January 23, 2023

Mr. Ed Lamb
Waterford Sand & Gravel Ltd.
70 Ewart Avenue, R. R. #8
Brantford, ON N3T 5M1

Re: Response to MNRF Comments
Proposed Law Quarry Extension
WSP Project No. 111-53023-11

Dear Mr. Lamb:

We are pleased to provide our response to comments on the Level 1 and 2 Water Report for the proposed Law Quarry Extension aggregate licence application.

The Level 1 and 2 Water Report prepared by WSP Canada Inc. was submitted as part of the ARA Licence Application package in June 2022. Comments related to the Level 1 and 2 Water Report were provided by the Ministry of Natural Resources and Forestry (MNRF) Aggregates Section in their correspondence dated January 9, 2023.

A copy of the MNRF comments (blue text) and our responses are provided below.

Hydrogeology

4. It is important to fully understand the degree of hydrological connectivity between the Wainfleet Wetland and groundwater. The report provides references to studies that indicate perched conditions at the Wainfleet Wetland. Please provide specifics of those studies including location of the monitoring wells used during studies and other relevant information. This is needed to ensure that the conclusions in the referenced reports are based on methodology adequately corresponding with the scale and location of the proposed expansion and are valid.

Concerns regarding potential groundwater interference between the Wainfleet Bog and the existing Law Quarry have a long history. A study was undertaken in 2002 by the National Water Resources Institute (NWRI) and Niagara Peninsula Conservation Authority (NPCA) (Crowe et al., 2002) to determine if there were any potential long-term impacts of the quarry dewatering on the Wainfleet Bog (see attached). As noted by Crowe et al. (2002) in the final sentence of the study abstract, “current quarry and future expansion will have minimal impact on the bog”, and we agree with this conclusion.

As shown on Figure 1 and Table 1 of the Crowe et al. (2002) study, a total of six (6) deep monitoring wells and seven (7) water table monitoring wells were installed within and around the Wainfleet Bog, including at one location between the existing quarry and the bog. Water level monitoring was completed for a period of at least

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three (3) years, and numerical groundwater modeling was completed to simulate the impacts of quarry dewatering on the bog water levels.

The Crowe et al. (2002) study was reviewed as part of the Level 1 and 2 Water Report study for the Law Quarry Extension, and the numerical groundwater modeling completed by WSP was consistent with the conclusions of the 2002 paper.

5. Please provide a map showing calculated drawdowns in the upper layers to visualize a real distribution of the drawdown. Further, please use 0.5 m drawdown as a cut off to produce the contours to better understand potential impacts to the water features located within the zone of influence.

Drawdown in the shallow bedrock aquifer is shown on **Figure 17A** (appended). The 0.5 m drawdown contour in the shallow bedrock aquifer extends on the order of 100 m or less from the proposed Licence boundary, hence it was not shown in a separate figure in the Level 1 and Level 2 Water Report.

Figures 17, H-10 and H-11, showing the drawdown in the shallow and deep bedrock for the Law Quarry extension and Reeb Quarry cumulative impacts scenarios, were also revised to show the 0.5 m drawdown contour as requested (appended).

The 0.5 m drawdown contour in these revised figures encompasses the Quarry Lakes to the south of the Site and Horseshoe Lake to the east. We note that these lake features were simulated in the predictive model scenarios and an impact assessment is provided in Section 3 of the Level 1 and Level 2 Water Report. The 0.5 m drawdown contour also encompasses additional potential groundwater users. The well interference mitigation plan provided in Section 4.3 of the Level 1 and 2 Water Report will address potential impacts to any additional water well users due to the proposed Law Quarry extension.

CLOSURE

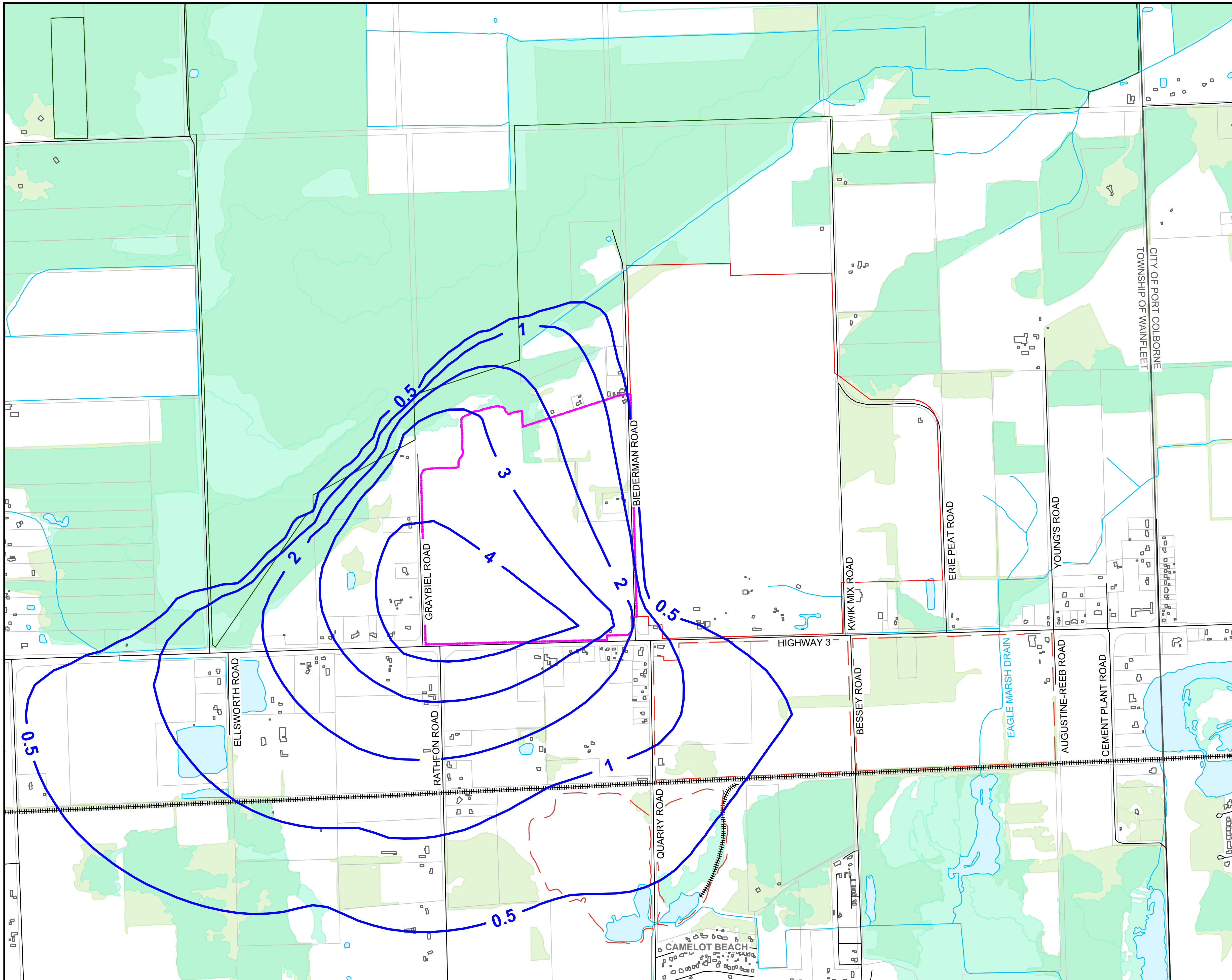
We trust that these responses and supporting information are sufficient for your needs. Please contact us if there are any further questions.

Yours truly,
WSP Canada Inc.

Kevin Fitzpatrick, P.Eng.
Senior Project Engineer, Earth & Environment

Leigh Davis, M.A.Sc., P.Eng.
Project Engineer, Earth & Environment

Attachments: **Figure 17 – Predicted Drawdown in Deeper Bedrock Units (revised)**
Figure 17A – Predicted Drawdown in Shallow Bedrock Units (new)
Figure H-10 – Cumulative Impacts at Full Quarry Development – Shallow Bedrock Aquifer (revised)
Figure H-11 – Cumulative Impacts at Full Quarry Development – Deeper Bedrock Units (revised)
Crowe et al., 2002. Impact of a Large Quarry on the Restoration of the Water Table at the Wainfleet Bog, Ontario, Canada.



LEGEND

- PROPOSED WEST EXTENSION
- EXISTING QUARRY LICENCE
- APPROXIMATE LAND PARCEL
- REEB QUARRY LICENCE
- WAINFLEET BOG CONSERVATION AREA
- WOODLOT
- WETLAND
- PERMANENT STREAM
- INTERMITTENT STREAM
- 1 SIMULATED DRAWDOWN CONTOURS, 1 m INTERVALS (m)

N

0 300 600 m

PREDICTED DRAWDOWN IN DEEPER BEDROCK UNITS

LEVEL 2 WATER STUDY REPORT
LAW QUARRY EXTENSION
WAINFLEET, ON
For Waterford Sand & Gravel Ltd.

DATE: JANUARY 2023	
PROJECT: 111-53023-06	
SCALE: 1 : 15,000	55 KING STREET, SUITE 700 ST. CATHARINES, ON L2R 3H5 T 905-687-1771 | F 905-687-1773 | www.wsp.com
DRAWN BY: JLD	FIGURE No: 17

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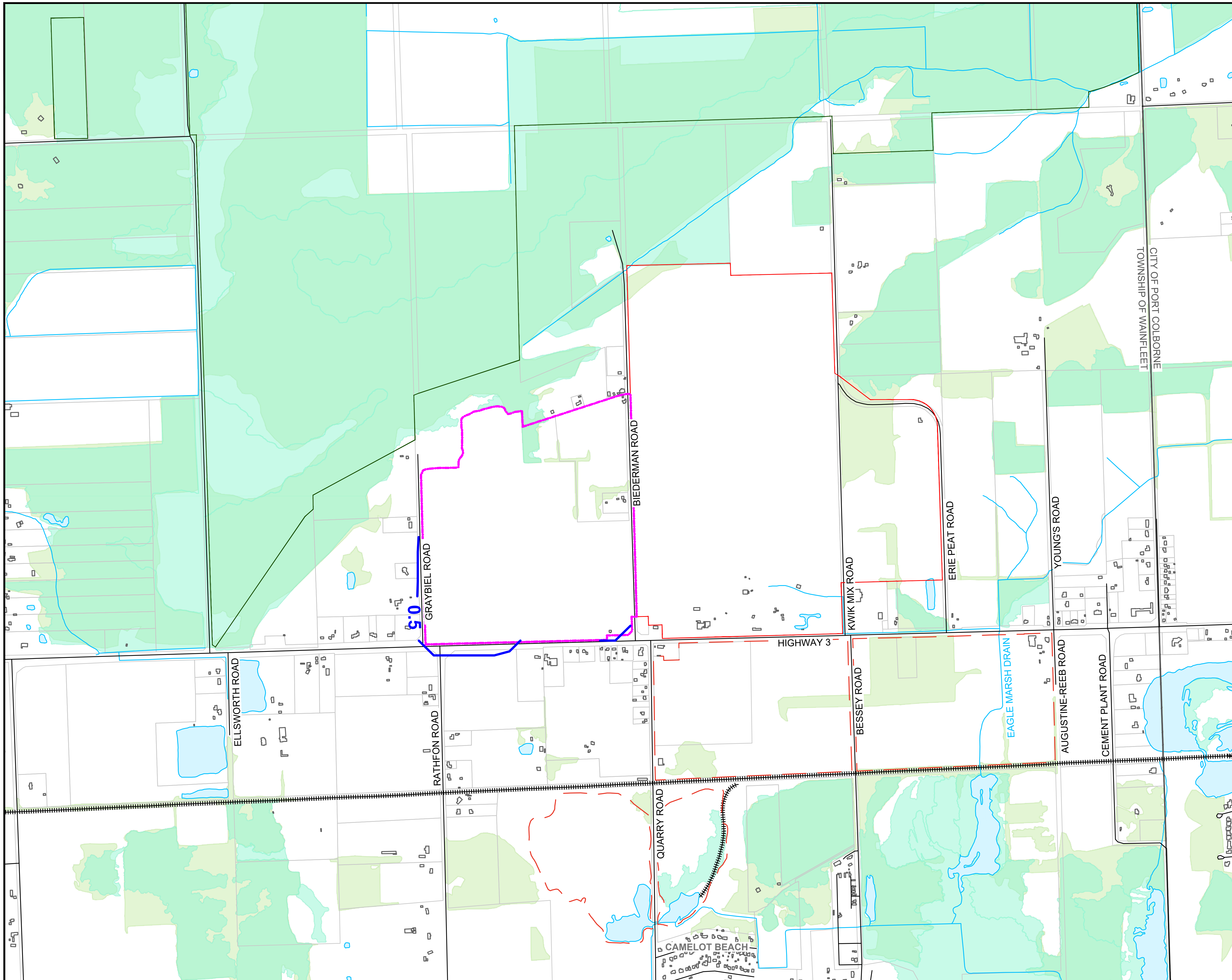

LEGEND

- PROPOSED WEST EXTENSION
- EXISTING QUARRY LICENCE
- APPROXIMATE LAND PARCEL
- REEB QUARRY LICENCE
- WAINFLEET BOG CONSERVATION AREA
- WOODLOT
- WETLAND
- PERMANENT STREAM
- INTERMITTENT STREAM
- 1 SIMULATED DRAWDOWN CONTOURS, 1 m INTERVALS (m)

PREDICTED DRAWDOWN IN SHALLOW BEDROCK UNITS

LEVEL 2 WATER STUDY REPORT
LAW QUARRY EXTENSION
WAINFLEET, ON
For Waterford Sand & Gravel Ltd.

DATE:	JANUARY 2023
PROJECT:	111-53023-06
SCALE:	1 : 15,000
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55 KING STREET, SUITE 700
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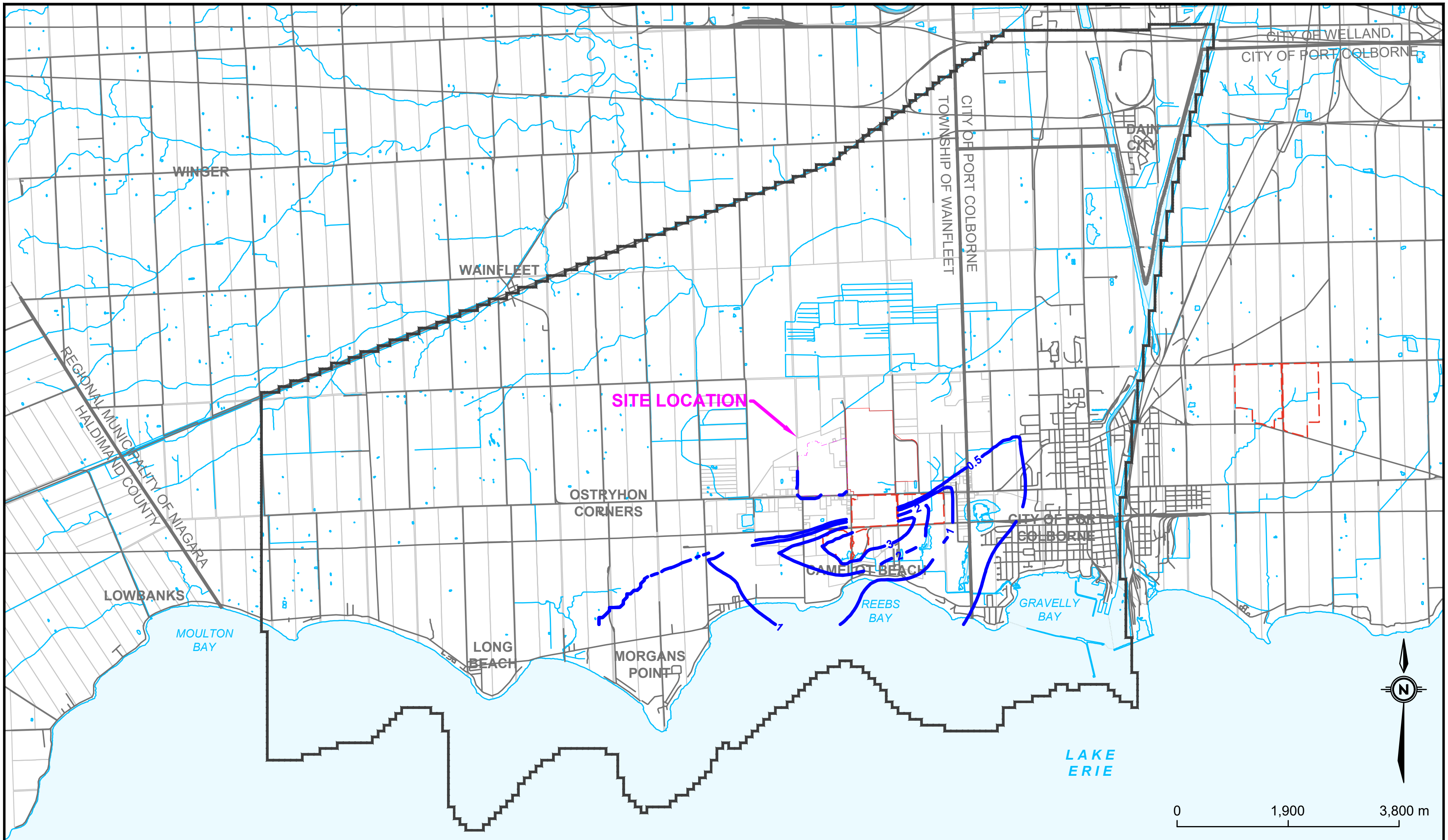
S:\PROJECTS\2011\111-53023 LAW QUARRY\06 2018 LEVEL 2 HYDROG REPORT\GRAPHICS\2023 REVISED FOR RESP TO MNRF COMMENTS\111-53023-06-F17-GWA.DWG



LEGEND

ACTIVE MODEL DOMAIN

1 SIMULATED DRAWDOWN CONTOURS, 1 m INTERVALS (m)

CUMULATIVE IMPACTS AT FULL QUARRY DEVELOPMENT - SHALLOW BEDROCK AQUIFER

NUMERICAL GROUNDWATER MODEL REPORT
LAW QUARRY EXTENSION
WAINFLEET, ON
For Waterford Sand & Gravel Ltd.

DATE:	JANUARY 2023
PROJECT:	111-53023-05
DRAWN BY:	JLD
SCALE:	1 : 95,000
FIGURE No:	H-10

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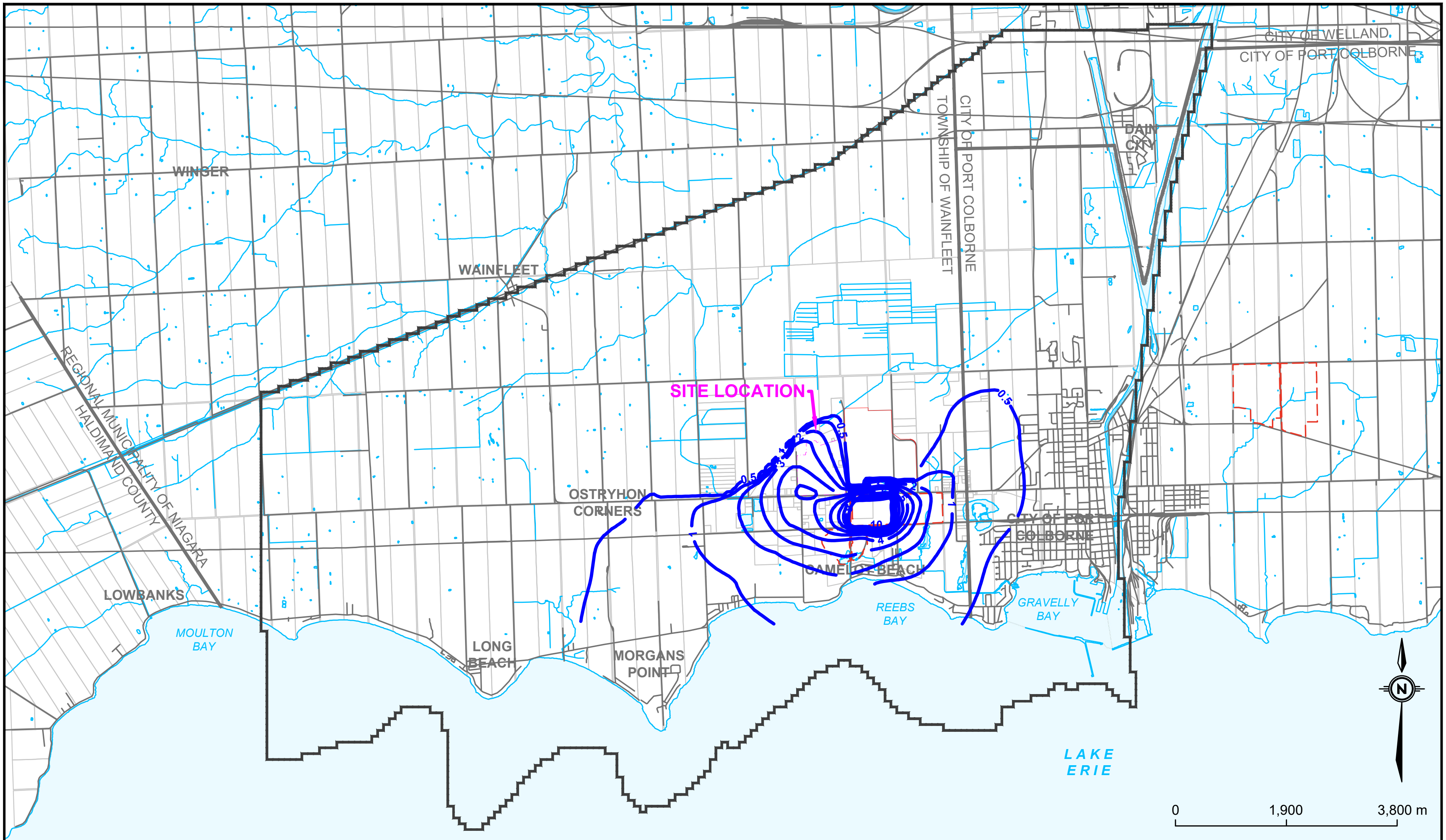

LEGEND

ACTIVE MODEL DOMAIN

1 SIMULATED DRAWDOWN CONTOURS, 1 m INTERVALS (m)

CUMULATIVE IMPACTS AT FULL QUARRY DEVELOPMENT - DEEPER BEDROCK UNITS

NUMERICAL GROUNDWATER MODEL REPORT
LAW QUARRY EXTENSION
WAINFLEET, ON
For Waterford Sand & Gravel Ltd.

DATE:	JANUARY 2023
PROJECT:	111-53023-05
DRAWN BY:	JLD
SCALE:	1 : 95,000
FIGURE No:	H-11

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IMPACT OF A LARGE QUARRY ON THE RESTORATION OF THE WATER TABLE AT THE WAINFLEET BOG, ONTARIO, CANADA

Allan S. Crowe, National Water Research Institute, Burlington, Ontario, Canada
Steve G. Shikaze, National Water Research Institute, Burlington, Ontario, Canada
James E. Smith, School of Geography and Geology, McMaster University, Hamilton, Ontario, Canada

ABSTRACT
Restoration of the Wainfleet Bog requires raising the water table 1-2 m to ground surface. This may not be possible because dewatering at a large quarry ~500 m to the south may introduce drainage from the bog. The base of the bog is separated from bedrock by ~25 m of clay, preventing significant leakage through its base. However, the southern end of the bog either abuts bedrock (Onondaga Escarpment) or is separated by a few metres of clay. Our studies indicate that these few metres of clay form an effective barrier to drainage. Even if the clay was absent, upon restoration, a lower water table caused by drainage along the escarpment-bog contact would extend <50 m into the bog. The large surface area of the bog, relative to the area of the contact means more water enters the bog as infiltration than as drainage along the contact. Hence, current quarry and future expansion will have minimal impact on the bog.

RÉSUMÉ
La restauration de la tourbière ombrotrophe Wainfleet requiert l'élévation du niveau de la nappe phréatique de 1 à 2 m sous la surface du sol. Cependant, cette tâche pourrait s'avérer impossible en raison du drainage effectué dans une grande carrière située à ~500 m plus au sud qui pourrait engendrer l'assèchement de la tourbière. Le fond de la tourbière est séparé du substrat rocheux par environ 25 m d'argile, lesquels préviennent une perte d'eau significative par le fond. Cependant, la limite sud de la tourbière est soit en contact direct avec le substrat rocheux (l'affleurement Onondaga) ou séparée par quelques mètres d'argile. Nos études montrent que ces quelques mètres d'argile représentent une barrière efficace à l'écoulement. Du point de vue de la restauration, même s'il n'y avait pas d'argile, l'impact du drainage de la carrière s'étendrait à moins de 100 m à l'intérieur de la tourbière. Le rapport entre la superficie entière de la tourbière et celle couverte par le contact affleurement/tourbière signifie globalement un apport d'eau plus important que les pertes d'eau dues au drainage de la carrière. Ainsi, l'exploitation actuelle et future de la carrière aura un impact minimal sur le niveau de l'eau dans la tourbière.

1. BACKGROUND

The Wainfleet Bog, located in the Niagara Peninsula near Port Colborne (Fig. 1), is the largest remaining bog in Southern Ontario (Frohlich, 1997). Since the early 1800's, human activities have resulted in a considerable decrease in the size of the bog. The expansion of agricultural lands into the bog and peat extraction from the bog have occurred along with the construction of numerous drainage canals around the periphery of the existing bog and within the bog itself. These drainage canals have resulted in extensive changes to the hydrology and hydrogeology of the Wainfleet Bog, as well as dramatic changes to its vegetative communities.

The Niagara Peninsula Conservation Authority (NPCA), with support from the Ontario Ministry of Natural Resources, and the Nature Conservancy of Canada is currently undertaking a long-term restoration program to improve the degraded habitat and vegetative community within the current boundaries of the Wainfleet Bog (Frohlich, 1997). An important component of the restoration program focuses on the hydrology and hydrogeology of the bog, and the need to raise the water table within the bog to near ground surface or 1-2 m.

A important feature of the area which could limit the ability of the water table within the bog to rise is a large quarry located on the Onondaga Escarpment. This quarry produces crushed stone from bedrock and is located about 500 m south of the Bog. The quarry is approximately 1.2 km (N-S) by 0.8 km (E-W) by 24 m deep. Quarry operations require dewatering and this has lowered regional groundwater levels within the highly fractured bedrock to a distance of several kilometres from the quarry.

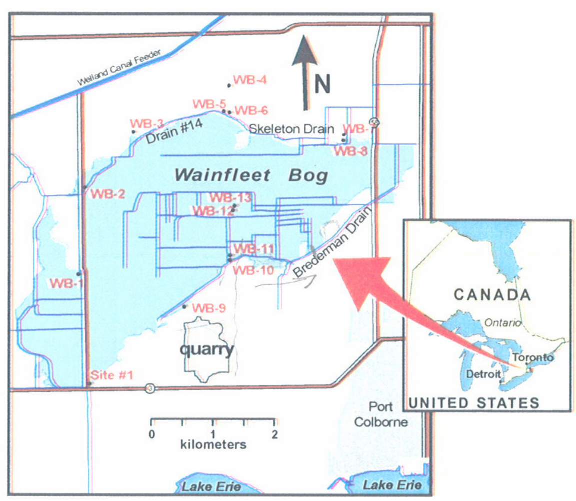

Figure 1. Location of the Wainfleet Bog, monitoring wells, and drainage ditches.

The objectives of this study are to determine:

- the hydrogeological connection between the quarry and the Wainfleet Bog;
- if current dewatering activities at the quarry will limit the ability of the NPCA to restore (raise) the water table within the Wainfleet Bog by 1 to 2 m; and
- if future quarry expansion will adversely affect the hydrology of a restored Wainfleet Bog.

2. FIELD INVESTIGATION

During June 1999, six deep piezometers and seven shallow water table wells were installed within the bog and around its perimeter using the National Water Research Institute (NWRI) drilling rig and drilling crew. The purpose was to determine the local hydrogeological system within the Bog and its relationship to the regional groundwater flow regime. In addition, one deep test hole was drilled to a depth of 100 feet, but a well was not completed here. Two water table wells (WB#10, WB#12) were installed within the bog. All other water table wells were installed either north or south of the bog's perimeter drain. The location of all monitoring wells is shown on Figure 1, and details listed in Table 1.

Table 1. Monitoring Wells at the Wainfleet Bog

Well #	well type	total depth (m)	bedrock depth (m)	screen length (m)	screened sediments
WB#1	piez.	28.0	28.0	1.5	gravel
WB#2	piez.	29.9	29.9	1.5	gravel
WB#3	w.t.	6.1	-	3.0	clay
WB#4	w.t.	6.1	-	3.0	clay
WB#5	piez.	24.7	24.7	1.5	gravel
WB#6	w.t.	7.6	-	3.0	clay
WB#7	piez.	24.4	24.4	3.0	gravel
WB#8	w.t.	4.9	-	3.0	clay
WB#9	w.t.	5.5	-	3.0	clay
WB#10	w.t.	3.4	3.4	1.5	clay
WB#11	piez.	20.1	20.1	1.5	gravel
WB#12	w.t.	2.1	-	1.5	peat
WB#13	piez.	24.1	24.1	1.5	gravel
WB#14	w.t.	2.3	-	1.5	peat
WB#15	w.t.	2.4	-	1.5	peat

Both the water table wells and the deep piezometers were installed with 1" ID PVC casing and screen, except WB#9, which was installed with 1.5" ID casing and screen. All casing and screen were screwed together. A sand pack was placed from the base of the screen to about 2' above the top of the screen. Two bags of bentonite ("Well Seal") were inserted above the sand. Water table wells installed within the bog were set approximately 0.3 m into the clay beneath the peat and completed with a 3.0 m length of screen from the base of the peat. Water table wells outside the bog were completed such that a 3.0 m screen intersected the water table. Deep piezometers were completed with a 1.5 m screen within a gravel deposit located immediately above the bedrock and below the clay. Steel well protectors cover all wells. Wells were located using GPS. Water levels are monitored monthly from June 1999 to present.

2.1 Geological Setting

A major geological feature to the immediate south of the Wainfleet Bog is the Onondaga Escarpment (Fig. 2). The escarpment is comprised of a cap of limestone of the Onondaga and Bois Blanc Formations overlying dolostone of the Bertie Formation and alternating shale and dolostone of the Salina Formation (Chapman and Putman, 1973). These units exhibit considerable fracturing along bedding planes and joints which dip near vertical (Gartner Lee Assoc., 1979). Quarrying occurs within the fractured limestone and dolostone of the Bois Blanc and Bertie Formations. The escarpment trends northeast-southwest, with a north-facing scarp. Very little of the face of the escarpment is exposed because the region is buried by a regional extensive deposit of till and lacustrine sediments.

Data obtained from this drilling/well installation program provided detailed information on the glacial sediments in and around the Wainfleet Bog. Bedrock is covered by extensive deposits of clay and till known as the Haldiman clay plain (Chapman and Putman, 1973). In the vicinity of the Wainfleet Bog, the surface of the Haldiman clay plain, is essentially flat due to being submerged in glacial Lake Warren. As a result, the depth to bedrock is 0 to 2 m south of the Onondaga Escarpment and 20 to 40 m north of the escarpment (Figure 3). A thick, ~15 m deposit of soft grey clay overlies ~13 m of a soft brownish clay.

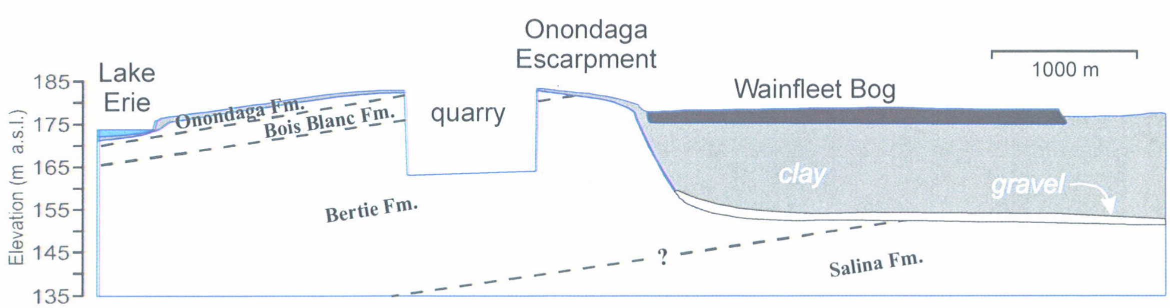

Figure 2. South to north geological cross section from Lake Erie, through the quarry and the Wainfleet Bog.

Underlying the clay below the Wainfleet Bog, and immediately on bedrock is a deposit of gravel. This gravel is between 0.5 m and 5 m thick (Fig. 3). It was probably deposited in the post-glacial bedrock channel trending along the base of the escarpment.

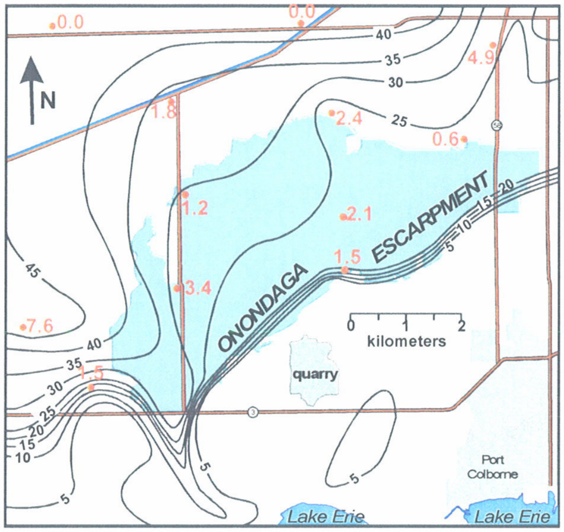

Figure 3. Contours of thickness of glacial sediments, and the thickness of gravel on bedrock at specific wells

2.2 Hydrology

The Wainfleet Bog was created as an accumulation of water within a surface depression on the poorly drained Haldimand clay plain adjacent to the Onondaga Escarpment. The presence of the escarpment impeded the southward drainage of this water and subsequent vegetative successions during the past 5,000 years, and eventually led to the development of the bog (Frohlich, 1997).

There is no natural surface water drainage system connected to the bog. With the introduction of drainage ditches throughout the region during the past century, the source of water within the bog remains principally precipitation. However water is now removed from the bog through three drains (the Biederman Drain, the Skeleton Drain, and Drain #14 (see Fig. 1)), as well as groundwater flow, and evapotranspiration.

The mean daily temperatures within the region range from a minimum of -8.2°C during January to a maximum of 27.4°C duringn July. The average annual precipitation is approximately 730 mm, with most of this occurring during the spring (March-May). The mean annual snowfall is approximately 1770 mm. During 2000, the total annual precipitation was 894 mm, while average daily January minimum and July maximum temperatures were -9.5 °C and 24.9 °C, respectively.

2.3 Hydrogeology

The field program undertaken for this study has revealed that three separate and distinct groundwater flow systems are present within the Wainfleet Bog area. A shallow perched or water table regime exists within the bog. Here, the depth to the water table is relatively shallow, varying from 0 to 2.5 m throughout the bog, and the water table can fluctuate by as much as 1.5 m seasonally. The water table is primarily affected by infiltration of precipitation and snow melt, evapotranspiration, and the internal and perimeter drainage ditches. The elevation of the water table (WB#10 and WB#12) within the bog is higher than the water table outside the bog (Fig 4). Groundwater within the bog flows from the central portion of the bog towards the surrounding drainage ditches, and is affected by the major connected drainage canals within the bog and the spacing of these internal drains (Crowe et al., 2000). The perimeter ditches around the bog appear to be effective in separating groundwater conditions within the bog from those in the surrounding farmland.

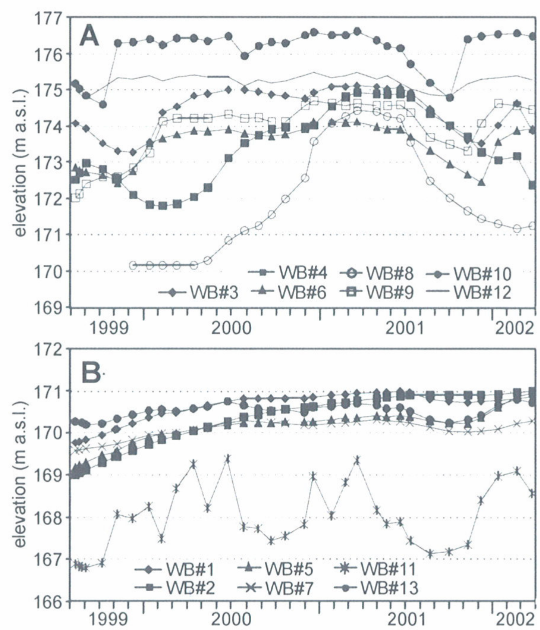

Figure 4. Water levels measured in (A) water table wells and (B) deep piezometers.

A shallow and perched groundwater flow system also exists within the clay of the surrounding farmland. The elevation of the water table varies considerably more than the water table within the bog (Fig. 4), fluctuating by up to 4.5 m. This water table is also affected by infiltration of precipitation and snow melt, evapotranspiration, and drainage ditches.

A deep groundwater flow system has been identified within the gravel unit which lies on the bedrock. The hydraulic head within this unit at the Wainfleet Bog is 3-6 m lower that the elevation of the water table (Fig. 4). The hydraulic heads of the deeper groundwater flow regime generally show considerably less range and variability than the water table. It is suspected that there is a strong connection between this basal gravel unit and the underlying fractured bedrock.

Dewatering within the large quarry to the south of the Wainfleet Bog has had a major impact on hydraulic head and the direction of groundwater flow within the bedrock. Previous studies (Gartner Lee Assoc, 1979, Jackman, 1980) have shown that dewatering at the quarry has reduced the elevation of hydraulic heads within the bedrock by about 5 m several kilometres northeast of the quarry. Hydraulic heads within the quarry have been lowered to the base of the quarry or 18 m. These studies did not report the extent of drawdown in the bedrock beneath, or to the north of, the Wainfleet Bog. But the present monitoring program shows that only the well closest to the quarry (WB#11) appears to be significantly affected by the quarry dewatering. Hydraulic head in the other deep wells are all at essentially the same elevation and follow the same long-term trends.

Prior to the introduction of the quarry, the Onondaga Escarpment acted as a groundwater divide with flow north and south from the escarpment. In response to dewatering, groundwater now flows towards the quarry from all directions (Gartner Lee Assoc., 1979, Jackman, 1980). However, present data indicates that the groundwater divide has moved about 0.5 km north of the escarpment near the quarry, and groundwater flow within the bedrock below the Wainfleet Bog is still towards the north.

Field measurements of the saturated hydraulic conductivity of the peat indicate that the field-saturated hydraulic conductivity of the peat is approximately 10^{-5} m/s (Badley and Wong, 2000). The hydraulic conductivity of the clay was not measured as part of this study. But it was measured in the Wainfleet area at 3.1×10^{-10} m/s by Desaulniers et al. (1981). Desaulniers et al. (1981) also measured the porosity of the clay at 0.34 to 0.60.

Because of the hydraulic-head difference between the two flow systems, groundwater slowly diffuses downward from the Wainfleet Bog towards the bedrock. However, the clay unit beneath the bog, with its very low hydraulic conductivity, provides a effective barrier to the leakage of groundwater from the peat to bedrock. Given that the hydraulic conductivity of the clay is 3.1×10^{-10} m/s, a hydraulic head difference between the peat and bedrock of 5 m, and a porosity of 0.4, the downward average linear velocity through the clay is 1.55×10^{-10} m/s, or 4.88 mm/yr. This means it would take over 5000 years for the water in the bog to move through 25 m of clay to the bedrock. Thus, this clay forms an effective seal to separate the impact of the quarry dewatering on the bog. The downward average linear velocity through the through the clay in the Wainfleet area was calculated by Desaulniers et al. (1981) to be 8 - 37 mm/yr.

3. MODELLING ANALYSIS

Computer modelling was undertaken to provide insight into the behaviour of the groundwater flow regime within the bog to hydrological changes caused by dewatering at the quarry. Specific objectives of the modelling analyses are:

- to examine the effect of the presence of clay between the bog and the bedrock south of the bog
- to examine the effects of expansion of the quarry northwards towards the bog

3.1 Description of the Model

All simulations were undertaken using the GW-WETLAND model (Shikaze and Crowe, 1999). This model is designed to simulate transient groundwater flow and contaminant transport in a variety of groundwater-wetland environments. Groundwater flow is simulated in only the saturated zone within a two-dimensional, heterogeneous cross section. A specified flux boundary at the water table will allow the groundwater flow system to gain water through infiltration and lose water through evapotranspiration, both of which can vary both spatially and temporally. The upper boundary of the saturated zone (i.e., top of the computational domain) is a free surface (water table), and is allowed to rise and fall in response to the distribution of hydraulic head within the saturated domain and transient boundary conditions. Because both the distribution of hydraulic head within the saturated zone and the geometry of the computational domain (i.e., the position of the water table) are unknown at each time step, the solution for a specific time step is non-linear and requires an iterative approach. The transient groundwater flow equation is solved using a standard finite element technique, which uses triangular elements. In order to maintain computational integrity as the shape of the flow domain changes, elements along the water table undergo a limited amount of stretching, or if the change is large, nodes and elements at the water table are removed/added to ensure that the position of the nodes matches the value of hydraulic head along the water table. Addition or removal of nodes and elements also ensures that the geometry of heterogeneous hydrostratigraphic units within the groundwater flow domain is maintained throughout the simulation.

The model can be used to simulate a variety of surface water bodies (e.g., a wetland) which may expand and contract with respect to both surface elevation and lateral extent along the shore line in response to changing meteorological and groundwater conditions. Wetlands are represented by a transient specified-head boundary along the top of the computational domain where it intersects the ground surface. The values of hydraulic head are equal to the elevation of the surface of the wetland. Constant head nodes along the surface of the computational domain are switched on and off to represent the lateral extent of the wetland as the wetland rises and falls. Wetlands can be simulated in two ways. First, if the user knows the history of surface elevation fluctuations, those values can be entered, thus defining the elevation of the wetland surface at each time step throughout the simulation. Secondly, the model can calculate the surface elevation of the wetland. In this instance, the change in the volume of water in the wetland per unit width is calculated from precipitation and evaporation occurring at the wetland surface as well as flux across the sediment-wetland interface (i.e., into and out of the groundwater flow system).

3.2 Regional Model

The model represents a north-south, two-dimensional cross section from Lake Erie, through the quarry and the bog, approximately one kilometre into the farmland north of the bog (Fig. 2). The model consists of 58 rows of elements with a 1 m vertical spacing, and 435 columns of elements. A datum for modelling has been set at 0 m at the base of the computational domain. A variable Δx spacing was used, with Δx ranging from 5 m between to quarry and south end of the marsh to 100 m at the ends of the cross section. The region is represented by four hydrostratigraphic units, representing bedrock, the basal gravel, clay, and peat of the bog. Values assigned to the hydrogeological parameters of these units are listed in Table 2.

Table 2. Hydrogeological parameters.

Unit	K (m/d)	S (1/m)	n	Sy
bedrock	8.64×10^{-2}	0.0005	0.3	0.2
gravel	8.64×10^{-1}	0.00001	0.5	0.4
clay	8.64×10^{-5}	0.0005	0.5	0.2
peat	8.64×10^{-2}	0.00001	0.9	0.4

The boundary conditions consist of the following: (a) the upper boundary is a free surface (water table) boundary set initially 1 m below ground surface, with both the hydraulic heads and elevation of the boundary allowed to rise and fall in response to hydrogeological changes, (b) the lower boundary is a no-flow boundary, representing a depth in the bedrock where we expect no influence from the quarry and the peat (approximately 50 metres below ground surface) and (c) the side boundaries are no-flow boundaries representing groundwater divides. In all cases the position of the water table was allowed to adjust in response to the drainage to the quarry and meteorological conditions.

In all simulations, actual temperature and precipitation data measured at Port Colborne were used. Evapotranspiration data used in the model represents that which occurs from Birch trees (M. Browning, pers. comm.). The average total annual precipitation and evapotranspiration is 835 mm and 611 mm, respectively. In the model, the values of infiltration and evapotranspiration applied at the water table, is 75% total precipitation and 100% evapotranspiration in the peat, 3% total precipitation and 0% evapotranspiration in the bedrock, 0% total precipitation and 0% evapotranspiration in the clay. Evapotranspiration and infiltration is distributed throughout the year, with for example, more infiltration in the spring. These values are based on previous modelling analyses (Crowe et al., 2000).

4. MODELLING RESULTS

Transient simulations were run to assess how drainage to the quarry would affect the water table in the vicinity of the Wainfleet Bog. All simulations started with the water table at an elevation of 51 m above the base of the computational domain, except within the quarry where the water table was set an elevation of 38 m above the model base, representing a dewatered base of the quarry. Over time, the hydraulic head distribution within the saturated domain and the position of the water table was allowed to adjust to drainage to the quarry, infiltration and evapotranspiration. Simulations were run to 100 years.

The following sections contains plots of the elevation of the water table vs. time, with the water table plotted at four locations along the flow domain. Two locations are in bedrock at 3300 m and 3350 m, which corresponds to 75 and 25 m south of the southern boundary of the bog. Two other locations are in the Wainfleet Bog at 3375 m and 3580 m or 1 m and 205 m north of the southern boundary of the bog.

4.1 Case 1: Current Pit, Clay South of Bog

The first case simulates current conditions at the quarry, in which the quarry is 800 m wide and situated approximately 800 m south of the Wainfleet Bog. A 25 m wide unit of clay, or clay "plug", is assumed to exist between the bog and bedrock everywhere along the southern boundary of the bog.

The water table in the bedrock adjacent to the quarry begins to fall immediately in response to drainage to the quarry (Fig. 5). Further away from the quarry, the water table rises due to infiltration exceeding annual evapotranspiration. After approximately 20 years the water table south of the quarry reaches a steady state with the amount of infiltration balancing the loss due to drainage to the quarry and Lake Erie. The cone of depression extends almost 1000 m south of the quarry.

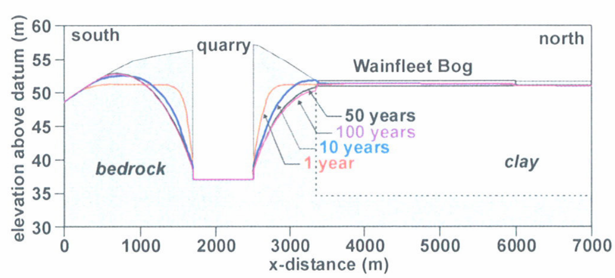

Figure 5. Change in the elevation of the water table in the bog and bedrock due to dewatering at specific times. Case 1: a 800 m wide quarry, 800 m south of the bog, and clay between the bog and bedrock.

Between the quarry and the bog, the water table falls and after approximately 10 years the cone of depression has reached the south edge of the clay plug (Fig. 5). During the next 90 years, the water table in the bedrock continues to fall as groundwater discharges into the quarry, but at an increasingly slower rate (Fig. 6).

The water table within the bog initially rises due to infiltration (Fig. 6). After approximately 15 years it reaches a steady state, fluctuating seasonally with a rise in the spring due to snow melt and spring rains, and declining during the summer and fall due to evapotranspiration. As the water table immediately south of the bog falls due to dewatering at the quarry, a small thickness of clay at the southern boundary of the bog is sufficient to prevent the dewatering from impacting on water levels within the bog. Figure 6 shows that even only 1 m into the bog, the water table is not affected by the drawdown in the bedrock.

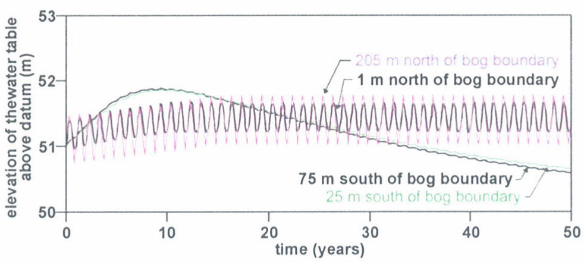

Figure 6. Plot of the water table vs. time at 25 m and 75 m south, and 1 m and 205 m north, of the bog-clay boundary. Case 1: a 800 m wide quarry, 800 m south of the bog, and clay between the bog and bedrock.

4.2 Case 2: Current Pit, Bedrock South of Bog

The second case simulated uses the same current quarry conditions described above. But the clay plug between the southern end of the Wainfleet Bog and the quarry is absent. The bog is assumed to have a direct contact with the bedrock everywhere along the southern boundary of the bog. The zone formerly occupied by clay is now assigned hydrogeological values of peat.

Water table and hydraulic head adjustments south of the quarry, are exactly the same as that described above in Case 1. However, groundwater conditions between the quarry and the bog have changed slightly (Fig. 7). As above, the cone of depression caused by groundwater flow to the quarry reaches the bog-bedrock interface after approximately 10 years. Although water levels north of the quarry continue to fall during the next 90 years, the water table immediately south of the bog is slightly higher (~0.3 - 0.4 m) after 100 years than the previous case because water is draining from the bog into bedrock.

Because water is draining from the bog into the bedrock, the elevation of the water table in the bog immediately north (1 m) of the bedrock-bog boundary is approximately 0.1 m-0.2 m lower than case 1 (Fig. 7). Also, the range of the seasonal fluctuation of the water table here is much less than that in case 1 because drainage along the perimeter of the bog is removing much of the infiltration. However, 205 m into the bog the water table is not affected by the drainage across the bedrock-bog boundary (Fig. 7). Thus, relative to the amount of water entering the bog as infiltration, the drawdown in the bedrock and hence the drainage through the bedrock-bog boundary is insufficient to have a significant impact on the hydrogeology of the bog.

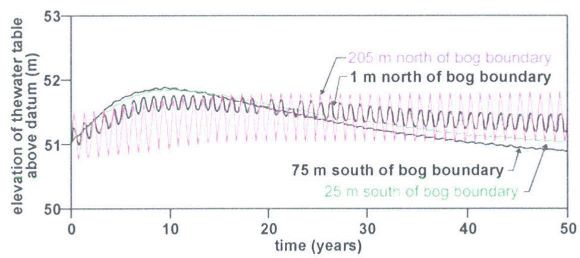

Figure 7. Plot of the water table vs. time at 25 m and 75 m south, and 1 m and 205 m north, of the bog-bedrock boundary. Case 2: a 800 m wide quarry, 800 m south of the bog, and no clay between the bog and bedrock.

4.3 Case 3: Enlarged Pit, Clay South of Bog

This case examines a possible expansion of the quarry 500 m north towards the Wainfleet Bog. The expansion brings the quarry to approximately 300 m from the southern boundary of the bog. As in case 1, a 25 m wide unit of clay is assumed to exist between the bog and bedrock along the southern boundary of the bog.

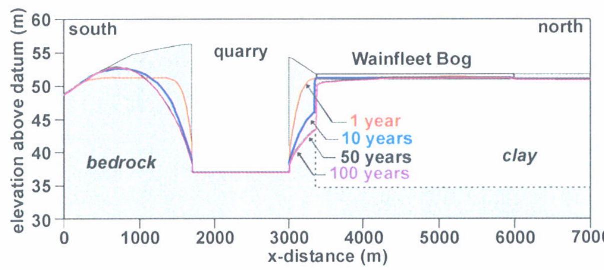

Figure 8. Change in the elevation of the water table in the bog and bedrock due to dewatering at specific times. Case 3: a 1300 m wide quarry, 300 m south of the bog, and clay between the bog and bedrock.

The water table in the bedrock adjacent to the quarry begins to fall immediately in response to drainage to the quarry (Fig. 8). Further away from the quarry towards the south, the water table rises due to infiltration exceeding annual evapotranspiration. As in the previous cases, the water table south of the quarry reaches a steady state after approximately 20 years the with the amount of infiltration balancing the loss due to drainage to the quarry and Lake Erie. The cone of depression extends almost 1000 m south of the quarry.

Between the quarry and the bog, the shorter distance to the boundary of the large clay unit north of the escarpment, cause the water table to fall and rapidly. After 1-2 years the cone of depression has reached the south edge of the clay plug (Fig. 8). The drawdown is considerably greater than the previous cases, with drawdown of 8 m after 50 years in the bedrock 25 m from the southern boundary of the bog. Over time, rate of drawdown decreases and starts approaches a steady state at about 50 years (Fig. 9).

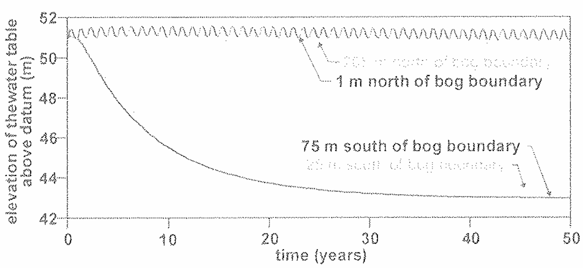

Figure 9. Plot of the water table vs. time at 25 m and 75 m south, and 1 m and 205 m north, of the bog-clay boundary. Case 2: a 800 m wide quarry, 800 m south of the bog, and no clay between the bog and bedrock.

The water table within the bog fluctuates seasonally with a rise in the spring due to snow melt and spring rains, and declining during the summer and fall due to evapotranspiration. It initially rises very slightly due to infiltration over the first 15 years (Fig. 9). As in case 1, the small thickness of clay at the southern boundary of the bog is sufficient to prevent dewatering of the bog. Unlike the previous cases, the water table within the bog starts to falls as the water table immediately south of the bog falls due to dewatering at the quarry. However, the water table decline within the bog is very small and is only noticeable near the southern edge of the bog. In fact the water table 1 m and 205 m from the southern boundary of the bog falls 0.2 m and 0.1 m, respectively after 50 years due to the dewatering at the quarry. Groundwater is slowly drained from the clay, and as shown by Figure 9, after a couple of hundred years, the dewatering will eventually cause sufficient drainage in the clay to impact on the groundwater system within the bog. But within the next hundred years, should a northward expansion of the quarry occur, clay along the southern boundary of the bog will prevent a detrimental drop in the water table within the Wainfleet Bog.

4.4 Case 4: Enlarged Pit, Bedrock South of Bog

This case again examines a possible expansion of the quarry 500 m north towards the Wainfleet Bog. The expansion brings the quarry to approximately 300 m from the southern boundary of the bog. But the 25 m wide unit of clay between the bog and bedrock along the southern boundary of the bog is assumed to be absent.

As in case 3, the water table between the quarry and the bog begins to fall considerably immediately in response to drainage to the quarry (Fig. 10) and the close proximity of the large clay unit north of the escarpment. After 1-2 years, the cone of depression has reached the south edge of the bog. The drawdown in the bedrock here about 8 m after 50 years, or slightly less (<0.2 m) than case 3 (Fig 10). Over time, rate of drawdown decreases and starts approaches a steady state at about 70 years.

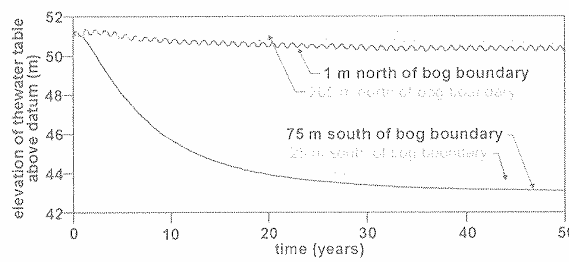

Figure 10. Plot of the water table vs. time at 25 m and 75 m south, and 1 m and 205 m north, of the bog-bedrock boundary. Case 2: a 800 m wide quarry, 800 m south of the bog, and no clay between the bog and bedrock.

The water table within the bog fluctuates seasonally rising during the spring due to snow melt and spring rains, and declining during the summer and fall due to evapotranspiration. It initially rises very slightly due to infiltration over the initial couple of years (Fig. 10). At 1 m from the bog-bedrock boundary, the water table at the southern edge of the bog (Fig. 10) starts to falls after 3 years due to dewatering at the quarry and the absence of clay between the bog and bedrock. It continues to fall for about 30 years then almost attains steady stated. After 50 years, the elevation of the water table here has fallen approximately 0.8 m. Further into the bog (205 m from the southern boundary) the water table decline is very small, declining by less than 0.4 m after 50 years due to the dewatering at the quarry (Fig. 10). Groundwater is slowly drained from the clay, and after a couple of hundred years, the dewatering will eventually cause sufficient drainage in the clay to impact on the groundwater system within the bog. Should a northward expansion of the quarry occur, and should clay be absent along the southern boundary of the bog, it will be approximately 100 years before a 1 m drop in the water table occurs more than 200 m into the Wainfleet Bog.

5. CONCLUSIONS

Dewatering at the quarry has lowered the hydraulic heads within bedrock several kilometres from the quarry. However, groundwater flow system in the bog is separated from bedrock conditions by a thick layer of clay between the base of the bog and bedrock. At the southern end of the bog, the bog is separated from bedrock at the Onodaga Escarpment by a few metres of clay, which may or may not be continuous along the entire southern boundary of the bog. If clay is present everywhere, even a few meters of clay is a sufficient barrier to groundwater flow from the bog to bedrock, and hence hydrogeological conditions within the bog are essentially unaffected by quarry dewatering. If the clay plug is absent everywhere along the southern boundary of the bog, groundwater will flow from the bog into bedrock due to dewatering at the quarry. However drawdown extends only ~50 m into the bog because the total volume of infiltration over the large surface area of the bog equals total drainage through the relatively small bedrock-bog interface. Should the quarry expand to the north, the groundwater within the bedrock between the quarry and the bog will be dewatered, resulting in a dramatic lowering of the water table. However, a few m of clay along the southern boundary of the bog will again be a sufficient barrier to draining of the bog. If the quarry expands north and if the clay along the southern boundary of the bog is absent, the bog will not be significantly affected by drainage due to dewatering for almost 100 years.

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