HYDROLOGICAL PROCESSES
Hydrol. Process. **26**, 1818–1826 (2012)
DOI: 10.1002/hyp.9266

Effect of mine dewatering on peatlands of the James Bay Lowland: the role of bioherms

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Abstract:

The James Bay Lowland host one of the largest wetland complexes in the world in part due to the low permeability of marine sediments that suppress groundwater seepage losses. Dewatering of an open-pit diamond mine in the area has depressurized the regional bedrock aquifer. Bioherms, fractured limestone outcroppings formed from ancient coral reefs that protrude to the peatland surface, lack this mantle of low-permeability sediments and provide a direct connection between the peatland (surficial) and the regional (bedrock) aquifers. Well transects and piezometer nests were installed around seven bioherms in the depressurized zone and one in a non-affected zone (control) to monitor the water table drawdown and change in hydraulic gradients around the bioherms. Water tables in the affected bioherms decreased between 2 and 4 m in the first 4 years of dewatering. The drawdown in the bioherms caused a localized water table drawdown in the peat surrounding the bioherms that extended to approximately 30 m from the edge of the bioherm during a dry period. Under wet conditions, drawdown was similar to that at the control site. Hydraulic gradients in the peat (which typically are very small) increased over the field seasons and in a few locations exceeded 1. These gradients represented significant losses to the local, near bioherm, system as at many of the locations surrounding the bioherms vertical seepage losses ranged between 1 and 4 mm/day, which are similar to the seasonal average evaporative water loss of ~ 3 mm/day. The bioherms are acting as efficient drainage nodes; however, their influence is localized to the peat immediately (~ <30 m) surrounding them. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS James Bay Lowlands; Bioherm; Dewatering; Mining; Peatlands

Received 15 August 2011; Accepted 10 January 2012

INTRODUCTION

Peatlands (mostly bogs and fens) cover nearly 90% of the Hudson Bay Lowland (Tarnocai, 1998) and are formed by the high water tables, which are a consequence of the extremely low relief and thick low-permeability marine sediment deposits that suppress runoff and groundwater seepage loss, and the cool subarctic climate, which limits evapotranspiration. In addition, isostatic rebound (greater near the coast) continually lowers the regional gradient away from the coast, which Glaser *et al.* (2004a) determined to be a key factor in the development of the landscape. The Hudson Bay Lowland represents one of the largest wetland complexes in the world (Riley, 2011), and understanding their hydrological response to environmental stressors is important because they affect freshwater discharge to major river systems and Hudson Bay itself and thus the transport of nutrients and contaminants (Kirk and St. Louis, 2009), regional climate (Rouse *et al.*, 1992) and global carbon cycle (Gorham, 1991; Roulet, 2000).

Discovery of kimberlite (diamondiferous) pipes in an area of the James Bay Lowland (which is part of the Hudson Bay Lowland) has led to open-pit diamond mining, which requires substantial groundwater pumping to dewater the mine, thus causing depressurization of the regional bedrock aquifer. This depressurization has the potential to significantly affect the peatlands, depending on the nature and strength of the connection between them and the regional (bedrock) aquifer. Because of their hydrogeomorphic setting, peatlands can be isolated from a more permeable bedrock substrate (Price and Woo, 1988), and because vertical hydraulic gradients in peatlands are typically very small (see Fraser *et al.*, 2001; Price and Maloney, 1994), and in the order of 0.01–0.0001 are not uncommon, any connection would not result in a significant loss of water from the system (direction dependant, of course). However, this is not to say that there is no connection with the fine-grained marine sediments that typically underlie peatlands. Fen peatlands often have a groundwater input component bringing with it nutrient-rich geogenous water (Glaser *et al.*, 2004b). Reeve *et al.* (2001) determined that mechanical dispersive mixing with shallow mineral soils as a result of lateral groundwater flow (in part from the raised water table of bogs supplying water to the bordering fens) can be the dominant mass transport mechanism in large peatlands. They concluded that these flows can be a determinant for the formation of bogs: where these fluxes are significant, bogs will not form (Reeve *et al.*, 2001).

However, the presence of bioherms, fractured limestone formed from ancient coral reefs that protrude from the surface as partially vegetated mounds of exposed bedrock (Cowell, 1983), could provide a direct and efficient

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connection between the aquifers, bypassing the marine sediments. The presence of peatlands that surround the bioherms indicates that, currently, vertical recharge near the bioherms is sufficiently small for saturated conditions to be sustained to a degree favourable to peatland development. The fact that many of the peatlands are bogs (ombrogenous) implies groundwater discharge (i.e. upward flow from the aquifer) is either minimal or at least localized.

Horizontal groundwater flow in peatlands can efficiently shed water through the relatively undecomposed, high-permeability upper layer of the peat deposit (acrotelm) in times of high water tables, mainly spring melt. At other times, flow is directed mostly through the relatively well-decomposed low-permeability deeper peat (catotelm). The low-permeability catotelm inhibits drainage of peat beyond 30 m from a drainage ditch (Boelter, 1972; Silins and Rothwell, 1998). Consequently, lateral flows toward drain nodes (e.g. bioherms) through peat may be low.

The area that bioherms affect may be double the total surface area that the exposed portion of the bioherms occupy, that is, approximately 21% of the area (North Granny Creek Zone, see below) pertinent to this article (or ~ 0.5% of the total model domain area) (HCI, 2004). This article will examine how complexities in the geological structure (notably bioherms) influence the potential effects of mining development. Therefore, the specific objectives of this article were (i) to determine if bioherms promote drainage of the peatlands in response to aquifer depressurization and, if so, (ii) to quantify the lateral extent of this effect and (iii) to determine the recharge rates through the peat toward the bioherms both horizontally and vertically.

STUDY SITE

The study site is approximately 500 km north of Timmins, Ontario, at the De Beers Canada Victor Diamond mine (52°49′15″N, 83°53′00″W) (Figure 1). There are a complex arrangement of bogs and fens with peat up to 4 m thick (Sjörs, 1963) overlying fine-grained clay-sized marine sediments, which can be up to several hundreds of metres thick, mantling Silurian bedrock of the Upper and Lower Attawapiskat formation (Martini, 1981; McDonald, 1989). Bioherms resting on the Upper Attawapiskat formation either protrude to the surface where exposed limestone is visible (cropping bioherms) or do not extend above the surface (subcropping bioherms) but may be visible due to vegetation community anomalies (e.g. tree density increases). The main study area is approximately 90 km from the James Bay coast (0 m.a.s.l.), and the surface of the peatland within the study area is generally located between 85 and 87 m.a.s.l. (higher on top of bioherms). The headwaters of the Attawapiskat are approximately 600 km from the coast at an elevation of approximately 241 m.a.s.l. Near the study site, the Attawapiskat River has an elevation of approximately 65 m.a.s.l. A regional flow map completed by HCI (2007) shows pre-mining over a distance of approximately 100 km (50 km radius from the mine) water levels, at the top of bedrock change from approximately 130 to 40 m.a.s.l. or a rate of approximately 0.9 m/km.

Data on the regional extent of bioherms are scarce. However, using a DEM created from LiDAR data, which covers approximately 500 km^2 in an approximately 12 km radius around the mine, a topographic derivative was computed showing local patterns of relief within a 150 × 150 m moving window (30 × 30 pixel at a 5-m resolution). The resulting map clearly emphasized local topographic highs. From this, it was possible to identify more than 100 ‘topographic highs’ in three distinct bans (~2 km wide) running northwest to southeast, approximately 10 km apart. We believe most of these to be bioherms based on personal observations during helicopter flights. Unfortunately, palsas would also show up as ‘topographic highs’ causing an overestimate of the number of bioherms; conversely, subcropping bioherms would not show up. In the study area immediately surrounding the mine, the number of palsas is roughly the same as the number of subcropping bioherms, and the ratio of bioherms–palsas/subcropping is approximately 7:1, meaning it is probably reasonable to assume that the majority of the ‘topographic highs’ are bioherms.

Within the area the mine is predicted to affect, HCI (2004) identified six enhanced recharge zones, typified by a local abundance of bioherms (i.e. located in one of the bands noted earlier). This article focuses mostly on one of these zones (North Granny Creek Zone, see the heavily pooled area in the top half of Figure 1) that is located approximately 2.5 km northwest of the open-pit mine. Within this area, there are at least four cropping and two subcropping bioherms. This article will focus on data from five cropping bioherms: north bioherm (NB), south bioherm (SB), north road bioherm (NRB), south road bioherm (SRB) and north north bioherm (NNB); and two subcropping bioherms: north middle bioherm (NMB) and south middle bioherm (SMB). A sixth cropping bioherm, control bioherm (CB), is located approximately 25 km south west of mine (~ 100 m.a.s.l.), outside the zone of influence. (Note that SB is outside of the North Granny Creek Zone mentioned earlier.) The height and the lateral extent of each of these bioherms are shown in Table I. A non-bioherm site is located in a fen water track (FWT) also shown in Figure 1.

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

METHODS

To determine the near-surface stratigraphy surrounding the NB, three transects were selected that extended

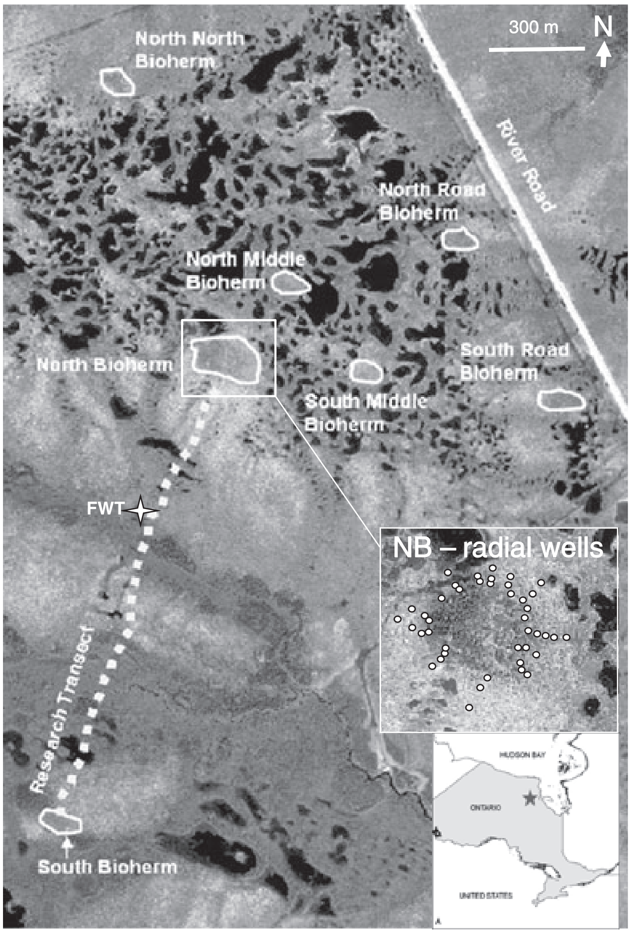

Figure 1. Bioherms located in the study area. The dashed line (research transect) between SB and NB is ~1500 m long. FWT is the fen water track location. The open pit is located ~2 km from the lower right hand corner of the image. The control bioherm is located ~25 km south west

outwards from the edge of NB to approximately ~25, ~35 and ~40 m, respectively. These transects were located on the northwest, southwest and east sides of NB close to a nearby well transect (see below). Along each transect, a hand auger was used to determine the thickness of the peat and marine sediments as well as the depth to bedrock. NB was selected as it is the most heavily instrumented of all the bioherms (see below).

Bedrock monitoring wells were installed using a drill rig that created a 15 cm diameter hole. Polyvinyl chloride (2.5 cm diameter) standpipes were installed with 3 m screens open at specified depths, sand packed and sealed with bentonite. At the NB, the screened openings were centred at 25.5, 58.5 and 64.5 m below ground surface (mbgs) in the upper Attawapiskat limestone formation. At the SB, the screened openings (3 m) were also located in the upper Attawapiskat limestone formation at 10 and 30 mbgs. At CB, they were at 1.3 and 10.85 mbgs, respectively, in the lower Attawapiskat limestone. These wells were equipped with a pressure transducer set to record every 12 h.

Peat piezometers and wells were constructed from 2.5 cm diameter polyvinyl chloride pipes and were installed in the peat by preauguring a hole using a hand auger slightly smaller than the diameter of the well. Each nest typically had three piezometers (with 30 cm slotted intakes) usually centred at 0.9, 1.5 and 2+ m (with the deepest near the peat/marine sediment interface, which ranged in depth from 1.9 to 3.0 m, with the majority in the 2.1 to 2.7 m range). Piezometers were located within approximately 50 cm laterally of each other. In fine-grained mineral sediments, 20 cm diameter stainless steel drive point piezometers (Solinst Model 615) were installed using a compression rock hammer (Pionjaar 120). At select locations, two drive points were installed, one just below the peat/mineral sediment interface and the other to refusal (typically between 4 and 8 m). Flexible plastic tubing connected to a nipple in the drive point passed through sections of steel pipe to the surface. 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.

Pipe top elevations were surveyed using a dual-frequency survey-grade GPS in real-time kinematic survey mode (Topcon GMS-2). The base station was setup over a known benchmark near the mine, and the rover was never further than approximately 4 km from the base. The acceptable precision for the DGPS was manually selected within the software and set at vertically at 0.003 m and horizontally at 0.005 m. The DGPS only records the point when these conditions are met. The 0.003 m software setting is misleading, as in practice the relative accuracy of the DGPS was approximately 1 cm.

Table I. Bioherm instrumentation table

Name		Dimensions (m)	Peat piezometers
South bioherm	SB	3.5; 43 × 80	N + 5, **15**, **35**, **70**
North bioherm	NB	4; 100 × 115	S + 2, **10**, **30**, **50**
South road bioherm	SRB	1.5; 30 × 30	S + 10; N + 5, 10, 15
North road bioherm	NRB	1.5; 60 × 77	E + 5, 10, **20**, 50; S + 10, **20**
North north bioherm	NNB	1; 100 × 60	E + 20
Control bioherm	CB	3; 100 × 130	S + **5**, **20**
North middle bioherm	NMB	0; 77 × 80	0
South middle bioherm	SMB	0; 80 × 53	0

The numbers in the Peat piezometers column indicate the distance, in metres, from the edge of the bioherm each nest is located, and on which side. For example, the NRB has six nests, four on the east side and two on the South side, with the south side nests being 10 and 20 m from the edge (a value of 0 indicates the only nest is located in the middle of a subcropping bioherm). Nests with distances in bold font also include a drive point piezometer. Dimensions are maximum bioherm height above surrounding peatland (0 indicates subcropping), length and width dimension.

Well networks (for an example of their arrangement, see inset NB—radial wells in Figure 1) radiating out from the bioherms were installed using the same techniques and materials as the peat piezometers described earlier; however, the wells were slotted along their entire length and were approximately 1 m long. Wells were located in a radial pattern away from the bioherms at distances of (i) 1–5 m from the bioherm, (ii) ~5–10 m away from that and (iii) ~15–30 m from that. Each of the instrumented bioherms (NB, NRB and SRB) had approximately 9 of these mini-transects and labelled as transects 1–9.

RESULTS

The subsurface stratigraphy was similar in pattern but differed in depth and lateral extent around NB (Figure 2). At each location, there was a zone (ranging from 5 to 22 m from the bioherm edge) where the peat mantled the bedrock directly. After this distance, a layer of marine sediment started to emerge (ranging in thickness from 0.15 to 1.8 m) between the peat and the bedrock.

Bedrock water levels at all sites show a seasonal pattern of snowmelt recharge followed by drawdown over the duration of the year. At NB and SB, water levels have decreased between 2 and 4 m from April 2007 to January 2010 (Figure 3) but have not declined at CB.

The 2010 field season had an atypically shallow snow pack, which melted early and provided little groundwater recharge to the system. By the end of June, the peatland and the creek water levels were at the lowest of the four field seasons (2007–2010). However, after heavy rain (58 mm on 28 July 2010) and cooler temperatures, water levels rebounded to typical seasonal conditions. The lowest water tables in the radial wells surrounding the bioherms occurred at the end of June (Figure 4a). During the dry period (e.g. 29 June 2010), water levels within the first 25–30 m around NB, NRB and SRB were lower than that at CB, but beyond this distance, water table depths were similar and were generally within 30 cm of the surface. (Note that water table depths plotted at depths less than −100 cm represent the bottom of a dry well, and actual water table is unknown.) During the wet period (e.g. 30 July 2011), some of the transects had water tables similar or higher than at CB, and most the transects had water tables within 30 cm of the surface within approximately 10 m (Figure 4b). The SRB still experienced slightly more drawdown than NB and NRB. However, all transects had water tables near the surface within 30 m, and most by 20 m of the bioherm.

Gradients (calculated from the deepest to the shallowest piezometers) were downward (negative) at every bioherm nest in the affected area for the entire study period (Figure 5). At the affected bioherms (Figures 5b–5f), the hydraulic

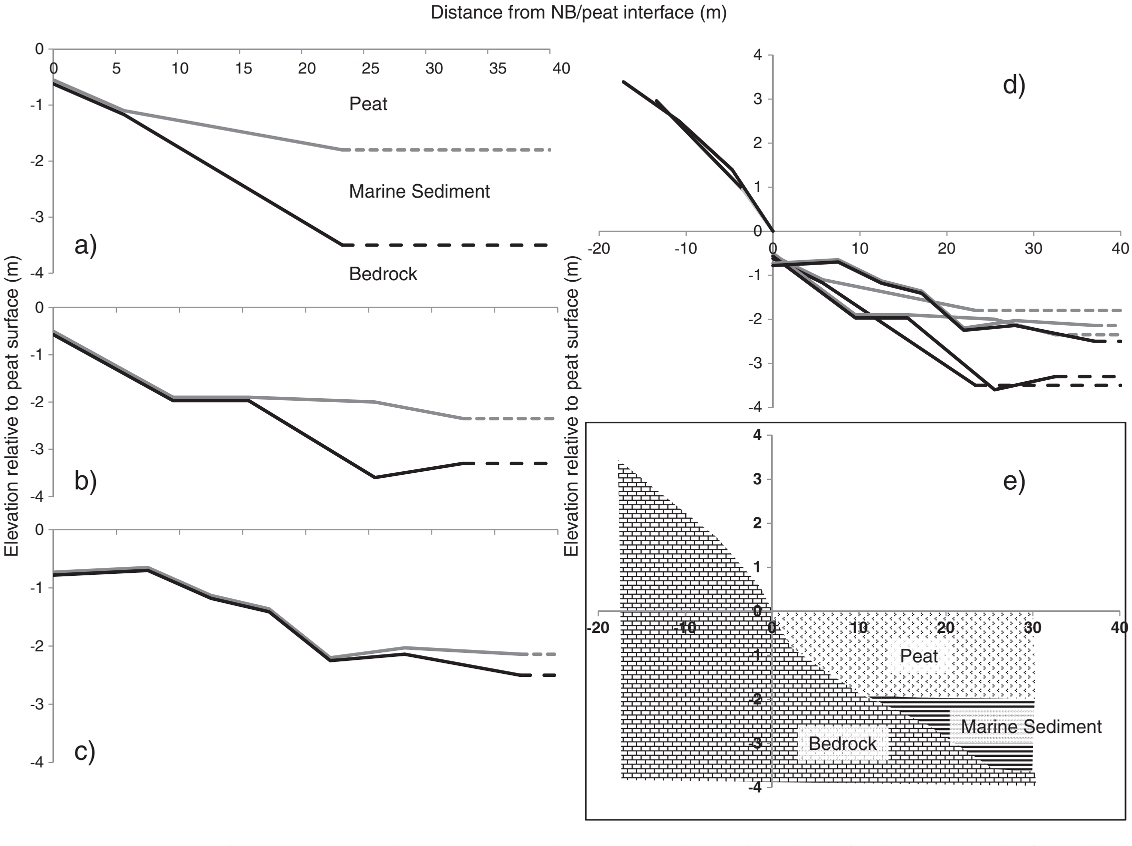

Figure 2. NB stratigraphy cross section on the (a) east side, (b) southwest side and (c) northwest side. The surface is assumed to be flat and is represented by the *x*-axis. The area below the *x*-axis and above the grey line is peat, between the grey and the black lines are marine sediments (ranging from sand to clay) and below the black line is bedrock. Dashed lines begin where auguring ended. (d) Cross section with all three transects as well as the bioherm elevation profile. Note that there are two lines for the bioherm elevation profile and are the north and south sides of NB. (e) Idealized stratigraphy of bedrock (brick shade), peat (speckled) and marine sediments (horizontal shade)

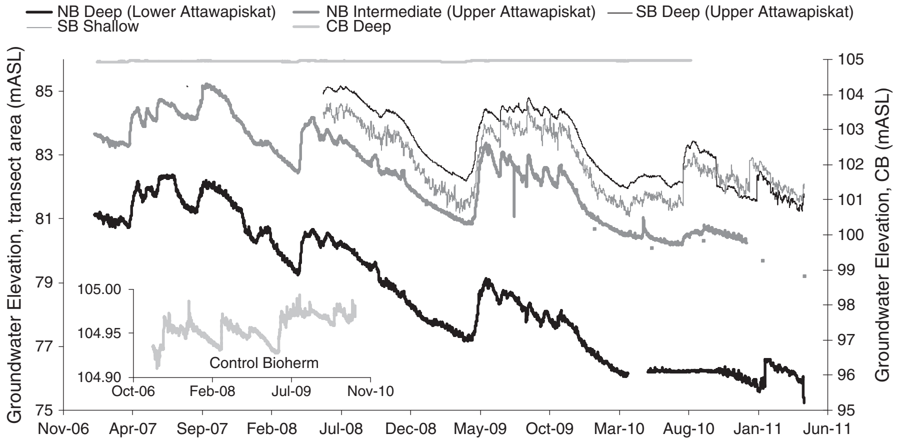

Figure 3. Bedrock water levels at NB and SB (primary *y*-axis) and CB (secondary *y*-axis). The inset graph is the CB on its own scale: note the *y*-axis scale difference between main (10 m) and inset (0.1 m) graph

gradients generally decreased over the season but became stronger (more negative) from year to year. Gradients at six locations exceeded 1.0 (Eaton, 2010; Hart *et al.*, 2008) for some period of time as head in the deep piezometers adjacent to the mineral sediment dropped markedly (not shown). At all sites, these gradients are 1–3 orders of magnitude larger than at CB (Figure 5a) where gradients were between −0.017 and −0.002. These trends were not universal throughout the affected area; the FWT is located within the affected area, although approximately 500 m from the closest bioherm. Gradients (not shown) at this site were positive (albeit small) for parts of each year, likely due its location along the edge of the domed bog.

Hydraulic conductivity (horizontal unless noted otherwise) values in the peatland ranged 5 orders of magnitude and offered few trends (Figure 6a). Locally (with a nest), *K* did tend to decrease with depth. However, this was not universal at all nests. A slight trend of decreasing *K* with increasing distance from a bioherm was observed within the first 20 m from a bioherm. After this distance, *K* appeared to increase with increasing distance. The marine sediments in the study area and in the CB area were

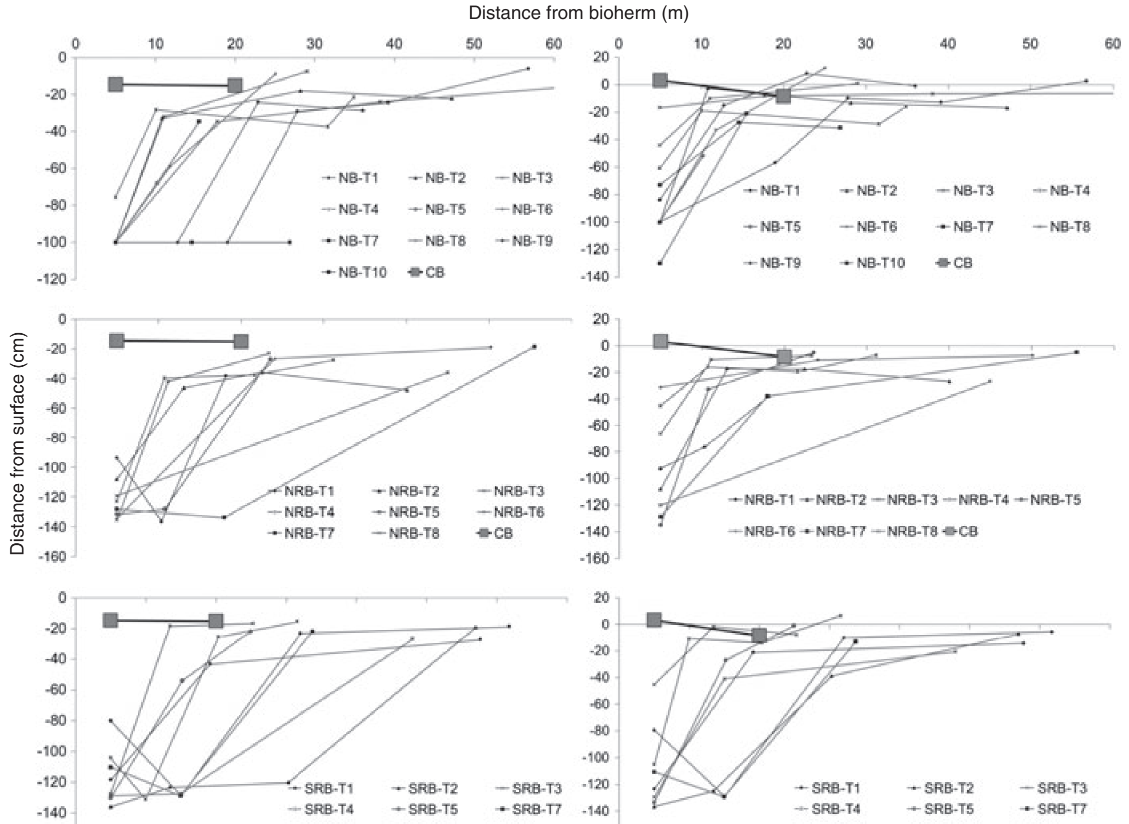

Figure 4. Water table drawdown in the radial wells around the NB, NRB and SRB for a) dry (29 June 2010) and b) wet (30 July 2010) periods. CB dates were 30 June 2010 and 14 August 2010 for dry and wet, respectively. The later wet date at CB reflects the difficulty in accessing the remote site (via helicopter) and would likely be higher than shown. The T# is the transect number around the respective bioherm

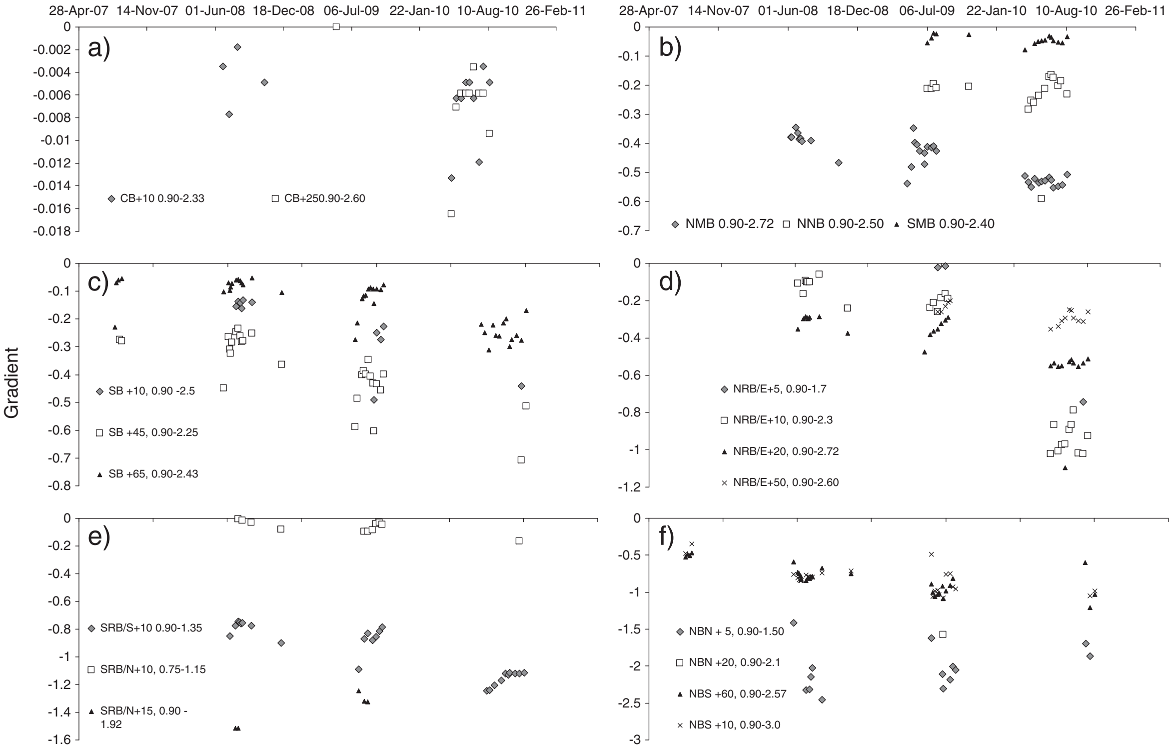

Figure 5. Head change from shallowest to deepest peat piezometer at the bioherm peat nests at all sites, through time. The distance from the edge of the bioherm is reported as the +*X* value followed by the depths of the piezometer midpoints used to calculate the gradient. Note that the scales of the vertical axes are not the same between graphs, increasing from panels a to f

similar with most *K* values around 0.1 cm/day. Bedrock *K* values were similar at all sites and ranged from approximately 300 to 1000 cm/day (Figure 6b).

DISCUSSION

During the study period, the water table in the pit decreased to a depth of approximately 60 m below the local surface, which is only a third of the projected final drawdown of >150 m. Recent modelling reports (Itasca Denver 2011) (n.b., HCI was renamed Itasca Denver Inc.) predict the depressurization of the bedrock in the North Granny Creek Zone will range from -10 to -30 m, meaning that the current drawdown (~ -2 to -4 m, Figure 3) experienced in the bioherms is between 10% and 40% of the projected final value. Regardless, it is clear from the results that aquifer dewatering is already affecting the peatlands surrounding the bioherms, although perhaps only fractionally compared with the eventual drying, because the water levels in the bedrock have not reached their final drawdown. What is unclear is whether the drawdown experienced in the surrounding peatlands is a result of horizontal drainage to the bioherm, vertical drainage as a result of a thinner or absent marine sediment layer (Figure 2) or both. First, however, it will be useful to determine the theoretical maximum lateral extent of drawdown with a relatively impermeable marine sediment layer.

In this hypothetical scenario, a similarity exists between the drawdown experienced at a pumping well (see Theis, 1935) and the drawdown experienced around the bioherm where the bioherm behaves like a large diameter pumping well. There is a well-established logarithmic decrease in drawdown with distance from a pumping well given the transmissivity and storativity of the medium being dewatered (see Fetter, 1994; Freeze and Cherry, 1979). Some simple modelling (not shown) of the Theis (1935) equation suggests that even under extreme drawdown (much greater than the predicted effect from the mine) in the bioherm, the drawdown in the surrounding peat becomes asymptotic to a water level of ~ -0.08 m at ~ 25 m from the edge (assuming the water table was initially at the surface). Thus, for the following section, we will limit our analyses to within 30 m surrounding NB on the date of the driest condition (29 June 2010).

Using the information from the stratigraphic transects, we can develop an idealized cross section and partition the horizontal and vertical fluxes within it (see Figure 2e). The cross section is divided into three 10 m annular segments (0–10, 10–20 and 20–30 m): the first (i.e. closest to the bioherm) with no marine sediments, the second with thin (1 m thick) marine sediments and the third with thick (2 m) marine sediments. Peat depths are 2 m throughout. The specific discharge (q, L/T) version of Darcy's Law will be used to calculate the fluxes of water from the various compartments and distances using Equation (1),

$$q = \frac{Q}{A} = K\frac{dh}{dl} \tag{1}$$

where Q is discharge (L^3/T), K is the hydraulic conductivity (L/T) and dh and dl (dimensionless) are the change in head and length between the measurement points, respectively.

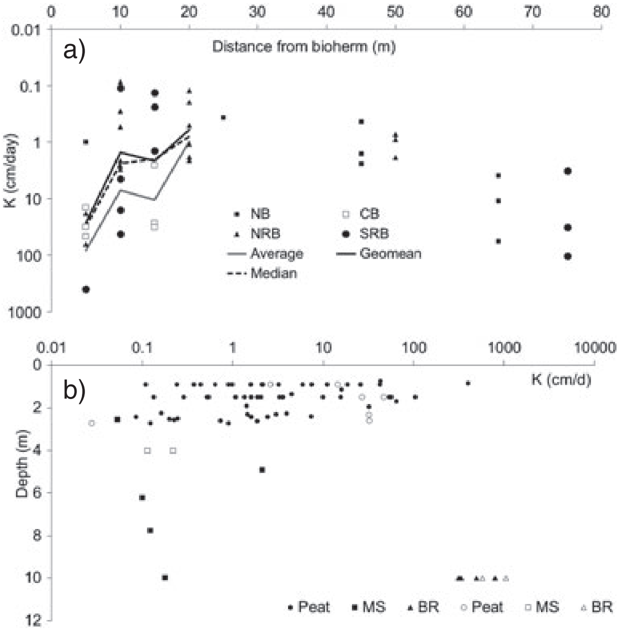

Figure 6. Hydraulic conductivity values for piezometers and wells installed near or in bioherms. Note that the peat *K* values are the same between panels a and b but shown with different metadata. (a) Peat *K* with distance from the respective bioherm. (b) All peat *K* values from near the bioherms as well as marine sediments (MS) (not necessarily near a bioherm) for the study area (dark) and near CB (white), as well as bioherm (BR, bedrock) *K* values from NB, SB and CB. Note that the bioherm values are artificially placed at 10 m depth for graphing purposes

Hydraulic conductivity in peat surrounding the bioherms is highly variable (Figure 6). For all calculations of horizontal flow, the geomean and median *K* value for the appropriate distance from the bioherm will be used (Figure 6). The average was omitted as it is very susceptible to outliers. For vertical fluxes, the lowest value in the profile will be used as that layer will ultimately control the vertical seepage losses.

The average, minimum and maximum gradient (*dh*/*dl*) used for the horizontal flow were calculated from the nine radial well transects surrounding NB (Table II). Horizontal specific discharge ranged from 0.8 to 3.6 mm/day. The average, minimum and maximum vertical gradients as well as the geomean and median *K* for the no marine sediments zone were obtained from the relevant nests in Figure 5. Vertical loses through the peat (no marine sediment zone) ranged from 0.2 to 7.1 mm/day. The gradient in the thin marine sediment zone was calculated assuming the water table was near the surface in the peat with an elevation of 87 m.a.s.l., which is 6 m higher than the NB intermediate water level (81 m.a.s.l., Figure 2). It was assumed that the NB water level under the marine sediments would be the same as in the bioherm where it is measured, and over the scale of less than 30 m is a reasonable assumption. As the peat is 2 m thick and the marine sediments assumed to be 1 m thick, the *dl* is 3 m, which yielded a gradient of 2 and specific discharges of 2.5 and 3.8 mm/day (Table II). Where the marine sediments were thicker (i.e. 2 m), the gradient decreased decreasing the specific discharge to 1.8 to 2.8 mm/day (Table II).

The idealized-bioherm specific discharge values (Table II) are similar to those that were calculated using actual *in situ* gradients and *K* values for that particular nest (Table III), rather than assumed or averaged (e.g. geomean or median) values for the idealized bioherm. These ‘real’ values range from 0.41 to 4.8 mm/day, and thus the idealized bioherm offers good agreement with field observations.

Ultimately, we are interested in the loss of water from the peatland system as it relates to the water balance; large losses that are unmatched with recharge will result in desiccation of the peat and damage to its ecological and carbon storage function. Annual precipitation is estimated to be 690 mm/year (Environment Canada, 2008) and actual evapotranspiration 431 mm/year (Singer and Chen, 2002) (averages of Moosonee and Lansdowne House), which is approximately 3 mm/day during the growing season. AMEC (2004) estimated runoff in nearby basins to be 260 mm/year. These figures essentially balance (i.e. precipitation versus evapotranspiration + runoff), and thus the groundwater recharge of 10 mm/year estimated by HCI (2004) is in order. Therefore, because most the calculated specific discharges (i.e. groundwater recharge) are between 1 and 4 mm/day, these represent a significant

Table II. Horizontal and vertical specific discharge values for the three zones surrounding an idealized bioherm

	K (cm/day)			*q* (mm/day)	
	Geomean	Median	*dh*/*dl*	Geomean	Median
Horizontal					
Average	1.5	2.4	0.07	1.1	1.7
Max	1.5	2.4	0.15	2.3	3.6
Min	1.5	2.4	0.05	0.8	1.3
Vertical					
No marine sediments					
Average	0.58	0.63	0.47	2.7	3.0
Max	0.58	0.63	1.13	6.6	7.1
Min	0.58	0.63	0.03	0.2	0.2
Thin marine sediments					
Average	0.19	0.12	2	3.8	2.5
Thick marine sediments					
Average	0.19	0.12	1.5	2.8	1.8

Table III. Specific discharge and *K* values for piezometer nests near bioherms on 30 June 2010 (dry day)

Location	*dh/dl*	*K* (cm/day)	*q* (mm/day)
CB + 10, 0.90–2.33	*−0.006*	*14.5*	*0.91*
CB + 25, 0.90–2.60	*−0.004*	*2.6*	*0.09*
NMB, 0.90–2.72	−0.526	0.9	4.72
NNB, 0.90–2.50	−0.164	0.2	0.41
NRB E + 10, 0.90–2.3	−0.866	0.5	4.67
NRB E + 20, 0.90–2.72	−0.517	0.1	0.63
NRB E + 50, 0.90–2.60	−0.252	0.7	1.85
SB N + 10, 0.90–2.43	−0.299	1.6	4.80
SMB, 0.90–2.40	−0.035	7.4	2.61
SRB S + 10, 0.90–1.35	−1.131	0.1	1.24

The distance from the edge of the bioherm is reported as the +XX value followed by the depths (m) of the piezometer midpoints used to calculate the gradient.

loss to the local, near bioherm, system (in the order of annual evapotranspiration).

It is also evident that the vertical losses are a larger and more important component of the water lost from the system. The horizontal losses are limited to the zone closest to the bioherm because beyond 10–15 m, the water table begins to flatten rapidly with increasing distance (flattened by 20 m), greatly reducing the gradient and thus horizontal flow. The North Granny Creek Zone was identified as an enhanced recharge zone because of the localized abundance of bioherms. This abundance is due the bedrock being closer to the surface (and thus the bioherms are able to protrude) with the corollary being a thinner marine sediment layer. Therefore, the distance to bioherm (horizontally) is likely not as important as distance to bedrock (vertically) for the affected area as a whole. The horizontal distance of affected peat to bedrock range between 0 and 30 m; however, vertically this distance is simply the depth of the marine sediments (~ 0–2 m in the bioherm zone), 10 times smaller. The *K* of the marine sediments was similar to that of the deepest peat samples and thus does not provide the protection of a very low permeability aquitard (e.g. clay); instead, it is the thickness of the marine sediments that provides the protection. In the FWT location (Figure 1), gradients were positive for periods of the 2010 season, despite being within the affected zone and only several hundred metres from NB. The marine sediment in this location, however, is estimated to be well more than 100 m thick, providing the protection required to keep the peatland wet, minimizing vertical seepage losses.

CONCLUSION

The area studied was predicted to be an enhanced recharge zone because the bedrock is much closer to the surface, on average, than in other areas. The bioherms are draining the peatlands in the immediate area surrounding them and are acting as efficient drainage nodes and the lateral extent appears to be limited to approximately 30 m. However, the proximity to bedrock (non-bioherm or bioherm) is perhaps more important as vertical recharge rates in well-connected areas (i.e. thin marine sediments) are similar or larger than immediately adjacent to the bioherms. These losses represent a significant and irreplaceable (until aquifer recovery following the end of mine dewatering) loss in the water balance both within a peatland form and within the peatland complex. The area that the bioherms occupy is very small (~ 0.5% of the affected area); however, the area that the enhanced recharge zones occupy is much larger (~ 8%), further supporting that proximity to bedrock as the more important factor.

The geological and hydrological connection found in this study between the upper peatland aquifer and the groundwater bedrock aquifer provides background for future research and provides valuable information for regulators and industry concerning how to manage proposed mining activity in the James Bay Lowland. It is particularly pertinent given the ‘Northern Ontario Ring of Fire’ development occurring a few hundred kilometres west of our study site.

ACKNOWLEDGEMENTS

The authors thank C. Cook, S. Ketcheson, M. Leclair, the ‘Fox’, PAM and P. Jeffries for helping with data collection. They also thank Dr Richardson for GIS-related help. Thanks also to K. Tindale for stratigraphy coring. Special thanks to the Environment Crew (especially B. Steinback and the Environment Monitors) at De Beers for all the help. Funding was provided by the NSERC CRD and De Beers Canada. Thanks also to the comments of two anonymous reviewers.

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