MAXIMUM FLOOD HAZARD ASSESSMENT FOR OPG'S DEEP GEOLOGIC REPOSITORY FOR LOW AND INTERMEDIATE LEVEL WASTE

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ABSTRACT

Ontario Power Generation (OPG) has entered a process to seek Environmental Assessment and licensing approvals to construct a Deep Geologic Repository (DGR) for Low and Intermediate Level Radioactive Waste (L&ILW) near the existing Western Waste Management Facility (WWMF) at the Bruce nuclear site in the Municipality of Kincardine, Ontario. In support of the design of the proposed DGR project, maximum flood stages were estimated for potential flood hazard risks associated with coastal, riverine and direct precipitation flooding.

The estimation of lake/coastal flooding for the Bruce nuclear site considered potential extreme water levels in Lake Huron, storm surge and seiche, wind waves, and tsunamis. The riverine flood hazard assessment considered the Probable Maximum Flood (PMF) within the local watersheds, and within local drainage areas that will be directly impacted by the site development. A series of hydraulic models were developed, based on DGR project site grading and ditching, to assess the impact of a Probable Maximum Precipitation (PMP) occurring directly at the DGR site.

Overall, this flood assessment concluded there is no potential for lake or riverine based flooding and the DGR area is not affected by tsunamis. However, it was also concluded from the results of this analysis that the PMF in proximity to the critical DGR operational areas and infrastructure would be higher than the proposed elevation of the entrance to the underground works.

This paper provides an overview of the assessment of potential flood hazard risks associated with coastal, riverine and direct precipitation flooding that was completed for the DGR development.

1. INTRODUCTION

Ontario Power Generation (OPG) has entered a process to seek Environmental Assessment and licensing approvals to construct a Deep Geologic Repository (DGR) for Low and Intermediate Level Radioactive Waste (L&ILW) near the existing Western Waste Management Facility (WWMF) at the Bruce nuclear site in the Municipality of Kincardine, Ontario. In support of the design of the proposed DGR project, maximum flood stages need to be estimated as these could potentially affect the DGR project. This paper provides an overview of the assessment of potential flood hazard risks associated with coastal, riverine and direct precipitation flooding.

2. DESCRIPTION OF DGR

The proposed DGR project will be constructed in competent sedimentary bedrock beneath the Bruce nuclear site. The layout of the DGR project area is presented in Figure 1. The general built features of the proposed DGR development include:

- Roadway crossing of the railway ditch
- Vegetated buffer and perimeter ditch
- Stormwater retention pond
- Waste Rock Management Area (WRMA)
- Primary working areas of the DGR including the waste package receiving building
- Electrical substation and emergency generator

Of particular relevance to the flood risk assessment are four surface features that are directly connected to the underground workings of the DGR site. These four features, including main shaft, intake plenum, exhaust plenum and ventilation shaft, are potential ingress points for flood water to the underground areas. The electric and emergency power facilities, critical to DGR operations, are also relevant with regard to this flood risk assessment.

The Light Detection And Ranging (LIDAR) data collected during a detailed topographic survey of the Bruce nuclear site indicates that the lands designated for the DGR project have elevation changes between 181 m above sea level (in the northern portion of the site) and 187 m (in the southern portion of the site). For comparison, Lake Huron has a surface water elevation of 176 m.

3. SURFACE FLOOD HAZARD ASSESSMENT

The surface flood hazard assessment for the DGR site focuses on two aspects, namely:

- Riverine Flood Hazards
- Flood Hazard due to Direct Rainfall on the DGR site

The assessment of each of these flood hazards is described in detail in the following sections. Please note that any potential impacts described herein relate to only flood hazards.

Figure 1. Layout of the DGR project area

3.1 Design Rainfall

The design flood event used to determine the flood hazard for this assessment is the PMP/PMF event. The PMF is the flood that may be expected from the most severe combination of critical meteorological and hydrologic conditions that are reasonably possible in a particular drainage area. Probable Maximum Precipitation (PMP) is defined as the greatest depth of precipitation for a given duration meteorologically possible for a given size storm area at a particular location at a particular time of year, with no allowance made for long-term climatic trends [1], [2]. It is common practice that the PMF is the flood which is a direct result of the PMP.

Two basic methodologies are available for PMP estimation; meteorological and statistical.

- Meteorological approaches as outlined in [1] use estimates of atmospheric moisture, moisture maximization, wind maximization, storm transposition, transposition adjustments, etc. as the basis for PMP estimation
- Statistical approaches (an example is the Hershfield Method) can be used wherever sufficient precipitation data are available. Statistical estimation techniques are generally applicable to smaller watersheds up to 1000 km^2 in area. These approaches are useful when data to support meteorological approaches are not available.

Consideration was given to a number of PMP estimates for the study area, namely:

- Province of Ontario Regulatory PMP as defined in the "Lakes and Rivers Improvement Act Technical Guidelines" (LRIA) [3]
- Draft information providing updated estimates of PMP for the Province of Ontario provided in the "PMP for Ontario" OMNR report [4]
- Site specific PMP estimation techniques (e.g., Hershfield Method)
- National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) PMP estimates.

PMP estimates, based on each of the sources noted above, were determined for a variety of durations ranging from 5 minutes to 72 hours.

A comparative analysis of the estimates concluded that:

- the Hershfield Method PMP estimate was inconsistent with the other estimate and was therefore removed from further consideration
- OMNR has commented that the PMP estimates provided in the LRIA are out of date. However, these are still the current "approved" values for the Province of Ontario
- The US NWS PMP estimates are the most conservative. However, these estimates are based on data analyses from continental US weather stations only. The underlying analyses did not include weather stations located in Canada and may not be reflective of rainfall patterns on the lee side of Lake Huron
- The revised PMP for Ontario report values [4] represent the most up-to-date assessment of Province wide PMP estimates taking into consideration recent severe rainfall events

The range of PMP estimates determined for this analysis is outlined in Table 1 below.

It was, therefore, recommended that the revised PMP estimates for Ontario [4] be adopted as the most appropriate design rainfall estimates for subsequent flood risk analyses for the DGR site. Notwithstanding, it was also recommended that the other PMP estimates be evaluated for comparative purposes.

Table 1. Probable Maximum Precipitation estimates – summary

Storm Duration	Total Rainfall by Source (mm)			
	OMNR 2004 statistical	NWS 1978 statistical NWS 1982	OMNR 2006 statistical	Environment Canada Hershfield Method 2010
72 hrs	N/A	818	630	313
48 hrs	460	773	637	332
36 hrs	445	N/A	n/a	n/a
24 hrs	440	711	596	328
12 hrs	420	660	570	n/a
6 hrs	405	572	550	n/a
3 hrs	365 [6]	515 [5]	495 [6]	n/a
2 hrs	337 [6]	476 [5]	458 [6]	n/a
1 hrs	280 [6]	395 [1]	380 [6]	n/a
30 min	216 [6]	305 [2]	293 [6]	n/a
15 min	152 [6]	215 [3]	207 [6]	n/a
5 min	96 [6]	135 [4]	130 [6]	n/a

Notes:

1. NWS 1 hour from [5] Figure 24 page 79
2. NWS 30 minutes from [5] 1982 Figure 38 page 96
3. NWS 15 minutes from [5] 1982 Figure 37 page 95
4. NWS 5 minutes from [5] 1982 Figure 36 page 94
5. NWS PMP estimates for the other durations were used as the basis for graphical interpolation to estimate PMP for 2 and 3 hour duration events.
6. Statistical PMP estimates for OMNR data [3] and [4] were based on a percentage reduction similar to that computed for the 'NWS' estimates.

3.2 Riverine Flood Hazard Assessment

The DGR site is located within the area known as the Lake Fringe Watershed. The Lake Fringe Watershed is a narrow strip of land along Lake Huron stretching from Kincardine to South Hampton. A number of Lake Fringe Watershed watercourses flow through or adjacent to the DGR site, including Little Sauble River, Underwood Creek and Stream 'C', as illustrated in Figure 2. These watersheds bound surface drainage from the Bruce nuclear site.

Stream 'C' is the only natural watercourse that traverses the Bruce nuclear site. Stream 'C' is a former tributary of the Little Sauble River that was diverted, and presently flows in a constructed channel [6], to Baie du Doré during the initial development of the Bruce nuclear site in the 1960s [7]. A portion of Stream 'C' is located in proximity to the DGR site (within about 600 m). No historical data on Stream 'C' water levels through the Bruce nuclear site are available nor is there any documented or anecdotal evidence of flooding problems associated with this watercourse [8].

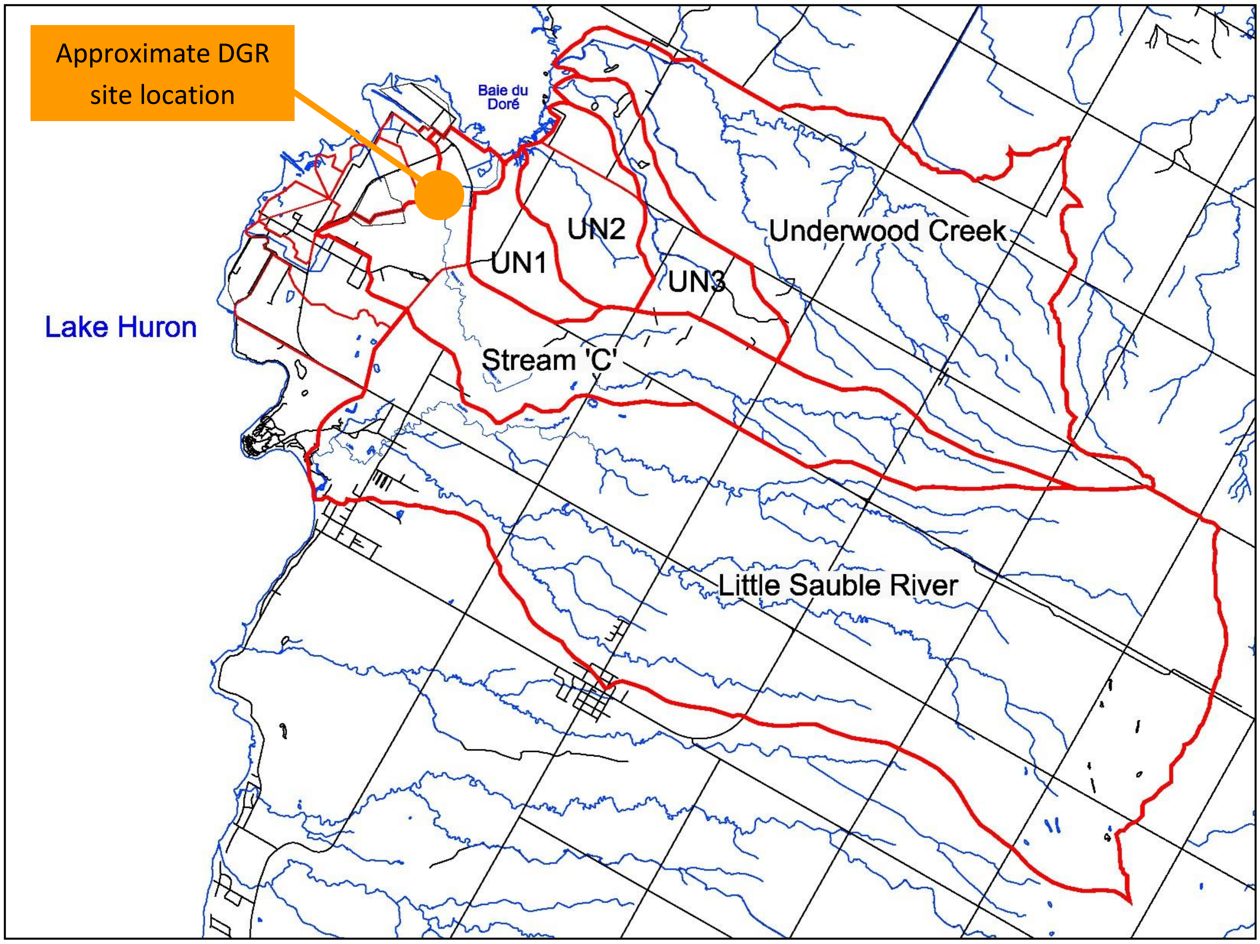

Figure 2. Local watersheds in proximity to the Bruce nuclear site

The distance between the Little Sauble River and Stream 'C' just below the shoreline of the old Lake Algonquin and Lake Nipissing is only about 1 km. The watershed divide in this approximate location is only about 1 m above the top of bank of the Little Sauble River and Stream 'C' (abstracted from LIDAR data). This suggests the possibility of floodwaters breaching this boundary and flowing into the adjacent watershed.

Other relevant comments with regard to flooding potential in these watersheds include:

- No water retaining structures (such as dams) have been identified from the available information
- Numerous roadway culverts have been identified along the subject watercourses. Flooding resulting from transient obstructions (such as debris and/or ice) is a relevant consideration.

Reports focused on floodplain calculations for the Little Sauble River upstream of the 2nd Concession Road were also obtained from the SVCA [9], [10], [11]. A review of these documents indicated the following:

- Floodplain calculations were based on the 100 year and Regional Floods
- No spill was identified from the Little Sauble Creek to Stream 'C'.

A site reconnaissance visit was conducted by AMEC staff on April 14 and 15, 2010. No observations were made during this site visit that indicated information contrary to that documented in the background materials.

The review of the remainder of the background material did not identify any reference to historical flooding in the subject watersheds.

3.2.1 Hydrologic Model Development

A single event hydrologic modeling approach, based on the program Visual Otthymo (v2.0), was used to compute estimates of stormwater runoff rates (i.e., peak flows) and volumes for the subject drainage areas. This approach is considered appropriate for this analysis given that the PMP is a single event design rainfall.

3.2.2 Critical Probable Maximum Precipitation Duration

The duration of PMP that causes the most critical flood at a site is termed the "critical duration" for that drainage basin [2]. In general, the critical duration is short for a small basin and increases with the size of the drainage area. To determine the critical duration, peak flows resulting from PMP of several durations should be derived. The duration of the PMP that causes maximum peak flows at the subject location is the critical duration.

The hydrologic model was used to compute peak flows for the various drainage areas for the range of PMP estimates. From the comparison of PMP results, for the Little Sauble River and Stream 'C', a PMP duration of 6 hours produced maximum peak flows. The 6 hour PMP was therefore used for the assessment of potential surface flooding from riverine sources for the Bruce DGR site.

3.2.3 Hydraulic Model Development

A one-dimensional steady flow modeling approach, based on the program HEC-RAS, was adopted for this assessment given the linear nature of the subject watercourses.

3.2.4 Assessment of Potential Surface Flooding at the Bruce DGR Site

The computed PMF water surface elevations based on the 6 hr PMP as defined from OMNR [4] with a starting Lake Huron water surface elevation of 176.43 m (mean annual) were delineated as illustrated in Figures 3 and 4.

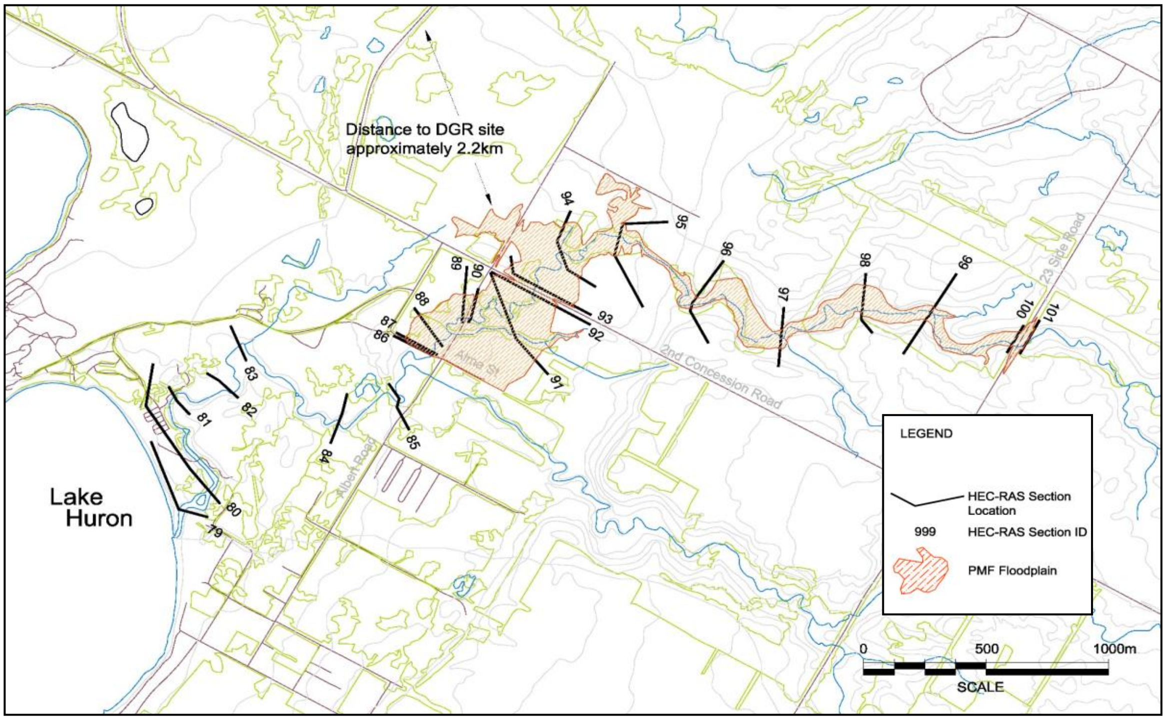

Figure 3. Partial floodplain representation – Little Sauble River

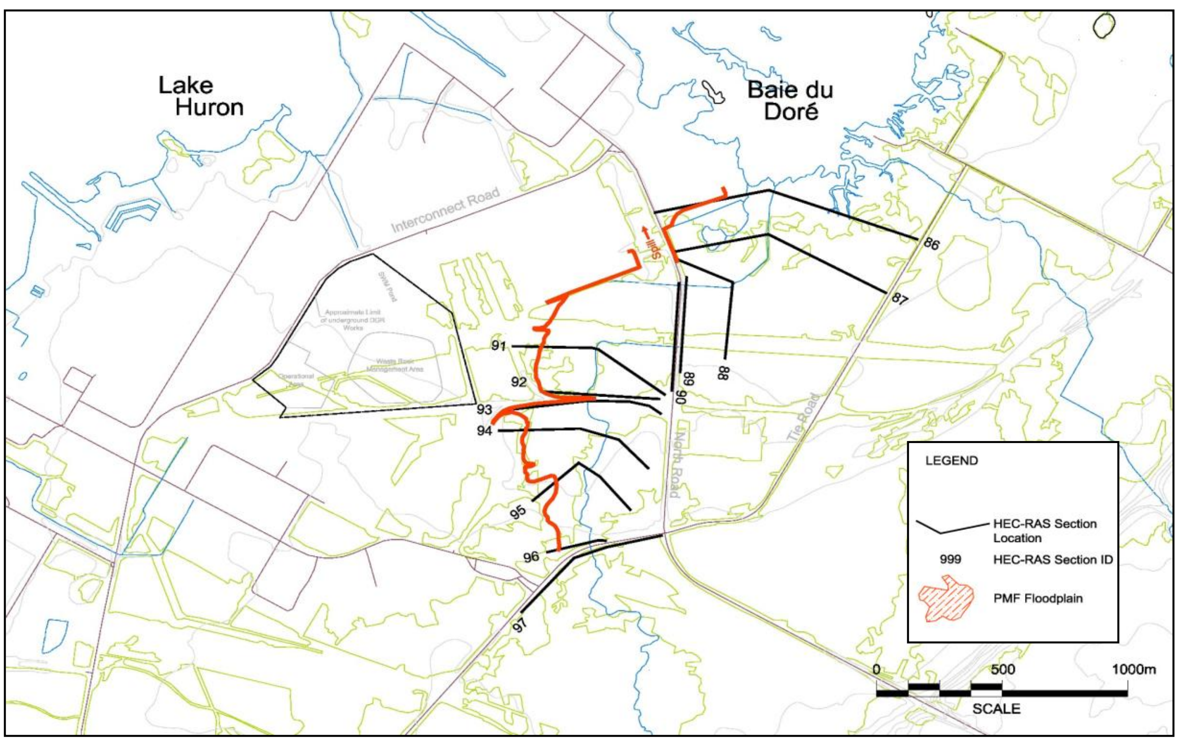

Figure 4. Partial floodplain representation – Stream 'C'

Two conclusions are apparent from these figures, namely:

- The computed Little Sauble River PMF floodplain does not extend into the DGR site. Further, transfer of flood water from the Little Sauble River to Stream 'C' during a PMP/PMF event is not anticipated given the topography that separates the watercourses
- The computed Stream 'C' PMF floodplain does not extend into the DGR site.

As noted previously, numerous roadway culverts have been identified along the Little Sauble River and Stream 'C' watercourses. Flooding resulting from transient obstructions (such as debris and/or ice) is a relevant consideration. This possibility was investigated by constricting critical culvert dimensions in the hydraulic model. It was concluded that for both the Little Sauble River and Stream 'C' watercourses, blockage of critical culverts would not increase computed PMF water levels sufficiently to cause a flooding impact at the DGR site.

3.2.5 Sensitivity Analysis

A sensitivity analysis was conducted to facilitate better understanding of the impacts to flood risk at the DGR site resulting from changes in modeling input parameters. Changes to computed water surface elevations at the DGR site have been quantified for peak flows resulting from alternate 6 hour duration PMP definitions and alternate starting water surface elevations.

The following conclusions were apparent from the sensitivity analysis:

- Computed water surface elevations, for both the Little Sauble River and Stream 'C', across the three definitions of PMP (i.e., [3], [4], [12]) discussed in this report, are within a few centimetres (max 13cm) for the base scenario (i.e., [4] with the mean annual lake level being used as the starting water surface elevation at Lake Huron). The differences in computed water surface elevations between the base scenario and the PMP definition of [12] is negligible
- Computed water surface elevations at Lake Huron in the Little Sauble River are governed by flows in the river and not by lake levels. As such, the Lake Huron starting water surface elevations do not influence upstream computed water surface elevations
- Computed water surface elevations at Lake Huron in Stream 'C' are governed by flows in the river at lower lake levels only. For starting water surface elevations using Lake Huron mean annual and mean monthly annual levels no changes in computed upstream water surface elevations were noted. When the starting water surface elevation was increased to the Lake Huron 100 year and 500 year level some increases in computed water surface elevations were noted.

This sensitivity analysis reinforces the conclusion that riverine flood potential resulting from a PMP/PMF event, for all of the combination of events reviewed, will not impact the DGR site given currently planned elevations of the operational areas.

3.3 Assessment of Flood Hazard Due to Direct Rainfall

3.3.1 Local Site Drainage

The Bruce nuclear site, including areas controlled by OPG, has an extensive system of catchbasins, sub-surface storm sewers, manholes and open ditches and culverts [13]. Stormwater runoff from the site discharges to Lake Huron through several outfalls and natural features. The sub-surface storm sewer system has been generally designed to a 10year standard [7]. The delineation of drainage areas within the Bruce nuclear site is illustrated in Figure 5 from Golder [14].

The DGR site, in its predevelopment state, is located within the Stream 'C' (about 30%) and MacPherson Bay South (about 70%) subcatchments. This DGR development area is generally flat with an average overland slope of 0.006 m/m and is drained via a system of ditches within railway and road right-of-ways. These drainage ditches are expected to contain water only as a result of rainfall events. Land cover across the proposed DGR site is generally open brush areas with construction debris is some locations. No paved areas are presently located within the DGR development zone [13].

A feature of the DGR development is a perimeter ditch system that encompasses the site. This system will encompass both the 'built' area of the DGR and the Waste Rock Management Area (WRMA). The purpose of the perimeter ditch system is to avoid discharge of potentially contaminated stormwater runoff into the Stream 'C' watershed. A secondary purpose is to ensure that all drainage from the DGR site can be treated for potential contaminants at one location [13].

Stormwater runoff from the 'built' area of the DGR and the WRMA will be collected in a network of vegetated, trapezoidal drainage ditches.

The perimeter ditch system will discharge through a stormwater retention pond designed for the purposes of management of stormwater runoff water quality. The design basis for the on-site drainage system including the stormwater quality retention pond, drainage ditches, etc. is the 1:100 year 24 hour rainfall event [15].

The retention pond has been designed [15] based on the following basic criteria:

- Retaining the 6 hour, 25 mm design rainfall event for a period of 24 hours
- Safely passing the 1:100 year design rainfall event without overtopping of the dyke and erosion of the outlet system.

Water from the retention pond will then be discharged via a controlled outlet into the existing drainage ditch network along Interconnect Road and ultimately to Lake Huron through the MacPherson North subcatchment.

The shaft pad area of the DGR has a preliminary design elevation of 186.0 m [15].

3.3.2 Hydrologic Model Development

The overall watershed delineation for drainage areas internal to the Bruce nuclear site was detailed previously. Subcatchment delineation for the purposes of hydrologic model development and runoff computation is outlined in Figure 5 for drainage areas internal to the Bruce nuclear site. From the site reconnaissance visit conducted in April 2010, the following drainage areas were not considered to be relevant to the present assessment:

- Bruce B South and North (B1 and B2)
- Douglas Pt South and North (D1 and D2)
- MacPherson Bay North (M2).

This is due primarily to their small drainage areas, local topography precluding trans-boundary spills and direct outlets to Lake Huron.

Figure 5. Drainage areas internal to the Bruce nuclear site

3.3.3 Critical Probable Maximum Precipitation Duration

A critical PMP duration analysis was completed for the site specific flood risk assessment. From this analysis it is concluded that the 1 hr duration is critical for this drainage area. Therefore, the base PMP case for analysis of site specific PMF conditions is the 1 hr PMP based on [4].

3.3.4 Hydraulic Model Development

The hydraulic modeling approach for DGR drainage features is similar to that described for the riverine analysis. The computer simulation program, HEC-RAS, was also used for this analysis. The HEC-RAS models developed for this assessment were based on the following:

- The cross section data was abstracted from available 0.5m LIDAR contour data supplemented with Site Grading and Drainage data, provided by OPG

3.3.5 Derivation of Probable Maximum Flood

PMF water surface elevations were computed based on the 1 hr PMP as defined from (OMNR 2006) with a starting Lake Huron water surface elevation of 176.43m (mean annual).

Three scenarios were assessed as follows.

- Only confined channel flow:
  - For this scenario the PMF was confined to the defined sections of the hydraulic model. No flow was allowed to leave the system (i.e., spill out of the channel thereby reducing downstream flows). This represents the maximum potential PMF scenario. Existing culverts at Interconnect Road and elsewhere are included in this scenario
- With potential spill zones:
  - This scenario builds on scenario #1 by adding four potential spill zones (as illustrated in Figure 6). For this scenario the PMF was allowed to spill out of the defined channel/ditch where computed water levels exceeded the maximum section overbank elevation. Spills out of the channel have the effect of reducing downstream channel flows and possibly reducing computed water levels both downstream and upstream of the spill location
- With potential spill zones and internal DGR culvert network:
  - This scenario builds on scenario #2 by adding an internal DGR culvert network at roadway channel/ditch crossings as identified in PSR [15]. The PSR did not provide specific information with regard to design of the culvert crossings, only locations. As culverts are not typically designed to accommodate the PMF it was initially assumed for the purposes of this assessment that the culverts were sized to accommodate the 100 year flood while maintaining freeboard requirements at the crossings. Culvert inverts were defined as equal to the channel bottom. At some locations this culvert configuration was not possible due to insufficient channel depth. In these locations a smaller culvert was modelled maintaining freeboard and channel invert assumptions

3.3.6 Assessment of Potential Flooding due to Direct Rainfall at the Bruce DGR Site

At the time of this assessment the detailed design of the facility was not completed. However, a preliminary design elevation of 186 m was established for critical features at the DGR site relevant to this flood risk assessment including the main shaft, intake and exhaust plenums and ventilation shaft.

It was determined through this assessment that computed PMF elevations exceeded 186m to a maximum computed water surface elevation of 186.86 m (for scenario #1), at a number of locations around the operational area of the DGR site. Similarly, results were computed for scenario #3 with a maximum computed water surface elevation of 186.58 m (Figure 6).

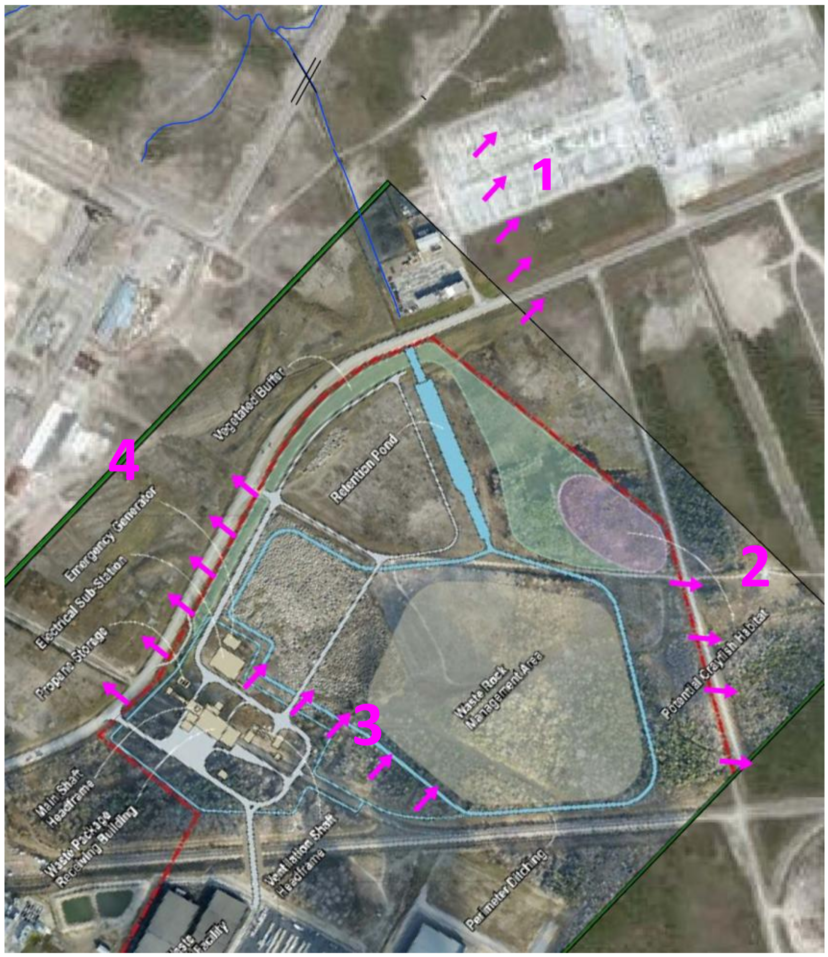

Figure 6. Hydraulic modelling scenarios 2 and 3 - potential spill zones

The conclusion from this assessment is that a PMP event occurring across the DGR site has the potential to generate flood levels in excess of the DGR site preliminary design elevation of 186 m.

The following comments regarding this assessment are relevant:

- The DGR stormwater drainage design, reflected in this assessment, was not at the detailed design phase. As such, some aspects of the drainage infrastructure, such as culverts, have are as yet to be quantified/sized. Therefore, assumptions, in this regard, were required to facilitate this assessment

- A conservative approach to the hydraulic analysis was adopted for this project. As such, the resultant computed PMF water levels in proximity to the DGR operational area are considered to be conservative
- The potential for floodwater entering the underground works can be mitigated by setting collar elevations at the maximum computed PMF elevation plus an appropriate freeboard
- Increasing the general DGR operational site elevation (presently set at 186m) is not anticipated to result in higher computed PMF water levels
- Increasing the elevation/grade of Interconnecting Road in the vicinity of the DGR site is anticipated to increase PMF water levels across the DGR site
- If the final design for drainage works (e.g. ditches and culverts) is of a similar nature to that depicted in the Preliminary Safety Report, then computed PMF water levels will be similar to that documented in this report. "Upsized" drainage infrastructure could, however, potentially have a positive influence on computed PMF water levels (i.e., lower water level) and conversely downsizing could have a negative impact.

3.3.7 Sensitivity Analysis

A sensitivity analysis (similar to that completed for the riverine flooding assessment) of peak flows resulting from a 1hr PMP and Lake Huron starting water surface elevations was conducted for the DGR site specific analysis for scenario #1. The following conclusions are apparent from this sensitivity analysis:

- Computed water surface elevations, for both the drainage features around the DGR site across the three definitions of PMP (i.e., [3], [4], [12]) discussed in this report, are within a few centimetres (max 32 cm representing the maximum difference between computed water surface elevations for the three PMP definitions) of the base scenario (i.e., [4]) with the mean annual lake level being used as the starting water surface elevation at Lake Huron. The difference in computed water surface elevations between the base scenario and a PMP definition from [12] is negligible
- Computed water surface elevations at Lake Huron in the discharge ditch are governed by flows in the river and not by lake levels. As such, Lake Huron starting water surface elevations do not influence upstream computed water surface elevations for the drainage features associated with the DGR site

This sensitivity analysis reinforces the conclusion that a PMP event occurring across the DGR site has the potential to generate flood levels in excess of 186m (i.e., the DGR site preliminary design elevation).

4. COASTAL FLOOD HAZARD

The estimation of lake flooding for the Bruce nuclear site considered potential extreme water levels in Lake Huron, storm surge and seiche, and wind waves, and tsunamis.

4.1 WATER LEVELS IN LAKE HURON

Lake Huron, which contains Georgian Bay, is the second largest of the Great Lakes by surface area and third largest by volume. The lake is 332 km in length, 245 km in width, with an average depth of 59 m and maximum depth of 229 m. Lake Huron has a chart datum of 176 m IGLD 1985.

Lake levels are variable both in the short-term and long-term and are influenced by natural causes and human intervention. Natural causes by far induce the greatest magnitude of change and include precipitation, evaporation, inflow and outflow, wind, atmospheric pressure, or high water level, whereas human-induced changes include diversions, and water control structures.

Lake Huron regulation has been provided since 1921 by the International Lake Superior Board of Control Joint Commission [16]. Objectives of the regulation plan include determining a flow that attempts to keep the levels of Lake Superior, Michigan and Huron within their respective historical levels and tries to prevent the level of Lake Superior from rising above or falling below certain water levels. Even with regulation, full control of lake levels is not possible: precipitation over the lake, evaporation, and runoff, cannot be controlled, nor can they be accurately predicted over the long-term. These are the major factors affecting the water supply to the Great Lakes.

While water level recording began in the 1840s and systematic records from the Great Lakes commenced in 1860, the current network of multiple gages on each of the lakes came into operation in 1918. Figure 7 illustrates the annual and longer term variations for Lake Huron.

Mean levels range from 175.7 to 177.3 m, and average 174.7 m IGLD 1985. There is an annual seasonal cycle, with maximums in July, and minimums in February. A historical maximum: of 177.5 m, 1.5 m above chart datum, was measured in October 1986. Over the past 10 years the range has been 175.7 m to 176.4 m, or 0.3 m below to 0.4 m above chart datum.

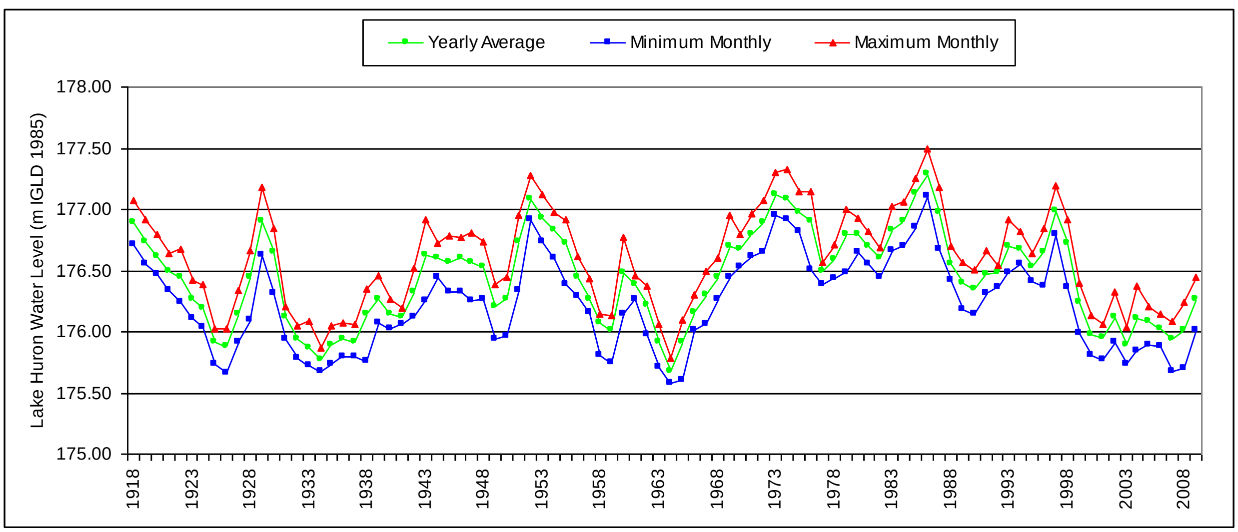

Figure 7. Lake Huron water levels 1918-2009

An assessment of possible future lake levels including potential climate change effects indicates that future Great Lakes water levels are uncertain, though in a survey completed there is a preponderance of predicted decreases in lake levels versus lake level increases. The predicted ranges are on the order of a 0.5 m rise to a 1.5 m fall.

4.2 FLOODING BY STORM SURGE AND SEICHE

Given the location of the site on the shore of Lake Huron, potential flooding by storm surge and seiche was taken into consideration in the flood analysis.

Storm surge is a pile-up of water at the coast due to a storm and resulting in higher than normal water levels. The strong winds can 'setup' a higher level by moving water up against the coast. Another factor is that low air pressure during storms further raises water levels at the coast. The underwater slope of the coast also influences how high a surge can grow locally, e.g., surges are higher on gently sloping coasts than on steep coasts.

Another phenomenon influencing lake levels is the seiche effect caused by both atmospheric pressure and wind-induced water level changes. The seiche effect can be described as the return flow of water from the lake end with an elevated level to the depressed end. This process can result in oscillations of lake levels similar to the sloshing action that occurs in an enclosed tank of water. During seiche effects any given shoreline location may experience alternate periods of elevated and depressed levels over a period of several hours with the initial seiche levels being at much lower elevations than the original wind setup.

An in-house AMEC numerical model of the hydrodynamics of Lake Huron was developed to assess the potential for generation of surge and seiche in response to extreme severe weather systems tracking through the region. The hydrodynamic model, HYDRO2D [17], represents the depth-averaged (two dimensional) currents and variations in water level that result from wind and atmospheric pressure forcing. It is based on the depth-averaged momentum and continuity equations (with usual Boussinesq hydrostatic and incompressibility approximations). The model includes the non-linear advection term, as well as the Coriolis acceleration and has standard quadratic bottom friction and second order lateral diffusion of momentum. For the assessment of storm effects, the forcing terms are the atmospheric pressure gradient and the wind stress.

Idealized atmospheric pressure and wind fields were used to represent the main types of severe storms that can affect Lake Huron. Characteristics of the storms are defined by the following parameters: low pressure at the centre of the storm, high pressure surrounding the storm, radius of the storm, maximum wind speed, angle by which the wind veers towards the centre of the storm, storm track direction, speed at which the storm travels, and section of the Lake over which the centre of the storm passes. Storm types selected included Post-Tropical Storms (such as Hurricane Hazel in 1954), Alberta Clippers (compact fast moving winter storms with sustained winds up to about 80 km/h and a pressure drop of about 970 mb), Colorado Lows, and Gulf Lows.

The model was run for a large number of combinations of the parameters representing the characteristics of the idealized storms. Analysis of the results provides good insight on the response of Lake Huron to various weather systems with different characteristics and allows determination of which storms, typical of the region, are the most likely to result in significant surge and possible subsequent seiche. Deeper depressions and stronger winds produce a stronger response in the model.

Each model run simulates the response of Lake Huron to a given storm for a period of 24 hours, allowing for development of the surge forced by the storm as it approaches the region and tracks across the Lake, and subsequent free response in the form of seiche as the storm leaves the region. Highest water levels attained at Bruce during each simulation generally range from about 0.15 m to 1.27 m.

Overall, the highest levels at Bruce are attained at the peak of the surge during storms that track close to the site. In these cases, the subsequent seiche in Lake Huron produces lower levels at the site than surge levels. Only in a few cases where the centre of the storm does not come close to Bruce, and therefore cannot produce a significant surge at the site, is the highest level occurring during subsequent seiche and is quite a bit lower than the maximum surge level. This is consistent with the fact that Bruce is in the central region of the Lake where seiche levels are expected to be much smaller than the levels occurring at the extremities of the Lake, or in Saginaw Bay.

The maximum water level at the Bruce nuclear site is 1.3 m during a surge generated by an Alberta Clipper from the west-northwest. This compact type of storm travelling over the north western part of the Lake towards the Bruce nuclear site is the most efficient for surge development along the shore in the region around the Bruce nuclear site. The water level anomaly over Lake Huron at the time of the peak surge at the Bruce nuclear site during this Alberta Clipper is presented in Figure 8.

4.3 FLOODING BY WAVES

Given the location of the Bruce nuclear site (and DGR area located immediately inland) on the shore of Lake Huron, wind-generated water waves (surface gravity waves) were taken into consideration in this assessment of potential lake flooding.

4.3.1 Shoreline Characteristics

The ground surface elevation on the Bruce nuclear site generally rises over distances up to 100 m from the lake to about elevation 179 m. This is followed by a flatter approach to the DGR project site, which is about 975 to 2500 m inland, where elevations are in the range of 181 to 187 m above chart datum IGLD 1985.

A north to south vertical cross-section of the site topography from the lake shoreline near MacPherson Bay to the southwestern boundary of the DGR operational area was taken as representing the shortest distance from the lake, and from inspection of site topographic maps, the profile was deemed representative of the lowest slope approaching the DGR from the lake, and thus a suitable shoreline slope for estimation of wave uprush.

A Lake Huron wind and wave hindcast, developed by WIS of the Office, Chief of Engineers, U.S. Army Corps of Engineers (USACE) [18] was selected to enable the assessment of wave flooding potential at the Bruce nuclear site. The WIS model grid consists of a 10 nautical mile (about 18 km) grid spanning 49 locations about the Lake Huron shoreline. The hindcast consists of three hourly significant wave height, peak wave period, mean wave direction, and wind speed, for 32 years (1956 to 1987). Deep water was assumed across the entire grid; therefore, no bathymetry was input. The winds were interpolated over the grid at 3-hour intervals to force a spectral wave model and verifications were made using long-term deployment NOAA buoys.

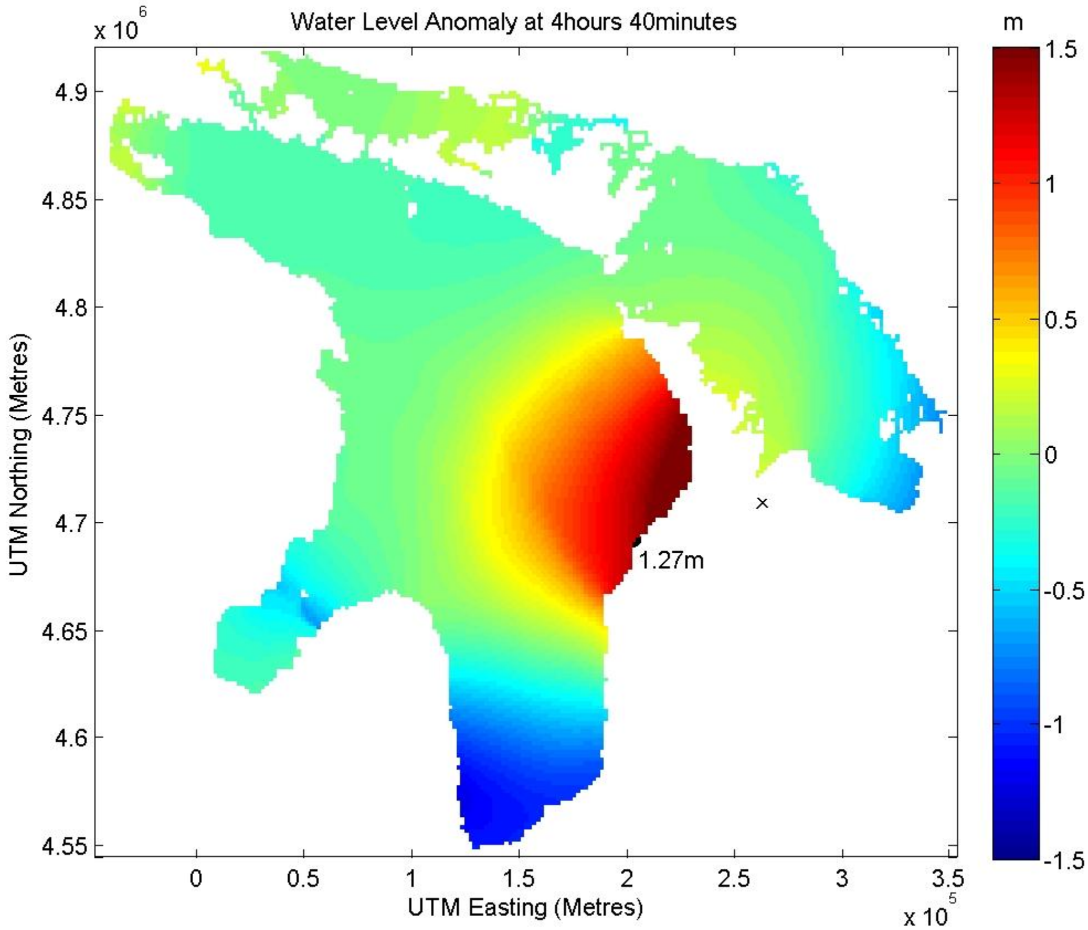

Figure 8. Maximum surge at southern end of Lake Huron

The wave model included the time-dependent wave action balance equation, wave growth based on the combined Phillips and Miles mechanism, weak nonlinear wave-wave interaction, equilibrium JONSWAP and Kitaigorodskii spectra and linear refraction, as well as shoaling and dissipation terms.

The SWAN wave model was developed by Holthuijsen et al. [19] and utilizes a finite difference scheme to compute random, short-crested, wind-generated waves and allows for spectral wave input at specified boundaries. The action density spectrum (equal to the energy spectrum divided by the relative frequency) is used since it is a quantity that is conserved in the presence of currents. SWAN incorporates physical processes such as wave propagation, wave generation by wind, white-capping, shoaling, wave breaking, bottom friction, reflection, subsea obstacles, wave set-up and wave-wave interactions in its computations. SWAN computes the wave field and other wave parameters over a specified range of geographical space, time, wave frequencies and directions. The model inputs include the NOAA gridded bathymetry and topography [20], stillwater and surge levels, and the WIS wind and wave hindcast.

4.3.2 Wave Hindcast Extreme Analysis

Extreme wave estimates were compiled using the 32 year (1956 to 1987) WIS node #H0043 data record. For each year of the node, the maximum value of significant wave height, Hs, was selected. A Gumbel cumulative probability distribution was fitted to the 32 points using the maximum likelihood algorithm [21]. Using the fitted distribution, Hs values for selected return periods from one to 100 years have been estimated. The associated peak wave period, Tp, is the period corresponding to each maximum Hs selected.

Estimated offshore (WIS hindcast) 100-year maximum wave heights range from 9.1 to 10.1 m offshore the site: Hs=10.1 m, Tp= 13.2s (from NW) as input to wave propagation/uprush models.

Two lake water levels considered on which waves are added. A 500-year water level of 178.4 m, and a 500-year water level plus probable maximum storm surge of 1.3 m yielding 179.7 m. These resulted in nearshore maximum wave height estimates of 5.5 and 6.0 m for the two lake levels, and maximum wave setup estimates of 0.475 m and 0.4 m for the two lake levels. Waves setup is the superelevation of mean water level caused by wave action (additional changes in water level may include wind setup or tide). The total water depth is a sum of still-water depth and setup. Higher water level results in less of a wave setup with waves breaking later.

Figure 9 illustrates the wave height and direction (companion figures of wave setup were also prepared) predictions at the Bruce site for the higher 500-year water level plus probable maximum storm surge value of 179.7 m.

There are a few conclusions to note regarding the results from the SWAN simulations. In Figures 9 the coastline (defined at 176 m, IGLD 1985) is presented as a reference to the current mean lake water level, while the areas in white represent the dry areas in the extreme scenario considered here. Thus, when the 500 year still lake water level and the water level setup due to waves (up to ~0.4m) are included, the SWAN model indicates some level of flooding along the shoreline of the Bruce nuclear site, with the most severe levels reaching the northern portion of the DGR Area, though not the operational area, from the direction of MacPherson Bay. Since the topography of the Bruce nuclear site above the mean lake water level is relatively crude (from the NOAA bathymetry compared with more recent high resolution LIDAR elevation measurements) and does not include man-made structures, these results are to be taken only as a general indication of the areas along the shoreline that are exposed to risk of flooding.

Wave uprush was estimated on the shoreline beaches at the Bruce site using a methodology accepted for Great Lakes flood hazard.

The maximum uprush estimates for the two scenarios are 1.51 m and 1.6 m, respectively, conservatively considering a sandy slope. Since the surface material is mixed sand and cobble, it is expected that the maximum realized values should fall between the values calculated for each surface in each scenario. For any detailed analysis of flooding impact on the infrastructure in the area these values together with the maximum water level estimates, storm surge and seiche levels and the wave setup levels can be considered.

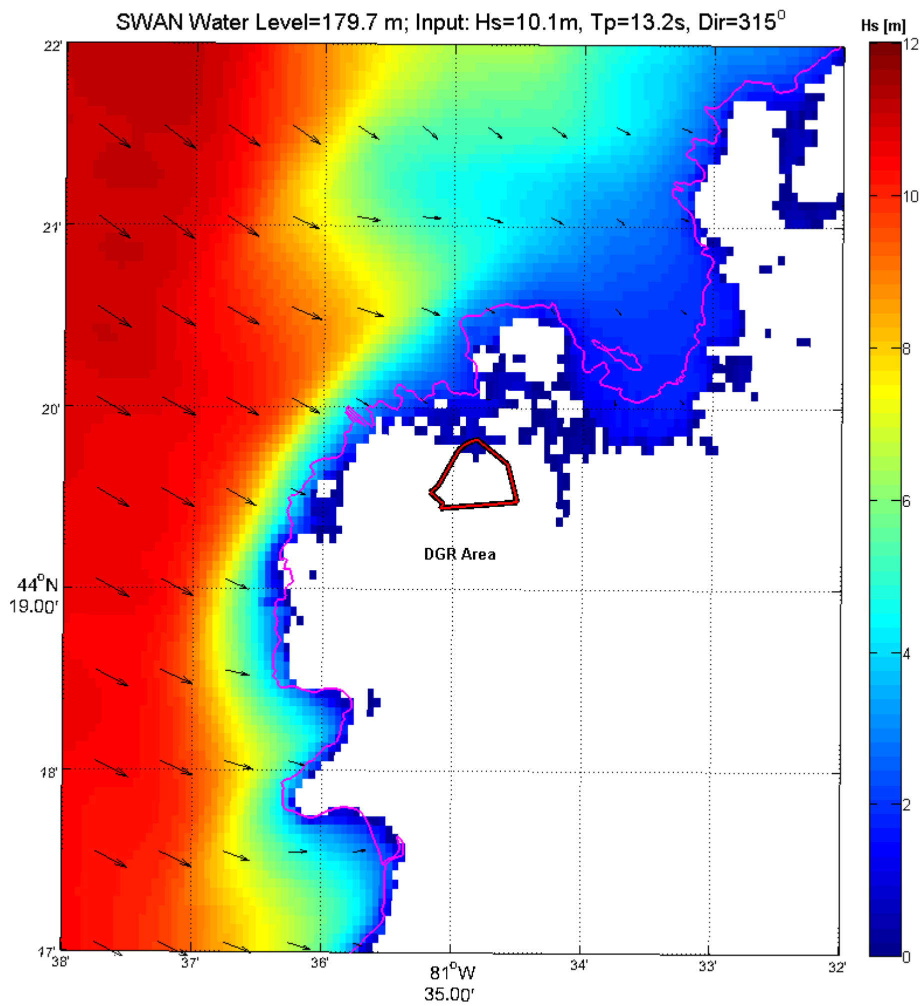

Figure 9. SWAN wave height and direction propagation result over extreme still lake water level, including storm surge, of 179.7 m above chart datum IGLD 1985

In terms of potential maximum inundation or horizontal extent, the extreme prediction of 181.8 m (176 m chart datum + 2.4 m 500-year lake level offset +1.3 m storm surge + 0.475 m wave setup +1.6 m uprush), along the north-south section considered, translates to a distance of approximately 500 to 550 m inland.

The 181.8 m flood level prediction is the sum of a number of extreme or maximum conditions which would behave on different time scales, thereby 'migitating' the flood level duration and magnitude. For example, the 500-year lake level offset of 178.4 m above chart datum IGLD 1985, 2.4 m above chart datum, would likely last for time scales of days to weeks. The predicted maximum storm surge of 1.3 m resulting from a passing severe Alberta Clipper storm would likely last for time scales of minutes to one or several hours. The wave flooding modelling showed significant wave height amounts of up to 6 m just 100 m from the shoreline. This translated into some 'wetting' of the northern tip of DGR area with wave heights close to zero and wave setups; however, predicted to be as high as about 48 cm for locations near the DGR stormwater management pond but distant from the operational area to the southwest. Finally, a wave uprush of an additional 1.6 m was estimated. This is a prediction of a top 2% uprush estimate value, so during the several hours that waves were most severe, about 2% of the time the uprush would be this large. In reality, the amount of uprush would vary with the range of wave heights seen during the storm. The uprush would oscillate between greater and lesser values, e.g., while a 6 m wave might produce a 1.6 m uprush, a 3 m wave might produce a 0.7 m uprush. The wave periods are on the order of 10 s. Such extreme wave setups and uprush as this would likely last, albeit with the noted rise and fall behaviour, for the storm duration for which the largest waves are produced, perhaps one to several hours. This discussion provides an indication of possible shoreline flooding events, again, as noted, estimated to occur within approximately 500 to 550 m inland, well-removed from the DGR operational area.

4.4 TSUNAMIS

A regional screening, which included review of the historical record and potential earthquake and landslide tsunamigenic sources, concluded that the Bruce nuclear site is not subject to tsunamis.

Tsunamis are long period gravity waves generated by seismic disturbances or landslides resulting in a sudden displacement of the water surface with the resulting wave energy spreading outwards across the ocean or lake at high speed. There is no record of tsunami occurrence in Lake Huron.

For consideration of the possible risk of tsunamis flooding for the Bruce Site, a high level tsunami hazard assessment was made based on the approach presented by U.S. Nuclear Regulatory Commission [22].

The first step was to assess whether the (Bruce) site is subject to tsunamis. The National Geophysical Data Center (NGDC) [23] and World Data Center (WDC) for Geophysics and Marine Geology: Historical Tsunami source and runup databases were searched. Seiches were the only credible entries.

The geological stability of Great Lakes region (largest measured seismic activities result in only small earthquakes typically of Magnitude 3 or 4 less than a Magnitude 6.5 or greater generally considered pre-requisite for a tsunami. There is a low risk of landslide based on Lake Huron shoreline slopes and light shoreline erosion potential.

A second step considering if the plant site (or DGR Area) might be affected by tsunamis was partially explored. While estimated with a high level of uncertainty, wave run up from a Lake Huron shore landslide-produced 'tsunami-type' wave of about 1-2 m together with wave uprush on shorelines with depths of about 5 to 20 m was found to be less than a combined 500-year water level plus extreme storm surge plus wind wave setup plus wind wave run-up, in other words, the horizontal extent of inundation caused by such an event would be less than the horizontal distance that the site (DGR area) is located from the coast.

5. MODIFICATION OF THE FLOOD HAZARD WITH TIME

5.1 Physical/Geographical Changes

Potential alteration of the flood hazard resulting from changes in the physical geography of a drainage basin, including the estuaries, changes to the offshore/lake bathymetry, coastal profile and catchment areas, and shoreline were considered; however, all are physically stable and there is no indication of any changes likely to occur with time.

5.2 Climate Change and the PMP

PMP estimation currently does not take into account the potential influences of a changing climate. Since the DGR has a long life span it is relevant to consider potential effects of climate change on estimates of Probable Maximum Precipitation.

Climate change could possibly impact PMP estimates in a number of ways. Firstly, as temperature increases, the capacity of the air to hold water vapour changes, and, secondly, the frequency of occurrence of extreme events changes [24]. Other influences may include storm types, depth-duration-area curves and relative storm efficiency [25].

The conclusions from the research and documentation reviewed for the DGR study concluded that there is no substantive basis for increasing current PMP estimates in order to account for climate change ([24], [25], [26]).

6. CONCLUSION AND RECOMMENDATION

Based on the assessment, there is no potential for lake or riverine based flooding and the DGR area is not affected by tsunamis or riverine flooding. However, a PMP event occurring directly at the DGR site has the potential to generate flood levels in excess of 186 m (the DGR site preliminary design elevation). The maximum water surface elevation was estimated to be about 186.6 m (i.e., maximum 60 cm PMF level) at a number of locations around the operational area of the DGR site based on scenario #3 of the evaluation which was based on general stormwater/channel ditch configurations, culverts internal to the DGR site and the allowance for out of channel spills. As such, it is recommended that future design efforts recognize and accommodate this potential flood hazard through conventional engineering means and methods.

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