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Effect of mine dewatering on the peatlands of the James Bay Lowland: the role of marine sediments on mitigating peatland drainage

Peter Whittington* and Jonathan S. Price
Department of Geography and Environmental Management, University of Waterloo, Waterloo, Ontario, Canada, N2L 3G1

Abstract:

The wetlands of the James Bay Lowland comprise one of largest wetland complexes in the world, in part due to the properties (thickness and hydraulic conductivity) of the marine sediment (MS) that underlay them. Dewatering of an open-pit diamond mine is depressurizing the surrounding Silurian bedrock below the MS. Prior to mining, it was assumed that these MS would largely isolate the overlying peatlands from the depressurized regional bedrock aquifer. To assess this isolation, we instrumented a 1.5 km long transect of wells and piezometers located within the zone of the mine's influence that crossed a sequence of bogs, fens, and bedrock outcrops (bioherms). Results were differentiated between those areas with no MS (near bioherms) and those underlain by MS (non-bioherm) along the transect. Between 2007 and 2010 at near-bioherm and non-bioherm locations, average peat water tables declined 71 and 31 cm, and hydraulic head declined 66 and 32 cm, in bioherm and non-bioherm locations, respectively. Gradients varied from near zero (−0.001) at the start of dewatering to −0.03 (after 5 years) in non-bioherm areas and from −0.20 to −0.45 in near-bioherm areas. These gradients corresponded to fluxes (groundwater recharge) of approximately −0.26 mm/day and −2.1 mm/day, in non- and near-bioherm areas, respectively. Specific discharge (recharge) determined using the known mine dewatering rate and drawdown cone heads and areas corresponded well with measured recharge determined in the non-bioherm transect locations. A simple rearrangement of Darcy's Law used to calculate the specific discharge highlighted how the ratio of hydraulic conductivity to the thickness of the MS can be used to assess vulnerable areas. Therefore, given the increasing development in Ontario's Far North, considerable attention must be given to both the thickness and hydraulic conductivity of MS. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS peatlands; dewatering; James Bay Lowland; marine sediments; hydraulic conductivity

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INTRODUCTION

The world's second largest wetland complex, the Hudson James Bay Lowland (HJBL), exists because high water tables are maintained by the extremely low relief, which delays lateral runoff; the subarctic climate which limits evapotranspiration losses and provides adequate rain and snow melt; and the thick, relatively impermeable (Price and Woo, 1988), marine sediments (MS) that prevent vertical seepage losses. These MS were deposited as the Laurentide Ice sheet melted about 8000 years ago, allowing the Tyrell Sea to flood the lowlands (Lee, 1960). This marine transgression resulted in a very large and flat basin underlain by a clayey silt (Dredge and Cowan, 1989; Glaser *et al*., 2004b) which can be up to several hundreds of metres thick, mantling Silurian bedrock of the Upper and Lower Attawapiskat formation. Higher isostatic rebound at the coast continues to decrease the regional slope (Glaser *et al*., 2004a).

Until recently, little was known about the origin of the wetlands in the HJBL due to their remote and generally inaccessible setting. Sjörs (1963) offered one of the earliest assessments as to the origin of the wetlands, and Klinger and Short (1996) provided a more comprehensive assessment essentially confirming Sjörs' and both agree that large domed bogs are the terminal point of the successional pathway, which require an isolated or perched water table to maintain a high acidity which decreases fen species and favours bogs species. The perched (or domed) water table in bogs has been explained by two relatively contrasting models (Clymo, 1984; Ingram, 1982) and regardless of which model is used, both either imply (Clymo, 1984) or specify (Ingram (1982), i.e. the Dupuit–Forcheimer assumption) that vertical flow is negligible (Belyea and Baird, 2006), or at least not considered, in the development of these bog systems, from which we can assume would require a relatively impermeable base layer, and/or no (large) vertical gradient.

Discovery of kimberlite (diamondiferous) deposits in an area of the James Bay Lowlands has led to open-pit diamond mining which requires substantial groundwater pumping to dewater the mine thus causing depressurization of the regional bedrock aquifer beneath the MS. (Whittington and Price, 2012) found that this depressurization caused a localized water table drawdown in the peat around exposed or sub-cropping bedrock features (ancient coral reefs called bioherms (Cowell, 1983)) which was limited to ~30 m from the edge of the bioherms where

*Correspondence to: Peter Whittington, Department of Geography and Environmental Management, University of Waterloo, Waterloo, Ontario, Canada, N2L 3G1
E-mail: whittington.pete@gmail.com

there are little or no MS. In a 12 km radius around the mine, approximately 100 bioherms can be found occurring in three distinct lateral bands (Whittington and Price, 2012), suggesting that their cumulative impact may be larger. Beyond this zone, the presence of MS was expected to play a role in protecting the peatland from excessive (vertical) recharge and desiccation (HCI, 2004a) but has yet to be properly assessed. Modelling simulations (supported with field data from both the Albany River Basin (HJBL) and Glacial Lake Agassiz (northern Minnesota), peatlands) by Reeve *et al.* (2000) indicated that vertical flow was negligible in large peatland complexes when the hydraulic conductivity of the MS (i.e. the base) was low (10^{-7} m/s or 8.6 mm/day); when the MS had a higher hydraulic conductivity, vertical flow became more important which is supported by various field studies (see Glaser *et al.*, 1997; Siegel and Glaser, 1987). However, in most of these cases, no significant (e.g. >0.1) vertical hydraulic gradients were present because the horizontal gradient was assumed to be much greater than the vertical.

In the feasibility study for the mine, HCI (2004a) used three field samples to determine the vertical hydraulic conductivity of the MS and found the mean to be 0.025 mm/day, which is several orders of magnitude lower than that specified by Reeve *et al.* (2000) as important to recharge, and on the high side of literature values for clay. Freeze and Cherry (1979) report 'unweathered marine clay' to range between 0.086 and 0.000086 mm/day. The K of the MS is only one aspect of its potential protective ability, the other being its thickness. In their model (HCI, 2004a), HCI varied both the thickness (from 0.5 m to 15 m) and the K (from 0.1 mm/day to 0.007 mm/day) and the corresponding rates of recharge from the peatlands ranged from 181 mm/year to 3 mm/year (or 70% and 1% of annual runoff). In addition, HCI (2004b) defined enhanced recharge zones (ERZs) that generally corresponded with the localized clusters of bioherms (in the bands noted earlier) and found that depending on the K of the limestone and MS, recharge in these zones could range from 21 to 148 mm/year.

With evidence that depressurization is occurring (Whittington and Price, 2012), the assumption of no vertical flow in these large peatland systems surrounding the mine is now invalid. Therefore, the impermeable nature, as well as the thickness of the MS, will be assessed. The objective of this paper is to determine the impact of aquifer dewatering to peatlands surrounding the mine and to use this information to make inferences about the protective properties of the MS.

STUDY SITE

The study site is located at the De Beers Canada Victor Diamond Mine, which is located ~90 km west of Attawapiskat and 500 km north of Timmins, Ontario, Canada. The James Bay Lowland is typified by a complex arrangement of bogs and fens, which comprise the majority of the landscape (60%) and when combined with open water and other wetland types, make up >90% of the landscape (Riley, 2011). Peat deposits range in thickness from 0 m where exposed bedrock is present (Cowell, 1983; Whittington and Price, 2012), to ~4 m (Glaser *et al.*, 2004a; Sjörs, 1963).

A 1500 m long transect was instrumented with wells and piezometers between 2007 and 2010 (Figure 1, Table I). The transect runs roughly south–north and is anchored at both ends by bioherms. The start of the transect is the South Bioherm (SB) and nests along the transect are named according to the distance away from the SB, e.g. SB + 1485 is a nest located 1485 m north from SB (note: as the transect is 1500 m long, SB + 1485 is located very close to the North Bioherm). In 2009, five additional nests were installed north of the transect area in the North Granny Creek ERZ (HCI, 2004b) called 8-1-D, Landbridge (LB), North Middle Bioherm (NMB), South Middle Bioherm (SMB), and North North Bioherm (NNB). In 2010, two nests were installed on the west side of the North and South Road Bioherms (NRB, SRB), approximately 75 m from the edge of the bioherm, outside of the zone of direct peat-bedrock influence (Whittington and Price, 2012), but within the ERZ.

The average annual January and July temperatures for Lansdowne House are −22.3 and 17.2 °C, respectively, and for Moosonee are −20.7 and 15.4 °C, respectively (Environment Canada, 2008). Lansdowne House (inland 300 km west–south–west) and Moosonee (250 km south–east near the coast) are the closest stations with long-term meteorological records available. Annual precipitation for Lansdowne House is 700 mm with ~35% falling as snow; and for Moosonee is 681 mm with ~31% falling as snow.

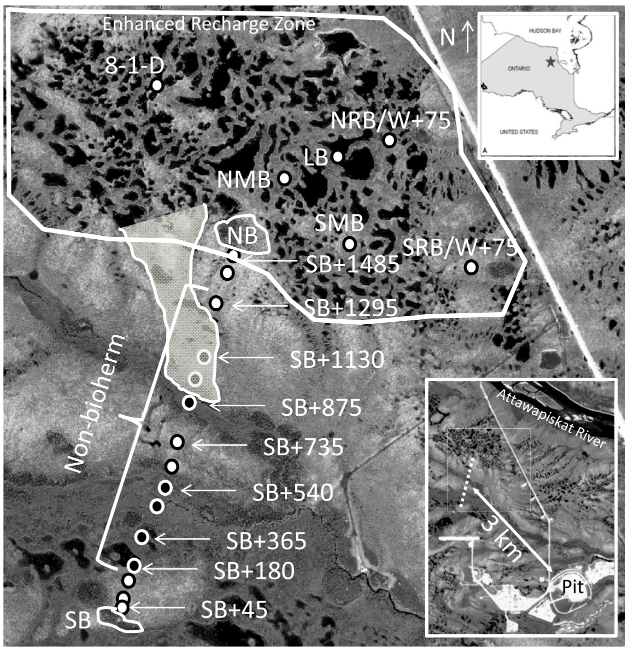

Figure 1. Location of selected nests along and north of the transect. White-centred circles are bog locations; black-centered circles are fen locations. The reader is directed to Table I for a complete list of the transect nest locations. Top inset: Site location within Ontario; bottom inset: location of the research area relative to the mine. The shaded section shows one of the fen water tracks coming off of the domed bog. North North Bioherm (NNB, not shown) is just out of the image above the word 'Enhanced'

Table I. Installation year, name (nest), peatland type, piezometer depths (metres below ground surface), elevation sensor rod (ESR), and whether the nest is in a Bioherm/Non-bioherm (BH/NBH) or enhanced recharge zone (ERZ) location. For the Nest column, S = south, B = bioherm, N = north, M = middle, R = road, W = west, and LB = land bridge

Year	Nest	Type	Piezometers (mbgs)	ESR	Location
2007	SB + 45	Bog - domed	0.9, 1.5, 2.4	No	BH
2007	SB + 65	Bog - domed	0.9, 1.5, 2.25	Yes	BH
2007	SB + 100	Bog - domed	0.9, 1.5, 2.43	Yes	BH
2007	SB + 180	Fen - floating mat	0.9, 1.5, 1.9	Yes	NBH
2007	SB + 365	Fen - channel	0.9, 1.5, 1.7	Yes	NBH
2007	SB + 430	Fen - channel	0.9, 1.5	Yes	NBH
2007	SB + 540	Fen - channel	0.9, 1.5, 1.7	Yes	NBH
2007	SB + 645	Bog - domed	0.9, 1.5	Yes	NBH
2009	SB + 735	Bog - domed	0.9, 1.5, 1.9	No	NBH
2007	SB + 875	Fen - channel	0.9, 1.4	Yes	NBH
2007	SB + 1005	Fen - water track	0.9, 1.5, 1.8	Yes	NBH
2007	SB + 1130	Fen - water track	0.9, 1.5, 2.4	Yes	NBH
2007	SB + 1295	Bog - domed	0.9, 1.5, 2.38	Yes	NBH
2007	SB + 1445	Bog - domed	0.9, 1.5, 2.57	Yes	BH
2007	SB + 1485	Bog - domed	0.9, 1.5, 3	Yes	BH
2009	8-1-D	Bog - domed	0.9, 1.5, 2.3	No	ERZ
2009	LB	Bog - domed	0.9, 1.5, 2.5	No	ERZ
2009	NMB	Bog - domed	0.9, 1.5, 2.72	No	ERZ
2009	SMB	Bog - domed	0.9, 1.5, 2.4	No	ERZ
2009	NNB	Bog - domed	0.9, 1.5, 2.5	No	ERZ
2010	NRB/W + 75	Bog - domed	0.9, 1.5	No	ERZ
2010	SRB/W + 75	Bog - domed	0.9, 1.5, 1.95	No	ERZ

METHODS

Local weather conditions have been measured at an on-site 10 m meteorological tower since March 2000 and include air temperature and relative humidity, rainfall, net radiation, photosynthetically active radiation, wind speed, and direction.

Bedrock monitoring wells (PVC, 2.5 cm diameter) were installed with 3 m screens open at specified depths, sand packed, and sealed with bentonite. Screened openings were centred at 25.5, 58.5, and 64.5 m below ground surface (mbgs) for each individual piezometer in the upper Attawapiskat limestone formation at the North Bioherm. At the SB, they were also located in the upper Attawapiskat limestone formation at 10 and 30 mbgs (3 m screens). All bedrock wells had a pressure transducer set to record every 12 h. MS wells (PVC, 2.5 cm diameter) were installed at various points along the transect in a similar fashion to the bedrock wells, although the slotted openings were only 0.3 m.

Peat piezometers and wells were constructed from 2.5 cm diameter PVC pipes and slotted for 30 cm (piezometers) or their entire length (wells). The peat wells and piezometers were installed by manually pre-auguring a hole using a hand auger slightly smaller than the diameter of the well. Each nest typically had three piezometers and a well with the shallowest piezometer installed to 0.9 m below ground surface. The next piezometer was installed to 1.5 m below ground surface (1.4 m at one location) and the deepest peat piezometer (when possible) was installed below that. The depths of the third piezometer ranged as they were installed near the peat/MS interface, which varied with location and ranged in depth from 1.7 m to 2.75 m, (see Table I). Piezometers were located within ~1 m laterally of each other. Hydraulic conductivity (K) was determined using bail tests (Hvorslev, 1951) by evacuating water with a Waterra foot valve and measuring the head recovery with a blow stick. For measuring K in the MS piezometers, a pressure transducer was used to record the water table rise of the period of recovery, which ranged from <1 to 2 days.

Pipe top elevations were surveyed using a Topcon GMS-2 dual frequency survey-grade GPS in real-time kinematic survey mode with the base station setup near the mine over a known benchmark; the rover was never further than about 4 km from the base. The acceptable precision for the DGPS was manually selected within the software and set at 0.003 m vertical and 0.005 m horizontal. The DGPS only records the point when these conditions are met. The 0.003 m software setting is misleading, as in practise, the accuracy of the DGPS was several cm, although with better than 1 cm precision (e.g. pipes in a nest relative to one another). Note: Errors in the order of a few cm would not have much of an impact on the flux calculations (see Results and Discussion) as the measured head gradients were much larger than the survey errors. In addition, the piezometers were installed at a coarse sampling interval (generally greater than 60 cm between slotted intakes) also minimizing errors in flux calculations based on DGPS accuracy.

Laboratory assessment of K anisotropy in peat was made from samples collected from three locations along the transect including two bog (SB + 65, SB + 1485) and one fen water-track (SB + 1005). A Wardenaar™ corer was used to collect relatively uncompressed $0.8\,\text{m} \times 0.13\,\text{m}$

0.1 m cores that were placed into a rigid wooden box of the same dimensions, sealed with plastic wrap and transported back the laboratory. The cores were sectioned into roughly 0.1 m sections (attempting to keep any obvious horizontal layers intact) and then were encapsulated in wax (Hoag and Price, 1997). Hydraulic conductivity (K) in both the horizontal (K_h) and vertical (K_v) directions were determined by cutting an opening in the respective ends of the waxed core and ponding water on the surface until a steady discharge from underneath was reached. Once this was achieved, the core was resealed, rotated, and the process repeated for the other direction. Darcy's Law was used to determine K.

RESULTS

Aquifer dewatering officially began in January 2007. However, following a 60-day pumping test in October and November 2006, the depressurization of the bedrock underlying the research transect at the end of the pumping test (November 28, 2006) showed an *interpreted* drawdown of ~5 m (HCI, 2007) (i.e. extrapolated data based on neighbouring instrumentation involved in the pumping test). Since instrumentation for this study began July, 2007, water pressure in the deep aquifer (i.e. in bioherms) was potentially already impacted (see Whittington and Price, 2012), for which we have no data. When dewatering of the pit began, pumping rates were ~8200–18 000 m^3/day and increased to ~85 000 m^3/day by February 2010 (Itasca Dever Inc., 2011) and averaged ~80 000 m^3/day for 2011 (ranging from ~3000 to 97 000 m^3/day). At the end of August 2011 (the end of these data presented in this paper), the pit was ~90 m deep (−10 masl) with a water table ~93 m deep (−13 masl) (Patrick Rummel, 2012, De Beers Canada hydrogeologist, personal communication). The final pit is expected to be 220 m deep with a corresponding depth to water table, meaning that in 2011, the mine depth was less than halfway completed.

Over the same period of dewatering mentioned above, the average monthly temperature of the onsite weather station generally fell between that of Lansdowne House and Moosonee, suggesting an average of those two stations offer a good surrogate for the long-term (30-year climate normals) climate at Victor. During the 2008 and 2009 field season (1 May to 31 August), the average temperature was cooler than the long-term average, whereas 2007, 2010 and 2011 were close to the long-term average (Table II). Most years were slightly drier than average (2008, 2010, 2011), with 2007 being much drier (220 mm) and 2009 being a lot wetter (380 mm) (Table II). Of note is that 2010 had no real melt period: a very shallow snow pack and early melt (February/March) provided little recharge to the system in the spring.

The hydrostatic pressure in bedrock wells from spring 2007 to spring 2011 declined between 4 and 5 m in NB and from summer 2008 to spring 2011 declined ~3.5 m in SB (Figure 3, Whittington and Price, 2012). Along the transect (i.e. non-bedrock) peat water tables from 2008 to 2011 in bioherm and non-bioherm locations declined 0.71 and 0.31 m, respectively, and within bogs and fens declined 0.52 and 0.35 m, respectively (Figure 2). In the ERZ, water levels declined 0.32 m from 2008 to 2011. Data shown for 2007 in Figure 2 are from August only (due to study site installation timing) and thus are not an average for the season. However, examination of some of the De Beers' monitoring wells has shown the same trend, with 2007 being drier than 2008/2009 and thus despite the later sample time, is representative of the conditions for that field season. The similarity between the non-bioherm and fen sites, and the higher absolute water tables in bioherm and bog locations, are because the bioherms are surrounded by bogs (in this study area) which are naturally raised above the surrounding landscape (Clymo, 1984; Ingram, 1982).

Between 2007 and 2011, the average hydraulic head in each nest of peat piezometers declined between 0.12 and 1.0 m. In bogs and fens, the decline was 0.54 and 0.33 m, respectively, and in bioherm and non-bioherm locations was 0.66 and 0.32 m, respectively. These changes were calculated as an average across the peat profile (i.e. of the 3 (or 2) piezometers) at each nest.

Hydraulic gradients in the peat profile (calculated from the water table to the mid-point of the deepest piezometer in the nest) declined along the transect (average of all nests), through time (Figure 3). The gradients in the bioherm nests were four to nine times larger than in the non-bioherm nests. When the two nests in the FWT are removed (rationale given in discussion), hydraulic gradients are at or below the detection limit (range −0.001 to −0.007) for 2007–2009, but increase an order of magnitude to −0.03 in 2010 and −0.01 2011. The

Table II. Meteorological variables from May 1 to August 31 for 2007 to 2011, respectively. LH and M are based on the 30 year (1971–2000) Canadian Climate Normals from Environment Canada for Lansdowne House (LH) and Moosonee (M), respectively (snow depth is the end of March)

	2007	2008	2009	2010	2011	LH	M
Average air temperature (°C)	13.0	11.9	10.4	13.0	12.5	13.4	12.0
Precipitation (mm)	220	298	380	276	284	333	294
*Snow (cm)	37	43	75	0.0	39	56	35
Snow date	April 9	April 5	April 9	-	April 12	March 31	

*Snow depths are from: 2007/2008 from unpublished field data; 2009/2011 from Whittington *et al*., 2012; 2010 no snow was present in April (and most of March).

ERZ maintained a relatively steady average gradient of 0.2 from 2009 to 2011, being less than the bioherm nests, but more than the transect area.

The MS subsided at every point along the transect (as measured from 2007 to 2011), ranging from 4 to 34 cm, with an average subsidence of ~12 cm along the transect (Figure 4). The difference between bioherm and non-bioherm MS subsidence, as well as between bog and fen MS subsidence, were both < 1 cm. Peat subsidence averaged 6 cm along the transect (Figure 4). At bioherm and non-bioherm locations, peat subsidence was 7.3 and 5.5 cm, respectively, and between bog and fen locations was 6.9 and 5.3 cm, respectively.

Hydraulic conductivity in the peat varied over four orders of magnitude between ~4 and 4000 mm/day with ~90% between 10 and 1600 mm/day and a transect average of 340 mm/day (Figure 5). K generally trended 0.90 m piezo > 1.50 m piezo > deep piezo with average values for those depths of 698, 230 and 58 mm/day, respectively. K in the (elevated) bogs tended to be less than the K in (lower lying) fens; K in bogs averaged 85 mm/day, whereas in fens, it averaged 597 mm/day. Hydraulic conductivity in the MS ranged 0.5 mm/day to ~30 mm/day, with an average of ~10 mm/day and median and geometric mean of ~5 mm/day.

Hydraulic conductivity (vertical and horizontal) of the upper 0.75 m of peat determined from the cores ranged between 20 and 10 000 mm/day with the majority (~80%) between 20 and 1100 mm/day, which is a similar range to those depths determined with piezometers. In ~90% of the samples, $K_h > K_v$ (n = 18), with a median anisotropy value ($log\ K_h/K_v$) of 0.23, or K_h being $1.8 \times K_v$.

DISCUSSION

The study period presented here covered 5 years of dewatering, from shortly after dewatering began to slightly less than half of the anticipated drawdown. Over this time period, annual weather conditions varied considerably and likely masked some of the effects that aquifer dewatering may have. The summer of 2007 was warm and dry (Table II); however the effect of pumping was only seen in the near-bioherm nests (Figure 3). In summer 2008, it was cool and wet resulting in higher water tables than in 2007, but still relatively unaffected by the mine in non-bioherm areas (Figure 2). The summer of 2009 was cold, very wet and started very snowy, which may have masked any dewatering in non-bioherm areas due to the 'surplus' of water, despite being the third summer of dewatering. As there was essentially no recharge in 2010 (no snow), large drops in water tables in 2010 were likely more a response to the minimal spring recharge event due to the absence of snow, than due to dewatering; the average temperature and slightly drier precipitation maintained the initial conditions of the season, but by this time 4 years of aquifer dewatering had also occurred and even the non-bioherm areas of the transect were beginning to be affected with lower water tables and larger gradients

As noted previously in Figure 3, two of the fen water track (FWT) nests were removed from the non-bioherm classification as these two nests are impacted, albeit

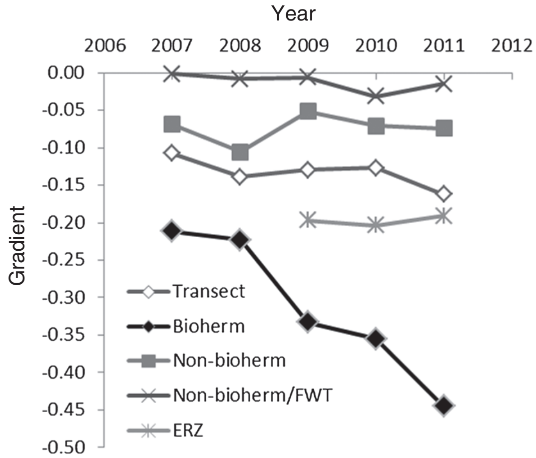

Figure 3. Average hydraulic gradient (from well to mid-point of deepest piezometer) from 2007 to 2011 along the transect, in bioherm nests, non-bioherm nests, and non-bioherm/non-fen water track (FWT) (see Figure 1) nests

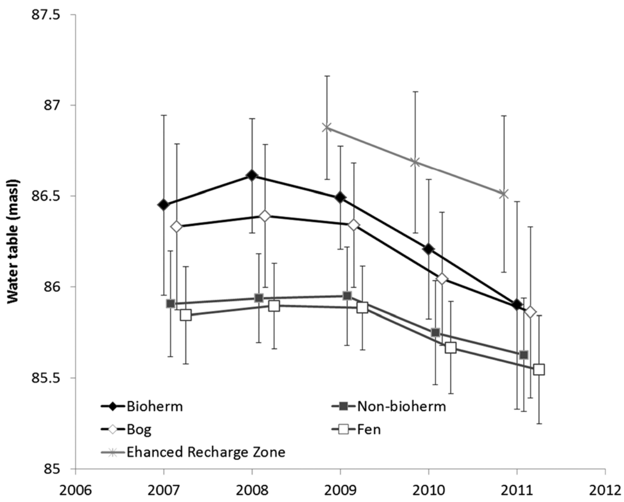

Figure 2. Water tables through time for both bioherm and non-bioherm and bog *versus* fen nests, and the ERZ. Points are shown offset in time (x-axis) for display purposes only. Data are the average of the field season measurements, generally from April/May to August (except 2007). Error bars are +/− 1 standard deviation

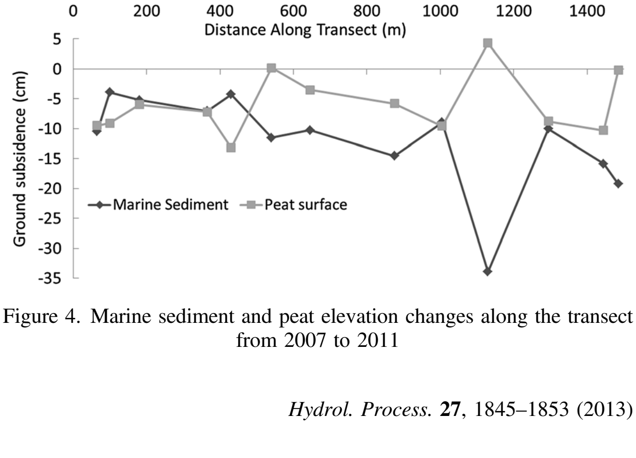

Figure 4. Marine sediment and peat elevation changes along the transect from 2007 to 2011

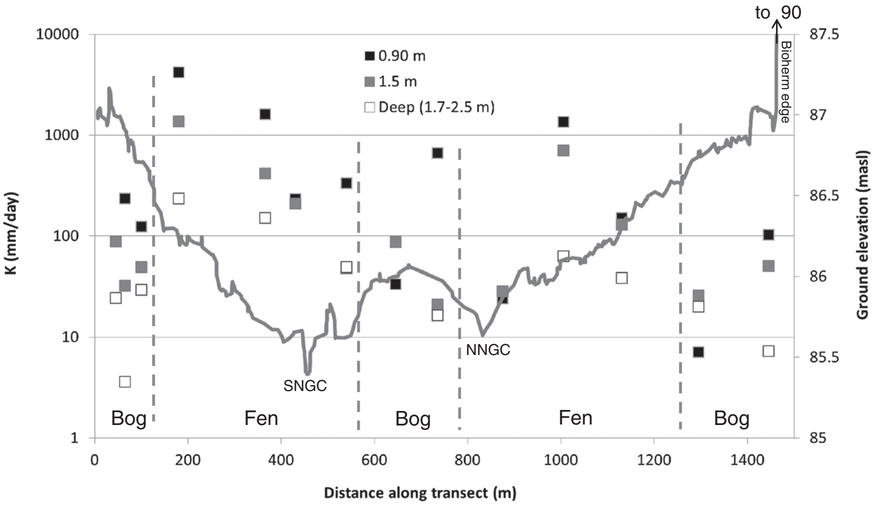

Figure 5. Average (2007–2011) hydraulic conductivity per piezometer (points) and ground elevation (2008) (grey line) along the transect. Ground elevation was determined using an eight-point-moving-average from a DGPS walking survey with points taken every 4–5 m; the NB (North Bioherm) is clearly seen at the far right of the figure and extends upwards to 90 masl over ~10 horizontal metres. The locations of bogs and fens are shown along the X-axis. SNGC and NNGC are the stream channels for South– and North–North Granny Creek, respectively

indirectly, by the bioherm. The ponds on the top of the domed bog (i.e. the ERZ, Figure 1) feed the FWT, which comes down off the bog to the stream channels, and as hydraulic gradients were higher in the bioherm and ERZ areas (the area supplying the FWTs), water in the FWT was cut off, drying these nests despite these nests being 100 s of m from a bioherm.

The regional scale surficial flow systems also help explain the different responses seen between bogs and fens to dewatering. Both water tables and hydraulic heads (Figures 2 and 3) declined more in the bog locations than in the fen locations. This is due to the ombrogenous nature of bogs – they receive inputs through precipitation only. Fens, however, may receive inputs of water from numerous sources. In this study area, the majority of the Granny Creek watershed is non-impacted, meaning the headwaters for NNGC and SNGC (the streams that feed the majority of the fens in the study area) are supplying (lateral) water to the (vertically) impacted fens, helping mitigate the effects of dewatering. The ERZ, however, is dominated by bogs and therefore ombrogenous and not additionally protected by the lateral flows of water.

At a study site located ~150 km south of Victor in the HJBL, Reeve (1996) found the peat K to vary between 10^{-7} and 10^{-4} m/s (~9 to ~9000 mm/day); however, the majority of Reeve's K values were between ~10 and ~1000 mm/day, which is very similar to the ~10 to ~1600 mm/day range found in this study area. Similarly, Reeve *et al.* (2000) use a value of 10^{-7} m/s (~8.6 mm/day) for the MS K, taken from Reeve (1996), which compares well with the values of ~5 to 10 mm/day found along the research transect. The K anisotropy value found in this paper (median was log(0.23)) is lower than the values reported by Beckwith *et al.* (2003), 0.55, and Schlotzhauer and Price (1999), 0.57; however, it is similar to those reported by Whittington *et al.* (2007), 0.35, as well as Chanson and Siegel (1986), 0.3.

As noted earlier Reeve *et al.* (2000) found that no vertical flow (bog) occurred where there was a MS K of ~9 mm/day or less, implying that this would be similar at Victor under natural conditions, as the range of K values are very similar. Whittington and Price, (2012) found near-zero gradients at a control bioherm, confirming this finding. However, the aquifer dewatering is increasing the natural, near-zero, vertical gradients to ~ −0.5 in bioherm areas, −0.2 in the ERZ, and ~ −0.03 in non-bioherm areas. Using these gradients and the hydraulic conductivities at each nest, it is possible to calculate the flux of water leaving the peat at each nest along the transect (Figure 6).

When considering the anisotropy-adjusted (0.23) hydraulic conductivity profile and gradients in the peat, no significant trends in the vertical flux of water (Figure 6) along the transect or through time are observed. This is due, in part, to the large range in K values found along the transect. Even through the gradients are small in the fens areas (Figure 3), the K is high (Figure 5) resulting in a calculated flux of water similar to those at bioherm sites, where the gradients are large but the K is low. Fluxes are higher in the bioherm or bog areas and lower in the fen areas; in 2011, the non-bioherm/FWT nests averaged −0.26 mm/day and for the same year, the bioherm nests averaged −2.1 mm/day based on calculations made with peat K. The ERZ fluxes averaged −1.2 mm/day in 2011 (Figure 7).

It is clear that the impacts of dewatering are being seen along most of the transect and that the MS (MS) are not isolating the peatlands from the aquifer below, but have been delaying or muting the impact as evidenced by relatively high recharge in the bioherm and ERZ areas (no or little MS) *versus* relatively small impact in non-bioherm (MS) areas.

Using current (August 2011) drawdown data, Itasca (2011) created a drawdown cone map (not shown). The shape of the current drawdown cone, as defined by the depressurization in the Upper Attawapiskat Limestone (i.e. the layer directly below the MS), is irregular, with the 2 m drawdown line extending out between 2 and 8 km from the mine. The area for each drawdown ring was found and from that the total area of drawdown was found to be ~65 km^2 (A_T). Knowing that the total dewatering rate averaged ~85 000 m^3/day in 2011 (Patrick Rummel, 2012, De Beers Canada hydrogeologist, personal communication) and that ~50% of that was attributable to 'recharge from surface water' (Itasca Dever Inc., 2011), the total muskeg dewatering would be about 42 500 m^3/day (Q_T). (n.b. The pumping rate is a very reliable value as it can be directly measured at the pump house; unfortunately, it is unclear from the report (Itasca Dever Inc., 2011) how they arrived at the 50% figure and what assumptions were made. However, different predictions in numerous reports dating back to 2004 have all hovered around the 45 000 m^3/day for 2011.) Therefore, knowing the total dewatering amount and area, as well as the change in head (Δh) as defined by the Upper Attawapiskat Limestone, it was possible to determine the specific discharge (q_i) for each 'ring' of drawdown around the mine using a simple rearrangement of Darcy's Law,

$$Q_T = KA_T\frac{\Delta h}{\Delta l} \tag{1}$$

where K is the hydraulic conductivity and Δl is, effectively in this case, the thickness of the MS. Isolating the ratio of K and Δl allows the calculation to be made without knowing (or assuming) a value of either and will be discussed more below. Rearranging Equation (1) yields

$$Q_T = \frac{K}{\Delta l}\sum_{i=1}^{n} A_i\Delta h_i \tag{2}$$

where the total area has been re-defined as the sum of each ring and rearranging Equation (2) by solving for the ratio of K and Δl gives

$$\frac{K}{\Delta l} = \frac{Q_T}{\sum_{i=1}^{n} A_i\Delta h_i} \tag{3}$$

The discharge at each individual ring, Q_i, follows from Equation (2) and substituting Equation (3)

$$Q_i = \frac{Q_T}{\sum_{i=1}^{n} A_i\Delta h_i}A_i\Delta h_i \tag{4}$$

And finally, dividing by the area of each specific ring gives

$$q_i = \frac{Q_i}{A_i} \tag{5}$$

The transect falls on roughly the 4 m drawdown line and from Equation (5) yields a value of about −0.21 mm/day, which matches remarkably well with the non-bioherm/FWT 2011 average of −0.26 mm/day with peat K noted above. The bioherm and enhance recharge zone fluxes, however, were half to an order of magnitude higher, though represented much smaller total areas. It is worth noting specifically that the values used to generate Table III are independent of those measurements presented in Figures 6 and 7. The only overlapping data would be those from the NB and SB bedrock water levels, which were used to determine the drawdown cone along the research transect; those values were not used in the calculation of the vertical fluxes along the transect.

The value of $K/\Delta l$ has dimensions of 1/[T], and in the case reported here has a value of 5.2×10^{-5}/day. As noted earlier, it is the combination of K and thickness of the MS that would provide its protective properties, and thus determining a relationship linking the two variables could prove extremely useful in making inferences about MS. Solving this equation (K of MS (mm/day) = 0.052 * MS thickness (m) determined solely from the drawdown data) for the three important values of K discussed in the paper (see caption) and the corresponding MS thickness is shown in Figure 8. Ratios plotting below the best fit line would indicate more protective properties than currently exist (i.e. a lower K for the same thickness), whereas above the regression line (black line) would indicate less protective properties (i.e. shallower thickness for the same K). For example, near the bioherms, the MS are thinner (a few metres) and with a K of 5 mm/day would plot in the upper left-hand corner of the graph, above the regression line. The curve becomes asymptotic to an infinitely thin and low K MS layer, at which point the flow would no longer be governed by Darcy's Law (Freeze and Cherry, 1979), and

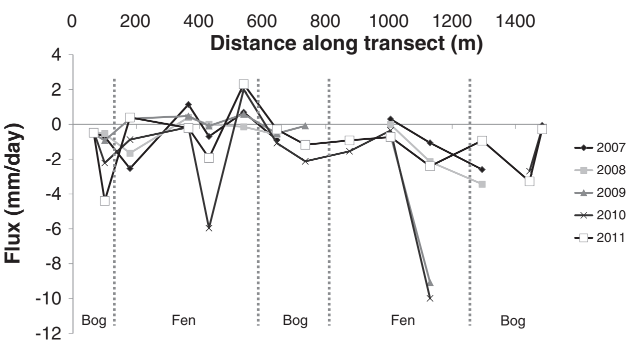

Figure 6. Fluxes of water through the peat, through time, along the transect. a) using only the marine sediment K value of 7 mm/day and b) using the K in the peat profile

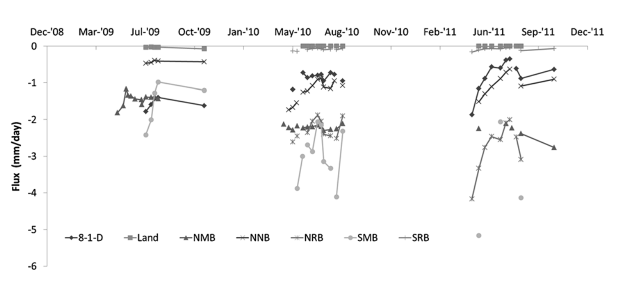

Figure 7. Fluxes of water through the peat in the ERZ from 2009 to 2011

Table III. Specific discharge (q) within the 2011 drawdown cone. The bold row (h = 4) indicates the row that best matches the transect distance

Drawdown (h)	Area (km^2)	q = mm/day
2	17.53	0.10
4	**20.15**	**0.21**
10	11.39	0.52
20	5.26	1.04
30	3.51	1.56
40	2.63	2.08
50	1.75	2.60
60	0.88	3.12
70	0.88	3.64
80	0.88	4.16
	64.8	

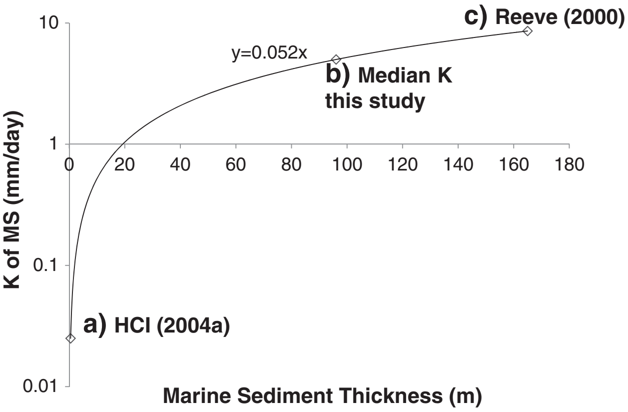

Figure 8. K *versus* marine sediment thickness using the K/ΔL ratio = 5.2 10^{-5}/day. The K values used are: a) 0.025 mm/day, value used by HCI (2004a); b) 5 mm/day, median value of MS found in this paper, c) 8.6 mm/day, Reeve *et al*'s (2000) 'no flow' base

instead osmotic processes (Neuzil and Provost, 2009) as the 'MS' would essentially be an impermeable membrane.

CONCLUSION

Considerable attention is given to the hydraulic conductivity of aquitards when their protective properties are important, e.g. a liner in a landfill or the MS presented here. However, the thickness is almost equally as important. Under normal field conditions (i.e. no depressurization of the regional aquifer), the properties of the MS are rarely tested; in fact, high water tables can be maintained directly beside bioherms where no MS are present. In the post-glacial landscape, the MS likely played a critical role in reducing recharge to more permeable deposits (like sand) and thus allowing for the establishment of the wetlands; however, this also would have occurred with a minimal vertical gradient. When determining the effects of (vertical) dewatering in peatlands, the lateral transmission of surface waters must also be considered, as the fens in this study area appear to be less impacted due to their hydrogeomorphic setting (i.e. non-ombrogenous). Currently, because of regional aquifer depressurization, the MS are being stressed and are not acting as a perfect aquitard as assumed in the original feasibility studies.

REFERENCES

Beckwith CW, Baird AJ, Heathwaite AL. 2003. Anisotropy and depth-related heterogeneity of hydraulic conductivity in a bog peat. I: laboratory measurements. *Hydrological Processes* **17**: 89-101

Belyea LR, Baird A. 2006. Beyond "the limits to peat bog growth": cross-scale feedback in peatland development. *Ecological Monographs* **76**(3): 299-322

Chanson DB, Siegel DI. 1986. Hydraulic conductivity and related physical properties of peat, Lost River Peatland, Northern Minnesota. *Soil Science* **142**(2): 91-99

Clymo R. 1984. The Limits to Peat Bog Growth. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* **303**(1117): 605-654

Cowell DW. 1983. Karst hydrogeology within a subarctic peatland: Attawapiskat River, Hudson Bay Lowland, Canada. *Journal of Hydrology* **61**: 169-175

Dredge LA, Cowan WR. 1989. Quaternary geology of the southwestern Canadian Shield. In Chapter 3 of Quaternary Geology of Canada and Greenland, Fulton RJ (ed.), Geology of Canada no. 1. Geological Survey of Canada: Ottawa.

Environment Canada. 2008. Canadian Climate Normals or Averages 1971-2000. http://www.climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html (accessed 15 June 2011).

Freeze RA, Cherry JA. 1979. Groundwater. Prentice-Hall: Englewood Cliffs, N.J.; xvi, 604 pp.

Glaser PH, Hansen B, Siegel D, Reeve AS, Morin P. 2004a. Rates, pathways and drivers for peatland development in the Hudson Bay Lowlands, northern Ontario, Canada. *Journal of Ecology* **92**(6): 1036-1053

Glaser PH, Seigel DI, Reeve AS, Janssens J, Janecky D. 2004b. Tectonic drivers for vegetation patterning and landscape evolution in the Albany River region of the Hudson Bay Lowlands. *Journal of Ecology* **92**(6): 1054-1070

Glaser PH, Siegel D, Romanowicz EA, Shen Y. 1997. Regional linkages between raised bogs and the climate, groundwater and landscape of north-western Mnnesota. *Journal of Ecology* **85**(1): 3-16

HCI. 2004a. Dewatering of the Victor Diamond Project. Predicted Engineering, Cost, and Environmental Factors. HCI-1779, Prepared by Hydrologic Consultants Inc of Colorado.

HCI. 2004b. Dewatering of Victor Diamond Project Predicted Engineering, Cost, and Environmental Factors. Addendum I: Update of Ground-Water Flow Model Utilising New Surface-Water Chemistry and Flow Data from Nayshkootayaow River and Results of Sensitivity Analyses.

HCI. 2007. Dewatering of the Victor Diamond Mine. Predicted Engineering and Environmental Factors. HCI-1779, Colorado.

Hoag RS, Price JS. 1997. The effects of matrix diffusion on solute transport and retardation in undisturbed peat in laboratory columns. *Journal of Contaminant Hydrology* **28**.

Hvorslev MJ. 1951. Time lag and soil permeability in groundwater observations, Waterways Experimental Station Bulletin 36. US Army Corps of Engineers: Vicksburg, Mississippi.

Ingram HAP. 1982. Size and shape in raised mire ecosystems: a geophysical model. *Nature* **297**: 300-303

Itasca Dever Inc. 2011. Dewatering of Victor Diamond Project, March 2011 update of March 2008 Groundwater flow model, Denver, Colorado.

Klinger L, Short S. 1996. Succession in the Hudson Bay lowland, northern Ontario, Canada. *Arctic and Alpine Research* **28**(2): 172-183

Lee HA. 1960. Late Glacial and Postglacial Hudson Bay Sea Episode. *Science* **131**: 1609-1611

Neuzil CE, Provost AM. 2009. Recent experimental data may point to a greater role for osmotic pressures in the subsurface. *Water Resources Research* **45**: 14

Price JS, Woo M-k. 1988. Studies of subarctic coastal marsh. 1. Hydrology. *Journal of Hydrology* **103**: 275-292

Reeve AS. 1996. Numerical and mutlivariate statistical analysis of hydrogeology and geochemistry in large peatlands. Syracuse University: Syracuse, New York.

Reeve A, Siegel D, Glaser P. 2000. Simulating vertical flow in large peatlands. *Journal of Hydrology* **227**(1-4): 207-217

Riley JL. 2011. Wetlands of the Ontario Hudson Bay Lowland: An Regional Overview. Nature Conservancy of Canada: Toronto, Ontario, Canada; 156.

Schlotzhauer SM, Price JS. 1999. Soil water flow dynamics in a managed cutover peat field, Quebec: Field and laboratory investigations. *Water Resources Research* **35**(12): 3675-3683

Siegel DI, Glaser PH. 1987. Groundwater Flow in a Bog-Fen Complex, Lost River Peatland, Northern Minnesota. *Journal of Ecology* **75**(3): 743-754

Sjörs H. 1963. Bogs and Fens on Attawapiskat River, Northern Ontario. Canada Dept. of Northern Affairs and National Resources.

Whittington P, Strack M, Van Haarlem R, Kaufman S, Stoesser P, Maltez J, Price J, Stone M. 2007. The influence of peat volume change and vegetation on the hydrology of a kettle-hole wetland in Southern Ontario, Canada. *Mires and Peat* **2**: 1-14.

Whittington P, Price JS. 2012. Effect of mine dewatering on peatlands of the James Bay Lowland: the role of bioherms. *Hydrological Processes* **26**(12): 1818-1826. DOI: 10.1002/hyp.9266

Whittington PN., Ketcheson SJ., Price JS, Richardson M., Di Febo A. 2012. Areal differentiation of snow accumulation and melt between peatland types in the James Bay Lowlands. *Hydrological Processes* DOI: 10.1002/hyp.9414