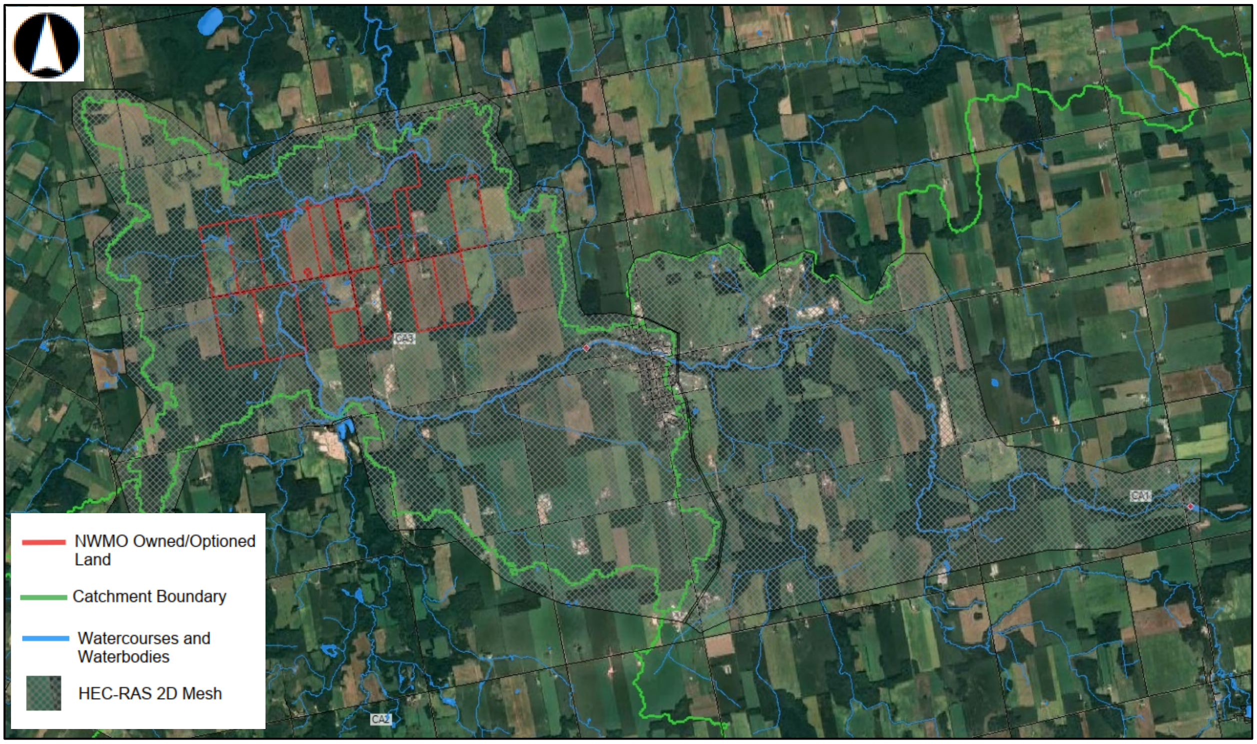

Figure 19: HEC-RAS Model Domain for Impounded Water Sensitivity Analysis

6.2.1.2 Boundary Conditions

The main boundary conditions assigned to the model are excess precipitation for catchment CA3 and inflow hydrographs from catchments CA1 and CA2 that enter the model domain. This approach is consistent with previous simulations, however only one rainfall scenario is applied. As noted at the start of Section 6.2, the PMP event with the 95% percentile climate change risk projected to 2080 was used to evaluate the impact of impounded water. These simulations are also known as Scenarios 13 and 14 and the PMP precipitation and flow are presented in Table 23.

Table 23: PMP Precipitation and Flow Inputs Applied to the Impounded Water HEC-RAS Model

Scenario*	Period	Total Precipitation (mm)	Peak Flow (m^3/s) CA1	Peak Flow (m^3/s) CA2	Excess Precipitation (mm) CA3
Scenarios 13-14 +66.5%	End-of-Century	769	1730	593	670

*PMP Climate Change percentages based on Golder (2020) projections included in Table 11

It was recognized as part of the preliminary flood hazard assessment that each scenario contains two flooding hazard types (i.e., rainfall on-site and flooding from upstream catchments). Similarly, it is not feasible to separate one scenario type from the other (i.e., the rainfall event that can create flooding on-site is likely happening on upstream catchments simultaneously).

Therefore, the hydraulic model continues to pair scenarios and present them together as the combined effect of rainfall on-site and flooding from upstream areas.

Furthermore, to maintain consistency with previous hydraulic simulations, the boundary condition at the Teeswater River outlet was set with a normal channel slope with a value of 1% assigned downstream of Concession Road 10. This location was chosen to account for the hydraulic effects of the road which could act as a weir if water overtopping occurs. This road is a horizontal restriction in the topography and therefore it was included in the 2D model domain to estimate the downstream water levels for catchment CA3. The normal slope value of 1% was calculated from SWOOP 2015 terrain downstream of catchment CA3; however, this boundary condition is not considered to be critical due to its location and the hydraulic control provided by the Concession Road 10 crossing.

Additionally, a main channel was added to the surface terrain model by inferring channel depths and width from aerial images. This channel is required to account for the dam geometries and impounded water volumes. In contrast, the hydraulic model for the preliminary flood hazard assessment only included the Teeswater River to the elevation of water that was included in the SWOOP 2015 surface terrain model. The channel that was incorporated into the terrain has an average depth of 2 m with a trapezoidal geometry which extends from bank to bank of the Teeswater River. The bank locations were estimated using the available waterbody polygon layer and aerial images.

6.2.1.3 Manning’s Roughness Coefficient

The Manning’s roughness coefficients simulate the friction forces that are exerted by land surfaces on the water flow. For all catchment areas land cover types were defined from the Ontario Land Cover Compilation Layer V.2 (MNRF 2014) and shown in Table 2 and Figure 5. The expansion of the model domain resulted in one additional land cover type applied to the hydraulic model and hence the Manning’s coefficients were also expanded. For the assessment of impounded water, Table 24 presents the Manning’s coefficients applied. The values in Table 24 also include those used for the preliminary flood hazard assessment presented in Table 19. The additional land cover code present within the expanded model domain is described as bog (land cover code 8).

Table 24: Selected Manning's Roughness Coefficients for Impounded Water Analysis

Land Cover Code	Description	Manning's Coefficient
1	Clear Open Water	0.001
5	Marsh	0.06
6	Swamp	0.06
8	Bog	0.06
12	Treed Upland	0.04
13	Forest – Dense deciduous	0.1
14	Mixed Treed	0.1
15	Coniferous Treed	0.1
16	Plantations – Treed Cultivated	0.04
17	Hedge Rows	0.06
25	Sand / Gravel	0.04
27	Community / Infrastructure	0.05
28	Agriculture and Rural Land Use	0.035

6.2.1.4 Dam Characteristics

Two dams were identified on the Teeswater River and their locations are presented in Figure 8. The dams are both owned and operated by the Saugeen Valley Conservation Authority (SVCA). Inspection reports for each dam from the 1980s (SVCA 1982) and 1990s (SVCA 1991a and 1991b) were obtained from SVCA by NWMO. Characteristics of both dams were obtained from these reports and a summary of the characteristics of each dam are presented in Table 25. Beyond what is described in these reports, limited information is available regarding the current condition and operation of the dams.

Table 25: Characteristics of the Dams on the Teeswater River Upstream of the South Bruce Site

Location	Name	Material Type	Length (m) across Teeswater River	Height (m)	Width (m)	Number of Piers
Upstream Dam on Teeswater	North of Belmore	Concrete with earth berm	55	3.26	4.5	2
Downstream Dam on Teeswater	Little Mill	Concrete	33.5	3.81	4.0	6

6.2.1.5 Dam Break Parameters

Following the modifications made to the hydraulic model, dam breach parameters were added to the model for each structure and breach conditions were assigned during the passage of the PMP event.

A review of information available for each of the dam sites (presented in Table 25) was used to estimate potential dam breach parameters. The upstream structure, which is described as North of Belmore Dam is formed by a concrete spillway with an earthen embankment. The downstream structure known as Little Mill Dam is a concrete structure.

Dam break parameters are difficult to estimate because of the limited data availability regarding previous dam failure events, the large variation between dam structures in terms of their design, construction methods, dam materials, current condition, as well as the many possible causes of failure and environmental parameters that influence such events.

The dam break parameters include accounting for dam features such as geometry of the opening, the time to full breach and the mode of failure (i.e., overtopping or piping). Due to the concrete features contained within both structures, the selected failure mechanism was assumed to be sliding or overturning of a dam section. The sliding or overturning of a dam section is considered an instantaneous break. Therefore, the selected breach formation time for both dams was 20 seconds which is middle of the recommended range included in Table 3 of *Training Document 39 – Using HEC-RAS for Dam Break Studies* (USACE 2014).

For the PMP event, the dam breaks were setup in HEC-RAS to occur at the time of the occurrence of the peak water elevation in order to maximize the effects on the resultant floodplains. Since one dam is upstream of the other, the impact of the breach of the upstream dam (North of Belmore) is assumed to impact the peak flow at the downstream dam (Little Mill). Therefore, for the dam break assessment, the upstream dam is breached first in HEC-RAS at its peak water elevation and the dam break time of the second dam (Little Mill) was delayed to receive the transient wave from the North of Belmore Dam.

6.2.2 Derivation of Probable Maximum Flood Levels for Impounded Water

The HEC-RAS model simulations that were completed for floodplain delineation within catchment CA3 are presented in Figure 20.

The maximum water depth results (Figure 20) include flooding from upstream areas as well as flooding on-site on the same figure, as explained previously.

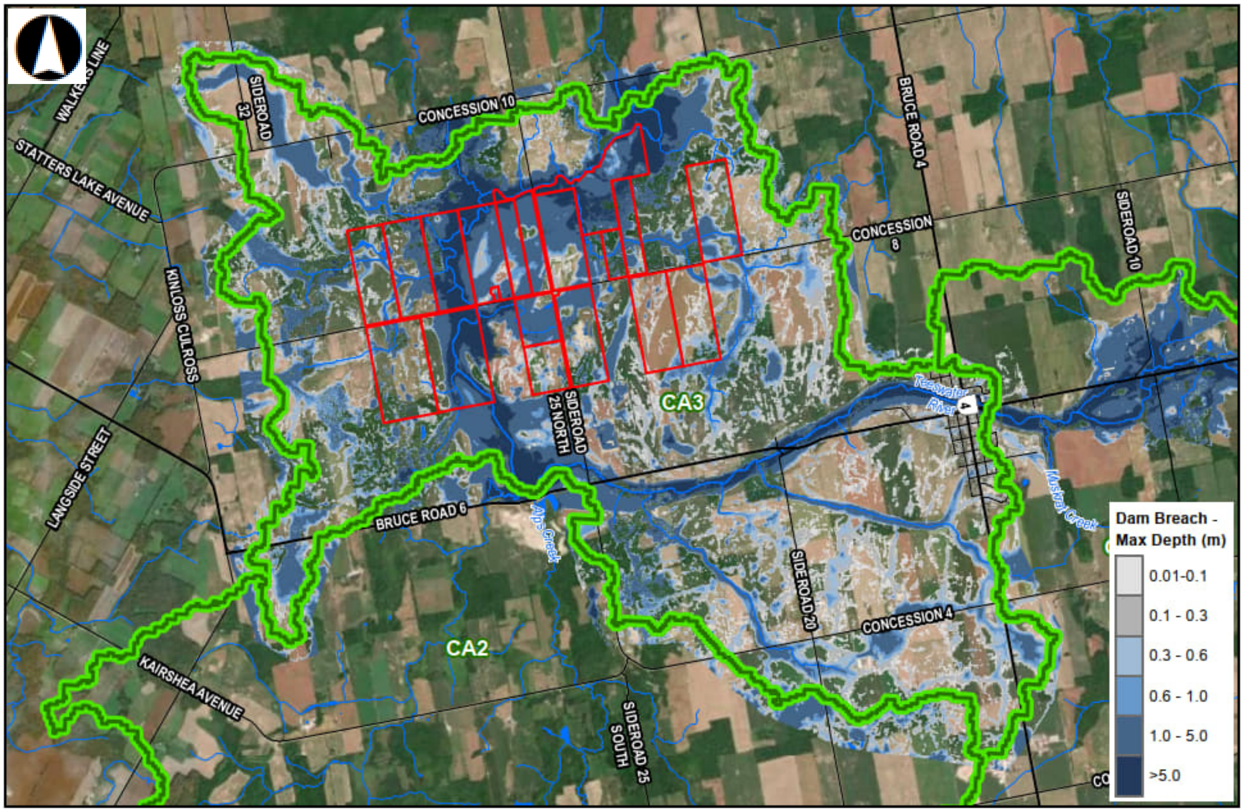

Figure 20: Scenarios 13 and 14 – Floodplain Boundaries for End-of-Century (95%) for Dam Breach showing Maximum Depth of Water

The floodplain boundaries resulting from the release of impounded water at both dam structures produce minimal increases in floodplain boundaries when compared to the base scenario without a sudden release of impounded water. The increases in floodplain boundaries are minimal and not clearly visible at the scale presented in this report.

The model results show that a sudden release of impounded water at both structures are not able to significantly alter the flow hydrographs for Scenario 13. Furthermore, the North of Belmore dam size and distance from the study area minimize the potential impacts due to sudden dam breach, while the Little Mill dam provides a larger input to the flow hydrograph but not within the level that is required to significantly increase floodplain elevations

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are made for the South Bruce study area:

- A qualitative hazard assessment was carried out following the *Specific Safety Guide SSG-18 by the International Atomic Energy Agency* (IAEA 2011), specifically the items included in Section 5 of the document which provides recommendations regarding the analysis of hydrological hazards. The results of the qualitative analysis show that, based on the available information and site conditions, flooding hazards due to extreme precipitation events require further consideration and other hydrological hazards are determined to be of no significance.

- Catchment delineations were completed using the Ontario Flow Assessment Tool (OFAT) and then refined using GIS software with the available SWOOP 2015 Digital Elevation Model data. The catchment areas were labeled CA1 to CA3, where catchment CA3 contains the proposed South Bruce Site land parcels.

- The location of the South Bruce study area downstream of two catchments which includes the Town of Teeswater makes the site potentially vulnerable to flooding from upstream areas, given that there is more catchment area available to capture surface runoff which must be conveyed towards the outlet.

- A total of 16 scenarios were included in this preliminary flood hazard assessment. These scenarios are divided by period (current, mid-century, and end-of-century), climate change scenario (three PMP risk projections) and 500 year storm (current climate change scenario) and by type of flood (direct rainfall on-site and rainfall on upstream catchments).

- This modelling focused on an extreme bounding event, referred to as the Probable Maximum Precipitation (PMP). This exceeds the conditions normally used as a design basis. The selected PMP value reported by OMNR (2006) was used in this assessment (462 mm) for the South Bruce study area.

- In addition to the PMP storms, the 500-year storm (174 mm) was also used to evaluate the impact of flooding on the South Bruce study area.

- A hydrologic model of the study site was developed for this assessment with the software HEC-HMS. Based on the results of the hydrologic model, the SCS Type II distribution with a duration of 24 hours was the critical rainfall distribution.

- A hydraulic model was created with the software HEC-RAS to transform excess precipitation amounts into surface runoff. The results of the model for all 16 scenarios were mapped and show areas where surface ponding occurs as well as the floodplain boundaries for the Teeswater River and its tributaries within the study site.

- The results from HEC-RAS show that surface ponding may occur across portions of the site based on current topography (before site grading and ditches). This is indicated by potential for surface ponding and overtopping along the stream in catchment CA3 for all land parcels within the South Bruce study area. It is recommended to repeat the analysis of surface flooding once there is a specific site location, grading and general arrangement of the surface facilities.

- The sensitivity analysis for peak flows (hydrologic model) and water elevations (hydraulic model) at the sampled points show that a change in model parameters have a limited impact on the model results, suggesting that the hydrologic and hydraulic models simulate all scenarios and maintain a narrow range of results even with changes in parameters.

- The impact of impounded water from two existing dams upstream of the study site in the Teeswater River was evaluated through a dam break assessment using the PMP with 95% percentile climate change risk to 2080. The assessment was a sensitivity analysis to gauge the flood impact on the site if both dams were breached. Results indicate that the incremental flood impact due to a dam failure is minimum.

- The results of the preliminary flood assessment indicates that many road crossings within and around the South Bruce study area will be affected by overtopping during a PMP flood event, affecting access to the site temporarily (during the flood event) or for a longer time (i.e., if a road crossing is damaged and impassible). Some areas within the site could become isolated during such an event (see intersection of Sideroad 25 North and Concession 8).

- Based on the previous item, it is recommended to evaluate storm events that are suitable for road design, and if needed to develop a site access contingency plan if access to the site is impacted or becomes inaccessible due to flooding.

ABBREVIATIONS AND ACRONYMS

AECOM – AECOM Canada Ltd.

AEP – Annual Exceedance Probability

BCCAQ – Bias Correction/Constructed Analogues with Quantile

CDA – Canadian Dam Association

CN – Curve Number

DEM – digital elevation model

DGR – Deep Geological Repository

GIS – Global Information System

Golder – Golder Associates Ltd.

HEC – Hydrologic Engineering Center

HMS – Hydrologic Modeling System

IAEA – International Atomic Energy Agency

IDF – Intensity-duration-frequency

LOCA – Localized Constructed Analogs

LRIA – Lake and Rivers Improvement Act

MIFM – Modified Index Flood Method

MNR – Ministry of Natural Resources

MNRF – Ministry of Natural Resources and Forestry

MTO – Ministry of Transportation

NOEGTS – Northern Ontario Engineering Geology Terrain Study

NRCan – Natural Resources Canada

NWMO – Nuclear Waste Management Organization

OFAT – Ontario Flow Assessment Tool

OLCC – Ontario Land Cover Compilation

PMP – probable maximum precipitation

RCP – Representative Concentration Pathways

RAS – River Analysis System

SCS – Soil Conservation Service

SVCA – Saugeen Valley Conservation Authority

SWM – stormwater management

SWOOP - Southwestern Ontario Orthophotography Project

UFPP – Used Fuel Packaging Plant

UOFM – Unified Ontario Flood Method

USACE – United States Army Corps of Engineers

WMO – World Meteorological Organization

REFERENCES

AAFC. 1998. Agriculture and Agri-Food Canada. Soil Classification Working Group. The Canadian System of Soil Classification. Third Edition. Publication 1646, (Revised). 187 pp.

AAFC. 2013. Agriculture and Agri-Food Canada. ISO 19131 Soils of Canada, Derived – Data Product Specification. Ottawa, Canada. 89pp.

AECOM. 2021. Preliminary Flood Hazard Assessment at the Ignace Study Site. NWMO-TR-2021-26. AECOM Canada Ltd. Canada.

AMEC. 2011. OPG's Deep Geologic Repository for Low and Intermediate Level Waste Maximum Flood Hazard Assessment. NWMO DGR-TR-2011-35. AMEC NSS Ltd. Canada. 158pp.

Barnett, P.J., W.R. Cowan and A.P. Henry. 1991. Quaternary Geology of Ontario Southern Sheet. Ontario Geological Survey. Map 2556. Scale 1:1,000,000.

CDA. 2007. Canadian Dam Association. Dam Safety Guidelines. Toronto, Canada. 86pp.

Environment Canada. 2022. Water Survey of Canada Daily Discharge Graph for Teeswater River at Teeswater (02FC020) [ON]. https://wateroffice.ec.gc.ca/report/historical_e.html?stn=02FC020

ESRI. 2022. Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community. Maps were created using ArcGIS® software by Esri. ArcGIS® and ArcMap™ are the intellectual property of Esri and are used herein under license. Copyright © Esri. All rights reserved.

Golder. 2020. Climate Change Impacts on Climate Variables for a Deep Geological Repository (South Bruce Study Area). Nuclear Waste Management Organization Technical Report NWMO-TR-2020-09. Toronto, Canada.

IAEA (International Atomic Energy Agency). 2011. Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations: Safety Guide. Jointly sponsored by the International Atomic Energy Agency and the World Meteorological Organization. Vienna, Austria. 172pp.

MNR. 2002. Ontario Ministry of Natural Resources. Water Resources Section. Technical Guide – River and Stream Systems: Flooding Hazard Limit. Peterborough, Canada. 118p.

MTO. 1997. Drainage Management Manual. Drainage and Hydrology Section, Transportation Engineering Branch. Ontario Ministry of Transportation. Toronto, Canada. 257 pp.

MTO. 2016. Ontario Ministry of Transportation, IDF Online Lookup Tool. http://www.mto.gov.on.ca/IDF_Curves/map_acquisition.shtml

NRCan. 2009. National Research Canada. Atlas of Canada 6th Edition. Ottawa, Canada.

OMNR. 2004. Ontario Ministry of Natural Resources. Lake and River Improvement Act Technical Guidelines – Criteria and Standards for Approval. Ontario, Canada.

OMNR. 2006. Ontario Ministry of Natural Resources. PMP for Ontario. Prepared by IBI Group.

Pysklywec, D.W., K.S. Davar and D.I. Bray. 1968. Snowmelt at an Index Plot. Water Resource. 4(5), 937-946

Sehgal, K. 2016. A Unified Ontario Flood Method: Regional Flood Frequency Analysis of Ontario Stream Using Multiple Regression. Toronto, Canada. 158 pp.

SVCA. 1982. Dam Survey No. 39. Teeswater, Canada. 4pp.

SVCA. 1991a. Southwestern Region Ministry of Natural Resources 1991 Dam Inventory and Reservoir Assessment SVCA 028. Teeswater, Canada. 6pp.

SVCA. 1991b. Southwestern Region Ministry of Natural Resources 1991 Dam Inventory and Reservoir Assessment SVCA 030. Teeswater, Canada. 6pp.

USACE. 1984. Shore Protection Manual. Volume I. Coastal Engineering Research Center, U.S. Army Corps of Engineers. Washington, USA. 337pp.

USACE. 2014. Training Document 39 – Using HEC-RAS for Dam Break Studies, U.S. Army Corps of Engineers, Washington, USA. 64pp.

WMO. 2009. Manual on Estimation of Probable Maximum Precipitation (PMP). WMO-No. 1045. Secretariat of the World Meteorological Organization. Geneva, Switzerland. 291pp.

WMO. 1998. Guide to Wave Analysis and Forecasting. Secretariat of the World Meteorological Organization. Geneva, Switzerland. 168pp.