Evaluation of the Impact of the Proposed NorthMet Mine on Local Wetlands

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INTRODUCTION

Background

I am a Professor of Geography at the University of Waterloo in Waterloo, Ontario, Canada. I teach physical hydrology and various courses related to wetlands. My academic interests and experience relate to a broad range of issues pertaining to wetland hydrology. In particular, my focus is on peatlands, including reclamation of peatlands, restoration of damaged peatlands and the impact of resource development, such as mine dewatering and contaminant transport on peatlands. My research examines pore-scale to watershed scale hydrologic processes in wetlands. This research is applied research and focuses on impacted systems caused by mining (e.g. De Beers Victor Diamond Mine impact on peatlands of the James Bay Lowland); oil sands extraction (e.g. constructing a fen peatland and watershed on the post-mined landscape); and peat harvesting (e.g. restoration of fens and bogs in eastern Canada). I have authored and co-authored over 160 peer-reviewed journal publications related to my research. A complete *curriculum vitae* is attached as Exhibit A to this report.

I was contacted by WaterLegacy and asked to review various materials related to the proposed PolyMet NorthMet copper-nickel mine in northeastern Minnesota to offer an expert opinion regarding the methods of securing information and the conclusions reached regarding the potential impacts of mine drawdown on wetlands and peatlands. I have reviewed a number of documents related to the NorthMet mine prepared by PolyMet, its consultants, government agencies and other experts.

SUMMARY

My conclusion after reviewing the documents pertaining to the proposed NorthMet mine is that the assertions regarding mine site wetlands impacts made by PolyMet and its consultants and adopted by the agencies in the Final Environmental Impact Statement ("FEIS") based on an analog model are poorly supported. The analog model used is superficial, due to the failure to rigorously assess the hydrology of the PolyMet mine site and the differences between this hydrology and that of the proposed analog. This failure of analysis creates an unacceptable degree of uncertainty.

As an applied scientist who has worked with mining facilities and other extractive industries, the lack of information regarding the PolyMet mine site hydrology was striking. At the Victor Mine in Canada, for example, dozens of monitoring wells were required to identify area hydrogeology. In contrast, underlying consultants' reports and the PolyMet FEIS appear to rely heavily on a short-term pump test in a single well in one of the pertinent rock formations to reach their conclusions about the impacts of mine drawdown on wetlands and peatlands. From a scientific point of view, the information

disclosed in the PolyMet FEIS and its underlying studies is inadequate to estimate impacts on wetlands.

The inadequacy of data presented in the FEIS and its underlying documents prevents me from providing an estimate of the number of acres of peatlands that would be affected by the proposed PolyMet mine site drawdown. However, in my opinion it is reasonably certain that PolyMet's reports and the PolyMet mine FEIS substantially underestimate the impacts to wetlands and peatlands of mine site dewatering.

It is also my opinion that it would have been feasible and reasonable to secure sufficient data and use customary hydrologic modeling, such as the MODFLOW model, along with calibration and sensitivity analysis to provide a scientifically justifiable set of drawdown scenarios from the PolyMet mine and its potential impacts on wetlands and peatlands. Since PolyMet has used the MODFLOW model to estimate water inflow to its mine pits, a working model that could evaluate drawdown, and its sensitivity to the potential range of hydrogeological conditions in the bedrock underlying wetlands, is already available. PolyMet and its consultants disingenuously argue that the model cannot be relied on to make accurate predictions, yet rely on it to estimate water flows to the mine.

This report is organized as follows:

A. Minnesota and NorthMet mine site peatland and fen sensitivity to drawdown.
B. Modeling approaches to estimate impacts of NorthMet mine site drawdown on wetlands
C. Mine Site Infrastructure Water Capture
D. Lessons applicable to the NorthMet mine based on Victor mine analysis
E. Brief response to U.S. Army Corps of Engineers draft proposal to provide assurance for indirect wetlands impacts
F. Required next steps to credibly predict and mitigate NorthMet mine drawdown of wetlands.

A. Minnesota Bog Peatland and Fen Sensitivity to Mine Drawdown

Peatlands in Northern Minnesota were initiated following deglaciation ~11,000 years ago, over top of a relatively flat ground moraine with interspersed outwash sands (Boelter and Verry, 1977). Peatland development over this complex stratigraphy reflects the nuances of local and regional flow regimes (Winter, 1999). Initially, localized accumulations of peat occur where water persists in the landscape because of poor drainage or because of a supplemental water supply, such as groundwater discharge. Over time, as the peat accumulates, its water relations with the adjacent landscape change because the hydraulic gradients that drive water toward the peatland diminish. This water is important for maintaining wetness but also for delivering dissolved solids that buffer the acidity produced by decomposing vegetation (Rochefort et al., 2012).

In peatlands where groundwater with ample dissolved minerals persists, fen or swamp occurs; fens dominate when the water supply creates a relatively stable water table.

Eventually the peat layer may accumulate sufficiently that the water table of portions of the peatland most remote from adjacent mineral soils rises above that in adjacent mineral soils and the system becomes isolated from the supply of groundwater with its dissolved minerals. The system is then only fed water from direct precipitation, which is low in dissolved minerals, and the acidity increases (pH drops) (Rochefort et al. 2012). These peatlands are bogs. The presence of fens relies on groundwater pressure to sustain inflows, and the development into the bog stage, while no longer receiving groundwater, relies on the regional groundwater system to maintain pressure sufficient to limit downward groundwater seepage; this was documented in Minnesota peatlands by Siegel and Glaser (1987). A decrease in the pressure of the regional aquifer can increase the small natural recharge function of bog peatlands into a substantial and unsustainable water recharge condition that will impact peatland function (Leclair et al. 2015).

The sensitivity of a bog peatland to regional groundwater pressures is also related to the hydraulic conductivity of the substrate, since this also affects the wetland connectivity. In areas where the substrate hydraulic conductivity is greater than 1 foot per day (ft/d), wetlands are not isolated because of the high groundwater connectivity (Winter et al. 2003). Where the hydraulic conductivity is less than 1 ft/d localized groundwater regimes are more common, and the flow fields become more complex.

Given that the overburden sediments in the vicinity of the NorthMet site are 0.012 – 31 ft/d (Barr, 2014b), some wetlands may be isolated but many will be connected, as observed in other Minnesota peatlands (Siegel and Winter, 1980). There is a regional component to impacts of a groundwater regime on wetlands, as well a component based on a more proximate hydrologic connection. This connection can be from wetland to wetland, but also with the deeper groundwater regime in the bedrock (See Figure 1).

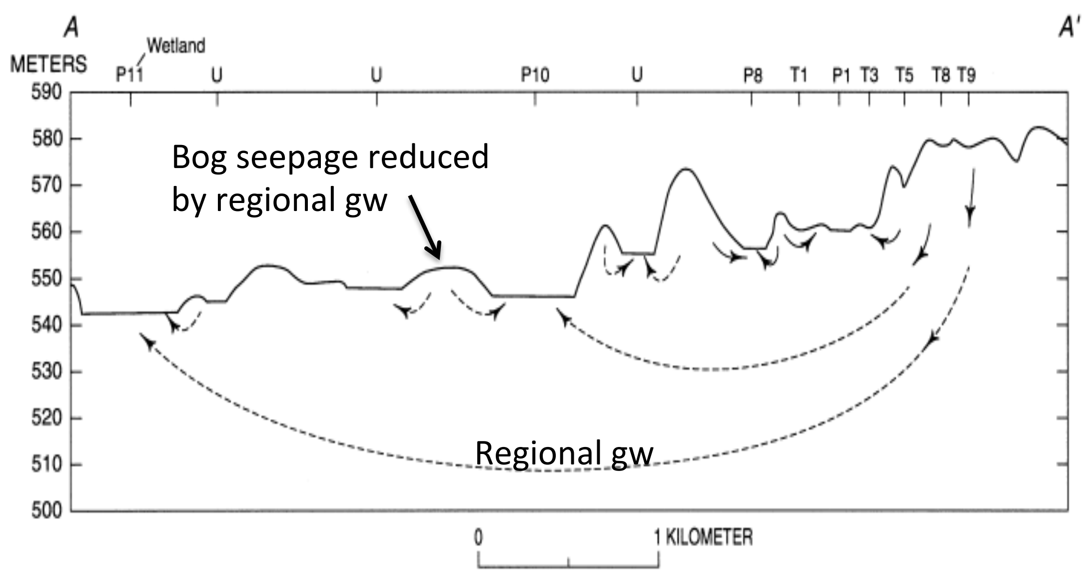

Figure 1. Interaction of local and regional groundwater flow regimes illustrating groundwater connectivity between wetlands on a complex stratigraphy (modified from Winter et al. 2003).

The distance from wetland to wetland is relatively large compared to the distance from a wetland to the underlying bedrock. In the case of the NorthMet mine site area, distance to bedrock is equivalent to the ~3.5-17 ft of relatively permeable overburden (Barr 2014b). Consequently, changes in the water pressures in the bedrock will have an immediate effect on the water table in the peatland. Lowering groundwater pressure in underlying bedrock, even where the substrate hydraulic conductivity is much lower, enhances peatland desiccation. This was illustrated in an Ontario peatland complex (the De Beers Victor Mine, discussed in more detail in Part D of this report) where mine dewatering depressurized the bedrock ~4 kilometers (km) from the mine, and increased the recharge from ~26 millimeters per year (mm/y) to over 300 mm/y (Whittington and Price, 2013). The amount of water required to satisfy this deficit and maintain the high water table can be determined from the difference between annual precipitation (P) and evapotranspiration loss (Et).

The 30-year normal for precipitation (P) in the vicinity of the proposed NorthMet mine ranges from 744 mm (29.3 in) at Marcell to 765 mm (30.1) in Babbitt, MN (NOAA, 2016). Evapotranspiration (Et) from peatlands at the Marcell Experimental Forest, ~70 miles west of the mine site between May 1 and Nov 1 ranged from 465 – 536 mm (8.3 to 20.7 in.), averaging 505 mm (19.1 in) over a six year period (Boelter and Verry, 1977).

Thus, P-Et, which represents the total available water, can be estimated at 208 – 279 mm (9.4 – 11.8 in) annually. This represents the water available for peatland recharge to groundwater (G) and runoff (R). Given that snowmelt produces the largest annual runoff event in Minnesota peatlands (Coleman Wasik et al. 2015), the water available for recharge is substantially less than this. Boelter and Verry (1977) indicate that most of the recharge in Minnesota peatlands occurs over a three-week period in April, followed by slower recharge until mid-June. Over the rest of the summer recharge is minimal because rain simply replenishes water lost by Et (Boelter and Verry, 1977).

Annual runoff from a forested bog in Minnesota over a 5-year period was 172 mm (7 in), where rainfall was 762 mm (31 in) (Bay, 1969). Using a simple water budget approach

$$G = P - Et - R \pm \Delta S$$

where ΔS is change in storage (negligible over 5-years), groundwater recharge is approximately 104 mm/y (4.1 in/y) (Table 1).

This equation is highly significant in understanding the sensitivity of Minnesota peatlands. The equation demonstrates that the average recharge rate is ~0.3 mm/d (0.01 in/d) -- a very small portion of the water budget. It is only because of these restricted recharge rates that peatlands can develop and persist in temperate continental climates. This factor underscores the sensitivity of peatlands to increases in recharge that will occur with abstraction of water from the regional groundwater system, such as with mine drainage. The limited recharge is what makes a Minnesota peatland system, like that at the NorthMet site, highly vulnerable to mine drawdown. The depressurization of the deep groundwater associated with the cone of depression will increase the hydraulic gradients between the near-surface groundwater in the wetlands, and the regional groundwater, and thus increase the rate of water loss (recharge) affecting the capacity of the system to sustain wetlands.

Table 1. Water budget for Minnesota forested bogs at Marcell Experimental Forest.

	G	P*	Et**	R*	ΔS
Inches	4.1	31	19.9	7	0
mm	104	787	505	178	0

* Bay, 1969
** Boelter and Verry, 1977

Given the sensitivity of peatland hydrology to water abstractions and substrate hydraulic properties, a closer examination of the uncertainty associated with the use of the analog method used by PolyMet to predict the impact on peatlands is warranted. The uncertainty can be illustrated by examining the range of hydraulic conductivity values determined by PolyMet and others, which is key to assessing the potential depressurization of the bedrock aquifer beneath the peatlands.

B. Modeling approaches to estimate NorthMet mine site wetlands impacts and alternatives.

1. The NorthMet "analog" to predict mine site wetlands drawdown is unreasonable.

The analog method used by PolyMet and in the FEIS to estimate NorthMet mine site wetlands impacts was wholly inadequate. "Analog" means that one situation serves as a representative of another situation. By definition, a coherent use of an analog requires that the hydrogeology of the two "analogs" be the same. This condition was demonstrably not met with the NorthMet "analog."

The potential impacts on wetlands from the NorthMet mine were estimated based on an "analog method" that relied on transposing the effects on other mines in the region (Canisteo and Minntac) to the NorthMet mine site. This analog method relies on the analog sites having similar hydrogeological properties to those at the NorthMet site. As summarized in Table 2 below, there is convincing evidence that the comparison sites were not reasonably analogous.

The analog estimate of NorthMet mine drawdown is based primarily on results from the Canisteo pit. To be a reasonable analog, the hydraulic conductivity of the layers of the two systems (NorthMet and Canisteo) need to be similar. This might be the case if only Duluth Formation bedrock were compared to the Canisteo pit (Table 2), although even for this formation the reported range of hydraulic conductivities are up to four orders of magnitude greater than the value reported for Canisteo.

Table 2. Overburden thickness, and overburden and bedrock saturated hydraulic conductivity (Ksat) values at NorthMet and analog sites Canisteo and Minntac (Barr, 2011i). Values also reported for Victor mine, ON.

	NorthMet	Canisteo 50-100	Minntac	Victor Mine
Overburden Thickness (ft)	3.5-17	50-100	20-100	25
Ksat_overburden (ft/d)	0.012 - 31	0.01 - 121	425	0.016 – 0.03+
Ksat_bedrock (ft/d)	DLTH Ph.I 0.002* DLTH** 1.0 (0.15-16) VIRG Ph.II 0.17* VIRG Ph.III 0.7*	0.007	0.2-16	0.00016 WB 32 UAP-HCI

* Barr (2014b) NorthMet
** Siegel and Ericson, 1980 Upper Duluth; (range)
+ Whittington and Price, 2012 (range)
WB weathered fractured limestone (upper 15 ft) – fractures clogged with fine sediments
UAP-HCI Upper Attawapiskat fractured limestone (HCI, 2007)

However, for the Virginia Formation bedrock that dominates the north portion of the NorthMet site (and underlies 100 Mile Swamp) the geometric mean hydraulic conductivity is ~ 2 orders of magnitude (100 times) higher than that for the bedrock at Canisteo. This will result in a much more expansive cone of depression (see Theis analysis below). FEIS (2015, at 5-112) reported that wells within 700 ft of the Canisteo Pit showed a strong response and six wells within 900 to 2,625 ft from the pit showed a measurable, but weak, response.

Based on the differences in hydraulic conductivity between NorthMet Virginia Formation bedrock and bedrock at the Canisteo pit, wetlands at various distances from the NorthMet site will have a much stronger response than was registered at Canisteo at equivalent distances. The magnitude of this response, and the sensitivity of the system to the ranges of hydraulic conductivity and thicknesses of the overburden reported could be effectively shown using the MODFLOW simulations already relied on for determining discharge into the mine, with appropriate calibration and sensitivity analysis.

2. **MODFLOW should have been used to predict wetlands drawdown at the NorthMet mine site.**

Even though MODFLOW was used to predict the volume of water discharging into the mine and for determining groundwater flowpaths to estimate water quality effects, it was rejected as a tool to analyze the potential effects of mine drawdown. It was suggested in the FEIS that localized variations in aquifer structure (fracturing) and overburden thicknesses would result in potential errors greater than the "few feet or less as would be desirable for assessing potential effects on …wetlands" (FEIS, 2015 at 5-112). The contradiction in using MODFLOW extensively to evaluate mine effects yet rejecting MODFLOW to assess the range and sensitivity of the system with regard to impacts on wetlands was pointed out by Lee (2014).

In contrast with the analog method, which is, by its nature, a crude method of analysis with few parameters, MODFLOW is a more sophisticated tool. MODFLOW allows analysis of multiple layers of data and development of potential drawdown scenarios, which can then be reviewed in a transparent way to evaluate the reliability of their predictions.

It is my opinion that, even though the data collected for the NorthMet mine was insufficient, MODFLOW results predicting mine site drawdown cones should have been presented by PolyMet's consultants and in the Final Environmental Impact Statement (FEIS). These results should have provided a range of potential drawdown cones and sensitivity even with current data. Then, the project proponents should have been required to defend their choice of most probable scenarios within the range of potential cones as well as to justify not doing additional testing to improve the reliability of the drawdown cone.

Failure to use MODFLOW, when that modeling was available and used for other NorthMet mine purposes, to make a more informed statement of the impacts of NorthMet mine groundwater pressures on peatlands, is a significant deficiency. This deficiency undermines the scientific reasonableness of the conclusions made by PolyMet's consultants and in the FEIS about the probable impacts of the NorthMet mine drawdown on wetlands and peatlands.

3. **The Theis solution illustrates why an analog approach disregarding differences in bedrock hydraulic conductivity and mine pit depth cannot be used to estimate NorthMet mine wetlands impacts**

The Theis solution is not a substitute for proper modeling, such as could be done with MODFLOW to test the sensitivity and range of potential drawdown. However, using the Theis aquifer test solution is useful to illustrate that drawdown in the bedrock can be substantial depending on the hydraulic conductivity of the bedrock – and that using the hydraulic properties of the bedrock dominating the Canisteo mine is inappropriate for predicting the effects of pumping at the NorthMet mine. The NorthMet mine would include a mine pit much deeper than the Canisteo pit and would be adjacent to Virginia Formation bedrock, which has a much higher hydraulic conductivity than the bedrock at the Canisteo mine.

The Theis solution is typically used to predict the position of the water table given the drawdown caused by a pumping well. This has some analogies to pumping from a mine pit.

To illustrate the range of conditions potentially being considered in the mine scenario, the Theis equation was solved for hydraulic conductivity of the bedrock ranging from 0.1 to 1 ft/d in the Virginia Formation (Barr 2014b) assuming pumping from the full

NorthMet East Pit mine depth (696 ft)(Barr 2014b), aquifer storativity for fractured crystalline bedrock of 1 to 10 % (Singhal and Gupta 2010), over a period of 20 years being pumped at the predicted rate of 455 gpm (average rate over 20 year period of pumping; FEIS, 2015 at 5-111). This is done for the East Pit only, not the whole mine site.

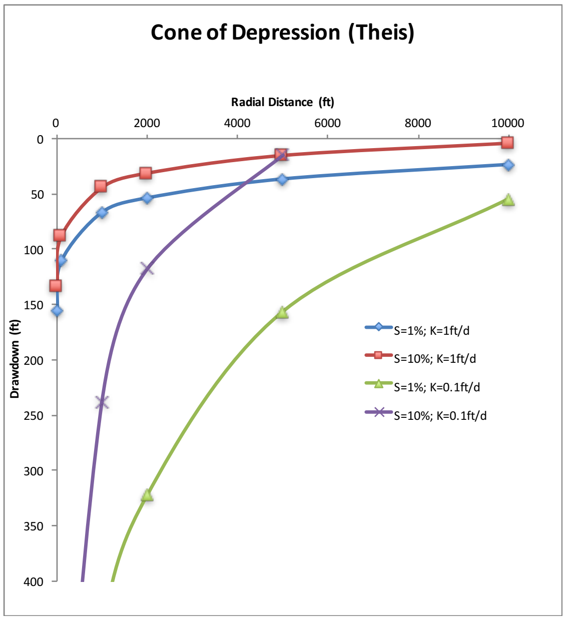

Figure 2. Theis solution for 20 years pumping of a 696 ft deep well for a range of hydraulic conductivity (K) and aquifer storativity (S) values, at an average pumping rate of 455 gpm.

Once again the reader is reminded that the Theis analysis is not to be taken as a prediction of drawdown from the NorthMet mine, even though its parameters and inputs are guided by the reported values for the mine project. The intention is to show how sensitive drawdown is to the input conditions, particularly hydraulic conductivity. Figure 2 shows the depth and radial extent of calculated drawdown cones using a published range of storativities (1 and 10%) for fractured bedrock (i.e. the ability of a matrix to take in or release water) and a relatively small range of hydraulic conductivities (0.1 and 1.0 ft/d; note: this is one order of magnitude, while reported values of hydraulic conductivity for the Virginia Formation are up to two orders of magnitude greater than used in the analog approach based on the Duluth formation properties).

While the storativity clearly influences the projected drawdown (blue vs. red line, and purple vs. green line), the most profound difference is due to the range of hydraulic conductivities. The blue and red lines represent calculated drawdown for a relatively high hydraulic conductivity formation (1 ft/d), and the purple and green lines represent the case for lower hydraulic conductivity (0.1 ft/d). The deeper drawdown associated with the lower hydraulic conductivity reflects the larger hydraulic gradient required pull fluid through the lower hydraulic conductivity matrix. The other feature to note in Figure 2 is that for a storativity of 10%, the radial extent of the drawdown for the higher hydraulic conductivity scenario is greater than for the low hydraulic conductivity scenario. This again underscores the importance of high quality site-specific data and the inaccuracy of predicting the extent of drawdown without such data.

While the potential depressurization of the bedrock aquifer may be extensive, it is mostly covered by overburden material whose thickness and hydraulic conductivity are highly spatially variable. Where overburden is relatively thick and hydraulic conductivity low, drawdown of the water table will be less. However, current research has shown that even under these conditions peatlands can be impacted because they are adapted to the long-term rate of groundwater exchange (Leclair et al. 2015; see discussion of Victor Mine dewatering, below).

While the Theis solution is not a reliable representation of the NorthMet mine given its simplifying assumptions (Freeze and Cherry, 1979) and the complexity of the actual hydrogeological setting, it does exemplify the sensitivity of drawdown to a relatively small range of parameter variability.

The illustration is above is conservative. The range of hydraulic conductivity tested is much smaller than the range of values reported by Barr, 2014b, (Table 2). Also note that the total water-taking permit issued for the NorthMet East Pit of 2,340 gallons per minute (gpm) (PolyMet Water Appropriation Permit Application April 2017) is over 5x greater than the Theis illustration above. Moreover, (real) aquifers have limited extent, so boundary effects will typically result in greater drawdowns than those calculated assuming infinite extent as in the Theis solution (Kunkel 1960; USGS Circular 433).

C. Mine Site Infrastructure Water Capture

Hitherto, the analysis has focused on drawdown effects of the proposed mine. In addition, the water capture associated with mine infrastructure must be considered. The average annual rate of water capture from the waste rock pile (Mine Site Infrastructure) is estimated at up to 500 gpm (995,000 m^3/y). (PolyMet Water Appropriation Permit Application, v. 5, April 2017, Table 5-3). The maximum annual withdrawal rate is estimated to be 2250 gpm (4.5×10^6 m^3/y). This water is “captured”, treated and removed from the watershed. Consequently, it will no longer be available for recharge. To assess the potential impacts of this, the estimated volumes of water transferred out of the watershed can be expressed as a water depth, as is typically done for other water fluxes like precipitation.

To do this, the volume of water must be considered (normalized) relative to the area to which it could potentially recharge. This volume of water normalized to the area of wetlands in the prescribed analog zones represents a significant depth. For example, for the annual average pump rate (500 gpm) normalized to the wetland area within 1000 ft of the mine is 184 mm; normalized to those within 2000 ft of the mine is 126 mm, etc. (see Table 3). This water withdrawal represents a substantial proportion of the water budget (Table 1); the water withdrawals represent 24%, 16%, 11% and 5% of the average annual precipitation (787 mm).

If the maximum annual withdrawal rate of 2250 gpm (4.5×10^6 m^3/y) is used for these calculations, the equivalent area normalized water depths are about 5x higher than the percentages reported above. The implications of this water withdrawal are that in addition to the increased water loss to deep drainage caused by the cone of depression surrounding the mine, there will less water available for recharge, since a substantial portion of the rainfall will be collected and transferred out of the watershed.

To further contextualize this, the amount of water to be captured and transferred out of the system is of a similar magnitude to the average annual recharge (see Table 1). This will increase the stress on wetlands, as the regional water table is likely to decrease even further than it would in response to mine dewatering alone. Importantly, the implications of this water withdrawal were never considered in the analog approach to assessing wetland impacts.

During various phases of mine operations, water transfer from mine site infrastructure may represent as much as nearly one-third of the water that is being extracted from all mine site appropriations that will collectively impact area wetlands over the life of the mine[1]. However, if the NorthMet project is implemented as represented in the FEIS, water withdrawal from the waste rock facility would also represent a long-term water loss, extending well beyond the operational life of the mine, and seriously impeding the recovery of wetlands when mine operations cease.

Table 3. Annual volume of water pumped from the waste rock pile, normalized to the cumulative area of wetlands in the prescribed analog zones. Depth+ (mm/y) is calculated as water volume divided by area. Max Depth++ is calculated similarly, but with the maximum annual pump rate.

Analog Zone Radius (ft)	Wetland Area (ac)*	Cumulative Area (ac)	Cumulative Area (x 10^6 m^2)	Depth (mm/y)+	Max Depth (mm/y)++
0-1000	1328	1328	5.4	184	841
1000-2000	618	1946	7.9	126	575
2000-3500	1162	3108	12.6	83	361
3500-10 000	2718	5826	23.6	42	193

* Based on total wetland areas within stated analog zone FEIS, 2015 Table 5.2.3-3

+ Based on average annual Mine Site Infrastructure pumping rate of 500 gpm (2726 m^3/d) (Table 5-3; PolyMet, Water Appropriation Permit Applications (April 2017).
++ Based on maximum annual Mine Site Infrastructure pumping rate of 2250 gpm (12,265 m^3/d)(Table 5-3; source as above).

D. Lessons for the NorthMet mine from De Beers Victor mine analysis

A comprehensive study of impacts of mine pumping on surrounding peatlands is associated with the De Beers Victor mine in northern Ontario; it provides some valuable lessons for the NorthMet mine. The Victor mine example illustrates how sensitive the system is to relatively small differences in the key hydraulic parameter, namely hydraulic conductivity. The Victor mine, with a pit depth similar to the NorthMet East Pit,

[1] Based on upper range of average annual estimated pumping rates reported by PolyMet, Water Appropriation Permit Applications, Table 5-3; April 2017.

had an area of impact of approximately 300 square kilometers. The most profound impacts of the Victor mine drawdown were on bogs rather than on fens, and in areas of bedrock outcropping, potentially reflecting localized fractures. Drying of peatlands had a measurable effect on vegetation within two years, beginning a feedback loop that could permanently alter peatland functions.

Based on modeling of the flow domain with MINE-DW, the drawdown at the Victor mine caused by mine dewatering was initially estimated based on the surface recharge (P-Et-R) and limited samples of hydraulic conductivity of the fractured bedrock (Table 2) and of the overlying marine sediment layer (HCI, 2004). Initial estimates of the drawdown cone at the Victor mine were that it would extend ~25 km radial distance for the 1-meter (m) drawdown contour.

When new data regarding thickness and hydraulic conductivity of the overburden were obtained -- from 20 m to 8 m, and 0.005 to 0.001 m/d, respectively -- the extent of the drawdown cone was revised to 6 to 10 km radial distance (HCI, 2007) (see Figure 3). However, the revised drawdown cone was associated with much higher recharge rates from the overlying peatlands. The predicted recharge rate through the overburden in the impacted area resulting from these changes, increased from 50 mm/y to up to 250 mm/y.

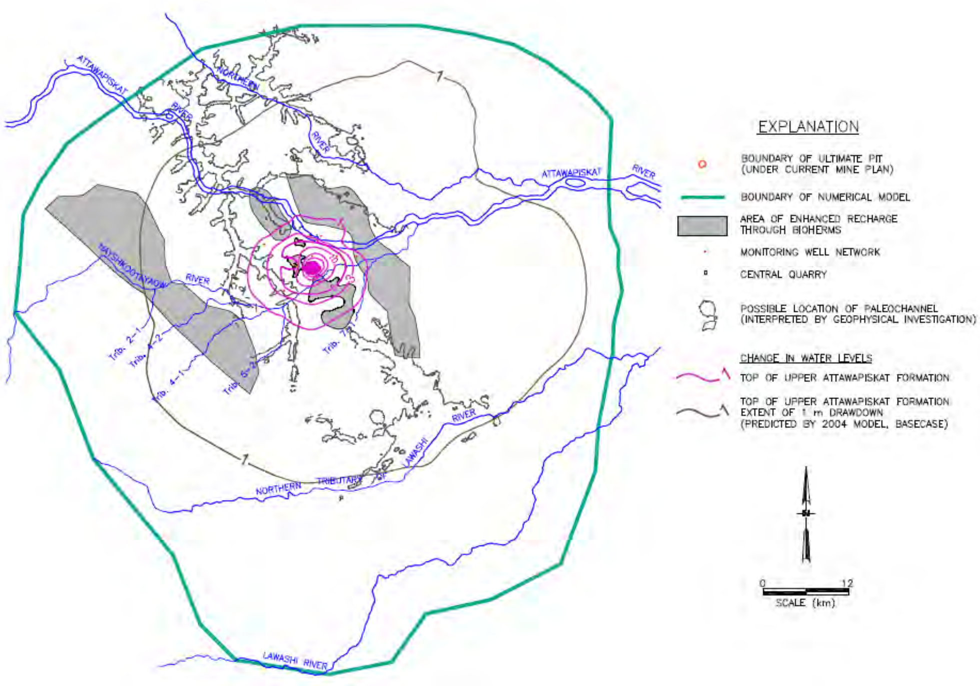

Fig. 3. Maps showing the differences in the initial predicted extent of the 1 m drawdown cone around the De Beers Victor mine (brown line), and the modified prediction based on new data that halved the hydraulic conductivity and estimated thickness of the overburden layer (HCI, 2007).

New Victor mine data that doubled hydraulic conductivity of the overburden layer resulted in a prediction of more than order of magnitude change in vertical recharge.

The predicted area of impact was reduced, but the extent of impact in that area was greater. Even with the smaller radius of impact, the area of impact of the Victor mine was approximately 300 km^2 – approximately 74,000 acres. The Victor mine pit is 220 meters in depth (~650 feet), a depth comparable to the proposed NorthMet East Pit.

The revised prediction of aquifer depressurization was a good match to the actual observed drawdown at the Victor mine after 4 years (AMEC, 2012). Recharge from local peatlands was measured in 2011 about 4 km from the pit, where the drawdown cone in the underlying bedrock aquifer was 4 - 6 m below the surface (i.e. within the marine sediment overburden) (Leclair et al. 2015). At this location, the vertical recharge increased from 2.6 – 26 mm/y to over 300 mm/y (Whittington and Price, 2013) as a result of mine drawdown.

The most profound impact was in bogs, which are fed only by precipitation, in contrast to fens, which in this location are replenished by water draining into them from up-gradient fens, beyond the impact of the mine (Leclair, 2015). This is evident in Figure 4, which shows the water table elevation in two reference sites 25 km from the Victor mine; these control sites (MS15 Bog and Fen) vary in response to weather patterns but maintain a steady base level over time. At the two impacted sites (NGC Fen and NGC Bog), there is a steady decline in the base level of the hydrographs each year, and the bog experienced a greater decline than the fen. Figure 4 also shows the decline in water table elevation in the bedrock that underlies the impacted peatlands.

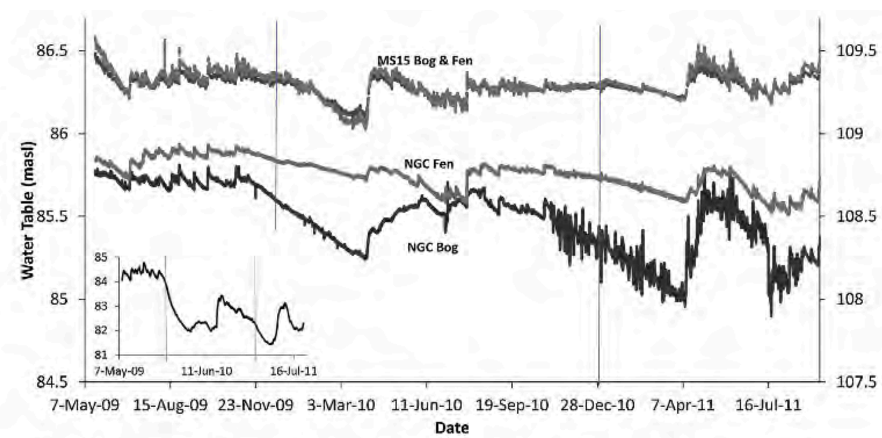

Fig. 4. Water tables in meters above sea level in the mine-impacted North Granny Creek (NCG) bog, fen and bedrock and at a bog and fen in the non-impacted MS15 site. The MS15 water levels are on a secondary y-axis for ease of viewing but has the same scale length as the primary y-axis (i.e., 2 m). The inset shows the North Granny Creek bedrock water tables on a compressed scale (4 m) (from Leclair et al. 2015).

While there was a general decline in water table in peatlands within the cone of depression associated with mine drainage (Leclair et al. 2015), there was more profound drainage in areas where there were fully cropping (protruding) or sub-cropping bedrock mounds (Whittington and Price, 2012). In these areas, the fine-grained marine sediments were thin or non-existent, and the peatlands lost water directly to the depressurized bedrock. The absence of the fine-grained overburden did not always exaggerate drainage; this suggests drainage into depressurized bedrock occurred mainly through localized fractures (Whittington and Price, 2012), especially where there are inter-bedded sands that improve the spatial connectivity to fracture zones (Ali, 2013).

At the Victor mine, drying of the mine-impacted peatlands had a measureable impact on vegetation after only two years, in which the accelerated growth of woody vegetation was observed (Talarico, 2009). The increase in tree growth following drainage occurs within the first 20 years (Dang and Lieffers 1989), and afforestation, in turn, increases water table decline since it increases interception of rainfall and transpiration losses (Waddington et al. 2015).

There are similarities between the conditions for mine dewatering studied and observed at the Victor mine and those at the NorthMet mine. Both sites include a low gradient peatland complex situated over stratified overburden that includes sandy layers, over a fractured bedrock aquifer that is subject to dewatering. The differences include bedrock type, where the intrinsic primary permeability of the carbonate rocks of the Victor mine is higher. However, in both cases the bedrock is highly fractured, and this secondary permeability far exceeds the primary permeability (Freeze and Cherry, 1979), thus is much more important in terms of the extent and depth of drawdown caused by mine dewatering. Secondly, it is well known that measurements of hydraulic conductivity are scale-dependent, and that well tests can produce values that are one-tenth of the regional value (Rovey and Cherkauer, 1995).

Both the Victor mine and the NorthMet mine are located in areas with fens and bog peatlands. At the Victor mine, it was originally assumed that the site was located on low permeability clay, and later found that the site was located on rock flour (Ali, 2013), which has low permeability, although greater permeability than clay. Unlike the NorthMet proposal, assumptions about the hydraulic conductivity of the bedrock at the Victor mine were based on extensive testing.

Lessons learned from the Victor mine suggest that NorthMet mine site wetlands drawdown is likely to be more extensive than predicted by the PolyMet analog hypothesis, will be affected by both primary and secondary permeability of bedrock, will affect bog as well as fen wetlands, and is likely to create ongoing impacts on peatland function. The Victor mine example underscores the need for a comprehensive hydrogeological study, far beyond the scarce data obtained and revealed at the NorthMet site, to credibly estimate and mitigate wetlands drawdown impacts.

The estimation of hydraulic conductivity at the Victor mine involved dozens of well installations, dozens more borehole logs and a 60-day pumping test (HCI, 2007). Regulators required a comprehensive hydrogeological study and based on this were able to predict correctly the extent of the drawdown (AMEC, 2012), if not all of the variations caused by local fractures where conditions were exacerbated. While general recharge rates increase from about 0.01 to 1 mm/d, the enhanced recharge areas reached 4 mm/d (Whittington and Price, 2013). Even with a relatively small modification of the parameters governing the hydraulic performance of the system, there was a substantial change in the area of the predicted drawdown cone (Figure 3) and the extent of impacts within that cone. Changes in recharge rates like those in the Victor mine recharge areas cannot be sustained without changes in wetland functionality except in areas where channel fen flow tracks provide water from up-catchment (Leclair et al. 2015).

At the proposed NorthMet mine there are very few monitoring wells and the single 30-day pumping test did not test the conditions in the primary aquifer of concern (Virginia Formation that underlies 100 Mile Swamp). This presents a high degree of uncertainty associated with the potential impact on this peatland system. While the proponents recognize the potential for localized impacts due to bedrock fractures (FEIS, 2015) the connectivity of fractures and the relatively high permeability of the overburden will distribute impacts over a larger area.

Had an appropriate hydrogeological study been done for the NorthMet mine, a more defensible map of the cone of depression could be drawn, as it was for the Victor mine – based on depth of overburden, primary conductivity of the bedrock, groundwater pressure and those fractures that were identified through testing. The area and extent of NorthMet drawdown impact on wetlands has not been reliably estimated because the NorthMet hydrogeology investigations rely on few direct measurements, and an analog that is not representative of NorthMet mine conditions.

A recurring statement in the NorthMet FEIS is that bog peatlands will experience little impact because they are not groundwater dependent (e.g. FEIS, p. 5-263; 5-279). This directly contradicts the findings at the Victor mine where bogs experienced the greatest water table drawdown (Figure 4). This finding can be explained by the relatively sensitive hydrological regime of bogs in which their water table is sustained by the residual of P – Et – Q, in which the groundwater seepage (G) is normally restricted by high groundwater pressures. At the Victor mine, despite relatively low hydraulic conductivity sediments beneath them, the water table declined to 70 cm (2.3 ft) in summer, then even deeper during the winter when there was no atmospheric recharge (snow stored on the surface), with the greatest declines (140 cm or ~4.7 ft below the surface) where mineral sediments were thin. The implication of the low winter water table is a distinct decrease in spring runoff (Leclair et al. 2015), which also has impacts beyond the peatland into the down-gradient aquatic systems.

The ombrotrophic wetlands of the 100 Mile Swamp cannot be assumed to have little connectivity with the deeper regional system. Its low annual recharge rate is a function of high groundwater pressures in the bedrock and overburden materials that underlie them, which are noted to be well connected (FEIS, 2015, p. 4-57 – although see 4-173 where this statement is contradicted). It is well-recognized (Siegel and Glaser 1987) that while ombrotrophic wetlands generally do not receive groundwater, they rely on maintenance of high regional groundwater pressure to maintain their water table even though they are precipitation-fed.

At the Victor mine site, the fens experienced less drawdown than the bogs, even though they rely on groundwater for a small component of their water balance (Leclair et al. 2015). The reason for this is that the bogs are typically stores of water, whereas fens are conveyors of water (Quinton, 2003). In peatland complexes like at the Victor site and the NorthMet area 100 Mile Swamp, bogs typically drain into adjacent fens, which helps sustain the water table in the latter. This distribution of pressures is aided by shallow groundwater flows associated with overburden deposits including outwash sands, such as at the NorthMet site.

At the Victor mine, the larger scale flows of water down channel fen water tracks, from peatlands in the upper (un-impacted) reaches of the watershed, helped sustain fen water tables. However, despite this, the dewatering effects at the Victor mine were cumulative on a seasonal basis. The drawdown cone will reach further up the system over time, so then the fens will likely experience more exaggerated drainage. At the NorthMet site, the 100 Mile Swamp is far less extensive. The down-gradient flow to fens from up-gradient un-impacted reaches is probably insufficient to sustain high water tables.

Finally, observations at the Victor mine, where woody vegetation showed increases after two years, and the feedback loop from this change suggest that the proposed NorthMet mine will have long-term effects on wetlands' function. The proposed mine activity at NorthMet is for ~11 years at the East Pit and ~20 years at the West Pit (FEIS 2015 at 3-2), with pumping scheduled for 20 years at both pits (PolyMet, Water Appropriations Permit Applications, April 2017, Tables 3-1, 5-1). The increase in woody vegetation will have an ongoing influence towards a drier condition, and it is unlikely that the original peatland function will return for a very long time, if ever.

D. U.S. Army Corps of Engineers March 2017 Draft Proposal on Assurance for Indirect Wetlands Impacts

A document from the U.S. Army Corps dated March 7, 2017 proposed financial assurance requirements for indirect wetlands based on the analog model, and reached a conclusion that up to 117 acres of wetlands could be converted to uplands and about 282 acres could have some change in duration or elevation of wetland hydrology.

The U.S. Army Corps of Engineers (USACE, 2017) utilized the FEIS (2015) to establish compensation for impacts to wetlands. It is noteworthy that FEIS presents two scenarios for areas impacted based on the analog approach. These predict damage to 2148 and 733 acres of wetland, respectively. USACE (2017) selected the lower estimate, without providing any justification, then used an arbitrary assessment of loss depending on distance from the mine.

The USACE method recognized complete loss of wetland hydrology to all wetlands including bog, alder thicket, swamp and marsh to occur only within 250 ft, and to non-bog wetland within 500 ft of the mine. Within the 1000 ft radius, but beyond 250 ft, the USACE assumed minor changes to bogs, and substantial impact to the (sparse) non-bog wetlands. Between 1000 – 2000 ft they assumed (without providing justification) that

10% of bog edges would be affected.   The USACE concluded that up to 117 acres of wetlands could be converted to uplands and about 282 acres could have some change in duration or elevation of wetland hydrology, requiring compensation for enhancing 175 acres and 84 acres, with compensation rates of 1.5:1 and 1:3, respectively.

The USACE (2017) proposal on assurance for indirect wetlands impact is unsupported. The USACE proposal uncritically accepted the analog approach, which is not scientifically credible, as explained in my discussion above, and ignored the loss of recharge cause by water capture. Then, without justification, the USACE selected the lower of the potential wetland impact predictions. Moreover, neither the USACE nor the PolyMet analyses incorporated the substantial reduction in recharge water caused by transferring out of the basin, the water captured for mine infrastructure.

The USACE potentially severely under-predicts the potential damage to wetland function and consequently, would require insufficient compensation for indirect wetlands impacts.

E. Required next steps to predict and mitigate NorthMet mine site wetlands drawdown

The data on the local hydrogeology at the NorthMet mine site disclosed in the FEIS and Barr (2014b) hydrology report is insufficient to provide confidence with regards to the potential impact on area wetlands. In the absence of data, the mine proponents have offered an "analog" simulation, but the system chosen as representative of the NorthMet Mine, namely the Canisteo Mine, is not a suitable analog. The bedrock adjacent to the NorthMet site that underlies 100 Mile Swamp, is of a different geological origin, and the little data available indicates that the upper Duluth Complex and the Virginia Formation have a hydraulic conductivity up to 100 times greater than that associated with the Canisteo site. Water captured and removed from the watershed for mine site infrastructure should also be modeled to evaluate impacts on wetland recharge.

The following steps should be taken before any decisions are made that depend on knowing the extent of impacts of NorthMet mine site drawdown on wetlands:

1. Additional hydrogeological testing must be done. At a minimum, monitoring wells into the Virginia Formation at the 200 ft and 1000 ft radial distance should be installed and be tested for hydraulic conductivity with a pump test at least 60 days in duration. Without this, the connectivity of the local hydrology of the 100 Mile Swamp to the NorthMet mining operation cannot be ascertained, and the sensitivity of the wetland to mine dewatering cannot be credibly argued.

2. Given that the mine dewatering pumping rates have been modeled with MODFLOW for the FEIS and water appropriations permit application, it is clear that the model domain and boundary conditions have been established, and the head distribution should be available. Model domain, boundary conditions, and head distribution along with pumping rate calculations should be presented, along with overburden thickness and a sensitivity analysis of hydraulic conductivity of the bedrock and overburden, to illustrate the range of potential

drawdowns. This should be done following improved calibration as suggested by USACE (2016). While the local conditions can be exacerbated by connected fractures, the general extent of water table drawdown should be reasonably predicted for the system.

3. The implications of relatively small changes in hydraulic head on peatland water table should be recognized and quantified in terms of the potential change in recharge rates, and the map of wetland impacts adjusted accordingly. Isopleths based on MODFLOW modeling should replace those derived from the inappropriate analog. Potential cones of depression should then be presented, along with a scientific argument outlining the range of potential effects.

4. The peatland system should be evaluated in terms of its recharge/discharge relations (rather inexpensively) with hand-augured piezometers, coupled with drive-point piezometers installed into the mineral overburden sediments, in at least five representative locations. Hydrological measurements over a wet and dry period would ascertain the strength of the hydraulic gradients, and pumping tests could be done so the flux can be calculated. These data on recharge should then be integrated with the modeling and maps (#2 and #3 above) and used to evaluate the change in recharge likely in the case of a lowered water pressures resulting from NorthMet mine site dewatering.

CONCLUSION

The hydrological and biogeochemical function of peatlands in Minnesota are sensitive to the local water budget, in which currently the water loss by recharge is~0.01 in/day. The limited recharge is what makes a Minnesota peatland system, like that at the NorthMet site, highly vulnerable to mine drawdown, which can increase the recharge rate by orders of magnitude and cause peatland desiccation (Whittington and Price, 2013).

It is imperative that a science-based estimate of the sensitivity of these peatlands be performed to guide the regulatory agencies. While a numerical model (MODFLOW) was used extensively to determine pumping rates, etc., the proponents incongruently argue that it cannot be used to predict a cone of depression that would identify wetlands potentially susceptible to impact. While it is acknowledged that identification of individual wetlands' susceptibility cannot be predicted without a detailed characterization of overburden thicknesses, a sensitivity analysis using the same model setup as that used to predict pumping rates, would constitute an appropriate scientific investigation that can identify the potential cone of depression that affect wetland function.

Instead, reliance on an analog approach, based on previous mining activities in which the hydrogeological characteristics of the bedrock aquifer are not analogous, is poor science, and wholly inappropriate for making sound management and regulatory decisions. The USACE estimate of indirect wetlands impacts and proposed assurance for those impacts based on the analog model, along with further unsupported assumptions previously discussed, would provide insufficient recognition of and compensation for wetlands drawdown impacts.

A science-based assessment of mining impacts in the James Bay Lowland, where there are extensive peatlands, illustrate that a mining company and regulators can properly assess potential drawdown impacts. At the De Beers Victor mine in Ontario, a detailed hydrogeological investigation, coupled with numerical modeling, made a good prediction of the cone of depression caused by mine dewatering. De Beers also committed to an extensive monitoring program, and funded University-based research on wetland impacts. Within the cone of depression bogs were impacted more seriously than fens, because bogs never receive inflowing water from snowmelt or rainfall from adjacent upland areas. The increase in recharge caused desiccation and loss of wetland function over an extensive area. In the PolyMet proposal, the assumption that bogs will not be seriously affected contradicts sound peer-reviewed published results to the contrary.

While mining is an important economic activity, the economic and environmental costs of its impacts must be incorporated into the regulatory framework. This can only begin to happen if the proposed mining activity is accompanied by a reasonable, science-based assessment of the potential impacts, and a commitment to monitor it. To-date, the PolyMet proposal has failed to attempt, let alone achieve, this standard.

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Degrees

- 1988/12	Doctorate, PhD, Geography, McMaster University Degree Status: Completed
- 1983/8	Master's Thesis, Master's of Science, Civil Engineering, University of Saskatchewan Degree Status: Completed
- 1977/5	Bachelor's Honours, Bachelor's of Science, Geography, Trent University Degree Status: Completed

User Profile

Researcher Status: Researcher
Research Career Start Date: 1988/09/01
Engaged in Clinical Research?: No

Research Interests: Hydrology, Peatlands, Wetlands, Microclimate, Carbon dynamics, Restoration, Reclamation, Solute transport in peatlands, hydrocarbon in peatlands

Research Specialization Keywords: hydrology wetlands transport

Research Disciplines: Earth Science

Areas of Research: Hydrological Cycle and Reservoirs

Fields of Application: Environment

Employment

1999/7	Professor Geography and Environmental Management, Faculty of Environment, University of Waterloo Full-time, Professor Tenure Status: Tenure
1994/9 - 1999/6	Associate Professor Geography, Faculty of Environment, University of Waterloo Full-time, Associate Professor Tenure Status: Tenure

1990/9 - 1994/8
Assistant Professor
Geography, Queen's University at Kingston
Full-time, Assistant Professor
Tenure Status: Tenure
Assistant Professor

1988/9 - 1990/8
Assistant Professor
Geography, Memorial University of Newfoundland
Full-time, Assistant Professor
Tenure Status: Tenure Track

Research Funding History (since 2010)

Awarded [n=14]

2013/1 - 2019/12
Principal Applicant

Water and mass exchange in mosses: Towards an understanding of the movement of solutes and hydrocarbons, Grant, Operating

Funding by Year:

2013/1 - 2019/12
Total Funding - 285,000 (Canadian dollar)
Portion of Funding Received - 100 (Canadian dollar)

Funding Sources:

2013/1 - 2018/12
Natural Sciences and Engineering Research Council of Canada (NSERC)
Discovery
Total Funding - 285,000 (Canadian dollar)
Portion of Funding Received - 100 (Canadian dollar)
Funding Competitive?: Yes

2016/5 - 2017/12
Principal Applicant

Evaluating the Constructed Fen: Funding Request for 2016-2017, Contract

Funding Sources:

2016/5 - 2017/12
Suncor Energy Inc.
Total Funding - 535,384 (Canadian dollar)
Portion of Funding Received - 50 (Canadian dollar)
Funding Competitive?: Yes

2013/1 - 2017/12
Co-applicant

Farm, restore and model: responsible management of peatlands for a sustainable Canadian horticultural peat industry

Funding Sources:

2013/1 - 2017/1
Natural Sciences and Engineering Research Council of Canada (NSERC)
CRD
Total Funding - 1,515,024 (Canadian dollar)
Portion of Funding Received - 206,887
Funding Competitive?: Yes

2012/1 - 2016/1
Co-investigator

NSERC Canadian Network for Aquatic Ecosystem Services, Grant

Funding Sources:

2012/1 - 2016/1
Natural Sciences and Engineering Research Council of Canada (NSERC)
Total Funding - 4,416,625 (Canadian dollar)
Portion of Funding Received - 220,831
Funding Competitive?: Yes

2013/1 - 2015/12
Principal Applicant

Discovery Accelerator - Water and mass exchange in mosses: Towards an understanding of the movement of solutes and hydrocarbons, Grant, Operating

Funding by Year:

2013/1 - 2015/12
Total Funding - 120,000 (Canadian dollar)
Portion of Funding Received - 100 (Canadian dollar)
Time Commitment: 5

Funding Sources:

2013/1 - 2015/12
Natural Sciences and Engineering Research Council of Canada (NSERC)
Discovery Accelerator
Total Funding - 120,000 (Canadian dollar)
Portion of Funding Received - 100 (Canadian dollar)
Funding Competitive?: Yes

2011/1 - 2015/1
Principal Investigator

Evaluating the success of fen creation in the post oil sands landscape, Grant

Funding Sources:

2011/1 - 2015/1
Natural Sciences and Engineering Research Council of Canada (NSERC)
Total Funding - 4,581,298 (Canadian dollar)
Portion of Funding Received - 2,290,649
Funding Competitive?: Yes

2008/1 - 2012/1
Principal Investigator

The impact of mine dewatering on the hydrology and mercury biogeochemistry of peatlands, Grant

Funding Sources:

2008/1 - 2012/1
Natural Sciences and Engineering Research Council of Canada (NSERC)
Total Funding - 1,006,439 (Canadian dollar)
Portion of Funding Received - 503,220
Funding Competitive?: Yes

2008/1 - 2012/1
Principal Investigator

Peatland Management, Research Chair

Funding Sources:

2008/1 - 2012/1
Natural Sciences and Engineering Research Council of Canada (NSERC)
Total Funding - 226,260 (Canadian dollar)
Portion of Funding Received - 226,260
Funding Competitive?: Yes

2008/1 - 2012/1
Principal Investigator

How does water move in mosses? Liquid and vapour flow in living Sphagnum mosses, Grant

Funding Sources:

2008/1 - 2012/1
Natural Sciences and Engineering Research Council of Canada (NSERC)
Total Funding - 176,000 (Canadian dollar)
Portion of Funding Received - 176,000
Funding Competitive?: Yes

2007/1 - 2010/1
Co-investigator

The capability of the Mfabeni Mire to respond to climatic and land-use stresses, Grant

Funding Sources:

2007/1 - 2010/1 Department of Water Affairs and Forestry (DWAF) (South Africa)
Unsolicited Competition
Total Funding - 347,000 (Canadian dollar)
Portion of Funding Received - 347,000 (Canadian dollar)
Funding Competitive?: Yes

2009/1 - 2010/1
Principal Investigator

Response of fen plants on peat contaminated with oil sands process-affected waters, Grant

Funding Sources:

2009/1 - 2010/1 Suncor
Unencumbered Grant
Total Funding - 426,811 (Canadian dollar)
Portion of Funding Received - 234,746
Funding Competitive?: Yes

2009/1 - 2010/1
Co-investigator

Evapotranspiration from the Nkazana Swamp forest and the Mfabeni Mire, Grant

Funding Sources:

2009/1 - 2010/1 Water Research Commission of South Africa
Total Funding - 121,600 (Canadian dollar)
Portion of Funding Received - 121,600
Funding Competitive?: Yes

2009/1 - 2010/1
Co-investigator

Regional wetland processes of the Maputaland Coastal Aquifer on the Zululand Coastal Plain, Grant

Funding Sources:

2009/1 - 2010/1 Department of Water Affairs and Forestry (DWAF) (South Africa)
Unsolicited Competition
Total Funding - 119,300 (Canadian dollar)
Portion of Funding Received - 119,300
Funding Competitive?: Yes

2008/1 - 2009/1
Co-investigator

Assessing the efficacy of current voluntary road salt management programs and practices: a case study of three cities in the regional municipality of Waterloo, Grant

Funding Sources:

2008/1 - 2009/1 Ontario Ministry of the Environment
Total Funding - 514,000 (Canadian dollar)
Portion of Funding Received - 51,400
Funding Competitive?: Yes

Courses Taught

Instructor, Geography and Environmental Management, University of Waterloo
Course Title: Wetland Hydrology
Course Code: GEOG 405
Course Level: Undergraduate

Instructor, Geography and Environmental Management, University of Waterloo
Course Title: Wetlands
Course Code: GEOG 647
Course Level: Graduate

Instructor, Geography and Environmental Management, University of Waterloo
Course Title: Applied Studies in Hydrology and the Environment
Course Code: GEOG 661
Course Level: Graduate

Instructor, Geography and Environmental Management, University of Waterloo
Course Title: Physical Hydrology
Course Code: GEOG 303
Course Level: Undergraduate

Student/Postdoctoral Supervision

Bachelor's [n=16]

2015/9 - 2016/4
Principal Supervisor
Elliot, James (In Progress) , University of Waterloo
Thesis/Project Title: Hydrological processes of Sphagnum restoration techniques: Optimizing surface pressure head for moss recolonization
Present Position: Undergraduate student, University of Waterloo, ON

2015/9 - 2016/4
Principal Supervisor
Leigh-Gauthier, Tasha (In Progress) , University of Waterloo
Thesis/Project Title: Effects of mechanical compression on Sphagnum moss in peat, Bois des Bel peatland
Present Position: Undergraduate student, University of Waterloo, ON

2015/5 - 2015/9
Co-Supervisor
Fraser, Melody (In Progress) , University of Waterloo
Thesis/Project Title: Impact of donor sites for fen reclamation in Fort McMurray, AB: Species recovery, microtopography and depth to water table, as influenced by disturbance history
Present Position: Undergraduate student, University of Waterloo, ON

2013/9 - 2014/9
Principal Supervisor
Menzies, Rosalind (Completed) , University of Waterloo
Thesis/Project Title: Hydrology of a rich fen in the Athabasca Region of Alberta
Present Position: Undergraduate student abroad, University of Western Australia

2011/9 - 2012/9
Principal Supervisor
Lam, Regine (Completed) , University of Waterloo
Thesis/Project Title: Effects of compaction on solute transport in peat
Present Position: Environmental Educator, YMCA, Toronto, ON

2011/9 - 2012/9
Principal Supervisor
Scarlett, Sarah (Completed) , University of Waterloo
Thesis/Project Title: The hydrological and geochemical isolation of a freshwater bogwithin a saline fen in north-eastern Alberta
Present Position: Recent graduate

2010/9 - 2011/9
Co-Supervisor
Wells, Corey (Completed) , University of Waterloo
Thesis/Project Title: Mineralization rates in a restored peatland
Present Position: Research Associate, University of Waterloo, ON

2009/9 - 2010/9
Principal Supervisor
McCarter, Colin (Completed) , University of Waterloo
Thesis/Project Title: Hydraulic properties of Sphagnum mosses
Present Position: PhD Student, University of Waterloo, ON

2007/9 - 2008/9
Principal Supervisor
Fox, Dave (Completed) , University of Waterloo
Thesis/Project Title: Identification of palsa and bioherms in James Bay Lowland
Present Position: Environmental Scientist, exp Energy Services, Toronto, ON

2007/9 - 2008/9
Principal Supervisor
Faux, Erica (Completed) , University of Waterloo
Thesis/Project Title: Solute transport in unsaturated moss
Present Position: Consulting

2007/9 - 2008/9
Principal Supervisor
Lance, Joseph (Completed) , University of Waterloo
Thesis/Project Title: Root distribution in moss and cutover peat
Present Position: Environmental Field Technician, Kitchener, ON

2006/9 - 2007/9
Principal Supervisor
Nicoll, Amy (Completed) , University of Waterloo
Thesis/Project Title: Impacts of quarry dewatering on peatland hydrology
Present Position: MSc student, University of British Columbia, BC

2005/9 - 2006/9
Principal Supervisor
Christie, Mike (Completed) , University of Waterloo
Thesis/Project Title: Sphagnum cushion moisture dynamics
Present Position: MSc student, University of Waterloo, ON

2003/9 - 2004/9
Principal Supervisor
Brock, Findlay (Completed) , University of Waterloo
Thesis/Project Title: Edge effects on peatland remnants
Present Position: Unknown

2003/9 - 2004/9
Principal Supervisor
Cagampan, Jason (Completed) , University of Waterloo
Thesis/Project Title: Compressibility of different peats
Present Position: Project Analyst, DNV GL, BC

2003/9 - 2004/9
Principal Supervisor
Mouniemne. Sarah (Completed) , University of Waterloo
Thesis/Project Title: Salt contamination of a peatland
Present Position: Masters (U. Calgary)

Bachelor's Equivalent [n=12]

2017/5 - 2017/8
Principal Supervisor
Emma Buczolits (In Progress) , University of Waterloo

2017/5 - 2017/8
Principal Supervisor
Emily Champion (In Progress) , University of Waterloo
Thesis/Project Title: Monitoring constructed fen hydrology

2015/5 - 2015/9
Principal Supervisor
Asten, Julia (Completed) , University of Waterloo
Thesis/Project Title: Hydrology research assistant. Monitoring the hydrological development of a constructed fen peatland in the Athabasca Oil Sands Region, AB
Project Description: Undergraduate research assistant
Present Position: MSc student, University of Waterloo, ON

2014/5 - 2014/9
Principal Supervisor
Kessel, Eric (Completed) , University of Waterloo
Thesis/Project Title: Hydrology research assistant in the Athabasca Oil Sands Region, constructing a fen wetland.
Project Description: Undergraduate research assistant
Present Position: MSc student, University of Waterloo, ON

2014/5 - 2014/9
Principal Supervisor
Taves, Robin (Completed) , University of Waterloo
Thesis/Project Title: Nutrient loading and wastewater treatment in fen peatlands, James Bay Lowland, ON
Project Description: Undergraduate research assistant
Present Position: Undergraduate student, University of Waterloo, ON

2014/5 - 2015/9 Co-Supervisor
Price, Dylan (Completed) , University of Waterloo
Thesis/Project Title: Field hydrology research assistant, peatland reclamation in the Alberta Oil Sands Region
Project Description: Undergraduate research assistant
Present Position: Undergraduate student, University of Waterloo, ON

2014/5 - 2014/9 Principal Supervisor
Fraser, Melody (Completed) , University of Waterloo
Thesis/Project Title: Ecology research assistant - vegetation development in a constructed fen peatland in the Athabasca Oil Sands Region, AB
Project Description: Undergraduate Research Assistant
Present Position: Undergraduate student, University of Waterloo, ON

2013/5 - 2013/9 Principal Supervisor
Buck, Kathleen (Completed) , University of Waterloo
Thesis/Project Title: Ecology research assistant, vegetation development at a constructed fen in the Athabasca Oil Sands Region, AB
Project Description: Undergraduate Research Assistant
Present Position: Fisheries Protection Biologist, Fisheries and Oceans Canada, ON

2012/5 - 2012/9 Principal Supervisor
Bocking, Emma (Completed) , University of Waterloo
Thesis/Project Title: Ecology research assistant - vegetation development at a constructed fen peatland in the Athabasca Oil Sands Region, AB
Project Description: Undergraduate research assistant
Present Position: Environmental Outreach Coordinator, Ducks Unlimited, NFLD

2007/5 - 2007/9 Principal Supervisor
Bryant, Sean (Completed) , University of Waterloo
Thesis/Project Title: Peatland restoration
Project Description: Undergraduate research assistant

2006/9 - 2007/9 Principal Supervisor
Brunet, Nathalie (Completed) , University of Waterloo
Thesis/Project Title: Laboratory assistant
Present Position: Hydrology, Saskatchewan Water Security Agency, SK

2006/9 - 2007/9 Principal Supervisor
Gilbert, Janine (Completed) , University of Waterloo
Thesis/Project Title: Peatland restoration
Project Description: Undergraduate research assistant
Present Position: Unknown

Master’s Thesis [n=31]

2016/9 - 2018/9 Principal Supervisor
Elliott, James (In Progress) , University of Waterloo
Student Degree Expected Date: 2018/9
Thesis/Project Title: Modelling irrigated Sphagnum farming
Present Position: Student

2016/9 - 2018/9 Principal Supervisor
Gauthier, Tasha (In Progress) , University of Waterloo
Student Degree Expected Date: 2018/9
Thesis/Project Title: Sphagnum compression to enhance CO2 uptake in a restored bog
Present Position: Student

2015/9 - 2017/8 Co-Supervisor
Osman, Chris (In Progress) , University of Waterloo
Thesis/Project Title: Geochemical characterization of a constructed fen in Northern Alberta
Present Position: MSc student, University of Waterloo, ON

2015/9 - 2017/8 Principal Supervisor
Asten, Julia (In Progress) , University of Waterloo
Thesis/Project Title: An assessment of hydrological change of a constructed fen in the Athabasca Oil Sands Region, AB
Present Position: MSc student, University of Waterloo, ON

2015/9 Co-Supervisor	Sarah Irvine (In Progress) , University of Waterloo Student Degree Start Date: 2015/9 Student Degree Expected Date: 2017/9 Thesis/Project Title: Dissolved Organic Carbon in a Constructed Fen
2014/9 - 2016/8 Principal Supervisor	Kessel, Eric (Completed) , University of Waterloo Thesis/Project Title: The hydrogeochemistry of a constructed fen peatland in a post-mined landscape in the Athabasca oil sands region Present Position: MSc student, University of Waterloo, ON
2014/9 - 2017/1 Principal Supervisor	Balliston, Nicole (Completed) , University of Waterloo Thesis/Project Title: Solute transport in a bog: NaCl spill Present Position: MSc student, University of Waterloo, ON
2014/9 - 2017/1 Principal Supervisor	Brown, Catherine (Completed) , University of Waterloo Student Degree Start Date: 2014/9 Student Degree Received Date: 2017/1 Thesis/Project Title: Hydrology and carbon dynamics of irrigated Sphagnum moss in a cutover peatland Present Position: Boreal Science Educator,, Northern ALberta Institute of Technology
2013/9 - 2015/9 Principal Supervisor	Scarlett, Sarah (Completed) , University of Waterloo Thesis/Project Title: Characterizing controls on plot-scale evapotranspiration and soil water dynamics of a constructed fen in the Athabasca Oil Sands Region, Alberta Present Position: Recent graduate
2012/9 - 2014/11 Principal Supervisor	Taylor, Neil (Completed) , University of Waterloo Thesis/Project Title: Hydrophysical evolution, soil water dynamics, and productivity of Sphagnum carpets in a regenerating cutover peatland Present Position: Humber Watershed Intern, TRCA, Toronto, ON
2012/9 - 2015/5 Co-Supervisor	Bocking, Emma (Completed) , University of Waterloo Thesis/Project Title: Analyzing the impacts of road construction on the development of a poor fen in Northeastern Alberta, Canada Present Position: Environmental Outreach Coordinator, Ducks Unlimited, NFLD
2012/9 - 2016/4 Co-Supervisor	Date, Vinay (Completed) , University of Waterloo Thesis/Project Title: Responseof peatland microbial community function to contamination by naphthenic acidsand sodium in the Athabasca Oil Sands Region, Alberta, Canada Present Position: MSc student, University of Waterloo, ON
2011/9 - 2014/5 Principal Supervisor	Goetz, Jonathan (Completed) , University of Waterloo Thesis/Project Title: An evaluation of moisture dynamics and productivity of Sphagnum and Tomenthypnum mosses in western boreal peatlands, Canada Present Position: Hydrologist, Ministry of Environment, Victoria, BC
2011/9 - 2014/4 Principal Supervisor	Langlois, Melanie (Completed) , University of Waterloo Thesis/Project Title: Landscape analysis & boundary detection of bog peatlands' transition to mineral land: The laggs of the eastern New Brunswick Lowlands, Canada Present Position: Geospatial Analyst, CAE, QC, Canada
2011/9 - 2014/5 Principal Supervisor	Wells, Corey (Completed) , University of Waterloo Thesis/Project Title: The hydrology and geochemistry of a saline spring fen peatland in the Athabasca oil sands region of Alberta Present Position: Research Associate, University of Waterloo, ON
2011/9 - 2016/4 Principal Supervisor	Perras, Emily (Completed) , University of Waterloo Thesis/Project Title: Hydrologicaland Geochemical Implications of Aquifer Depressurization on Expansive PeatlandSystems in the Hudson/James Bay Lowlands Present Position: MSc student, University of Waterloo, ON

2010/9 - 2015/5 Principal Supervisor
Leclair, Melissa (Completed) , University of Waterloo
Student Canadian Residency Status: Canadian Citizen
Thesis/Project Title: The hydrological interactions within a mine impacted peatland, James Bay Lowland, Canada
Present Position: Environmental Specialist, Detour Gold, Ontario

2010/9 - 2012/9 Principal Supervisor
McCarter, Colin (Completed) , University of Waterloo
Thesis/Project Title: The hydrology of the Bois Des Bel peatland restoration: A tale of two scales
Present Position: PhD Student, University of Waterloo, ON

2010/9 - 2013/1 Principal Supervisor
Malloy, Shannon (Completed) , University of Waterloo
Thesis/Project Title: Fen restoration on a bog cut down to sedge peat: A hydrological assessment of rewetting and the impact of a subsurface gyttja layer
Present Position: Water Resources Technician, CVCA, Mississauga, ON

2008/9 - 2011/9 Principal Supervisor
Di Febo, Antonio (Completed) , University of Waterloo
Thesis/Project Title: Peatland classification using LiDAR - James Bay Lowland
Present Position: Project Coordinator, Capital Infrastructure, Metrolinx/GO Transit, Toronto, ON

2007/9 - 2011/9 Principal Supervisor
Ketcheson, Scott (Completed) , University of Waterloo
Thesis/Project Title: Rewetting a cutover peatlands: hydrological changes
Present Position: PhD Student, University of Waterloo, ON

2006/9 - 2008/9 Principal Supervisor
Farrick, Kegan (Completed) , University of Waterloo
Thesis/Project Title: Hydraulic impact of ants in cutover peat and moss cushions
Present Position: Monitoring and Evaluating Assistant, Ministry of the Environment and Water Resources, Trinidad

2005/9 - 2007/9 Co-Supervisor
Zheng Zhang (Completed) , University of Waterloo
Thesis/Project Title: Beverley swamp riparian zone hydrology
Present Position: Consultant

2004/9 - 2010/9 Principal Supervisor
McIssac, Gerry (Completed) , University of Waterloo
Thesis/Project Title: VMC and EC using polyolefin-coated TDR probes
Present Position: Instrumentation design

2004/9 - 2006/9 Co-Supervisor
Montemayor, Marilou (Completed) , University of Waterloo
Thesis/Project Title: Plant reintroduction on a salt contaminated peatland
Present Position: Watershed Planning & Management Coordinator, NSWA, SK

2003/9 - 2005/9 Principal Supervisor
Whittington, Peter (Completed) , University of Waterloo
Thesis/Project Title: Drainage of a fen to mimic climate change
Present Position: Assistant Professor, Brandon University, MB

2001/9 - 2003/9 Principal Supervisor
Shantz, Michael (Completed) , University of Waterloo
Thesis/Project Title: Hydrological restoration of a peatland
Present Position: Research Professional, CCIW

2000/9 - 2002/9 Principal Supervisor
von Waldow, Harald (Completed) , University of Waterloo
Thesis/Project Title: Restoration hydrology at Bois des Bel peatland, Quebec
Present Position: Research Data Manager, EAWAG Aquatic Research Institute, Germany

2000/9 - 2002/9 Co-Supervisor
Lang, Yuxin (Completed) , University of Waterloo
Thesis/Project Title: Peat deformation mechanics and hydrology
Present Position: Engineering Consultant, Cambridge, ON

2000/9 - 2002/9 Principal Supervisor
Kennedy, Gavin (Completed) , University of Waterloo
Thesis/Project Title: Modeling hydrology in deformable peat
Present Position: Hydrogeology, Dept Natural Resources, NS

2000/9 - 2004/9
Principal Supervisor
Landriault, Laura (Completed) , University of Waterloo
Thesis/Project Title: Soil moisture dynamics in moss
Present Position: Community Training Developer, Carleton University, ON

Doctorate [n=12]

2015/9 - 2019/8
Principal Supervisor
Sutton, Owen (In Progress) , University of Waterloo
Thesis/Project Title: Determining fate and transport of sodium and naphthenic acids at a constructed fen in the Athabasca Oil Sands Region, Alberta
Present Position: MSc student, University of Waterloo, ON

2014/9 - 2018/8
Principal Supervisor
Gharedaghloo, Behrad (In Progress) , University of Waterloo
Thesis/Project Title: Characterization and monitoring of the fate and transport of hydrocarbons in peat and peatlands
Present Position: PhD Student, University of Waterloo, ON

2014/9 - 2018/8
Principal Supervisor
Elmes, Matthew (In Progress) , University of Waterloo
Thesis/Project Title: Exploring the hydrological, geochemical, and ecological function of a heterogeneous, low-relief moderate-rich fen in northern Alberta, Canada
Present Position: PhD Student, University of Waterloo, ON

2012/9 - 2016/9
Principal Supervisor
McCarter, Colin (Completed) , University of Waterloo
Thesis/Project Title: The hydrochemical fate and transport of treated domestic wastewater contaminants during a wastewater polishing experiment in a sub-arctic ladder fen peatland
Present Position: PhD Student, University of Waterloo, ON

2011/9 - 2015/12
Principal Supervisor
Ketcheson, Scott (Completed) , University of Waterloo
Thesis/Project Title: Hydrology of a constructed fen peatland: oilsands reclamation
Present Position: PhD Student, University of Waterloo, ON

2011/9 - 2017/1
Principal Supervisor
Simhayov, Rubi (Completed) , University of Waterloo
Thesis/Project Title: Contaminants in a constructed fen peatland: oilsands reclamation
Present Position: PhD Student, University of Waterloo, ON

2010/9 - 2014/9
Co-Supervisor
Clulow, Alistair (Completed) , University of Waterloo
Thesis/Project Title: Evapotranspiration from subtropical peatlands
Present Position: Lecturer, University of KwaZulu-Natal, CWRR, South Africa

2007/9 - 2013/2
Principal Supervisor
Whittington, Peter (Completed) , University of Waterloo
Thesis/Project Title: The impacts of diamond mining to peatlands in the James Bay Lowlands
Present Position: Assistant Professor, Brandon University, MB

2006/9 - 2014/12
Principal Supervisor
Grundling, Piet-Louis (Completed) , University of Waterloo
Thesis/Project Title: Hydrology of Mfabeni Peatland, South Africa
Present Position: Director at Centre for Wetland Research and Training, Johannesburg, South Africa

2006/9 - 2014/4
Principal Supervisor
Grundling, Althea (Completed) , University of Waterloo
Thesis/Project Title: Remote sensing and biophysical monitoring of vegetation, terrain attributes, and hydrology to map, characterise and classify wetlands of the Maputaland Coastal Plain, Kwazulu-Natal, South Africa
Present Position: Senior Researcher, Agricultural Research Council, Pretoria, South Africa

2000/9 - 2002/9
Co-Supervisor
Petrone, Richard (Completed) , University of Waterloo
Thesis/Project Title: Atmospheric carbon and water fluxes in a restored bog
Present Position: Professor, University of Waterloo

1996/9 - 2003/9
Principal Supervisor

Emili, Lisa (Completed) , University of Waterloo
Thesis/Project Title: Hydrochemical character of hypermaritime forested peatland
Present Position: Associate Professor, Penn State Altoona, USA

Post-doctorate [n=5]

2011/9 - 2014/12
Principal Supervisor

Kompanizare, Mazda (Completed) , University of Waterloo
Thesis/Project Title: Modeling mine drainage impacts on peatlands
Present Position: Junior Hydrogeologist, CH2M Hill, Kitchener, ON

2011/9 - 2012/9
Principal Supervisor

Andersen, Roxane (Completed) , University of Waterloo
Thesis/Project Title: Microbial response in contaminated peat
Present Position: Peatland Scientist, University of Highlands and Islands, Scotland

2009/9 - 2011/9
Principal Supervisor

Rezanezhad, Fereidoun (Completed) , University of Waterloo
Thesis/Project Title: Naphthenic acid and sodium transport in peat
Present Position: Assistant Professor, University of Waterloo, ON

2006/1 - 2006/12
Principal Supervisor

Strack, Maria (Completed) , University of Waterloo
Thesis/Project Title: Carbon and moisture dynamics in surface mosses
Present Position: Associate Professor and Canada Research Chair, University of Waterloo, ON

2002/3 - 2003/2
Co-Supervisor

Kellner, Erik (Completed) , University of Waterloo
Thesis/Project Title: Gas and water fluxes in a drained fen
Present Position: Hydrologist, Midvatten, Sweden

Research Associate [n=6]

2016/9 - present
Co-Supervisor

Kessel, Eric (In Progress, University of Waterloo
Thesis/Project Title: Technical Support: Fen creation for oil sands reclamation
Present Position: Project Support, University of Waterloo, ON

2015/5 - 2016/1
Academic Advisor

Weber, Tobias (In Progress) , University of Waterloo
Thesis/Project Title: Soil hydraulic properties of peat, solute transport and gas exchange in unsaturated peatland soils
Present Position: Research Associate, University of Waterloo, ON

2012/2 - 2017/12
Principal Supervisor

Sherwood, James (In Progress) , University of Waterloo
Thesis/Project Title: Project manager: fen creation for oil sands reclamation
Present Position: Project Manager, University of Waterloo, ON

2008/9 - 2011/9
Principal Supervisor

Ketcheson, Scott (Completed) , University of Waterloo
Thesis/Project Title: Mine impacts on peatlands
Present Position: PhD Student, University of Waterloo, ON

2007/9 - 2008/9
Principal Supervisor

Andrew-McBride, Peter (Completed) , University of Waterloo
Thesis/Project Title: Impact of mine drainage on peatlands
Present Position: Environmental Scientist, AMEC, Calgary

2005/9 - 2006/9
Principal Supervisor

Whittington, Peter (Completed) , University of Waterloo
Thesis/Project Title: Sphagnum permeability
Present Position: Assistant Professor, Brandon University, MB

1998/9 - 2002/9
Principal Supervisor

Fitzgerald, Dan (Completed) , University of Waterloo
Thesis/Project Title: Hydrology of hypermaritime forests
Present Position: Technician, University of Toronto

Publications

Peer Reviewed Journal Articles

1. Ketcheson, S. J., Price, J. S., Sutton, O., Sutherland, G., Kessel, E., & Petrone, R. M.(2017). The hydrological functioning of a constructed fen wetland watershed. Science of the Total Environment.
   In Press,
   Refereed?: Yes

2. Simhayov, R. B., Price, J. S., Smeaton, C. M., Parsons, C., Rezanezhad, F., & Van Cappellen, P.(2017). Solute pools in Nikanotee Fen watershed in the Athabasca oil sandsregion. Environmental Pollution.
   In Press,
   Refereed?: Yes

3. Wells, CM, Ketcheson, SJ, and Price, JS.(2017). Hydrology of a wetland-dominated headwater basin in the Boreal Plain,Alberta. Journal of Hydrology. 547: 168-183.
   Published,
   Refereed?: Yes

4. McCarter, C. P., & Price, J. S.(2017). The transport dynamics of chloride and sodium in a ladder fen during a continuous wastewater polishing experiment. Journal of Hydrology. 549: 558-570. ,
   Refereed?: Yes

5. Volik O, Petrone RM, Hall RI, Macrae ML, Wells CM., Elmes M. Price J. S.(2017). Long-term precipitation-driven salinity change in a saline, peat-formingwetland in the Athabasca Oil Sands Region, Canada: a diatom-based paleolimnologicalstudy. Journal of Paleolimnology.
   http://dx.doi.org/DOI: 10.1007/s10933-
   In Press,
   Refereed?: Yes

6. Scarlett, S. J., Petrone, R. M., & Price, J. S.(2017). Controls on plot-scale evapotranspiration from a constructed fen in theAthabasca Oil Sands Region, Alberta. Ecological Engineering. 100: 199-210. ,
   Refereed?: Yes

7. McCarter, C., Ketcheson, S.J., Weber, T.K.D., Whittington, P.N., Scarlett, S. and Price, J.S.(2017). A modified technique for measuring unsaturated hydraulic conductivity inSphagnum moss and peat. Soil Science Society of America Journal.
   In Press,
   Refereed?: Yes

8. Langlois, M., Richardson, M., Price, JS.(2017). Delineation of peatland lagg boundaries from airborne LiDAR. Journal of Geophysical Research - Biogeosciences.
   In Press,
   Refereed?: Yes

9. McCarter, C.P. & Price J.S.(2017). Experimental hydrological forcing to illustrate water flow processes ofa subarctic ladder fen peatland. Hydrological Processes. 31: 1578-1589.
   Published,
   Refereed?: Yes

10. Malloy, S., Price, JS.,. (2017). Consolidation of gyttja in a rewetted fen peatland: Potentialimplications for restoration. Mires and Peat. 19: 1-15.
    http://dx.doi.org/DOI: 10.19189/MaP.2015.OMB.200
    Published,
    Refereed?: Yes

11. Goetz* JD, Price JS. (2016). Ecohydrological controls on water distribution and productivity of moss communities in western boreal peatlands, Canada. Ecohydrology. 9: 138-152.
Published,
Refereed?: Yes, Open Access?: No

12. Ketcheson, S. J., Price, J. S., Carey, S. K., Petrone, R. M., Mendoza, C. A., & Devito, K. J.(2016). Constructing fen peatlands in post-mining oil sands landscapes:Challenges and opportunities from a hydrological perspective. Earth-Science Reviews. 161: 130-139.
Published,
Refereed?: Yes

13. Nwaishi* F, Petrone RM, Macrae M L, Price JS, Strack M, Slawson R, Andersen R.(2016). Above and below-ground nutrient cycling: a criteria for assessing the biogeochemical functioning of a constructed fen. Applied Soil Ecology. 98: 177-194.
Published,
Refereed?: Yes, Open Access?: No

14. Kelbe BE, Grundling* AT, Price JS. (2016). Modelling water-table depth in a primary aquifer to identify potential wetland hydrogeomorphic settings on the northern Maputaland Coastal Plain, KwaZulu-Natal, South Africa. Hydrogeology Journal. 24: 249-265.
Published,
Refereed?: Yes, Open Access?: No

15. Ketcheson, S. J., & Price, J. S.(2016). Initial variability and hydrophysical evolution of a reclaimed oil sands watershed and constructed wetland. International Journal of Mining, Reclamation.
Pending revision,
Refereed?: Yes

16. Nwaishi F, Petrone RM, Macrae ML, Price S, Strack M, Andersen R. (2016). Preliminary assessment of greenhouse gas emissions from a constructed fen on post-mining landscape inthe Athabasca oil sands region, Alberta, Canada. Ecological Engineering. 95: 119-128.
Published,
Refereed?: Yes, Open Access?: No

17. Ketcheson* SJ, Price JS. (2016). A comparison of the hydrological role of two reclaimed slopes of different age in the Athabasca Oil Sands Region, Alberta, Canada. Canadian Geotechnical Journal.
In Press,
Refereed?: Yes, Open Access?: No

18. Ketcheson* SJ, PriceJS. (2016). Snow hydrology of a constructed watershed in the Athabasca oil sands region, Alberta, Canada. Hydrological Processes. DOI: 10.1002/hyp.108
In Press,
Refereed?: Yes, Open Access?: No

19. Rezanezhad F, Price JS, Quinton WL, Lennartz B, Milojevic T, Van Cappellen P.(2016). Structure of peat soils and implications for water storage, flow and solute transport: A review update for geochemists. Chemical Geology. 429: 75-84.
Published,
Refereed?: Yes, Open Access?: No

20. Wood*, ME and Macrae, ML and Strack, M and Price, JS and Osko, TJ and Petrone, RM. (2015). Spatial variation in nutrient dynamics among five different peatland types in the Alberta oil sands region. Ecohydrology. DOI: 10.1002/eco.166
Published,
Refereed?: Yes

21. Clulow*, AD and Everson, CS and Mengistu, MG and Price, JS and Nickless, A and Jewitt, GPW. (2015). Extending periodic eddy covariance latent heat fluxes through tree sap-flow measurements to estimate long-term total evaporation in a peat swamp forest. Hydrology and Earth System Sciences. 19(5): 2513--2534.
Published,
Refereed?: Yes

22. Phillips, T., Petrone, RM., Price, JS.(2015). Characterizing dominant controls governing evapotranspiration within a natural saline fen in the Athabasca Oil Sands of Alberta, Canada.Ecohydrology.
Accepted,
Refereed?: Yes

23. McCarter, CP, Price, JS. (2015). The hydrology of the Bois-des-Bel peatland restoration: hydrophysical properties limiting connectivity between regenerated Sphagnum and remnant vacuum harvested peat deposit. Ecohydrology. 8: 173-187.
Published,
Refereed?: Yes

24. Goetz*, JD and Price, JS. (2015). Ecohydrological controls on water distribution and productivity of moss communities in western boreal peatlands, Canada. Ecohydrology.
Published,
Refereed?: Yes

25. Taylor, N., and Price, JS.(2015). Soil water dynamics and hydrophysical properties of regenerating Sphagnum layers in a cutover peatland. Hydrological Processes. Hydrological Processes. 29: 3878-3892.
In Press,
Refereed?: Yes

26. Nwaishi*, F and Petrone, RM and Price, JS and Ketcheson*, SJ and Slawson, R and Andersen, R. (2015). Impacts of donor-peat management practices on the functional characteristics of a constructed fen. Ecological Engineering. 81: 471-480.
Published,
Refereed?: Yes

27. Grundling, P-L, Clulow, AD, Price, JS and Everson, CS.(2015). Quantifying the water balance of Mfabeni Mire (iSimangaliso WetlandPark, South Africa) to understand its importance, functioning and vulnerability. Mires and Peat. 16: 1-18.
Published,
Refereed?: Yes

28. Strack, M and Zuback*, Y and McCarter*, C and Price, J. (2015). Changes in dissolved organic carbon quality in soils and discharge 10years after peatland restoration. Journal of Hydrology. 527: 345--354.
Published,
Refereed?: Yes

29. Caron, J and Price, JS and Rochefort, L. (2015). Physical Properties of Organic Soil: Adapting Mineral Soil Concepts to Horticultural Growing Media and Histosol Characterization. Vadose Zone Journal. 14(6)
Published,
Refereed?: Yes

30. Langlois*, MN and Price, JS and Rochefort, L. (2015). Landscape analysis of nutrient-enriched margins (lagg) in ombrotrophic peatlands. Science of the Total Environment. 505: 573--586.
Published,
Refereed?: Yes

31. Kelbe, BE, Grundling, AT, Price JS. (2015). Modelling water-table depth in a primary aquifer to identify potential wetland hydrogeomorphic settings on the northern Maputaland Coastal Plain, KwaZulu-Natal, South Africa.Hydrogeology Journal.
Accepted,
Refereed?: Yes

32. Wells*, CM and Price, JS. (2015). A hydrologic assessment of a saline spring fen in the Athabasca oil sands region, Alberta, Canada--a potential analogue for oil sands reclamation. Hydrological Processes.
Published,
Refereed?: Yes

33. Goetz*, JD and Price, JS. (2015). Role of morphological structure and layering of Sphagnum and Tomenthypnum mosses on moss productivity and evaporation rates. Canadian Journal of Soil Science. 95(2): 109--124.
Published,
Refereed?: Yes

34. Phillips*, T and Petrone, RM and Wells*, CM and Price, JS. (2015). Characterizing dominant controls governing evapotranspiration within a natural saline fen in the Athabasca Oil Sands of Alberta, Canada. Ecohydrology.
Published,
Refereed?: Yes

35. Leclair, M, Whittington, PN, Price, JS. (2015). Hydrological functions of a mine-impacted and natural peatland-dominated watershed, James Bay Lowland. Journal of Hydrology.
Accepted,
Refereed?: Yes

36. Montemayor*, MB and Price, J and Rochefort, L. (2015). The importance of pH and sand substrate in the revegetation of saline non-waterlogged peat fields. Journal of Environmental Management. 163: 87--97.
Published,
Refereed?: Yes

37. Nwaishi*, F and Petrone, RM and Price, JS and Andersen, R. (2015). Towards Developing a Functional-Based Approach for Constructed Peatlands Evaluation in the Alberta Oil Sands Region, Canada. Wetlands. 35(2): 211--225.
Published,
Refereed?: Yes

38. Kompanizare, M and Price, JS. (2014). Analytical solution for enhanced recharge around a bedrock exposure caused by deep-aquifer dewatering through a variable thickness aquitard. Advances in Water Resources. 74: 102--115.
Published,
Refereed?: Yes

39. Malloy*, S and Price, JS. (2014). Fen restoration on a bog harvested down to sedge peat: A hydrological assessment. Ecological Engineering. 64: 151-160.
Published,
Refereed?: Yes

40. McCarter*, CPR and Price, JS. (2014). Ecohydrology of Sphagnum moss hummocks: mechanisms of capitula water supply and simulated effects of evaporation. Ecohydrology. 7(1): 33-44.
Published,
Refereed?: Yes

41. Ketcheson*, SJ and Price, JS and Tighe, S L and Stone, M. (2014). Transport and Retention of Water and Salt within Pervious Concrete Pavements Subjected to Freezing and Sand Application. Journal of Hydrologic Engineering. 19(11): 06014005.
Published,
Refereed?: Yes

42. Ketcheson*, SJ and Price, JS. (2014). Characterization of the fluxes and stores of water within newly formed Sphagnum moss cushions and their environment. Ecohydrology. 7(2): 771-782.
Published,
Refereed?: Yes

43. Clulow*, AD and Everson, CS and Mengistu, MG and Price, JS and Nickless, A and Jewitt, GPW. (2014). Extending periodic eddy covariance latent heat fluxes through tree sapflow measurements to estimate long-term total evaporation in a peat swamp forest. Hydrology and Earth System Sciences Discussions. 11(12): 13607--13661.
Published,
Refereed?: Yes

44. Emili*, LA and Price, JS. (2013). Biogeochemical Processes in the Soil-Groundwater System of a Forest-Peatland Complex, North Coast British Columbia, Canada. Northwest Science. 87(4): 326-348.
Published,
Refereed?: Yes

45. Clulow*, AD, Everson, CS, Price, JS, Jewitt, GPW and Scott-Shaw, BC. (2013). Water-use dynamics of a peat swamp forest and a dune forest in Maputaland, South Africa. Hydrology and Earth System Sciences Discussions. 10(2): 1725-1768.
Published,
Refereed?: Yes

46. McCarter*, CPR and Price, JS. (2013). The hydrology of the Bois-des-Bel bog peatland restoration: 10 years post-restoration. Ecological Engineering. 55: 73-81.
Published,
Refereed?: Yes

47. Grundling*, AT, Van den Berg, EC, and Price, JS. (2013). Assessing the distribution of wetlands over wet and dry periods and land-use change on the Maputaland Coastal Plain, north-eastern KwaZulu-Natal, South Africa. South African Journal of Geomatics. 2(2): 120-138.
Published,
Refereed?: Yes

48. Whittington*, P and Price, JS. (2013). Effect of mine dewatering on the peatlands of the James Bay Lowland: the role of marine sediments on mitigating peatland drainage. Hydrological Processes. 27(13): 1845-1853.
Published,
Refereed?: Yes

49. Grundling*, P, Grootjans, AP, Price, JS and Ellery, WN. (2013). Development and persistence of an African mire: How the oldest South African fen has survived in a marginal climate. Catena. 110: 176-183.
Published,
Refereed?: Yes

50. Andersen, R, Wells*, C, Macrae, M and Price, JS. (2013). Nutrient mineralisation and microbial functional diversity in a restored bog approach natural conditions 10 years post restoration. Soil Biology and Biochemistry. 64: 37-47.
Published,
Refereed?: Yes

51. Kettridge, N, Kellner, E, Price, JS and Waddington, JM. (2013). Peat deformation and biogenic gas bubbles control seasonal variations in peat hydraulic conductivity. Hydrological Processes. 27(22): 3208-3216.
Published,
Refereed?: Yes

52. Scarlett*, SJ and Price, JS. (2013). The hydrological and geochemical isolation of a freshwater bog within a saline fen in north-eastern Alberta. Mires and Peat. 12(4): 1-12.
Published,
Refereed?: Yes

53. McLellan*, N, Gray*, L, Allin*, D, Damude*, K, Difebo*, A, McLean*, K, Sararas*, E, Stone, M and Price, JS. (2012). Transient storage and release of sediment and phosphorus in a small urban impoundment. IAHS-AISH publication. : 132-137.
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Hydrological functions of a mine-impacted and natural peatland-dominated watershed, James Bay Lowland

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ABSTRACT

Study region: This study was conducted in Northern Ontario, Canada, in the middle of the Hudson-James Bay. Lowland: one of the world's largest wetland complexes.
Study focus: Northern latitudes are expected to be the most impacted by climate change in the next century and adding to this stressor are increased mineral exploration activities, such as the De Beers Victor Mine, a large open-pit diamond mine. Because of the extremely low relief and presence of marine sediments, horizontal runoff and vertical seepages losses are minimal. As a consequence of this aquifer dewatering must occur to keep the open-pit mine dry. What is unknown is how the aquifer dewatering would impact the water balance of a peatland-dominated watershed. This study examines 3 years of aquifer dewatering from 2009 to 2011.
New hydrological insights: Deep seepage (groundwater recharge) varied with marine sediment thickness and represented a significant loss to the local system. Large downward fluxes were also measured in fen systems that are typically local discharge zones. Evaporation rates were also found to be lower in the bogs and fens and where impacted by lower water tables. When evaluating the water balance, with only 14.5% of the watershed impacted by the mine, the hydrological function of the entire watershed is more driven by seasonal climate variations than mine dewatering.

1. Introduction

The Hudson and James Bay Lowlands comprise the second largest peatland complex in the world and represent a significant contribution of the fresh water to the brackish James Bay (Rouse et al., 1992). These peatlands develop as a result of low topographic relief and a cool, moist subarctic climate. In the James Bay Lowland, ~85% of the area is covered by peatlands, with the remaining area consisting of mineral soil or fluvial systems (Glaser et al., 2004a). This area is underlain by a deposit of fine-grained marine sediments with low hydraulic conductivity (Glaser et al., 2004a), which along with the very low relief restricts drainage, thus contributing to high water tables and peat development. The peatlands of the James Bay Lowland sequester more than 12 million tons of carbon dioxide each year (MNR, 2012), making this landscape very important to the global carbon balance. Consequently, ongoing changes in global and regional processes (e.g., climate change) and local development (e.g., mining, transportation and infrastructure) and how they will affect the hydrology of this region is important to understand to create sound management and regulatory frameworks.

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Recent discovery of diamondiferous kimberlite deposits in the James Bay Lowland has prompted the development of the De Beers Canada Victor Diamond Mine. Pumping of dewatering wells surrounding the mine pit is required to maintain the dry conditions within the open pit for safe and efficient mining operations, which began in early 2007. This pumping is depressurizing the permeable Silurian aquifer that underlies the surrounding peatlands, increasing the percolation rate and causing their partial and spatially variable desiccation (Whittington and Price, 2013). What is currently unknown is how the depressurization of this system affects the hydrology and water balance of the peatlands, which overlie the bedrock and glacio-marine deposits, particularly the differential sensitivity of bogs and fens (the two dominant peatland types).

Mine pumping has resulted in a cone of depression in the limestone bedrock underlying the marine surficial deposits and peatlands. As of August 2011 the cone of depression, defined here as the 0.5 m head drawdown in the upper Attawapiskat bedrock formation, extends ~6 km (see Section 2) from the mine pit (AMEC, 2012), and encroaches on a series of small watersheds that may be impacted by increased seepage losses caused by the changing hydraulic gradients. While pre-mining percolation losses were estimated at 2.6–26 mm $year^{-1}$ (HCI, 2004b), the increase in head gradient caused by deep aquifer depressurization has resulted in vertical losses of 1–4 mm day^{-1} in the regions that have smaller vertical depth to bedrock (Whittington and Price, 2013). The spatial pattern of enhanced recharge is not uniform; the thickness and hydraulic conductivity of the overlying marine sediments (Whittington and Price, 2013), as well as the presence of interbedded sand layers (Ali, 2013) have a significant impact on the peatlands' ability to retain water. Therefore, enhanced recharge occurs where the relatively low permeability marine sediments are thin or non-existent, such as where bedrock subcrops or is fully exposed (Whittington and Price, 2012). These bedrock exposures are "bioherms", which are relict coral reef structures extending upwards from the Silurian bedrock (Cowell, 1983). Examination of the patterns of recharge around bioherms illustrates that their effectiveness as local drainage nodes is limited (to about 25 m from the bioherm edge) by the poor lateral transmissivity of peatlands surrounding them (Whittington and Price, 2012). Nevertheless, increased vertical gradients have resulted in declining water tables in some areas (Whittington and Price, 2013), which can affect peatland hydrological, biogeochemical and ecological function.

As previously noted, this area is covered by ~85% peatlands, mostly bogs and fens (Glaser et al.,2004a). The peatlands have developed over low-gradient low permeability marine sediments that have been lifted by isostatic rebound from beneath the waters of James and Hudson Bay (Glaser et al., 2004b; Price and Woo, 1988). Peat thickness averages 2.5 m, somewhat thicker in bogs, which have become raised above the base level to a greater extent than fens (Glaser et al., 2004b). Since bogs are raised above the surrounding environments in such a low gradient region they are oligotrophic, and only receive inputs from precipitation (Sjors, 1963). Bogs tend to act as storage units but discharge to fens when there is excess water (Quinton, 2003). Fens, in contrast, have developed as water conveyance systems that link directly to the stream network, providing drainage networks for bogs that occupy more interfluvial locations (Sjors, 1963). Fens are able to maintain high water tables as a result of surface and groundwater inflows, allowing them to support more constant runoff throughout the year (Verry and Boelter, 1975). The higher water table in fens also results in them losing larger amounts of water to evapotranspiration than bogs (Lafleur and Roulet, 1992). The nature and magnitude of hydrological processes operating in bogs and fens such as water storage changes, evapotranspiration and runoff are distinctly different. Consequently, the impact of seepage losses that affect water table position, for example, will affect bogs and fens differently. Moreover, the nature and extent of these impacts will alter the water budget of small peatland-dominated sub-watersheds located within or across the cone of depressurization caused by mine dewatering.

These peatlands are the zero- first-order sources/streams delivering fresh water to rivers draining into James Bay. Understanding how they are hydrologically connected will help determine the potential impacts development might have on the larger scale hydrology of the region. Decreasing water tables as a result of development could affect both the horizontal and vertical connectivity of these peatland systems. The potential for reduction in surface runoff will affect the peatlands ability to maintain baseflows for aquatic biological communities (although streams near the mine most likely affected have supplemental water lines in anticipation of this (HCI, 2003)). Increased flowpath length may occur as the system becomes more strongly connected to the deep groundwater system through enhanced vertical seepage losses. Increased flowpath lengths will impact the chemical balance within peatlands and suspended and dissolved sediment loads of streams, including the ability to regulate production and transport of methyl mercury from peatlands to major rivers (Siegel et al., 1995). However, the degree of this impact to the different hydrological components on the local bogs and fens is unknown. Therefore, the objectives of this study are to evaluate components of the hydrological cycle to (1) gain insight on the impact of mine dewatering on peatland hydrological functions and water balance (2) extrapolate the potential impact to the hydrology of the peatland systems at peak depressurization.

2. Study site

The study site is located ~500 km north of Timmins, Ontario, Canada, and 90 km West of Attawapiskat, in the James Bay Lowland (52°49′15″N and 83°53′00″W) near the De Beers Canada Victor Diamond Mine in Ontario, Canada (Fig. 1). The landscape is dominated by peatlands (bogs and fens) with a peat thickness generally between 1 and 3 m. The bogs in this area typically consist of a hummocky terrain dominated by *Sphagnum* spp., particularly *Sphagnum rubellum*, *Sphagnum magellanicum* and *Sphagnum fuscum*. The vegetation cover of the fens is mainly sedges (*Carex* spp.), but also has a significant amount of *Sphagnum* spp. and cotton grass (*Eriophorum spissum*) (Riley, 2011). Underlying the peat layer is Tyrell Sea marine sediments and glacial till deposits ranging from 0 to 200 m thick, with no marine sediments present where bedrock outcrops

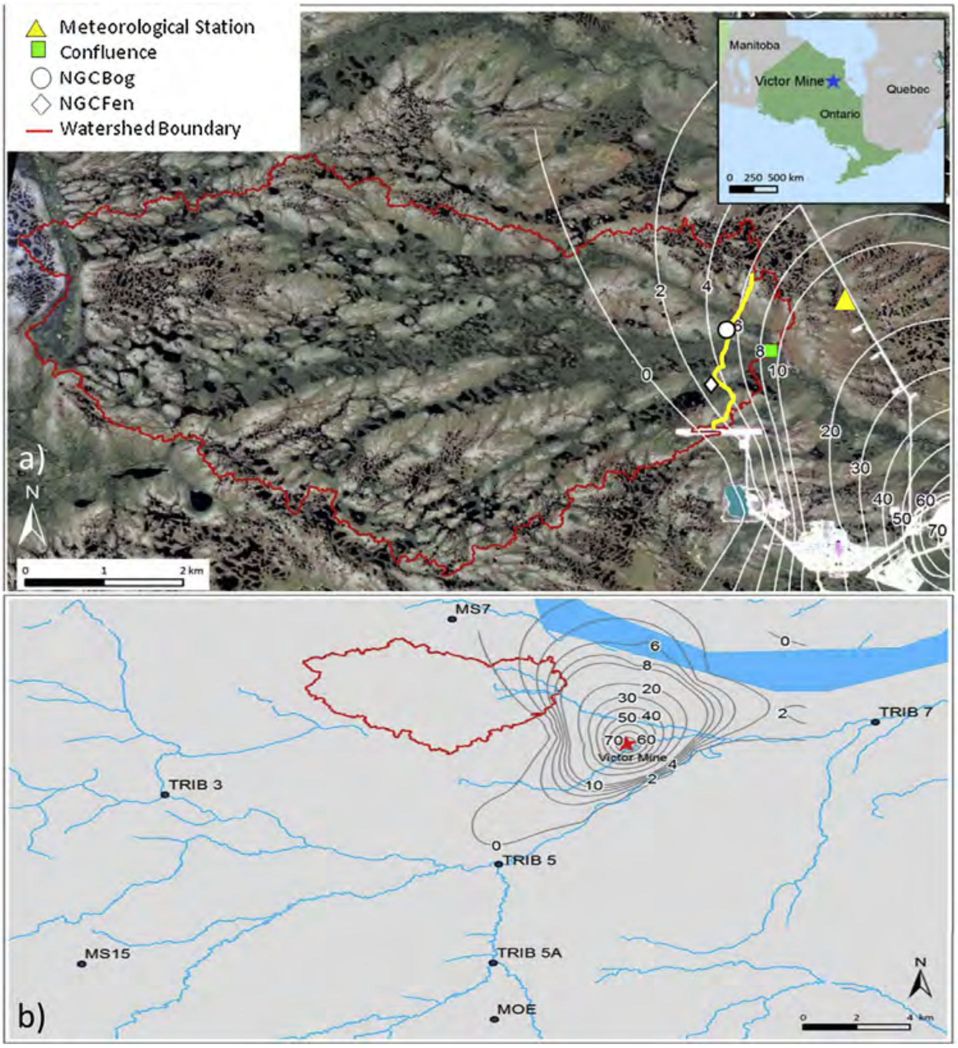

Fig. 1. (a) Location of the North Granny Creek watershed, outlined in red, relative to the mine site; the yellow line is the mine-impacted North Granny Creek study transect. The extent of the mine dewatering drawdown in the upper Attawapiskat bedrock formation as of 2011 is symbolized by the white lines. Inset: Location of Victor Mine site within northern Ontario. (b) Location of the non-impacted distal Tributary 5a used for estimating runoff, and the other non-impacted sites MOE (Ministry of Environment), MS7 and MS15, shown relative to the North Granny Creek watershed and the drawdown cone from the mine. The kidney shaped drawdown cone is due to heterogeneity in marine sediment thicknesses, which is in part due to the presence of bioherms. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

to the surface (AMEC, 2003). The underlying bedrock layer consists of a Silurian limestone, in some locations bedrock bioherms outcrop to the surface in small mounds. Bioherms can typically be identified on the surface as tree clusters (Cowell, 1983); due to their relatively high permeability they may also act as drainage nodes when the underlying bedrock aquifer is depressurized (Whittington and Price, 2012).

The site has a subarctic climate that experiences cold, harsh winters, and fairly short, mild summers. At the study site, long-term climate data are lacking; however, data are available at Lansdowne House (approximately 250 km west) and Moosonee (250 km south-east). Lansdowne House has an average (1971–2000) January and July temperature of −22.3 °C and 17.2 °C, respectively, with average total annual precipitation of 700 mm, ~30% falling as snow (2010). Moosonee has an average (1981–2010) January and July temperatures of −20.0 and 15.8 °C, respectively, and an average total annual precipitation of 704 mm, with ~31% falling as snow (2010). Whittington et al. (2012) evaluated the long-term averages at both these sites with the existing Victor Mine site weather station record (2000–2011, see Section 3) and determined that an average of Lansdowne House and Moosonee is a good approximation for the climate at the Victor mine. Given the cold climate and relatively short growing season, a frost table exists for the majority of the year. The study site is within the zone of sporadic permafrost (Riley, 2011) but permafrost is not extensive in the area, being restricted to palsas (raised mounds of expanded frozen peat) covering a few per cent of the study area.

Table 1
Water balance components and the methods used to estimate results each year in both the mine-impacted regions and non-impacted regions of this study. All mine-impacted data were acquired within the North Granny Creek (NGC) watershed. Non-impacted zone data were determined at sites located outside of the mine-impacted region, as noted.

	Mine-impacted			Non-impacted		
Component	2009	2010	2011	2009	2010	2011
Precipitation	Meteorological Station at Victor mine					
Evapotranspiration	2010–2011 calibration used with 2009 Victor mine MET data	Weighing lysimeters and Priestley–Taylor method using Victor mine MET data		Relationship between 2011 Victor MET and Eddy Covariance at MOE applied to Victor mine MET data		Eddy Covariance at MOE site
Runoff	Measured at NGC-Confluence			Measured at Tributary 5a		
Deep seepage	Nests along NGC transect			Five nests located at MS15		
Storage	Δh from wells along NGC transect, Sy from cores along NGC transect			Δh from 5 nests at MS15, Sy from cores from NGC transect		
% of watershed	6.7	11.2	14.5	93.3	88.8	85.5

The De Beers Victor Mine began operations in 2007. Each year as the open pit mine becomes deeper, increased dewatering is required to keep it dry. As a consequence, the cone of depression from the open pit radiates outward from the pumping wells, and stretches further into the surrounding landscape each year, herein called the "mine-impacted" region.

This study examines the water balance of a 34.4 km^2 sub-watershed called North Granny Creek, NGC (Fig. 1), the closest part of which is within 3 km of the mine, inside the mine-impacted region. Unfortunately, the instrumentation in North Granny Creek (research transect, Fig. 1) was within the mine-impacted area from the beginning of the study period (something that was not anticipated to occur so quickly) and the non-impacted areas were difficult to access on a regular basis. Therefore, data and parameters from representative non-impacted locations outside North Granny Creek are used as proxies for the non-impacted regions of the North Granny Creek watershed, with the assumption they are representative. These distal watersheds and instrumentation sites used for proxy data are all within 25 km of the North Granny Creek watershed. Hence there are four types of non-impacted reference study sites for the various component(s) of the water balance that represent the non-impacted part of North Granny Creek (see Fig. 1): (1) stream discharge (Tributary 5a); (2) groundwater fluxes (from wells and piezometers at MS15), (3) storage changes (MS15 & MS7) and (4) evapotranspiration (MOE, Ministry of Environment site). (MS stands for Muskeg Sampling and are the names used by De Beers for their locations.) The non-impacted study sites used for the specific data are described in Section 3 and summarized in Table 1. Data were available for the entire study period at each non-impacted study site (20 May–31 August for 2009, 2010, 2011) except where noted.

2.1. North Granny Creek watershed (main study area)

North Granny Creek watershed is approximately 9 km long by 5 km wide (34.4 km^2). The watershed contains two distinct channels of North Granny Creek (NGC); North-NGC and South-NGC. A 1.5 km transect (NGC transect, "mine-impacted") oriented north/south crosses both North-NGC and South-NGC and is anchored at either end by a bedrock exposure (bioherm). The North Granny Creek transect bisects a sequence of bog and fen landscape types (Fig. 2) indicative of the local area. In total there were 16 nests of wells and piezometers along the North Granny Creek transect. Classification of fused IKONOS and LiDAR images (DiFebo, 2011) of the North Granny Creek watershed reveal a complex landscape comprising 49% bog, 31% fen and 20% open water (either bog pools or fen pools); the distribution of these landscapes in the other non-impacted sub-watersheds was not measured but our visual observations suggest they are similar to North Granny Creek watershed.

2.2. Non-impacted sites

To provide a non-impacted reference baseline for vertical groundwater fluxes and storage change in the North Granny Creek watershed, the site MS15 was selected, since it had deep bedrock wells installed as part of the compliance (regulatory) monitoring network. MS15 is located approximately 25 km southwest of the mine, and had a transect stretching 150 m across a bog-fen transition, instrumented with 3 piezometer nests in the bog and 2 nests in the fen (each nest having 3 piezometers installed at 90 cm and 150 cm below the surface and one at the peat-marine sediment interface). Another site located 1 km north of the headwaters of the North Granny Creek (MS7) was used as continuous (logger) data were available to establish a regression for the storage changes at MS15 where only discrete (manual) water table data were available. The MS7 site was instrumented with 4 single monitoring wells all situated several hundred meters apart in two bog and two fen landscape types.

The non-impacted tributary, Trib 5a, is part of De Beers' compliance monitoring, it is located up-stream of the mine, well outside the mine-impacted region, it was used to quantify runoff from a non-impacted site. Trib 5a was used as a comparison because it is the closest in drainage size to the North Granny Creek watershed with a drainage area of 30 km^2 (Fig. 1) and is also dominated by a similar peatland configuration. Tributary 5a is incised into the marine sediments or its headwaters lie just on top of the marine sediment layer, similar to North Granny Creek. The flow regimes of this, and other tributaries shown in Fig. 1 were compared by Richardson et al. (2012).

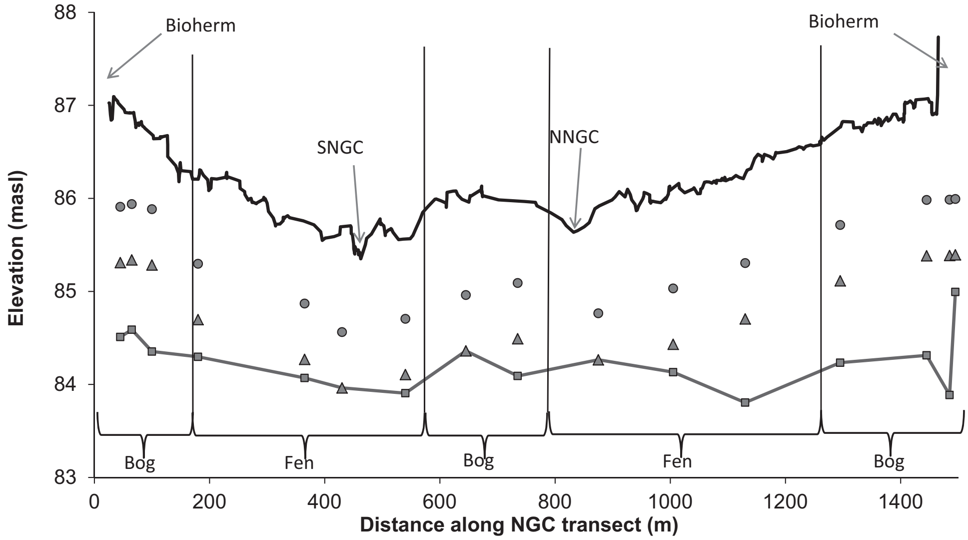

Fig. 2. Ground surface elevation of bogs and fens along the North Granny Creek study transect (black line, 8 point moving average of a DGPS elevation survey, with points taken every 4–5 m) and the bottom of the peat layer/start of marine sediments (grey line). The nest locations along the transect are indicated by the piezometers installed at depths of 90 cm (circles), 150 cm (triangles) and between 170 and 270 cm at the peat-marine sediment interface (squares) (in shallower locations, the 150 cm piezometer was installed at the interface). Figure modified from Whittington and Price, 2013.

The non-impacted site for measurements of evapotranspiration, operated by the Ontario Ministry of Environment (MOE), is located approximately 10 km south of the mine (Fig. 1). Eddy covariance systems were situated at a domed bog and at a ribbed fen. Data are only available for the complete 2011 season at the MOE site, so the relationship between the MOE and North Granny Creek sites derived for this period was used to estimate evapotranspiration at the non-impacted MOE site for the previous two study seasons.

3. Methods

To evaluate the potential changes in water availability in the North Granny Creek watershed caused by mine dewatering, a water budget was constructed for each year for the period from 20 May–31 August, as

$$P - \mathrm{ET} - Q - Q_\mathrm{d} + \Delta S = \xi \quad ,(1)$$

where P is precipitation, ET is evapotranspiration, Q is surface runoff, Q_d is deep seepage (the vertical flux of water), ΔS is change in storage and ξ is the residual value (all values in mm).

North Granny Creek watershed was split into two sections: mine-impacted and non-impacted. The mine-impacted area of North Granny Creek watershed was determined each year using the extent of the cone of depression in the upper bedrock aquifer, as determined with De Beers' monitoring wells (AMEC, 2010, 2011, 2012). As only the 2 m drawdown cone is reported, a distance vs. drawdown curve was created to extrapolate. The curve becomes asymptotic at about the 0.5 m drawdown isopleth, beyond which we assume the vertical hydraulic gradients imposed on the peatlands were negligible, hence non-impacted. Thus the extrapolated 0.5 m isopleth of drawdown in the upper bedrock aquifer determined the extent of the mine-impacted vs. non-impacted portions of the North Granny Creek watershed, for each study season; we did not consider changes to the cone of depression throughout the study season. To determine the water balance for the entire North Granny Creek watershed (i.e., including mine-impacted and non-impacted areas), data from mine-impacted (North Granny Creek transect) and non-impacted sites (i.e., using data from the proxy sites) were areally weighted (see Table 1).

A meteorological (MET) station installed in 2008 was located approximately 0.75 km from the confluence of the North Granny Creek watershed (Fig. 1). The meteorological station consisted of a data logger outputting an average (or total, for precipitation) value every 10 min. Air temperature was measured using a copper-constantan thermocouple in a radiation-shielded well-ventilated box. A net radiometer installed 1.5 m above the surface was used to measure the net radiation, and ground heat flux was measured with two self-calibrating soil heat flux plates installed 1–2 cm below the peat surface. Precipitation was measured using a tipping bucket rain gauge located inside an Alter windshield.

At the MOE site, meteorological stations were installed in a bog and in a fen in mid to late 2010. Instrumentation was similar to the North Granny Creek MET station, however, both MOE sites had eddy covariance instruments including latent heat flux sensors, sensible heat flux sensors and ambient air temperature probes.

Table 2
Average evapotranspiration rates and alpha values from moss, lichen, sedge and open water surfaces over the three study seasons, used to estimate evapotranspiration. The '*n*' value refers to the number of alpha values that were averaged to obtain the one shown, along with the associated standard deviation.

NGC	Water	Moss	Lichen	Sedges
2009 ET (mm day^{-1})	1.6	1.6	0.72	1.4
2010 ET (mm day^{-1})	2.2	2.1	0.95	1.9
2011 ET (mm day^{-1})	2.2	2.1	0.97	1.9
Alpha value	1.16	1.1	0.5	1.02
Standard deviation	0.5	0.2	0.2	0.2
n	2	18	6	6

Table 3
Average evapotranspiration rates from the main land types; bog, fen and open water along the mine-impacted North Granny Creek transect and at the MOE non-impacted site. The overall losses from North Granny Creek watershed were calculated using the weighted total of the two sites using the proportionate percentage of impacted vs. non-impacted, as indicated.

	NGC transect				MOE			Proportion of non-impacted area (%)	Total losses from NGC (mm)
	Bog (mm day^{-1})	Fen (mm day^{-1})	Open water (mm day^{-1})	Total losses (mm)	Bog (mm day^{-1})	Fen (mm day^{-1})	Total losses (mm)		
2009	1.3	1.4	1.6	141	1.6	1.7	165	93.3	163
2010	1.8	1.9	2.2	186	2.1	2.2	220	88.8	217
2011	1.8	1.9	2.2	189	2.2	2.3	224	85.5	222

3.1. Precipitation

Precipitation was measured at the North Granny Creek meteorological station and used for the entire North Granny Creek watershed for all years. Despite the distance between the headwaters of the North Granny Creek being approximately 10 km from the meteorological station, we believe the precipitation recorded at this location is indicative of the entire North Granny Creek watershed as topography does not factor at this location, and convective storms are uncommon. Additionally, Richardson et al. (2012) reported that the cumulative daily precipitation for June, July and August 2009 and 2010 for Lansdowne House (200 km west, and in the prevailing wind direction) varied by less than 5% of the cumulative precipitation at the North Granny Creek meteorological station.

3.2. Evapotranspiration

Evapotranspiration for the mine-impacted area of North Granny Creek watershed was found using the Priestley and Taylor (1972) combination method, calibrated with bucket lysimeters. The lysimeters were installed in different vegetation community types found in the mine-impacted area of North Granny Creek (*Sphagnum* moss, lichen and sedge), as well as in open water. The vegetation-filled lysimeters (24-moss, 8-lichen and 5-sedge) were constructed from white buckets with a depth of 40 cm and diameter of 28 cm, encompassing a monolith of vegetation-covered peat representative of the aforementioned cover types. The open water lysimeters (3 in 2010, 2 in 2011 due to wildlife interference) consisted of white buckets with a depth of 20 cm and diameter of 18 cm that were supported by light blue cut-out Styrofoam™ board to provide floatation and stability. To determine evapotranspiration, lysimeters were weighed periodically after two or more days with no precipitation to quantify the mass losses over the specified time period. Water was added or removed from lysimeters to make them more representative of the moisture conditions surrounding them. The actual evapotranspiration found using these lysimeters was used to calibrate the Priestley–Taylor (1972) equation,

$$\mathrm{ET} = \alpha \frac{s}{s+\gamma} \frac{Q^* - Q_g}{L\rho} \quad (2)$$

where ET is the evapotranspiration (mm d^{-1}), s is the slope of the saturation vapor pressure–temperature curve (kPa °C^{-1}), γ is the psychrometric constant (0.0662 kPa °C^{-1} at 20°C), Q^* is the net radiation flux (J d^{-1}), Q_g is the ground heat flux (J d^{-1}), L is the latent heat of vaporization (J kg^{-1}) and ρ is the density of water (kg m^{-3}). The alpha value, α, represents the slope of the relationship between the actual (lysimeter) evapotranspiration and equilibrium evapotranspiration, which is the outcome of Eq. (2) when $\alpha = 1$.

Different α values were found for each of the four surface types: *Sphagnum* moss (hummock and hollow species), lichen, sedges and open water. The separate α values were then used to determine rates of evapotranspiration from the different surface types. The α values from the different surface types were used in combination with each other to estimate losses from the bogs, fens and open water (see below) (Tables 2 and 3). Lysimeter data were only available for the 2010 and 2011 seasons, and the calibrated α values determined in these years for the four surface types, were also applied to 2009 meteorological data (Q^*, Q_g and air temperature) to determine evapotranspiration. Total seasonal evapotranspiration for the mine-impacted zone (ET_{IM}) of the North Granny Creek watershed was derived from areally weighted bog (49% of the area; 5% moss, 44% moss and lichen), fen (30% of the area; 11% sedges, 19% sedges and moss), open water (21%) classes (c.f. DiFebo, 2011, see Section 1.1.1), such that

$$ET_{IM} = \sum_{i=1}^{4} (x_i A_i)\, t \tag{3}$$

where x_i is the average daily evapotranspiration rate for each land cover, i, A_i is the areal fraction of each land cover and t is the time (days) that elapsed over the study period.

Evapotranspiration was also measured at the (non-impacted) MOE site in 2011 (data provided by MOE, 2011), using the eddy covariance vapor flux method which consists of a tower raised 4 m above the ground surface that has sensors measuring the latent heat exchange in the atmosphere above the surface. It does this by measuring the vertical turbulence of air and gas within the atmospheric layers above the ground surface. A flux tower was situated over a domed bog and another over a ribbed fen system. The flux towers measure the latent heat flux over the surface and non-impacted evapotranspiration ($ET_{NON\text{-}IM}$) is estimated as

$$ET_{NON-IM} = \frac{LE}{\lambda_{LE}\rho_w} \tag{4}$$

where LE is the latent heat flux (W m^{-2}), λ_{LE} is the latent heat of vaporization (MJ kg^{-1}, 2.501–0.002361 × T, T is temperature °C), and ρ_w is the density of water (kg m^{-3}).

Separate evapotranspiration rates were derived for both the bog and the fen at the MOE non-impacted site. The evapotranspiration rates from the MOE site were then areally weighted to the land cover classes for the non-impacted portion of the North Granny Creek watershed. The fen and open water classes were combined because there was no flux tower situated immediately over an open water system and fens tend to have more open water throughout the study period. The eddy covariance instrumentation above the fen captured the evapotranspiration from open water pools and standing water within the fetch of the eddy tower.

The instrumentation at the MOE site did not fully exist until 2011, so estimates of 2009 and 2010 $ET_{NON\text{-}IM}$ were made based on a relationship between 2011 E_{IM} and $ET_{NON\text{-}IM}$. The relationship between the 2011 evapotranspiration at the non-impacted site and the impacted site was determined by plotting up the daily evapotranspiration totals from the MOE eddy covariance tower and the daily evapotranspiration totals from the Priestley–Taylor combination method at the North Granny Creek impacted site; this was done separately for both bog and fen rates.

3.3. Runoff

Stream flow was measured at the confluence of the North Granny Creek watershed, using a flow meter, on a weekly basis. The water stage was recorded hourly using a pressure transducer within a stilling well located directly in the stream channel. For each of the study years a stage–discharge relationship was developed and applied to the continuous stage data to achieve hourly rates of discharge from the system. In these peatland systems snowmelt is a major contribution to the annual runoff from the system. Snowmelt was based on average depth and snow water equivalent measurements from Whittington et al. (2012). Snow water equivalent was measured every 30 paces (~20 m) using a plastic snow tube (1.2 m by 0.07 m i.d.) and weighed with a hanging scale; snow depth measurements were also taken using a ruler every 15 paces (~10 m). Snow water equivalent was calculated using the mass of the snow in the tube and a water density of 1 g cm^{-3}; snow density was calculated using the weighed volume of snow in the tube. Runoff was measured for the period of 1 April–31 August to incorporate the snowmelt data, snowmelt data sets only exist for 2009 and 2011 since there was no snow pack in April 2010 (very dry winter). Runoff study dates for the water balance calculation were chosen to start after the snow melt period (20 May–31 August) so there was a consistent period with all variables in the water balance. The water balance study period starts at the tail end of the snow melt period so some of the water gained from snow melt will be reflected in the stage changes and runoff values.

Runoff from the non-impacted Tributary 5a site was calculated in the same manner as the North Granny Creek, using a stage–discharge relationship. In 2009 for the first 20 days in April there was no runoff data for Tributary 5a due to unstable ice conditions in the stream. These 20 days of discharge data were estimated using a relationship between the Tributary 5a and another tributary (R^2 = 0.67) in the non-impacted area; which was the only tributary in 2009 with a full data set for the high flow period. Runoff ratios were calculated each year using the ratio of runoff to precipitation, including snowmelt, for the 1 April–31 August time period.

3.4. Deep seepage

To measure the vertical fluxes of water (deep seepage), wells and piezometers were installed into nests using a hand auger. Each nest was made up of one fully slotted well and three piezometers with 30 cm slotted intake (installed at 90 cm and 150 cm below the ground surface and one at the peat–marine sediment interface). All wells and piezometers were constructed from 2.54 cm inside diameter PVC pipe, with the slotted intakes covered by geotextile screen. The hydraulic head in these pipes was measured once a week during the study season. Field bail tests were conducted on the piezometers every season to determine hydraulic conductivity using the Hvorslev (1951) method.

Deep seepage was determined at North Granny Creek watershed (mine-impacted) piezometer nests using Darcy's law for specific discharge;

$$q = K\frac{\mathrm{dh}}{\mathrm{dl}}, \quad (5)$$

where K is hydraulic conductivity (cm d^{-1}) and dh/dl is the hydraulic gradient (the change in hydraulic head and the change in length between the two measuring points) across the profile. Deep seepage was calculated at each of the 16 nests across the 1.5 km transect. The hydraulic conductivity from the layer with the lowest K was used to calculate deep seepage using Eq. (5), since water in the profile can only move as fast as the slowest layer permits, and the gradient was assumed to reflect this. An anisotropy ratio of 0.23 ($\log K_h/K_v$; h and v are horizontal and vertical, respectively) was then applied to the hydraulic conductivity value, as established by Whittington and Price (2012), for this study site. The flux was calculated at each nest, each year, and then averaged by landscape type (bog or fen). The rate calculated for fens was also applied to open water area because all the classified fen nests are located adjacent to open water.

The deep seepage at the MS15 non-impacted site was calculated in the same manner as above for the 4 nests present there. Each nest consisted of 3 piezometers located at 90, 150 cm below the surface and at the peat marine sediment interface (approximately 250 cm below the surface). Fluxes were calculated at 2 bog nests and 2 fen nests. The rates found for the bog and fen at the MS15 site were applied to the non-impacted portion of the North Granny Creek watershed for each year. This, combined with the mine-impacted deep seepage determined a total loss or gain from the North Granny Creek watershed system as a result of deep seepage.

3.5. Storage

Change in storage (ΔS) was determined for bogs, fens and open water at North Granny Creek and MS15 transects, as

$$\Delta S = \Delta h S_y, \quad (6)$$

where Δh is the change in the water table height, and (S_y) is the average specific yield of the top 20–70 cm of peat, which represents the typical zone of water table fluctuation during the study period (note that while the 70 cm water table depth seems too deep for typical peatlands, in the mine impacted areas water tables were found to be that deep for periods of the summer. However, the majority of water tables were within 50 cm of the surface). Since there was no long term storage data at MS15 a regression was completed using the manual data at MS15 with water table data measured using pressure transducers at the MS7 site to establish long term storage fluctuations in the bog and fen landscapes at MS15. Cores (32 subsections in fen, 58 subsections in bog) were taken in the field using a Wardenaar peat corer for the top 40 cm of the profile and a Russian corer for the remaining depths, and transported to the laboratory. To determine S_y, cores were saturated, weighed, then drained for a 24-h period and weighed again to determine the proportion of water loss as a result of gravitational drainage. ΔS was spatially weighted using results from the mine-impacted and non-impacted sites to get an estimated total change in storage for the North Granny Creek watershed over the three study seasons.

4. Results

The De Beers Victor mine has been fully operational since January 2007; approximately 4.5 years by the end of this study period (2009–2011). A cone of depression of groundwater pressures in the Upper Attawapiskat bedrock aquifer has developed, which by 2011 encompassed 14.5% of the lower part of North Granny Creek sub-watershed (Fig. 1, Table 1). The progressive dewatering is reflected in declining average water tables in the NGC Bog and NGC Bedrock monitoring wells located in the mine impacted region (Fig. 3). The declining water table was most noticeable in the NGC Bedrock layer which displayed a drop of over 2 m between 2009 and 2011 over the winter months; these levels rebounded slightly after spring snowmelt but not to pre 2009 levels. The bog landscape (NGC Bog) in the North Granny Creek watershed did not display drops as large as in the bedrock but seasonal dewatering superimposed on a general downward trend also occurred there. The NGC fen landscape was not experiencing the same degree of long-term decline in water tables as the bog and bedrock. The MS15 non-impacted site water tables in both bog and fen landscape displayed no decline over the long-term; water tables in the bog and fen typically overlap each other and always rebounded in the spring to the same levels as the previous years. Based on the estimated extent of the cone of depression for 2009, 2010 and 2011, respectively, it was estimated that approximately 6.7, 11.2, and 14.5% of the North Granny Creek was impacted (Table 1), all at the lower (eastern) end of the watershed.

4.1. Precipitation and climate

Precipitation for each field season (20 May–31 August) totaled 357, 259 and 255 mm for 2009, 2010 and 2011, respectively. Precipitation events in 2009 were typically larger and more frequent than in 2010 and 2011 (Fig. 4). The 30-year climate averages for the same time period at Lansdowne House and Moosonee were 309 and 266 mm, respectively (Environment

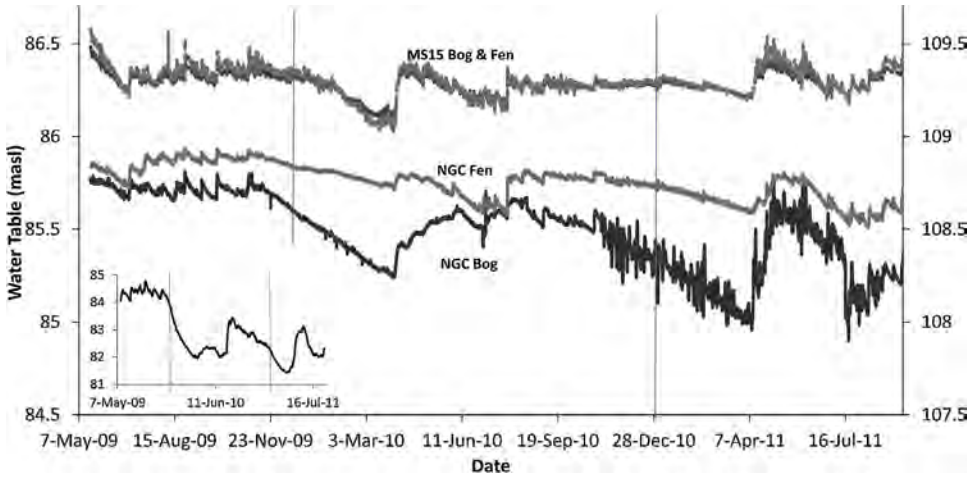

Fig. 3. Long-term water tables in the mine-impacted North Granny Creek bog, fen and bedrock and at a bog and fen in the non-impacted MS15 site. The MS15 water levels are on a secondary *y*-axis for ease of viewing, but has the same scale as the primary *y*-axis (i.e, 2 m). The inset shows the North Granny Creek bedrock water tables on a compressed scale (4 m) for ease of comparison.

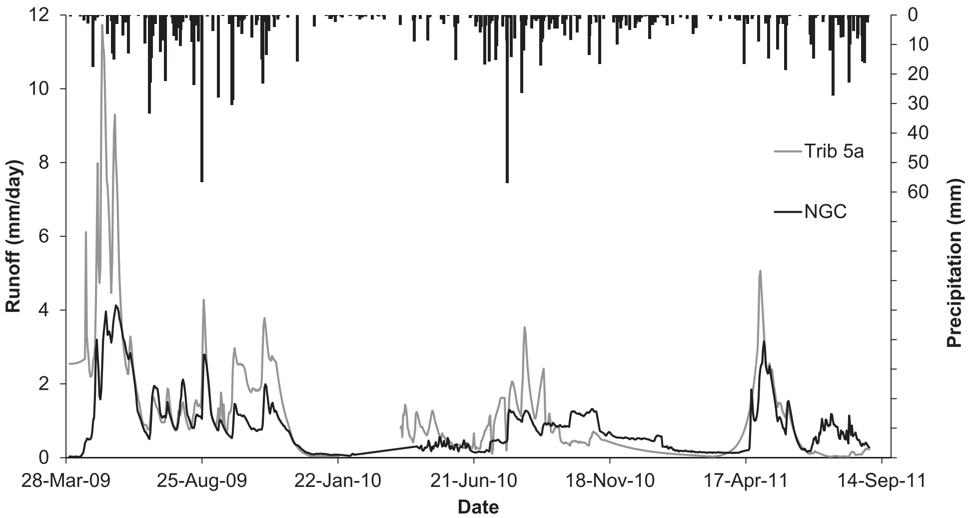

Fig. 4. Long-term hydrographs for the non-impacted Tributary 5a and the mine-impacted North Granny Creek, with responses to precipitation events from mid-2009 to mid-2011.

Canada, 2010, 2014). Additionally, spring of 2010 had no measureable snowpack, therefore snowmelt for that year was considered to have zero contribution to runoff (Whittington et al., 2012). The 2009 and 2011 seasons started off with a snow pack with average depths of 75 and 39 cm which had average snow water equivalence of 85 and 112 mm, respectively (Whittington et al., 2012). During the extended study period, used for runoff analysis only, the precipitation totaled 492, 292 and 423 mm for 2009, 2010 and 2011, respectively, including snowmelt. The 2009 season was colder with an average temperature of 12 °C and an average net radiation of 103 W m^{-2}, while the 2010 and 2011 seasons had average temperatures of 14.6 and 13.7 °C, respectively, and average net radiation of 111 W m^{-2} for both years.

4.2. Evapotranspiration

From the lysimeters installed in *Sphagnum* moss, lichen, sedges and open water, average α values were 1.1, 0.5, 1.02 and 1.16, respectively (Table 2). The average alpha values were determined to represent the respective surfaces (bog, fen and open water), with bog comprising a mix of moss and moss & lichen (α = 0.8), and fen comprising sedge and moss & sedge (α = 1.06). These alpha values were used to calculate the evapotranspiration and then the total evapotranspiration values were weighted in the proportions noted in the methods section to determine losses from bog, fen and open water. Open water had the highest rates of evaporation, averaging 2 mm day^{-1} over the three study seasons. Bogs and fens at the mine-impacted site had an average evapotranspiration of 1.7 and 1.8 mm day^{-1}, respectively (Table 3). Given the relatively high evapotranspiration rate from moss surfaces and their dominance in bogs (i.e., moss plus moss & lichen), which occupy

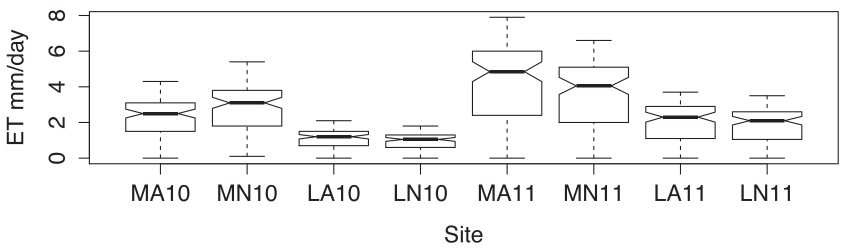

Fig. 5. Box and whisker plots of evapotranspiration rates in moss (M) and lichen (L) landscapes, near (N) and away (A) from a bioherm for 2010 (10) and 2011 (11). The upper and lower whiskers are the maximum and minimum rates experienced. The notches in the middle of the boxes can be used to determine significance, where non-over lapping notches between data sets can be considered to have significant difference, as in the moss vs. lichen landscapes.

the largest proportion of the landscape, bogs contributed the most to overall evapotranspiration losses from the system. Site wide evapotranspiration losses were 25% less in 2009 (the wettest, coolest year) than in 2010 and 2011. Additionally, evapotranspiration rates within the mine-impacted area were ∼13–14% lower than estimated rates at the non-impacted site.

At the MOE non-impacted site the average evapotranspiration loss in 2011 from bog and fen were 2.2 and 2.3 mm/day, respectively (Table 3). After applying rates from the MOE non-impacted site to the non-impacted portion of the North Granny Creek watershed and rates from the North Granny Creek transect to the impacted portion, total evapotranspiration losses from the North Granny Creek watershed were estimated to be 163, 217, 222 mm for 2009, 2010 and 2011, respectively, over the study season.

Within the mine impacted area the weighing lysimeters used to estimate evapotranspiration were situated either near a bioherm or outside of the bioherm's area of influence (about 30 m). Since bioherms are known to be localized preferential drainage nodes to the adjacent peatlands (Whittington and Price,2012) daily evapotranspiration rates were compared between moss and lichen landscapes both near and away from the bioherm in 2010 and 2011 (Fig. 5*)*. The notches on the boxplots can be used as a visual test of significance, whereby non-overlapping notches can be considered to have a significant difference (McGill et al., 1978). Differences between locations near and away from the bioherm were small or negligible. Evaporation from moss surfaces was significantly greater than from lichen and evaporation in 2010 was significantly less than in 2011. Only in 2010 was there a significant difference between near and away moss locations (very slight difference) and the trend reverses in 2011. All locations in all years were set to have a minimum evapotranspiration rate of zero instead of a negative value, which sometimes results from night time condensation.

4.3. Surface runoff

In 2009 the North Granny Creek watershed experienced 249 mm of runoff, and only 73 and 127 mm in 2010 and 2011 for the time period of 1 April–31 August (Fig. 4), which represents 70 and 50% less runoff for 2010 and 2011, respectively (Table 4). The lack of a snow pack in 2010 likely contributed greatly to the reduction in runoff for this year. The 2009 study season received about 100 mm more precipitation than the two consecutive years, which resulted in over 100 mm more runoff (Table 4). For 2009, 2010 and 2011 total runoff ratios were 0.51, 0.25, and 0.30, respectively (Table 5). In 2010 and 2011 when the area received less rainfall, the North Granny Creek experienced closer rates of runoff to the neighboring non-impacted tributary (Fig. 4).

The non-impacted Tributary 5a experienced a drop in runoff of 70% from 2009 to 2011. In 2009, a wet year, Tributary 5a, in addition to North Granny Creek experienced higher amounts of runoff (Table 4), but the hydrograph response was generally greater in the non-impacted watershed compared to the North Granny Creek (Fig. 4). In 2009 the non-impacted Tributary 5a experienced a runoff ratio of 0.88, by comparison the runoff ratio in North Granny Creek watershed was 0.51 (Table 5). By 2011 runoff ratios at the non-impacted tributary dropped to be 0.30 (Table 5), which was the same runoff ratio observed in the mine-impacted North Granny Creek watershed for that season. During the study period in which the water balance was conducted (20 May–31 August), post snowmelt, the North Granny Creek watershed experienced runoff of 179, 72 and 54 mm in 2009, 2010 and 2011, respectively.

4.4. Deep seepage

Along the mine-impacted North Granny Creek transect the average rates of deep seepage were up to an order of magnitude higher than rates found at the MS15 non-impacted site (Table 5). In all years bogs experienced net water losses from deep seepage at the North Granny Creek Site, and all bogs at the MS15 site experienced a net gain over all three years (Table 4 and Fig. 6). Within North Granny Creek the rate and variability of seepage loss in bogs increased between 2009 and 2011 (Fig. 6); while vertical fluxes in fens were smaller than in bogs, variability also increased between 2009 and 2011. At the non-impacted site the range of vertical flux rates for both bogs and fens increased slightly over the three study periods, with the largest spread in 2010. When the total losses for the North Granny Creek transect (mine-impacted area) and the MS15

Table 4
Runoff from the non-impacted distal Tributary 5a and the North Granny Creek from 1 April to 31 August during the 2009–2011 study seasons. Deep seepage rates and storage changes from the North Granny Creek transect, and the MS15 non-impacted site for the three study seasons and the aerally weighted average estimating the total losses from the North Granny Creek watershed (negative indicates downward flux or loss in storage, positive indicates upward flux or gains in storage).

		2009	2010	2011
Runoff (mm)	Trib 5A	435	145	126
	NGC	249	73	127
Deep seepage (mm day^{-1})	*Transect*			
	Bog	−1.6	−4.9	−3.6
	Fen	0.0	−1.5	−0.9
	MS15			
	Bog	0.2	0.5	0.1
	Fen	−0.3	−0.6	0.0
	NGC average rate			
	Bog	0.1	0.2	−0.2
	Fen	−0.3	−0.6	0.0
Change in storage (mm)	*Transect*			
	Bog	−5	4	−15
	Fen & open water	70	7	−32
	MS15			
	Bog	−7	−3	2
	Fen & open water	−9	−4	2
	NGC Average ΔS			
	Bog	−14	−5	1
	Fen	−17	−9	0
	Open water	−68	−34	0

Table 5
Runoff ratios from North Granny Creek and the non-impacted Tributary 5a for the three study seasons between 1 April and 31 August. Precipitation for this time period used to calculate the runoff ratios includes rainfall and snowmelt, as noted there was no measurable snowpack in 2010.

Tributary	2009 (mm)	2010 (mm)	2011 (mm)
Trib 5a	0.88	0.50	0.30
NGC	0.51	0.25	0.30
Rainfall (mm)	406	292	311
Snowmelt (mm)	85	–	112
Total precipitation (mm)	492	292	423

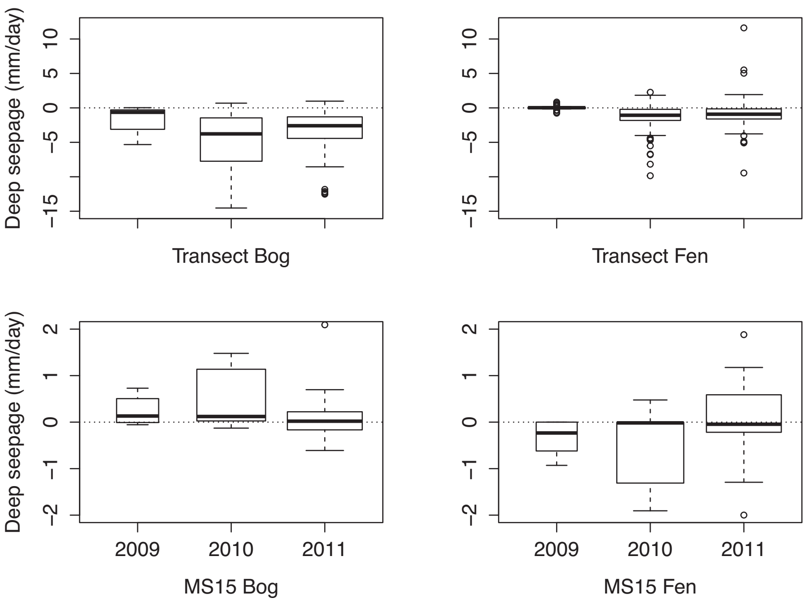

Fig. 6. Deep seepage rates along the North Granny Creek transect and MS15 transect for bog and fen for 2009, 2010 and 2011. Whiskers indicate maximums and minimums, dots represent outliers and box width are indicative of sample size (n).

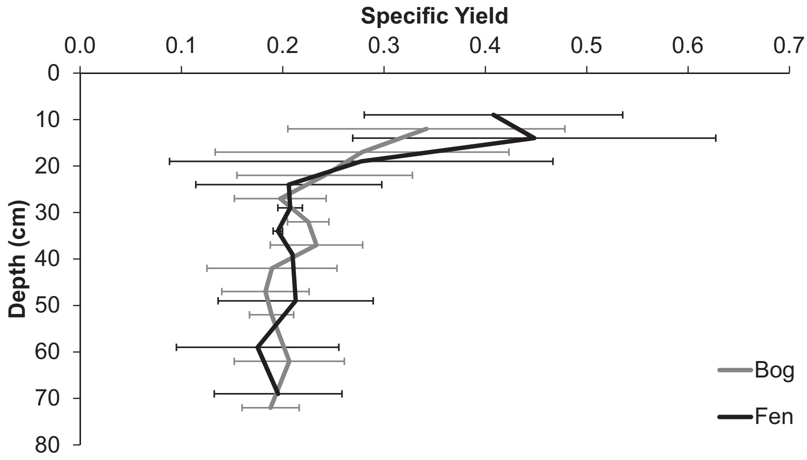

Fig. 7. Average specific yield values with depth in bog vs. fen landscapes in the NGC watershed. Bogs had average Sy of 0.22 (standard deviation of 0.05, $n = 58$); in fens it was 0.25 (standard deviation of 0.1, $n = 32$). Error bars are ±one standard deviation at each depth.

non-impacted site are areally weighted for their respective areas in the North Granny Creek watershed, seasonal fluxes amounted to −11, −25 and −9 mm for 2009, 2010 and 2011, respectively (Table 4) (i.e., losses).

4.5. Change in storage

Water storage change reflects the balance of inputs and outputs for a defined period, and is calculated from water table data (Fig. 3) in a (peat) soil on the basis of its specific yield, Sy (Fig. 7). As previously noted, there was a general decline in water table, hence water storage, in the North Granny Creek bog. This was not apparent in the North Granny Creek fen. In both North Granny Creek and MS15 bogs and fens there were distinct seasonal trends with the main recharge being in the spring, and declining over the summer and into winter. For the water balance period (20 May–31 August) the water storage change, ΔS, between the start and end dates reflect mostly the balance of the shorter term fluxes. These values are provided in Table 4. Over the 2009 study season in the mine-impacted zone the bogs lost water from storage while the fens and open water gained storage (Table 4). In 2010 along the North Granny Creek transect all land types gained storage over the study period. By the end of the study season in 2011 the opposite occurred and all the landscape types at the mine-impacted site lost storage over the season. For the study years 2009–2011, the storage changes measured along the mine-impacted North Granny Creek transect in the bog amounted to −5, 4, and −15 mm, respectively. In the fen along the North Granny Creek transect the changes in storage over these periods were 70, 7, −32 mm, respectively. At MS15 non-impacted site the changes in storage for all years and all site-types were small (<±10 mm) (Table 4).

Total storage changes were weighted areally for land cover type (bog, fen, open water) and then again for the amount of the watershed affected by the mine's cone of depression. The changes in storage along the mine-impacted section of North Granny Creek, and at the non-impacted areas represented by values from MS15, amounted to −26, −12 and 0.3 mm, respectively, for the three study periods (Table 4).

5. Discussion

5.1. Hydrological response

As a result of pit dewatering, part of the underlying limestone bedrock aquifer has become depressurized within the North Granny Creek watershed. With each year there is further encroachment of the mine's cone of depression into North Granny Creek watershed, from 6.7% in 2009, 11.2% in 2010 and 14.5% by 2011 (Table 1). The following discussion will evaluate the importance of this on the stores and fluxes of water in the North Granny Creek watershed; these will be examined in view of the seasonal precipitation patterns, which varied +20, −12 and −12% from climate normals in 2009, 2010 and 2011, respectively.

Both mine-impacted and non-impacted sites experienced lower evapotranspiration rates in 2009 compared to the two following years, as a consequence of the differences in weather patterns across these years. The 2009 season had lower temperatures and lower net radiation (Q^*) as a consequence of the atmospheric conditions that produced the relatively heavy rainfall for 2009. The North Granny Creek mine-impacted site experienced lower evapotranspiration rates over all three years (overall average of 1.7 mm day^{-1}), compared to the non-impacted site (overall average of 2 mm day^{-1}) (Table 3). We acknowledge that the difference between the North Granny Creek mine-impacted and the non-impacted MOE site is relatively small (Table 3), and that it could be explained by a combination of the difference in methods and error. The Priestley–Taylor method is dependent on the reliability of the lysimeter weights, which is affected by the representative moisture conditions inside the lysimeters (compared to the outside). It also relies on the accuracy of the energy budget measurements; however, errors in these terms are compensated for by their fit with the lysimeter data. The eddy covariance method relies only on direct measurement of the latent heat flux. While this may also have errors they can be assessed by comparison with the outcome of the energy budget for an independent assessment of accuracy (Drexler et al., 2004), notwithstanding potential errors in other energy balance fluxes.

Several studies (Boelter, 1972; Ingram, 1983; Ramanov, 1968; Verry, 1988) have shown that evapotranspiration rates from peatlands decrease rapidly when water tables drop to about 15–30 cm below the surface. In more southerly bogs higher temperatures over longer summer periods and milder temperatures during the shorter winter season, allow for increased vegetation growth, particularly ericaceous shrubs (Murphy et al., 2009). It is these shrubs and the extent of their root depth that helps determine when evapotranspiration rates will decrease relative to water table height (Admiral et al., 2006). In the James Bay Lowland the rooting zone is shallow because of persistent ground frost and cold climate, resulting in shrubs that require a higher water table for supplying evapotranspiration. However, a water table too close to the surface would reduce the aerobic rooting zone and shift the relative abundance of shrubs to sedges. Current drying of the mine-impacted portion of the North Granny Creek watershed is likely to promote growth of woody plants; this increased growth is already apparent in some drier locations (Talarico, 2009). This increased shrub growth may offset the tendency for lower evapotranspiration rates caused by mine dewatering, at least in the short-term until increased root depth enhances the potential water loss by evapotranspiration from drier peat systems (Admiral et al., 2006). However, greater vascular plant presence may boost evapotranspiration losses after mining ceases and the pumps are turned off, when water tables return to higher static levels.

Rooting zones also play a key role in the differing evapotranspiration rates between bog and fen landscapes. Evapotranspiration rates were slightly higher in fens (Table 3), which never experienced water tables lower than 20 cm below the surface, with correspondingly lower impacts on their vegetation assemblages (Admiral et al., 2006). Furthermore, bogs experienced lower water tables and in some areas along the North Granny Creek mine-impacted transect, water tables were 40–50 cm below the surface in 2010 and 2011, respectively. Bogs were more likely to have a substantial lichen cover, and lichen cover decreased the evaporative water loss (Fig. 4). The roles of lichen vs. mosses on the evaporation rates were also evaluated with respect to their proximity to bioherms, where substantially lower water tables have been documented (Whittington and Price, 2012). The only significant differences found were between moss close and more distant from the bioherm in 2010 and between moss and lichen in both years. Lichen evaporation rates were expected to be significantly lower than that of moss because lichens are restricted to the surface and do not have good connectivity to the underlying peat so any surface drying greatly reduces their evapotranspiration rates. Bello and Arama (1989) conducted a study in the Hudson Bay Lowland on lichen canopy interception and found that in this climatic region precipitation only occasionally finds its way to the moss layer below the lichen surface cover during the summer months. They determined that two days without rain was sufficient to create antecedent moisture deficits in lichen canopy that exceeded precipitation on most occasions. They also found that following rain events that produced drainage through the lichen canopy, drainage became insignificant after one hour following a rainfall event. The lack of drainage and moisture deficit indicate that lichen has poor connectivity with the underlying layers, which along with its poor water retention capacity results in relatively low evapotranspiration rates.

Lower water tables not only have a potential impact on evapotranspiration, the position of the water table is also highly reflected in rates of runoff. The variation in runoff from North Granny Creek in addition to the non-impacted Tributary 5a in 2009–2011 is an excellent indicator of how the weather patterns controlled the water balance over these three years. During 'wet' periods, such as 2009, it is evident that both of the watersheds were experiencing higher runoff than in subsequent years (Table 4; Fig. 4). It is also notable that the two watersheds are experiencing runoff at different rates, as a result of differences in their internal connectivity, channel orientation, as well as channel form, etc. (Richardson et al., 2012). These differences were less apparent at low-flows, when drainage was less dependent on the way source areas connect as they do in wet periods (Richardson et al., 2012). The non-impacted Tributary 5a hydrograph experiences greater runoff events than North Granny Creek. This greater runoff (at Tributary 5a) is likely an indication of less water being detained in storage. The reduced runoff at North Granny Creek could be indicative a greater storage capacity as a result of mine dewatering, but it could also be due to watershed characteristics. The runoff ratios (Table 5) determined for the North Granny Creek over the three years dropped by half from 2009 to 2011, in response to drier conditions that enhance depression storage in peatlands thus reducing surface runoff. The runoff ratios of 0.51, 0.25 and 0.30 for 2010 and 2011 were within the range of runoff ratios found at several other peatland systems (Brown et al., 1968; Dingman, 1971; McNamara et al., 1998; Quinton, 2003; Richardson et al., 2012; Roulet and Woo, 1988). The runoff ratios at the non-impacted tributary also experienced a large drop between the three study years (Table 5). Given that the reference non-impacted watershed also saw large reductions in runoff and considering the broad array of physical attributes of the different watershed systems (e.g., size, depth of incision, connectivity to internal source areas) it cannot be confirmed that the lower runoff rate in North Granny Creek was due to the effects of mine dewatering, especially since it was only the lower ∼15% of the basin that was within the drawdown cone at the time of the study. However, all the hydrological responses (lower water table, increased seepage loss, probable disconnection from water source areas) in the lower part of the North Granny Creek watershed are attributes that contribute to a reduction of runoff. In anticipation of potential reduced runoff caused by mine dewatering (Fig. 1), a pipeline connected to the Attawapiskat River was mandated by regulators, to supplement discharge just below the outfall of the North Granny Creek watershed, to maintain downstream flows (HCI, 2003).

Deep seepage rates along the North Granny Creek transect were typically more than an order of magnitude higher than pre-mining rates of approximately 2.6–26 mm years^{-1}, as reported by HCI (2004a). Recently Whittington and Price

Table 6
Components of the water balance measured between 20 May and 31 August in 2009, 2010 and 2011. These values are based on the aerially weighed results found from both the North Granny Creek mine-impacted site and the various non-impacted reference sites, with the exception of runoff the values, the values shown were measured only at the North Granny Creek site and not aerially weighted with the non-impacted site. Components include precipitation (P), evapotranspiration (ET), runoff (Q), deep seepage (Q_d), change in storage (ΔS), the residual value (ξ) and resulting potential error in the water balance.

	2009	2010	2011
P	357	259	255
ET	−163	−213	−217
Q	−179	−72	−54
Q_d	−11	−25	−9
ΔS	−26	−12	0.3
ξ	−22	−63	−25
Error	−6	−25	−10

(2012) determined that deep seepage losses from this landscape vary between 2.1 mm day^{-1} for bog/near bioherm areas and 0.26 mm day^{-1} for fen/non-bioherm areas. They determined that these measured rates match well with the modeled flow in response to the amount of water that is being pumped out of the mine daily (Itasca, 2011). In all three years the bogs in the impacted area lost water to recharge, with average losses as great as 4.9 mm day^{-1} in 2010. The fens along the impacted transect were losing water through deep seepage in 2010 and 2011 (Table 4; Fig. 6), albeit at a lower rate than in bogs. The higher percolation losses from bogs may reflect their higher position in the landscape (Fig. 2).

At the MS15 non-impacted site the average deep seepage rates, whether up or down, are an order of magnitude lower than those found along the mine-impacted transect (Table 4; Fig. 6). When the deep seepage losses from the mine-impacted North Granny Creek transect and non-impacted MS15 site are areally weighted for bog vs. fen/open water and impacted vs. non-impacted the North Granny Creek watershed, it is only losing a total of 11, 25 and 9 mm of water for 2009, 2010 and 2011, respectively, through deep seepage (Table 6). The rates found at the non-impacted site are consistent with what was stated for pre-mining rates. The non-impacted site displayed deep seepage rates that are in the range of what would be expected in a peatland. This is consistent with gradients of 0.01 found in Lake Agassiz peatlands by Siegel (1988), which when coupled with low hydraulic conductivities in peatlands result in low flux rates. Given the similarity in the hydraulic properties between the North Granny Creek substrates and those at MS15, the higher percolation losses at the former are exclusively due to depressurization of the deep aquifer which increased the downward hydraulic gradient.

When comparing the spread of the deep seepage data the mine-impacted area shows a much larger variation in the daily rate than the MS15 non-impacted site (Fig. 6). The range of non-impacted site rates is less than 4 mm day^{-1}, while the range of North Granny Creek site is over 20 mm day^{-1} (Fig. 6). This reflects the relative water table stability of the non-impacted site as a natural system (c.f. Rochefort et al., 2012) and highlights the impact the mine dewatering is having on the vertical fluxes within the affected region. The lower water tables in the mine impacted area experience storage changes lower in the soil profile where specific yield is less. Consequently, head changes caused by water gains or losses at the impacted site are larger, thus rendering more variable hydraulic gradients.

Due to mine operations causing enhanced deep seepage, available water storage capacity increased over the three study years in the mine-impacted zone, most predominately in the bedrock, but also in bog, as reflected in declining water levels (Fig. 3). However, over the three study seasons from 20 May to 31 August, water storage changes were generally small, with the exception of fen & open water (Table 4), which was an order of magnitude larger (70 mm) than most other changes. The decline in water tables was most notable during winter, when no surface inputs occurred (instead accumulating in the snowpack). The decline was greatest in the bedrock, notable in bog, and slight in fen. The water table in fen is likely sustained by drainage from adjacent bog sites, reflective of the role of bogs as water stores and of fens (particularly channel fens) as conveyors of water (Quinton, 2003). Moreover, during the non-winter period these functions continue. In particular, snowmelt and large rain events from the comparatively large up-slope catchment of fens will refresh water lost by deep seepage, as well as from discharge from the surrounding domed bogs; whereas bogs, being fed only by direct precipitation, will be more susceptible to drying and typically experience greater water table drawdown in summer (Price and Maloney, 1994). However, as drying continues, bog discharge could cease reducing a valuable water source to fens; therefore, fens will be most strongly impacted by mine dewatering, and bogs, though their position in the landscape, will continue to act as storage units.

6. Conclusions

After summing all components of the water balance there is a relatively small residual term of 6, 25 and 10% (determined as a proportion of precipitation) for 2009, 2010 and 2011, respectively (Table 6). Three years into mine operations (i.e., by 2009), the impact of mine drawdown was evident in the mine impacted region, which was 14.5% of the watershed in 2011. Precipitation was the main input into the North Granny Creek system but several outputs existed. The largest output of water was through evapotranspiration which is mainly driven by climate and moisture availability. Runoff also contributed to large losses from the system but since most of the water discharged still came from the non-impacted headwaters this number was likely minimally affected by mine drawdown. Deep seepage was the variable of the water balance that was most affected by mine drawdown, this is apparent in the large magnitude in the fluxes compared to the non-impacted site and typical natural fluxes. As groundwater inputs in the North Granny Creek are assumed to be minimal, the only input to the water balance is controlled by precipitation; it is apparent that variations in seasonal weather patterns had a much greater impact on the water balance than mine related drawdown, at least at this point of the mine's life. The extent of the mine's drawdown into the North Granny Creek at the time of this study was not enough for the impacts to out-weigh the inter-annual variations in climate. However, as mine operations continue, the cone of depression is expected to grow further into the watershed, and so the peatlands will likely continue to experience long-term negative storage change, reduced runoff and evapotranspiration, and increased deep seepage. These changes to the hydrology will have implications on the chemical and biological processes that are taking place in the peatland. However, given the vast extent of the James Bay Lowland, the effect of the mine on the regional water balance is very small.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ejrh.2015.10.006.

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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

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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

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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.

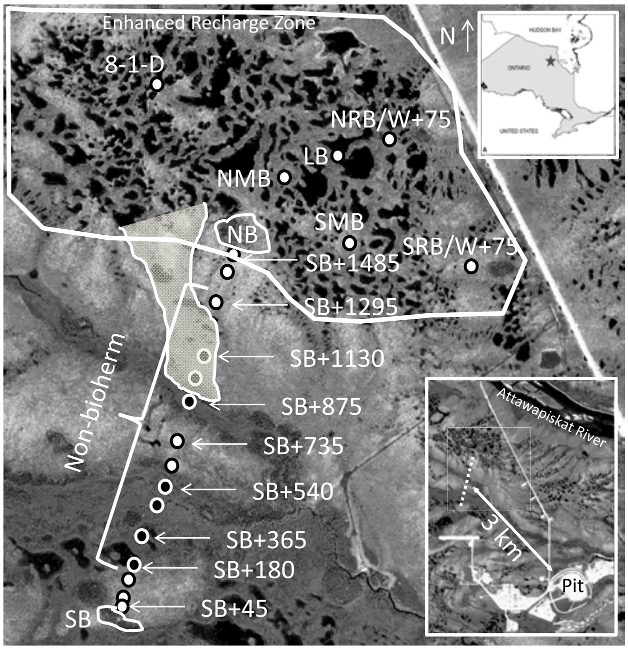

Figure 1. Location of selected nests along and north of the transect. White-centred circles are bog locations; black-centered circles are fen locations. The reader is directed to Table I for a complete list of the transect nest locations. Top inset: Site location within Ontario; bottom inset: location 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

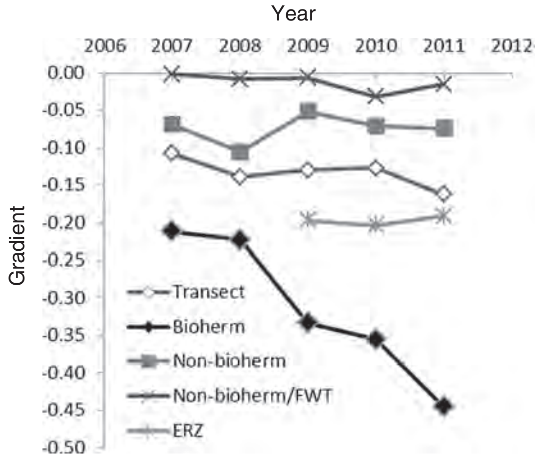

Figure 3. Average hydraulic gradient (from well to mid-point of deepest piezometer) from 2007 to 2011 along the transect, in bioherm nests, non-bioherm nests, and non-bioherm/non-fen water track (FWT) (see Figure 1) nests

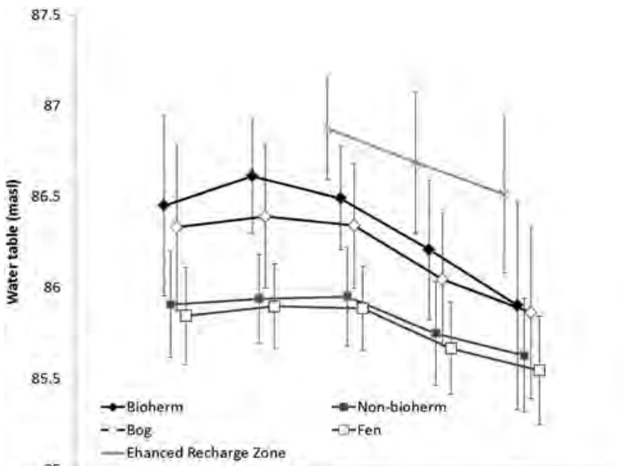

Figure 2. Water tables through time for both bioherm and non-bioherm and bog *versus* fen nests, and the ERZ. Points are shown offset in time (x-axis) for display purposes only. Data are the average of the field season measurements, generally from April/May to August (except 2007). Error bars are +/−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

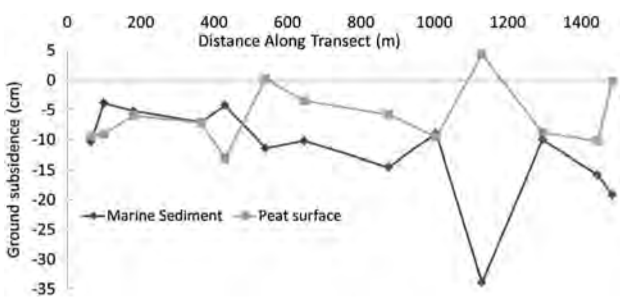

Figure 4. Marine sediment and peat elevation changes along the transect from 2007 to 2011

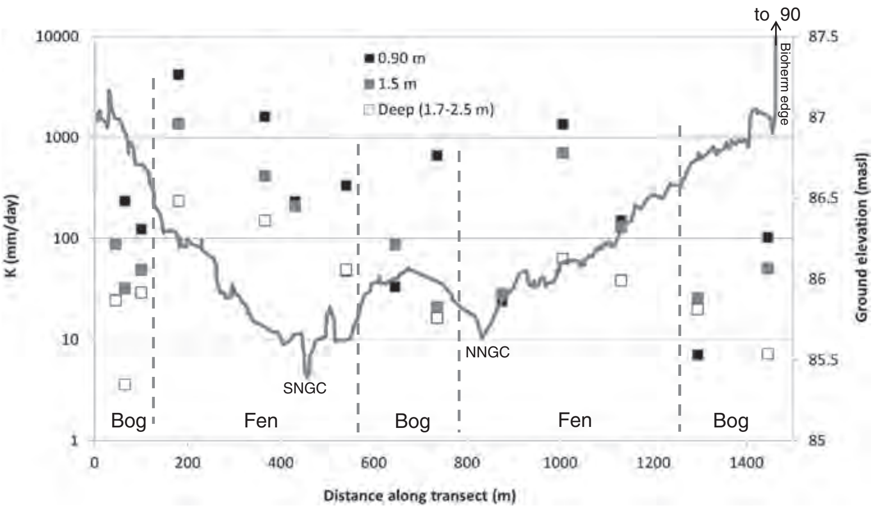

Figure 5. Average (2007–2011) hydraulic conductivity per piezometer (points) and ground elevation (2008) (grey line) along the transect. Ground elevation was determined using an eight-point-moving-average from a DGPS walking survey with points taken every 4–5 m; the NB (North Bioherm) is clearly seen 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,

$$Q_T = KA_T \frac{\Delta h}{\Delta l} \quad (1)$$

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

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

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

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

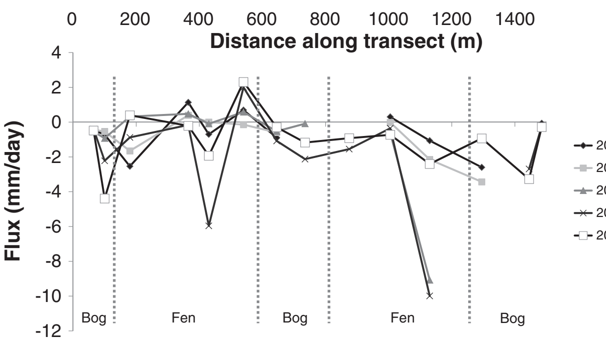

Figure 6. Fluxes of water through the peat, through time, along the transect. a) using only the marine sediment K value of 7 mm/day and b) using the K in the peat profile

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

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

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

$$q_i = \frac{Q_i}{A_i} \quad (5)$$

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

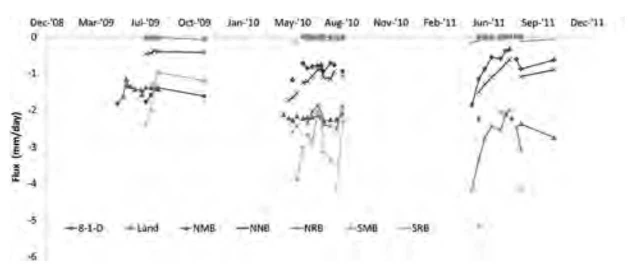

Figure 7. Fluxes of water through the peat in the ERZ from 2009 to 2011

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	

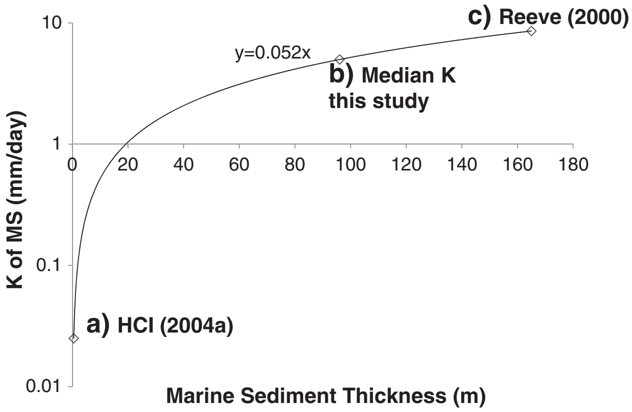

Figure 8. K *versus* marine sediment thickness using the K/ΔL ratio = 5.2 10^{-5}/day. The K values used are: a) 0.025 mm/day, value used by HCI (2004a); b) 5 mm/day, median value of MS found in this paper, c) 8.6 mm/day, Reeve *et al*'s (2000) 'no flow' base

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.

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