The hydrological interactions within a mine impacted peatland, James Bay Lowland, Canada

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of this thesis, including any required final revisions, as accepted by my examiners. I understand that my thesis may be electronically available to the public.

Statement of Contributions

This thesis contains data that was provided by other sources and used with their permission. The 2011 eddy covariance data was provided by the Ontario Ministry of Environment. The 2009 and 2010 North Granny Creek runoff data was calculated by Dr. Murray Richardson of Carleton University. The Tributary 5a data, as well as, the MS7 water table data was provided by DeBeers Group of Companies, Victor Mine.

Abstract

The development of a large open-pit diamond mine in the James Bay Lowland, one of the world's largest wetland complexes, provides insight into hydrological processes that sustain wetlands in the region. The bog and fen peatlands that dominate the landscape have developed as a consequence of the low relief and low hydraulic conductivity of the underlying marine sediments that restrict percolation. The peatlands and marine sediments overlie permeable Silurian limestone into which the mine-pit extends. Percolation losses (between 2009–2011) from the peatlands have been enhanced due to depressurization of the limestone aquifer caused by mine dewatering, experiencing rates of up to 15 mm day^{-1}. This is more than an order of magnitude higher than rates measured at a nearby non-impacted site, representative of the pre-mining condition. Large percolation losses were also measured in fen systems, which are typically local discharge zones. Where water tables were lowered by enhanced percolation losses, evapotranspiration rates were lower in the mine impacted site than the non-impacted site with average rates of 1.8 mm day^{-1} and 2.2 mm day^{-1}, respectively. Impacts of watershed runoff were masked by two consecutive dry seasons and the location of the watershed headwaters, which were mostly outside the cone of depression.

When assessing the relatively smaller scale processes, the connectivity of the bogs, fen water-tracks and channel fen peatlands that dominate the landscape is important in feeding the rivers that provide fresh water to James Bay. In addition to increased vertical fluxes the bogs and fens in the mine impacted region experienced average downward gradients of 0.09 and 0.04 in 2011, respectively. This is again more than an order of magnitude higher than gradients measured at the non-impacted site. In addition, the bogs and fens also experienced water tables 20 and 17 cm

further below the surface than the non-impacted site. Lower water tables in the bogs would result in the bog holding on to more water and provide less recharge to the adjacent fen systems. This would have a larger impact on a fen water-track system which relied on the bogs for half of their discharge. The channel fen system relied on its non-impacted head waters to help sustain water tables in the fen and to provide almost all of its recharge. The channel fen system received only about 1.5% of its total discharge from the adjacent bog.

With only 14.5% of the North Granny Creek watershed impacted by, the hydrological function of the entire watershed is more driven by seasonal climate variations than the mine dewatering. This area of impact is small relative to the size of the James Bay Lowland, but the changes are indicative of possible declining water tables in response to a warming climate, thus, declining connectivity of these bog-fen systems.

Acknowledgements

First of I'd like to start off thanking the one that initially sucked me into the study of Hydrology. Pete, starting out as my TA you have been my hydrological mentor for almost as many years as you were a grad student. Thank you for all the knowledge and experience you have shared with me and post importantly for teaching me how to utilize google search.

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This thesis would not have been possible without the endless hours spent in the field collecting data with the help of the muskeg crew. My two field seasons were probably the best part of this entire thesis despite all the booters and bugs. There were more of you than I can count over the years, thank you to every muskeger for contributing to the success of this thesis.

Special thanks also goes out to my brother, Kevin, and Murray Richardson's team for helping delineate my watersheds and prepare my awesome maps, I would have been another year without your support.

I also have to thank my family (including my love Brad) thank you all for your continuing support, encouragement and patience. You will finally get to see who wins the bet on when I would finish, I appreciate that most of you had confidence in me and under estimated my completion date.

Next I would like to thank De Beers Victor mine, specifically Brian Steinback and Terry Ternes for years of endless support on and off site. I would also like to thank my Snap Lake family for their continuous encouragement over these last couple years.

It would only seem fitting that I thank my supervisor, Jon last since I have been avoiding him for longer than I can remember. Thank you for the great opportunity and sharing your endless knowledge of wetlands with me, it is an experience I will never forget (for better and worse). Thank you for not giving up on me, as I'm sure there have been many days over the last several years we have both thought this end date would never come. I was just trying to win the title of your longest running master student from Scott. Thank you for everything you have done for me, it was and will always be greatly appreciated.

Dedication

To my family, thanks for putting your money on me.

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Note: Sections 2.0 and 3.0 within this thesis are written as independent manuscripts for submission for publication. As such some of the content within the manuscripts repeats previously stated information.

1 Introduction

The James Bay Lowland (JBL) is part of the second largest peatland complex in the world and provides a significant contribution of fresh water to the saline James Bay (Rouse et al., 1992). Approximately 90% of the area in the JBL is covered by peatlands, with the remaining area consisting of mineral soil or fluvial systems (Glaser, 2004). Understanding the hydrology of these systems is extremely important because it controls the biogeochemical cycling and transport of nutrients. The Hudson Bay Lowland in Northern Ontario stores approximately 27 Gt of carbon (McLaughlin, J. & Webster, K., 2013), 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 for the creation of sound management and regulatory frameworks.

Rouse et al. *(1992)* outlined the potential impacts that would occur if James Bay was dammed from east to west and only contained fresh water, as was proposed for the Great Recycling and Northern Development (GRAND Canal) project (Kierans, 1987). They concluded that if James Bay was dammed the currents would be disrupted, delaying spring sea-ice melt, causing temperatures to decrease, thus reducing evapotranspiration. Furthermore, if James Bay were to become a fresh water system the entire ecosystem would change as a result of cooler temperatures (caused by more persistent freshwater ice) including a change in vegetation composition, movement of the boreal forest away from the coast and the development of continuous permafrost. Currently, if the fresh water movement to James Bay were disrupted as a result of human development or even climate change, the opposite changes might be expected.

With increased temperatures and more saline waters there would be an earlier onset of spring melt and later freeze up in the fall. Current permafrost would thaw disrupting the landscape's stability and there would be a significant change in vegetation species to adapt to drier conditions and higher salinity along the coast. Therefore, because peatlands are the headwaters delivering fresh water to James Bay, understanding how they are hydrologically connected is important to determine the potential impacts development might have on the larger scale hydrology of the region.

Bogs and fens are the two dominant peatland types that make up the large peatland complex of the James Bay Lowland. Within the landscape bogs act as storage units, retaining large amounts of water in their pools and hollows (Quinton, 2003). However, when storage capacities are reached bogs are important for providing lateral and vertical discharge to adjacent fen systems. Fens are typically discharge zones and contribute to surface runoff by conveying water to local and regional stream networks (Quinton, 2003). Since bog and fen systems dominate the James Bay Lowland, and thus are responsible for providing regional fresh water, it is important to understand how these two systems interact and how they may be affected by hydrological changes brought on by increased development.

Regional climate is a driver for hydrological processes in all ecosystems. The dominant hydrologic fluxes in peatlands are evapotranspiration and precipitation which are driven by atmospheric conditions. Changing water tables caused by resource development or climate change could affect both the horizontal and vertical connectivity of these peatland systems. If water tables become low enough the vegetation may not be able to access required moisture contents and evapotranspiration rates may decline. It may also cause the peatlands to have a stronger connection with the regional groundwater, impacting the chemical balance within peatlands and suspended and dissolved sediment loads of streams, including the ability to regulate methyl mercury transport from peatlands to major rivers (Ulanowski, 2014). If water tables decline a large storage capacity is created thus reducing runoff response from both snowmelt and rainfall. This could have severe effects on the streams relying on runoff from peatlands to maintain necessary baseflows for biological communities.

This thesis was part of a larger NSERC CRD (Natural Science and Engineering Research Council, Collaborative Research and Development Grant) that aimed to study the hydrogeological linkages between the peatland and limestone aquifer that have been exposed to drainage as a result of mine dewatering. This thesis was conducted to meet some of the objectives of this large project and consists of two manuscripts. I was responsible for writing the first edition of both manuscripts which were aimed to meet the objectives set out in the original CRD plan. The first manuscript (Hydrological functions of a mine-impacted and natural peatland-dominated watershed, James Bay Lowland) assess the nature of changes caused by large-scale development, in particular mine dewatering, on the hydrology of a peatland watershed. More specifically it evaluates evapotranspiration, runoff, deep seepage and storage changes in bogs and fens over three years in the mine impacted area and at non-impacted reference sites. The second manuscript (Groundwater connectivity of bog and fen landscapes in a mine-impacted region, James Bay Lowland) aims to understand the connectivity between bog, fen and stream systems in a mine impacted environment.

2 Hydrological functions of a mine-impacted and natural peatland-dominated watershed, James Bay Lowland

2.1 Overview

The development of a large open-pit diamond mine in the James Bay Lowlands, one of the world's largest wetland complexes, provides insight into hydrological processes that sustain wetland processes in the region. The bog and fen peatlands that dominate the landscape have developed as a consequence of the low relief and low hydraulic conductivity of the underlying marine sediments that restrict percolation. The peatlands and marine sediments overlie permeable Silurian limestone into which the mine-pit extends. Percolation losses (between 2009 – 2011) from the peatlands have been enhanced due to depressurization of the limestone aquifer caused by mine dewatering, experiencing rates of up to 15 mm day^{-1}. This is more than an order of magnitude higher than rates measured at a nearby non-impacted site, representative of the pre-mining condition. Large percolation losses were also measured in fen systems, which are typically local discharge zones. Where water tables were lowered by enhanced percolation losses, evapotranspiration rates were also lower than non-impacted sites with average rates below 2 mm day^{-1}. Impacts of watershed runoff were masked by two consecutive dry seasons and the watershed headwaters being out of the cone of depression. With only 14.5% of the watershed impacted, the hydrological function of the entire watershed is more driven by seasonal climate variations than the mine dewatering.

2.2 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, 2004). This area is underlain by a deposit of fine-grained marine sediments with low hydraulic conductivity (Glaser et al., 2004), which along with the very low relief restricts drainage, thus contributing to high water tables and peat development. The Hudson Bay Lowland stores approximately 27 Gt of carbon (McLaughlin, J. & Webster, K., 2013), 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.

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 Study Site section) 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 to 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 *et al*, under revision) has 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.*, 2004). 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 flow path length may occur as the system becomes more strongly connected to the deep groundwater system through enhanced vertical seepage losses. This 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.

2.3 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 (N 52° 49’ 15” and W 83° 53’ 00”) near the De Beers Canada Victor Diamond Mine in Ontario, Canada (Figure 2-1). The landscape is dominated by peatlands (bogs and fens), peat thickness is generally between 1 and 3 m. The bogs in this area typically consist of a hummocky terrain dominated by *Sphagnum* spp., particularly *S. rubellum*, *S. magellanicum* and *S. 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 0-200 m thick, with no marine sediments present where bedrock outcrops 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 (Environment Canada, 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 (Environment Canada, 2014). 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 Methods section) 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 percent of the study area.

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 (Figure 2-1), 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, Figure 2-1) 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 Figure 2-1): 1) stream discharge (Tributary 5a); 2) groundwater fluxes (from 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 the methods sections and summarized in Table 2-1. Data were available for the entire study period at each non-impacted study site (20 May to 31 August for 2009, 2010, 2011) except where noted.

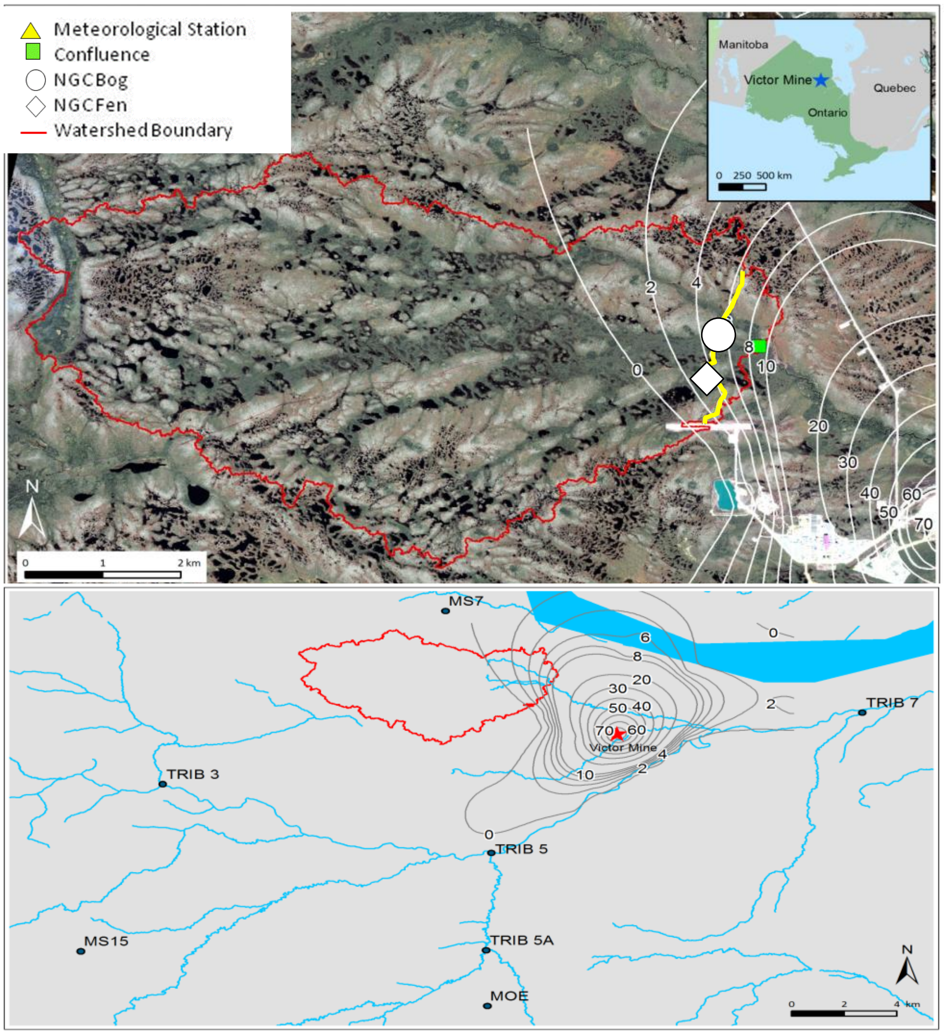


Figure 2-1 a) Location of the North Granny Creek watershed, outlined in red, relative to the mine site; the yellow line is the mine-impacted North Granny Creek study transect. The extent of the mine dewatering drawdown in the upper Attawapiskat bedrock formation as of 2011 is symbolized by the white 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.

Table 2-1– 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			Four nests located at MS15		
Storage	Δh from wells along NGC transect, Sy from cores along NGC transect			Δh from 4 nests at MS15, Sy from cores from NGC transect		
% of watershed	6.7	11.2	14.5	93.3	88.8	85.5

2.3.1 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 the 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 (Figure 2-2) 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 (Di Febo, 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.

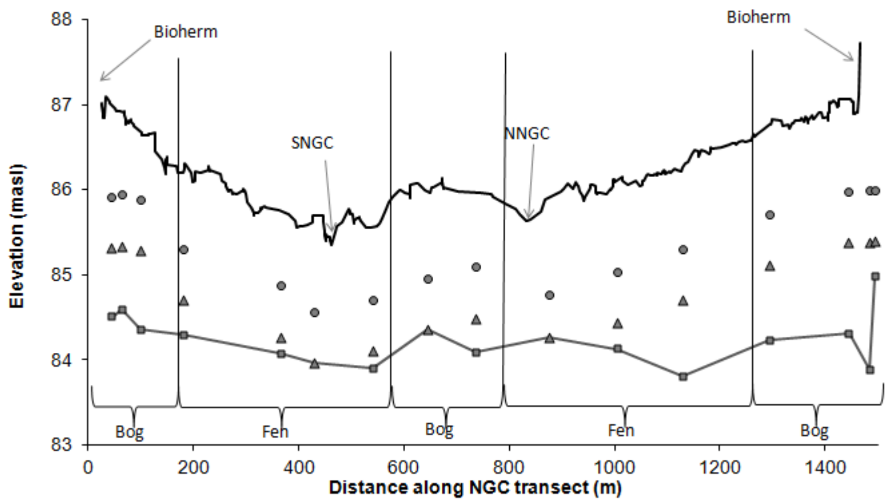


Figure 2-2 – Ground surface elevation of bogs and fens along the North Granny Creek study transect (black line, 8 point moving average of a DGPS elevation survey, with points taken every 4-5 m) and the bottom of the peat layer/start of marine sediments (grey line). The nest locations along the transect 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.

2.3.2 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 2 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 (Figure 2-1) 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 Figure 2-1, were compared by Richardson et al., 2012.

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 (Figure 2-1). 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.

2.4 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

$$\mathbf{P - ET - Q - Q_d + \Delta S = \xi} \quad , \qquad [2\text{-}1]$$

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; AMEC, 2011; AMEC, 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) was areally weighted. See Table 2-1.

A meteorological (MET) station installed in 2008 was located approximately 0.75 km from the confluence of the North Granny Creek watershed (Figure 2-1). The meteorological station consisted of a data logger outputting an average (or total, for precipitation) value every 10 minutes. 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.

2.4.1 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.

2.4.2 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,

$$\boldsymbol{ET} = \boldsymbol{\alpha} \frac{s}{s+\gamma} \frac{Q^{*} - Q_{g}}{L\rho} \quad , \qquad [2\text{-}2]$$

where ET is the evapotranspiration (mm d^{-1}), s is the slope of the saturation vapour pressure-temperature curve (kPa $^{o}C^{-1}$), γ is the psychrometric constant (0.0662 kPa $^{0}C^{-1}$ at 20^{o}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 vapourization (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 Equation 2-2 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 Table 2-2 & Table 2-3). Lysimeter data were only available for the 2010 and 2011 seasons, so 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

$$\boldsymbol{ET_{IM} = \sum_{i=1}^{4}(x_i A_i)\, t} \qquad [2\text{-}3]$$

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 vapour 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

$$\boldsymbol{ET_{NON-IM} = \frac{LE}{\lambda_{LE}\,\rho_w}} \qquad [2\text{-}4]$$

where LE is the latent heat flux (W m^{-2}), λ_{LE} is the latent heat of vapourization (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.

2.4.3 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 to 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 to 31 August time period.

2.4.4 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;

$$\boldsymbol{q = K \frac{dh}{dl}} \quad , \qquad [2\text{-}5]$$

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 equation [2-5], 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.

2.4.5 Storage

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

$$\boldsymbol{\Delta S = \Delta h S_y} \quad , \qquad [2\text{-}6]$$

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 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 above 50 cm below 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-hour period and weighed again to determine the proportion of water loss as a result of gravitational drainage. ΔS was areally 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.

2.5 Results

The De Beers Victor mine has been fully operational since January 2007; approximately 3.5 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 (Figure 2-1,Table 2-1). 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 (Figure 2-3). 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 2-1), all at the lower (eastern) end of the watershed.

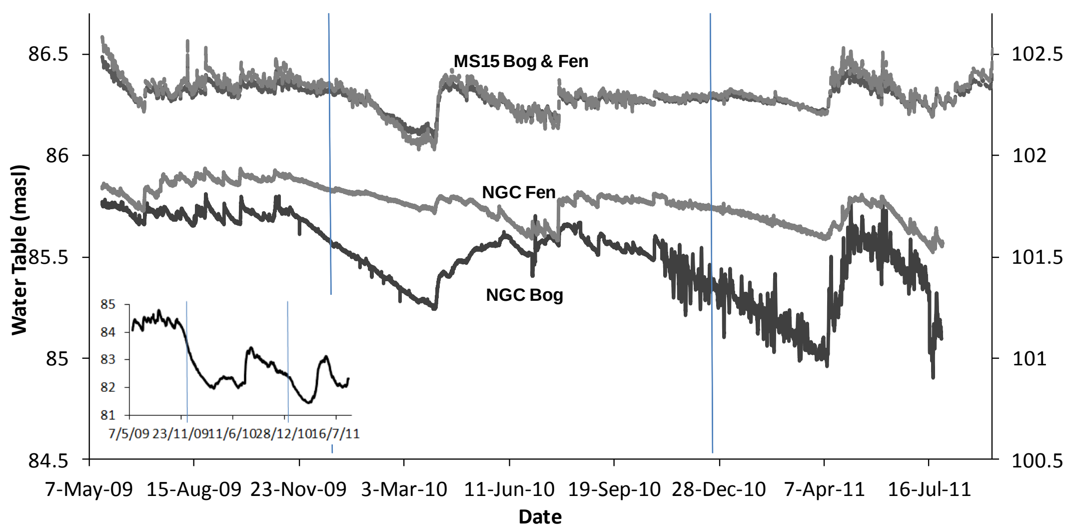


Figure 2-3- Long-term water tables in the mine-impacted North Granny Creek bog, fen and bedrock and at a bog and fen in the non-impacted MS15 site. The MS15 water levels are on a secondary y-axis for ease of viewing, but has the same scale as the primary y-axis (i.e, 2m). The inset shows the North Granny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

2.5.1 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 (Figure 2-4). The 30-year climate averages for the same time period at Lansdowne House and Moosonee were 309 and 266 mm, respectively (Environment Canada, 2010; Environment Canada, 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, 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.

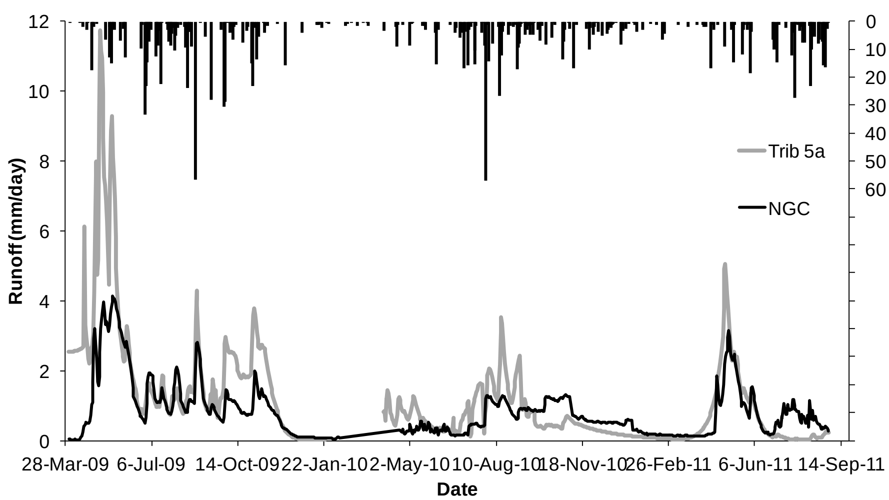


Figure 2-4– Long-term hydrographs for the non-impacted Tributary 5a and the mine-impacted North Granny Creek, with responses to precipitation events from mid-2009 to mid-2011.

2.5.2 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 2-2). 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 2-3). Given the relatively high evapotranspiration rate from moss surfaces and their dominance in bogs (i.e. *moss* plus *moss & lichen*), which occupy 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 2-3). 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 seasons.

Table 2-2– 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 2-3- 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 versus non-impacted, as indicated.

	NGC Transect				**MOE**				
	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)	**Proportion of Non-impacted Area** (%)	**Total Losses from NGC** (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**

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 (Figure 2-5). 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.

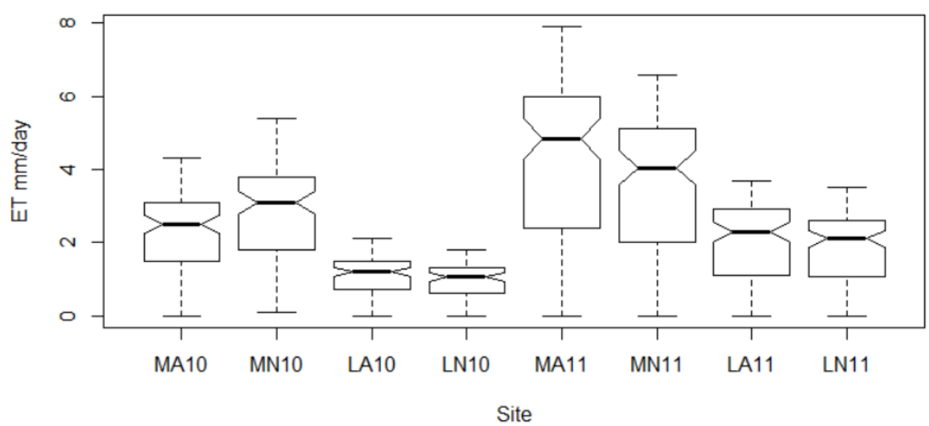


Figure 2-5- Box and whisker plots of evapotranspiration rates in moss (M) and lichen (L) landscapes, near (N) and away (A) from a bioherm for 2010 (10) and 2011 (11). The upper and lower whiskers are the maximum and minimum rates experienced. The notches in the middle of the boxes can be used to determine significance, where non-over lapping notches between data sets can be considered to have significant difference, as in the moss versus lichen landscapes.

2.5.3 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 (Figure 2-4), which represents

70 and 50% less runoff for 2010 and 2011, respectively (Table 2-4). 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 2-4). For 2009, 2010 and 2011 total runoff ratios were 0.51, 0.25, and 0.30, respectively (Table 2-5). In 2010 and 2011 when the area received less rainfall, the North Granny Creek experienced closer rates of runoff to the neighbouring non-impacted tributary (Figure 2-4).

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 2-4), but the hydrograph response was generally greater in the non-impacted watershed compared to the North Granny Creek (Figure 2-4). 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 2-5). By 2011 runoff ratios at the non-impacted tributary dropped to be 0.30 (Table 2-5), 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 to 31 August), post snowmelt, the North Granny Creek watershed experienced runoff of 179, 72 and 54 mm in 2009, 2010 and 2011, respectively.

Table 2-4– 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 ∆S			
	Bog	**-14**	**-5**	**1**
	Fen	**-17**	**-9**	**0**
	Open Water	**-68**	**-34**	**0**

Table 2-5 – 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

2.5.4 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 2-5). 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 2-4 and Figure 2-6). Within North Granny Creek the rate and variability of seepage loss in bogs increased between 2009 and 2011 (Figure 2-6); 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 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 2-4) (i.e., losses).

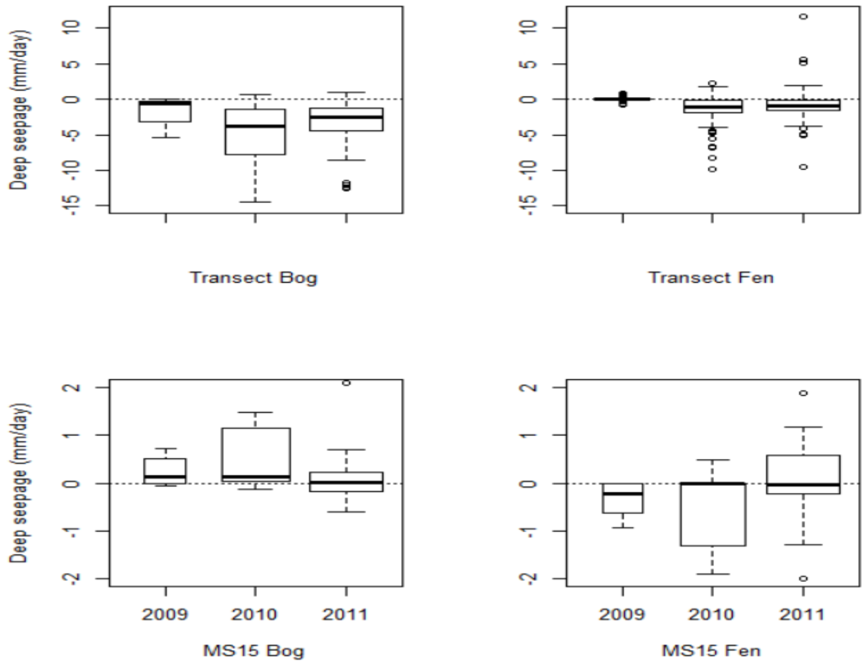


Figure 2-6– Deep seepage rates along the North Granny Creek Transect and MS15 transect for bog and fen for 2009, 2010 and 2011. Whiskers indicate maximums and minimums, dots represent outliers and box width are indicative of sample size (n). Note the different axis between the transect sites and the MS15 sites.

2.5.5 Change in Storage

Water storage change reflects the balance of inputs and outputs for a defined period, and is calculated from water table data (Figure 2-3) in a (peat) soil on the basis of its specific yield, Sy (Figure 2-7). 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 2-4. 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 2-4). 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 2-4).

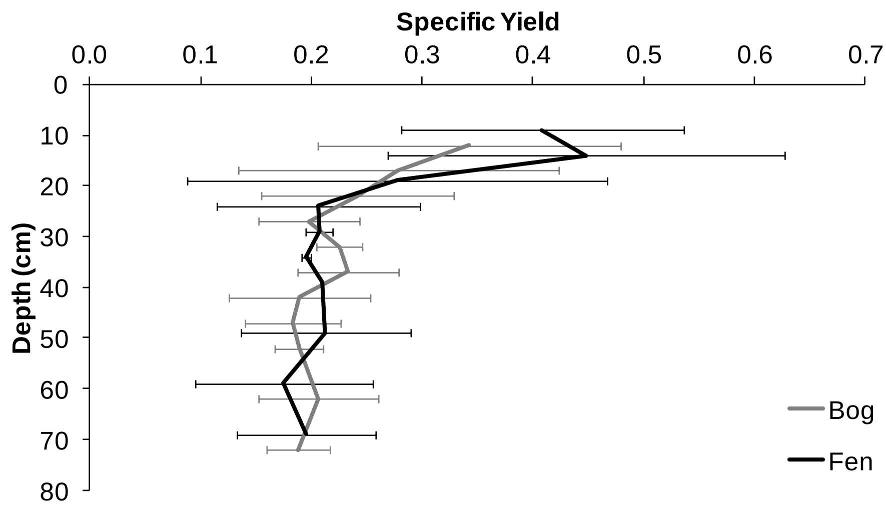


Figure 2-7– Average specific yield values with depth in bog versus fen landscapes in the NGC watershed. Bogs had average Sy of 0.22 (standard deviation of 0.05, n=58); in fens it was 0.25 (standard deviation of 0.1, n=32). Error bars are ± one standard deviation at each depth.

Total storage changes were weighted aerially 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 2-4).

2.6 Discussion

2.6.1 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 2-1). 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 2-3). We acknowledge that the difference between the North Granny Creek mine-impacted and the non-impacted MOE site is relatively small (Table 2-3), 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).

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. 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). 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 2-3); the fens never experienced water tables lower than 20 cm below the surface, and their more abundant vascular plant assemblage are less affected by water table drawdown (Admiral *et al.*, 2006). Furthermore, bogs experienced lower water tables and in some areas along the North Granny Creek mine-impacted transect, water tables 40-50 cm below the surface were observed in 2010 and 2011, respectively. Bogs were more likely to have a substantial lichen cover, and lichen decreased the evaporative water loss (Figure 2-4). The roles of lichen versus 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 near and away from the bioherm in 2010 and between moss and lichen in both years. Lichen evaporation rates were expected to be significantly lower than 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) did a study in the Hudson Bay Lowland on lichen canopy interception and found that in this climate during the summer months that only occasionally does precipitation find its way to the moss surface below the lichen in lichen dominated environments. 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 to 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 2-4*;* Figure 2-4). 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 is likely an indication of less water being detained in storage. This could be indicative of the North Granny Creek having a greater storage capacity as a result of mine dewatering, but it could also be due to watershed characteristics. The runoff ratios (Table 2-5) determined for the North Granny Creek over the three years dropped by half from 2009 to 2010 and 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, 2012; Roulet and Woo, 1988). The runoff ratios at the non-impacted tributary also experienced a large drop between the three study years (Table 2-5). 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 (Figure 2-1), 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 ten times higher than pre-mining rates of approximately 2.6 to 26 mm y^{-1}, as reported by HCI (2004). Recently Whittington and Price (2012) determined that deep seepage losses from this landscape vary between 2.1 mm day^{-1} for bog/near bioherm areas to 0.26 mm day^{-1} for fen/non-bioherm areas. They determined that these measured rates match well with the modelled 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 2-4 & Figure 2-6), albeit at a lower rate than in bogs. The higher percolation losses from bogs may reflect their higher position in the landscape (Figure 2-2).

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 2-4 & Figure 2-6). When the deep seepage losses from the mine-impacted North Granny Creek transect and non-impacted MS15 site are areally weighted for bog versus fen/open water and impacted versus 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 2-6). 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 (Figure 2-6). 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} (Figure 2-6). 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 (Figure 2-3). 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 2-4), 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.

2.6.2 Water Balance Error

Evaluating the water balance of a watershed can be used as a good measure of the health of the system, however the errors associated with estimating the different components of the water balance cannot be ignored. The following assesses the error associated with the methods used in this study to generate the water balance estimations.

The accuracy of tipping bucket rain gauges is approximately ±15% under ideal conditions (Price and Woo, 1988), but can also be affected by their location and orientation. In this study there was only one rain gauge used to represent an area over 30 km^2, this would not account for spatial variation in precipitation resulting from thunderstorms. If the orifice of the gauge is not protected the wind tends to generate aerodynamic anomalies at the orifice resulting in the underestimation of the precipitation (Ingram, 1983). The tipping bucket rain gauge in this study had the orifice shielded from the wind; however, it was in a very open and exposed area so aerodynamic influence still could have had some effect on the accuracy of the gauge.

Evapotranspiration is the most difficult part of the water balance to estimate and therefore using the Priestley-Taylor combination method has multiple potential sources of error. When using weighing lysimeters error can be introduced because the soil monolith becomes disconnected with the surrounding landscape environment. The lysimeter prevents rain from draining out the bottom of the lysimeter, so if not carefully monitored the lysimeter could have moisture contents not representative of the surrounding environment. In this study the moisture contents within the lysimeters were maintained as well as possible given the logistics of conducting research in such a large and remote study site. In addition to error with the lysimeters there are also several variables involved in the Priestley-Taylor equation such as the instrumental measurements for ground heat flux and net radiation. As Winter (1981) explained, the more values required to solve a model the more chance there is for error to occur.

When estimating runoff the most error arises as a result of irregular channel morphology. Inconsistent stream banks and bottoms can result turbulent eddies or missed flows, underestimating the total discharge through the stream. A flow meter was used in this study which has a velocity measurement error of ±1% (SonTek, 2015), when used under model conditions. Most of the error in estimating runoff arises from the use of a stage-discharge relationship to estimate flows at varying water table heights. The tributary 5a data and the 2009 and 2010 North Granny Creek data were provided from external sources so their error cannot be commented on. The 2011 runoff data for the North Granny Creek was estimated using a strong stage-discharge relationship with an R^2 value of 0.96.

Deep seepage in this study was estimated using Darcy's law in which several variables need to be calculated. Many of these variables are measured manually in the field, introducing the potential for measurement or instrumentation error. Hydraulic conductivity which was estimated using Hvorslev's method is an important part of estimating deep seepage. When conducting the bail tests for measuring hydraulic conductivity, readings must be taken manually presenting a chance for error especially if the recharge within the measurement well has a fast recovery. Several studies conducted on measuring hydraulic conductivity have shown that it has 50% error, but is usually closer to having a 100% error (Winter, 1981). This potential source of error would then be reflected in the estimates for deep seepage.

The last component of the water balance is the storage change over the season. The main source of error in the storage term is found when estimating the specific yield. The specific yield was estimated in the lab using cores taken from the study site. Sources of error can arise from core disturbance from the actual coring process, such as compaction of the peat and the cores can be disrupted during transport to the lab. Another difficult part of estimating the specific yield is the heterogeneity that is found in peatlands, the cores are taken in a few select locations but the specific yield in peatlands changes both with depth and microform.

Even though there are several chances to introduce error when estimating the different portions of the water balance it still remains one of the best ways to evaluate the hydrology within a watershed.

2.7 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 2-6). 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 weather. 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 overall effect of the mine on the regional water balance is very small.

Table 2-6– Components of the water balance measured between 20 May to 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
Qd	-11	-25	-9
ΔS	-26	-12	0.3
ξ	-22	-63	-25
error	-6	-25	-10

3 Groundwater connectivity of bog and fen landscapes in a mine impacted region, James Bay Lowland

3.1 Overview

The development of a large open-pit diamond mine in the James Bay Lowlands, one of the world's largest wetland complexes, provides insight into hydrological processes that sustain wetland processes in the region. The bogs, fen water-tracks and channel fen peatlands dominate the landscape and the connectivity of these systems is responsible for providing a large portion of the fresh water to James Bay. Mine dewatering caused depressurization of the underlying aquifer, thus enhancing vertical gradients in the overlying peatlands. The bogs and fens in the mine impacted region experienced average downward gradients of 0.09 and 0.04 in 2011, respectively. This is more than an order of magnitude higher than gradients measured at a nearby non-impacted site, representative of the pre-mining condition. In addition to larger gradients the bogs and fens also had water tables 20 and 17 cm further below the surface than the non-impacted site. Lower water tables in the bogs would result in less recharge being provided to the adjacent fen systems. This would have a larger impact on a fen water-track system which relied on the bogs for half of their discharge. The channel fen system relied on its non-impacted head waters to provide almost all of its recharge and received only about 1.5% of its discharge from the adjacent bog. The current area of impact is small relative to the size of the James Bay Lowland, but the changes are indicative of possible declining water tables in response to a warming climate, thus having a large impact on the connectivity of these bog-fen systems.

3.2 Introduction

Wetlands, mostly peatlands, cover more than 85% of the Hudson and James Bay Lowlands (JBL) (Riley, 2011). These peatland systems strongly influence runoff to river systems (Richardson et al., 2012), provide an important source of fresh water to the brackish James Bay (Rouse et al., 1992), and also control carbon cycling (Roulet, 2000) and nutrient transport (Reeve et al., 2001; Kirk and St. Louis, 2009). Despite these important roles, the connectivity between peatlands and fluvial systems is still poorly understood, particularly the groundwater exchanges in patterned peatlands. With the prospect of a warming climate and increased resource development (e.g., the ring of fire) in the north, it is important to understand how these peatlands will respond to these natural climactic and anthropogenic changes.

Bogs and fens are the two most common peatland types in the James Bay Lowland (Riley, 2011). Bog landscapes are typically raised above the surrounding land surface and only receive inputs from precipitation (NWWG, 1997). When bogs receive water they tend to hold onto it until capacities are reached and then discharge occurs to the surrounding landscapes (Quinton et al., 2004). Therefore, the discharge from a bog is controlled by the hydrological processes operating within it (Price and Maloney, 1994), and thus they provide a water storage function within the broader landscape. In contrast, fens are minerotrophic peatlands that receive inputs from surface and groundwater richer in dissolved minerals. Fens typically maintain higher water tables at or near the surface, which along with the telluric water inputs are able to produce a more consistent runoff regime (NWWG, 1997). While there are multiple types of fens in the James Bay Lowland and the water table position within the peat profile has a large effect on the lateral drainage, fens represent water conveyance networks within the landscape (Quinton et al., 2003).

Some fen landscapes do not have incised stream channels that readily move surface runoff; patterned peatlands such as those in the James Bay Lowland have more diffuse networks of fen water-tracks that act as preferential flow paths (Glaser et al., 2004). Fen water-track systems receive their inputs from the surrounding bog landscapes and pools up-gradient, many of which are located at the top of large domed bogs. These large domed bogs typically have a number of fen water-tracks cascading off of them, suggesting they have an important role on the hydrology of these systems (Glaser et al., 2004).

Patterned peatlands, including fen water-tracks are identified by a series of alternating sequences of parallel peat ridges and pools aligned perpendicular to the direction of flow (Price and Maloney, 1994). The runoff from these systems is strongly dependant on antecedent conditions, because the pools, which are separated by elevated peat ridges, have a large depressional storage capacity which must be full to efficiently pass water down-slope (Price and Maloney, 1994). Quinton and Roulet (1998) found that when inputs exceed the pool storage capacity, runoff occurs over and around the peat ridges, and when water tables recede the pools become disconnected and runoff ceases. Therefore, when peatlands are in a connected state, surface runoff is substantially greater than if in a drier, disconnected state. This is amplified during high water table conditions because peat near the surface (i.e., the acrotelm) has a high hydraulic conductivity, so the transmissivity is increased (Price and Maloney, 1994).

In addition to fen water-tracks, peatlands in the James Bay Lowland have channel fens in which small channels are incised into the peat layer that convey flow to the larger stream networks (Richardson et al., 2012). Thus, both fen water tracks and channel fens are essential for transmitting water to regional stream networks in landscapes where the majority of water discharging from the basin is derived from, and passing through peatlands.

In the James Bay Lowland there has recently been the development of a mine site operated by the De Beers Group of Companies. In early 2007 pumping of groundwater from the bedrock surrounding the open pit began, this is required to maintain conditions safe and efficient for mining operations. Consequently, the depressurization of the regional aquifer caused by mine dewatering is increasing the recharge from local peatlands (Whittington and Price, 2012, 2013) and lowering water tables potentially affecting groundwater discharge to fen systems. From studies already conducted in this area it is known that vertical ground water fluxes have increased by over an order of magnitude from pre-mining estimates in some areas (Whittington and Price, 2013). In addition to increased vertical fluxes it has been found that the bogs and fens within the mines impact radius are showing lower water tables and evapotranspiration rates. In particular the fens in the impacted regions are acting as discharge units as opposed to their natural function as recharge areas (Leclair et al., submitted).

Runoff rates in the sub-watershed in which the mine is located have not been significantly impacted by mine operations. This is due to the headwaters being upstream of the impacted area (Leclair et al. submitted), as well as the supplemental stream flow being provided from the Attawapiskat River as a condition of regulatory approvals for mine operations. In this area the streams and rivers are fed by runoff and ground water discharge from the surrounding peatlands. After snowmelt has occurred in the James Bay Lowland, runoff subsides substantially (Leclair et al., submitted). However, groundwater discharge from peatlands is still required to maintain base flows necessary for many ecological and biogeochemical processes. Therefore, it is important to understand the hydrological function and connectivity between bog-fen systems impacted by mine dewatering to better predict impacts of increased or future developments. Some of the processes associated with dry hydrological conditions such as those presented by mine dewatering can also provide insight into potential changes caused by a warmer climate. Therefore, the objectives of this study are to i) measure the groundwater connectivity between two bog and fen systems: a fen water-track, and the other a channel fen, in a mine impacted region and ii) evaluate how the hydrological processes in these systems operate under mine impacted conditions.

3.3 Study Site

The study sites are located in the James Bay Lowland approximately 90 km west of the community of Attawapiskat in the vicinity of the DeBeers Victor mine (N 52° 49’ 15” and W 83° 53’ 00”) (Figure 3-1). The two study sites are located within the North Granny Creek sub-watershed (34 km^2), whose outfall lies approximately 3 km from the open pit of the De Beers Victor Mine. The two areas of focus consist of different types of bog-fen transition landscapes that discharge into the North Granny Creek stream system. One is a fen water-track system (FWT) draining a large domed bog area, located approximately 500 m north west of the outlet of the North Granny Creek watershed. (Note that the supplemental water line noted in the introduction used to sustain low flows, as required by regulatory approvals, is below the outlet where flow was measured and did not impact our study areas.) The second area is a bog-fen transect (BFT) located approximately 2.5 km west of the North Granny Creek outlet, that characterizes the connection between a bog on the interfluve to the adjacent channel fen that connects to the stream network. The two sites are very different in structure, size and organization, but occur commonly in the JBL peatland complex. The drainage boundaries for FWT (Richardson, M. 2010, unpublished), BFT (Bouffard, J., 2011) and North Granny Creek were derived from LiDAR DEM data (see Di Febo et al., 2015).

Across both sites the bogs typically consist of a hummocky terrain dominated by *Sphagnum spp.*, particularly *S. rubellum*, *S. magellanicum* and *S. fuscum*. Other species within the bog include Black spruce (*Picea mariana*), Leatherleaf (*Chamaedaphne calyculata*), Labrador tea (*Rhododendron groenlandicum*) and Caribou lichen (*Cladina stellaris*). The vegetation cover of the fen is mainly sedges (*Carex spp.*) and cotton grass (*Eriophorum spissum*), but also has a significant amount of *S. Rubellum* and *S. Fuscum*.

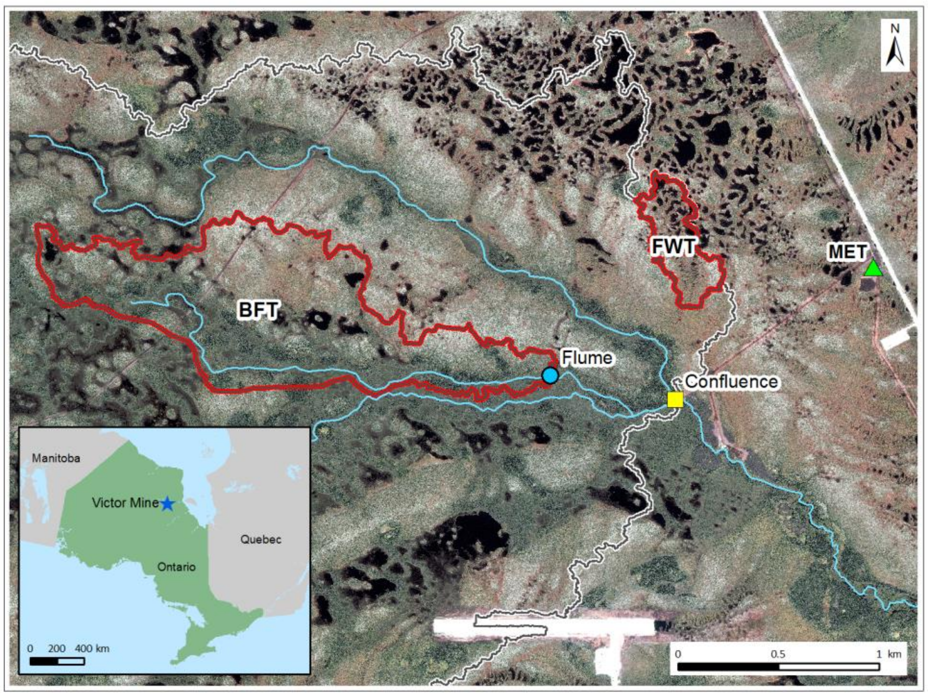


Figure 3-1- the FWT and BFT catchments relative to one another (both shown with red catchment boundaries), the white outline is the catchment boundary of the larger North Granny Creek watershed which discharges where the streams meet at the confluence location indicated by the yellow square. The meteorological station used to collect precipitation data for this study is also shown in the figure relative to the two study catchments (green triangle). The active mine site is approximately 4 km south-east of the study sites. The inset map shows the location of the study sites within northern Ontario, Canada.

The study sites are characterized by a subarctic climate; the region experiences cold harsh winters and fairly short mild summers. The closest long-term climate stations are Lansdowne

House, approximately 250 km west-southwest and Moosonee, approximately 250 km southeast of the study site. Lansdowne House has an average (1971-2000 were used as 1981-2010 climate normal were not available) annual temperature of -1.3°C, ranging from -22.3°C in January to 17.2°C in July, with annual precipitation of 700 mm, ~30% falling as snow (Environment Canada, 2010). Moosonee has an average (1981-2010) annual temperature of -0.5 °C ranging from an average of -20 °C in January to 15.8 °C in July, with annual precipitation of 704 mm, ~31% falling as snow (Environment Canada, 2014).

3.3.1 Fen water-track (FWT)

The catchment feeding FWT (Figure 3-2) is approximately 0.135 km^2, the boundary was determined based on surface elevations from a LiDAR derived DEM with a 4.5 cm vertical accuracy interpreted from a 1 m grid resolution (Richardson, M. 2010, unpublished). Instrumentation locations within the FWT are identified by cardinal direction; for example NWF refers to the north-west-fen station. The FWT consists of two water-track arms (NWF to SSF and NEF to SSF) draining off a large domed bog, and come together at SSF (south-south fen) to form a single water-track (ridge-pool sequence). The SSF location is where discharge was calculated as it is close to where the FWT drains into the North Granny Creek channel. The water-track is constrained by a raised bog on the east (NEB, SEB) and west (NWB, SWB). The FWT system consists of a pool-ridge sequence that runs perpendicular to the direction of flow. The peat ridges consist of firm peat that rises about 0.20-0.30 m above the surrounding surface, with an average peat thickness of 2.2 m overlying fine-grained sediments of low hydraulic conductivity (Whittington and Price, 2012). The pools that lie between the peat ridges are depressions with loose-structured peat below the water surface, having an average thickness of about 1.95 m to marine sediments, approximately 1 m of which is loose peat and the remaining depth is decomposed peat with a lower hydraulic conductivity. In both east and west fen water-tracks the pools and ridges are larger in area in the upper reaches of the systems (up to ~25 m^2) and gradually decline in size and depth towards the outlet (as small as 1 m^2). This pattern of diminishing pool size down-gradient is typical of other fen water-track systems in the area that drain domed bogs.

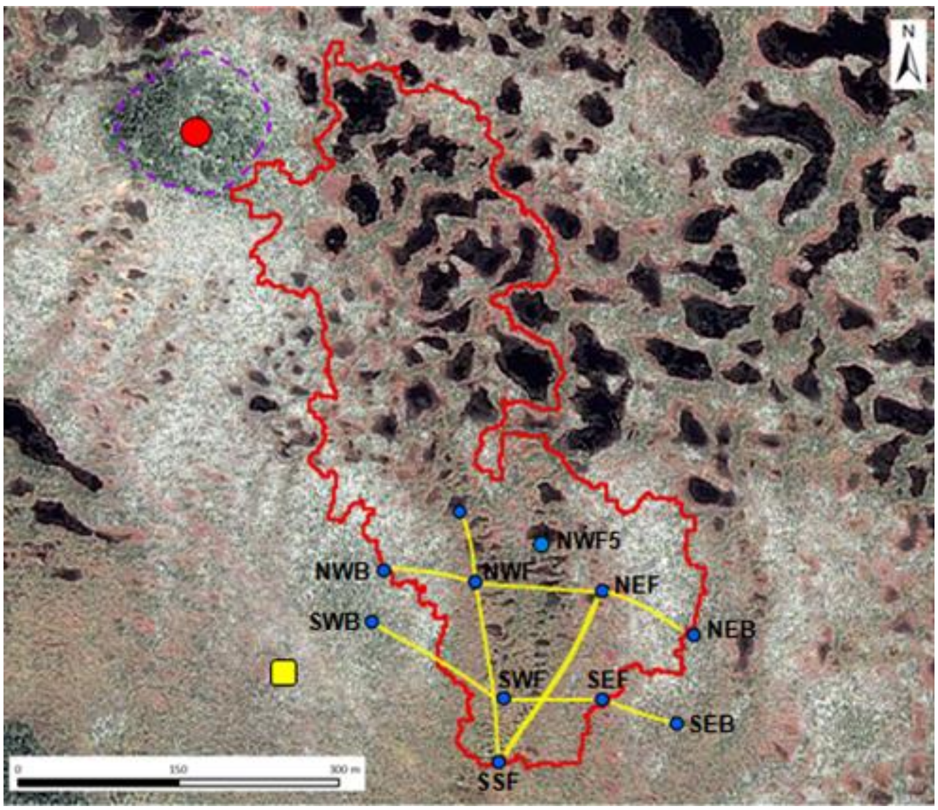


Figure 3-2 - the FWT catchment showing the contributing raised bogs (to the east and west), the domed bog (to the north) and the fen water-track conveying discharge. The blue circles represent the nest locations within the study site and the yellow lines within the red catchment zone are the transects along which longitudinal fluxes were calculated. The SSF nest was used as the discharge point for the FWT catchment. The north bioherm where the bedrock well was installed is shown in the north-west corner of the image (circle) and the square is the location of the long-term peat monitoring well (MS-8-F). The lighter areas to the east and west indicate the bog landscapes and the darker pathways with pool sequences are the water tracks.

To estimate flows within this system four transects were created, each anchored by a piezometer nest (Figure 3-2). Two transects were established running north-south along each of the water-track arms. Two more transects run east-west, traversing from the west bog, over the fen to the east bog (Figure 3-2). For simplicity the four transects are titled, north, south (each running west to east), east and west (each running north to south) according to their respective positions (Figure 3-2). Following the watershed delineation it was noticed that parts of the adjacent bogs (SWB and SEB) were outside FWT's watershed, thus were not used for flow calculations contributing to the water-track system. Single wells also located in the marginal zones between the bog and fen nests (not shown in Figure 3-2) were used for plotting the water tables.

Located about 200 m west of the FWT site was a long-term monitoring well, MS-8-F that was installed in the peat layer (Figure 3-2). This well was used by De Beers to monitor the long-term water tables in the bog it is installed in. Also located just north-west of the FWT in the north bioherm there was another long-term monitoring well installed in the upper Attawapiskat bedrock aquifer (Figure 3-2).

3.3.2 Bog-fen transect (BFT)

At the BFT there was one transect of piezometer nests running from a channel fen to the top of a domed bog. Nests are named with their approximate distance (metres) from the channel fen, with the nest approximately in the middle of the channel being +0. The domed bog is about 1 km^2, half of which is draining south into the channel fen catchment, LiDAR analysis of DEM indicated the drainage area is approximately 1.2 km^2 (Figure 3-3 *inset*). The fen channel is 20 m wide (at the BFT transect) but during the summer the majority of the flow runs through a preferential channel that is ~ 15-20 cm wide and about 30 cm deep. Approximately 100 m down gradient of the transect, within the channel fen a wooden flume was installed to channelize flow so discharge could be measured. The wings on the flume extended across the zone where surface flow was observed in an attempt to catch surface and near-surface flow. This channel has an average peat thickness of 120 cm; it consists of a buoyant, compressible fibric peat layer in which some sections may have floated during periods of high water table, but near the flume was continuous to the underlying mineral layer. The transition area from fen to bog has an average peat thickness of about 180 cm and the top of the bog has an average peat thickness of 210 cm. The watershed boundaries were developed based on a DEM derived from LiDAR imagery as described above, and by assuming the DEM fairly represents the underlying water table. However, where gradients are gentle this may not always be so. This is true for the BFT shown in Figure 3-3 where the nest on top of the bog (nest +185) is shown as being outside of the watershed boundaries, but water table and piezometer data suggests the majority of the flow from that nest profile still reports to the fen channel (Figure 3-4).

3.3.3 MS15

A remote site, MS15 (Muskeg Sampling location 15), located approximately 25 km south-west of the mine site, out of the mine's impact zone was used as a comparison site for water tables and hydraulic gradients. The MS15 site consisted of one transect of wells and piezometers crossing a bog landscape transitioning into a fen landscape (see Chapter 2, Figure 2-1). The bog and fen landscapes had similar vegetation to the other two study sites.

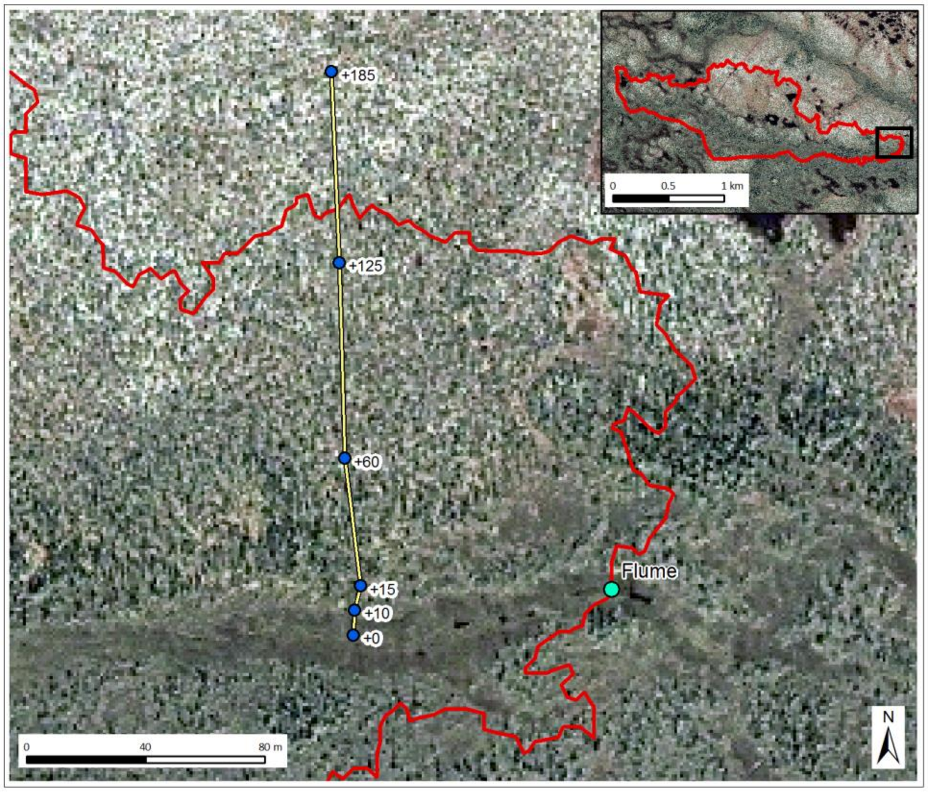


Figure 3-3 the bog-fen transect nest locations running from the channel fen up to the top of the domed bog. Also shown is the location of the flume, which is the discharge point for this catchment. The inset shows the transect relative to the entire catchment.

3.4 Methods

Hydrological data were collected from May to August in 2010 and 2011 at FWT and MS15 and only in 2011 at BFT.

3.4.1 Micrometeorological and frost table data

A Meteorological (MET) station was located approximately 0.75 km from the FWT site (Figure 3-1). Precipitation was measured automatically using a tipping bucket rain gauge and the ambient air temperature was measured using a copper-constantan thermocouple in a shielded well ventilated box. Frost table depth was measured using an incremented steel rod that was inserted into the peat layer until it encountered the frost table; this was performed in ten random locations around each nest to establish average depth to frost. Frost table thickness was estimated by hammering the steel rod through the frost layer; the bottom of the frost layer was measured when resistance on the rod was lost. Care was taken to take frequent measurements so that when the resistance was lost and the rod moved quickly, an accurate estimate of the frost depth could still be obtained. Occasionally, the first measurement location was discarded so that the approximate depth could be obtained for subsequent measurements. This was performed at each nest once a week during the spring season.

3.4.2 Groundwater data

De Beers had two long-term monitoring wells (MS-8-F in a bog and in the upper Attawapiskat bedrock formation) located in the vicinity of the FWT site, both of which had been recording the water table elevation since the beginning of mine operations. There was also a data logger installed in SSF at the FWT from August 2010 to August 2011, these data were used to develop a relationship (R^2=0.71) with the data at MS-8-F to provide a long-term water table record within a fen landscape. Both the FWT and the BFT had nests consisting of 1 well and 4 piezometers constructed of 2.54 cm i.d. PVC pipes (wells fully slotted, piezometers slotted at depths of 30, 50, 90 and 150 cm below ground surface at the FWT site; and 50, 90, 150 cm below the surface and one at the peat-mineral sediment interface at the BFT site). Piezometers at 30 and 50 cm depths in the FWT had a 15 cm slotted intake and the remaining piezometers at both sites had a 30 cm slotted intake. All piezometers were installed using a hand auger and surveyed using a DGPS to determine pipe top elevations. The DGPS unit was set to have a precision of 0.003 m vertically and 0.005 m horizontally, and the instrument would not record a value unless these standards were met.

Wells and piezometers at both sites were measured weekly each season for water table levels and hydraulic head. Hydraulic conductivity, K (cm d^{-1}), was determined from field bail tests in all pipes using the Hvorslev (1951) method. These hydraulic conductivity tests were conducted weekly on the wells, 30 and 50 cm piezometers, at the FWT site and twice over the season on all the remaining piezometers at the FWT site and all pipes at the BFT site. Bail tests were conducted weekly in 21 wells installed throughout the study site in both bog and fen landscapes to evaluate the transmissivity at varying water table elevations. For wells and piezometers that recovered too quickly to be measured manually, recovery was logged with a pressure transducer.

The vertical gradient, *dh/dl*, was determined at each nest in both study sites, where *dh* is the change in hydraulic head and *dl* is the change in length between the two measuring points across the profile. The longitudinal water flux was determined using a variation of Darcy's Law (Equation 3-1), applied across the cross-sectional flow area such that

$$Q = T \frac{dh}{dl} L \quad , \qquad [3\text{-}1]$$

where Q is the lateral discharge, T is the transmissivity (the saturated thickness multiplied by hydraulic conductivity, K), *dh/dl* is the gradient, and L is the length of the longitudinal flow area. Hydraulic conductivity, was determined at well nests on different dates, where the position of the water table affected the saturated length of the well intake, hence the measured value of K. The K for the deeper peat layers was determined in piezometers and measured only twice over the season. At the FWT site the total discharge leaving the system was found by calculating the longitudinal flux for both water-track arms (east and west) of the fen system (Figure 3-2). The flux was calculated between the NWF (north-west fen) nest and the SSF nest for flow through the west arm, and then the NEF (north-east fen) and SSF nests for flow through the east arm. Flow was calculated in two layers, which included 1) the top metre of the peat profile; and 2) the remaining peat layer, below one metre. Different rates of flow were determined for the top layer (saturated depth) based on its transmissivity as governed by the fluctuating weekly water table data. The longitudinal flux through the bottom layer of the profile was found using the horizontal gradients between the 150 cm piezometers, and the average layer thickness and breadth of the saturated flow face. Using the weekly estimates of discharge based on Darcy's Law, and the continuous record of water table at SSF, measured using a pressure transducer, a stage-discharge relationship was established for both the top and bottom peat layers to provide continuous discharge data over the entire season from the FWT system.

A similar approach was taken when calculating the inflow from the adjacent bogs into the fen water-tracks. The gradients were calculated between NWB (north-west bog) and NWF (north-west fen), and NEB (north-east bog) and NEF (north-east fen) and applied to both the east and west bogs margins flowing into the water tracks. Stage-discharge relationships were also established using the pressure transducer installed in the NWF5 (north-west fen 5, Figure 3-2) well, located along the north transect in the middle of the bog-fen-bog transition. All areas and lengths used for calculating the fluxes were measured in ArcGIS using an IKONOS image within the watershed boundaries.

At the BFT site the longitudinal flux was calculated in a similar manner, using Equation 3-1. The gradient from the top of the domed bog was calculated between the nest at the top of the bog (+185) and the nest in the channel fen (+0) in four different layers of the profile (Figure 3-4). The fluxes in each layer were calculated using hydraulic data measured from a piezometer installed at the mid-point of each layer. The longitudinal flux determined from this transect was applied to the entire length of the domed bog adjacent to the channel fen (Figure 3-3), based on the surface gradients across that section of bog, as measured using the DEM (DiFebo, 2011). The cross-sectional area used to calculate flow from the domed bog towards the channel fen was determined from the saturated flow-face calculated from the bog's total length and average peat thickness.

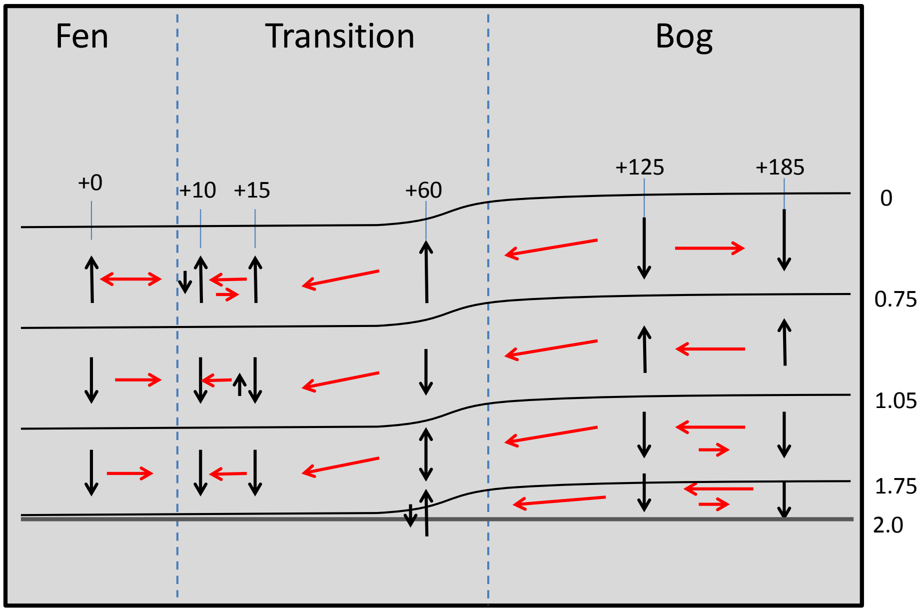


Figure 3-4 - a cross-sectional view of the different piezometer installation layers along the BFT, from the fen channel (left) to the top of the bog (right). The cross-section is divided based on piezometer installations which are slotted across each layer displayed, with the exception of the top layer which is only slotted from 0.35-0.65 m. Results are indicated by the black arrows indicative of vertical gradient direction (arrow size represents the relative magnitude), red arrows have the same meaning only in the lateral direction. Note the image is not to scale.

The MS15 site consisted of one 150 m long transect traversing across a bog and fen landscape. There were two nests installed in the bog and two nets in the fen, each nest consisted of piezometers installed at 90 and 150 cm below the surface and one at the peat-marine sediment interface, all with 30 cm slotted intakes, similar to the other study sites. Since this site was outside the mine's impact radius, vertical gradients were shown to be minimal (Leclair et al., submitted) so no wells were installed. The 90 cm piezometer water elevations were assumed to be the standing water table.

3.4.3 Runoff

Stream flow was measured in the North Granny Creek at the confluence of the two North Granny Creek stream channels in the watershed (Figure 3-1). Discharge at the BFT was measured using a flume box that was channeling flow from across a large portion of the channel fen in the BFT (Figure 3-3). Both the North Granny Creek and BFT flows were measured using a flow meter, on a weekly basis. These flow measurements were then used to develop stage-discharge relationships using stage measurements that were being recorded every half-hour from a pressure transducer within a stilling well located directly in the North Granny Creek stream channel and in the BFT fen channel.

3.5 Results

Both 2010 and 2011 had similar temperature trends during the study periods (20 May- 31 August) with average temperatures of 14.6 and 13.7 °C, respectively. Compared to long-term averages from nearby stations both study years were slightly drier than normal. The 2010 season was preceded by a small to negligible snowpack relative to 2011 (Whittington et al. 2012). Water tables gradually declined over the winter months in both the bog and bedrock layers and only slightly in the fen (Figure 3-5). Every year in the spring water tables rebound as a result of snowmelt, recovering completely in the bog and fen but incompletely in the depressurized bedrock aquifer below. In the three spring seasons shown in Figure 3-5 the peak hydrograph response in the bog and fen appears to happen earlier each year with peaks on May 29, May 18 and May 3, for 2009, 2010 and 2011, respectively. Each year the water tables also appear to decline earlier in the fall. Over the 2010-2011 winter the frost table developed to a thickness of about 25 cm in the fens and 15 cm in the bogs. In the spring the fens and hollows thawed first around mid-May and the hummocks remained frozen into June.

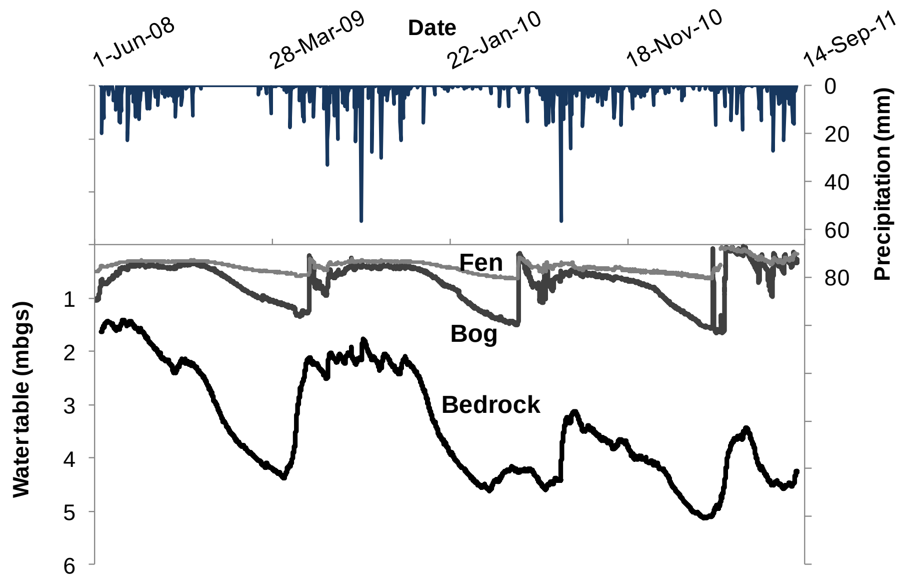


Figure 3-5- the long-term water tables below the surface in a well installed in the peat layer (MS-8-F) in a bog near the FWT site (dark grey line), in SSF in the FWT (light grey line) and in a well installed in the bedrock of the north bioherm (black line).

3.5.1 Vertical Gradients

The vertical gradients at the FWT site were measured in both 2010 and 2011. Within the bog landscapes there was an increase from -0.07 to -0.09 in the bog's average downward gradient from 2010 to 2011 (Table 3-1). The bogs had a higher vertical gradient than the fens, which also showed an increase from -0.01 to -0.04 in the average gradient in 2010 and 2011 (Table 3-1). Gradients measured at the FWT site are an order of magnitude larger than those measured at the MS15 non-impacted site for both bog and fen landscapes (Table 3-1).

Table 3-1 - seasonal average vertical gradients in the FWT, BFT and the non-impacted MS15 nests. The gradients shown are average gradients across the entire peat profile, measured using the deepest installed piezometer and the water table. Negative values represent downward gradients and '*' are indicative of fen/transition nests. The standard deviation for each year in the landscape types, as well as sample size is also shown.

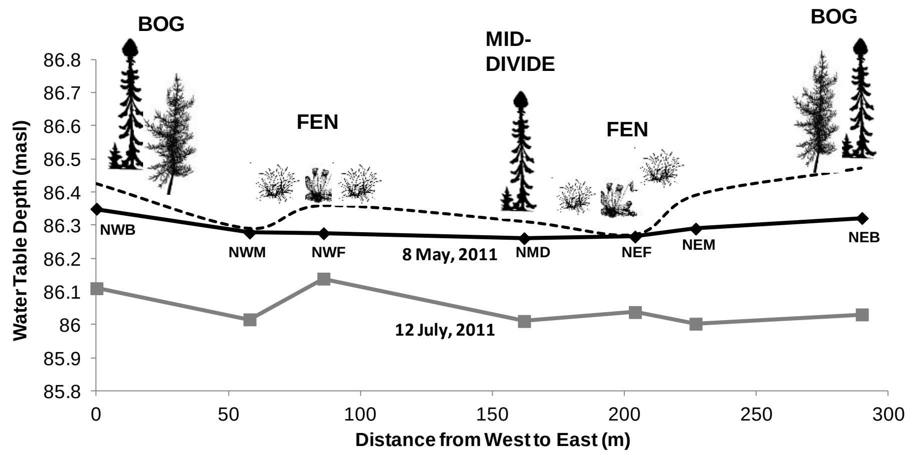
FWT	2010	2011	BFT	2011	MS15	2010	2011
SSF	-0.01	-0.02	**+0***	-0.01	**+25**	0.006	0.007
NEF	-0.01	-0.05	**+10***	-0.06	**+40**	0.000	-0.007
NWF	-0.02	-0.04	**+15***	-0.01	**+80***	-0.005	-0.004
NWB	-0.07	-0.10	**+60***	0.00	**+150***	-0.012	0.001
NEB	-0.07	-0.09	**+125**	-0.06			
			+185	-0.15			
Average Bog	-0.07	-0.09		-0.07		0.003	0.000
Average Fen	-0.01	-0.04		-0.03		-0.009	-0.002
SD Bog	0.020	0.051		0.07		0.004	0.019
SD Fen	0.021	0.029		0.03		0.007	0.006
n Bog	14	41		48		16	20
n Fen	19	60		48		16	20

At the BFT site data were only available for the 2011 field season. The average vertical hydraulic gradient in the bog for the season was -0.07 (Table 3-1), whereas in the fen the average seasonal vertical gradient was -0.03, similar to the gradients measured in the FWT site. The gradients at the BFT site were also an order of magnitude higher than the non-impacted site. At the BFT the vertical gradients were not consistently downwards (Figure 3-4). In contrast, there were more likely to be layers in the transition zone where upward gradients occurred. Horizontal gradients consistently directed from the bog to the transition zone. Horizontal gradients between the transition zone and the fen were also not consistently in one direction.

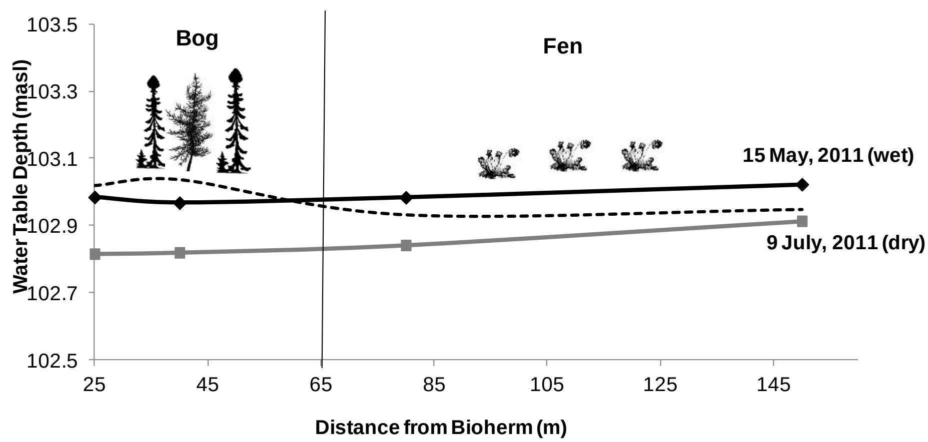
3.5.2 Water Tables

At the FWT site the bog and fen water tables had a range of ~ 20 cm from wet (May 8, 2011) to dry (July 12, 2011) periods (Figure 3-6a). In the spring when snowmelt associated runoff was occurring water tables were above the surface in the water tracks and close to the surface in the bogs. During wet periods the fens (NEF & NWF) had an average water table of 3 cm below the surface and the bogs (NWB & NEB) have an average water table of 7 cm below the surface (Figure 3-6a). At its driest the NWF water table descended to 23 cm below the surface and the NEB to 44 cm below the surface (Figure 3-6a), both of which are 23 and 17 cm lower than the water tables observed at the MS15 site over the season, for bog and fen, respectively (Figure 3-6a,b). The MS15 site had average water tables of +6 cm in the fen and 5 cm below the surface in the bog during the wet period and average water tables of 6 and 21 cm below the surface for the dry period in the fen and bog, respectively (Figure 3-6b).

a)



b)



c)

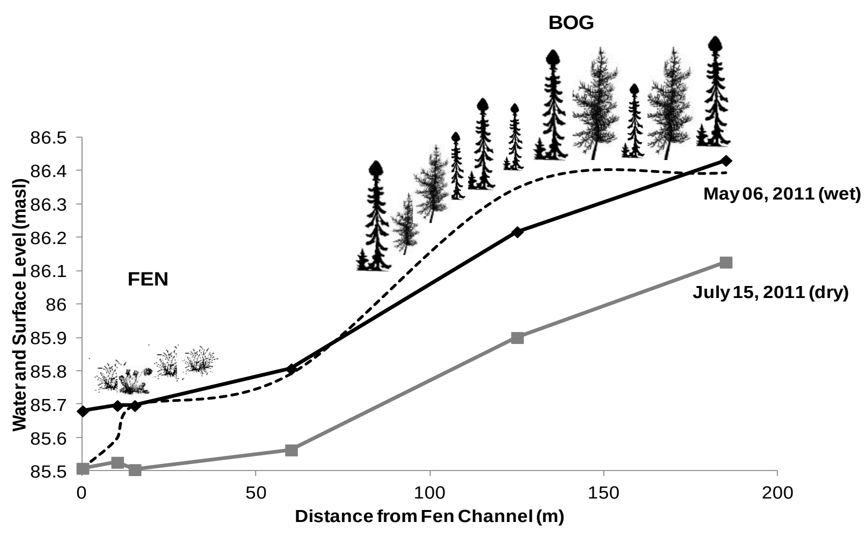


Figure 3-6 - a) water tables across the north transect of the FWT during the wet (May 8) and dry (July 5) periods. This transect transitions from bog to fen across the mid divide, then back to fen and bog; b) water tables within the MS15 site during wet (15 May) and dry (9 July) periods. This transect transitions from bog to fen; and c) the water tables at the BFT during wet (May 3) and dry (July 15) periods. This landscape transitions from a channel fen to bog, the dashed line indicates the ground surface in all three figures.

In the spring the BFT site experienced similar water table levels to those at the MS15 site (Figure 3-7) with average levels of +13 cm and 6 cm below the surface for the fen and bog, respectively (Figure 3-6c). The water table is above the surface witnin the fen channel as well as towards the edge of the channel. During drier conditions the water tables dropped below the levels measured at the MS15 site to a maximum of 18 cm in the fen and 45 cm in the bog, similar to maximum depths measured at the FWT site.

3.5.3 Longitudinal Connectivity

The longitudinal connectivity was evaluated using the changing transmissivity (T) of the top layer of the peat profile, on the basis of the water table fluctuations that occurred over the season (see Equation 3-1). The changes in T with water table in the bog and fen landscapes, that were used to determine longitudinal flow, are shown in Figure 3-8. The bog and fen values generally follow a trend of decreasing transmissivity with decreasing water table depth below the surface. The relationship between T and water table is weaker for the fen than in the bogs. The higher water tables in the fen resulted in a higher transmissivity for most of the period.

The water track in the FWT site was found to have a longitudinal gradient of 0.002. When the water table was close to the surface the longitudinal transmissivity was high (Figure 3-8). However, since measurements began after the majority of snowmelt runoff had subsided, the total longitudinal discharge recorded during this study period was small, with discharges of 38 and 42 m^3 in 2010 and 2011 (Figure 3-9), respectively, compared to total discharge out of the North Granny Creek watershed. FWT discharges are equivalent to 0.28 and 0.31 mm, over the 2010 and 2011 study periods, respectively. This contributes to less than 1% of the total discharge from the North Granny Creek watershed. When evaluating the connectivity between the fen and neighbouring bog landscapes, both bogs (east and west) collectively contributed around 45 & 43% (17 and 18 m^3) of the total FWT discharge for the 2010 and 2011 field seasons, respectively (Figure 3-9). In addition to the adjacent bogs, the flow in the fen itself was supplied from the pools to the north (up-gradient) of the water tracks, along with direct precipitation.

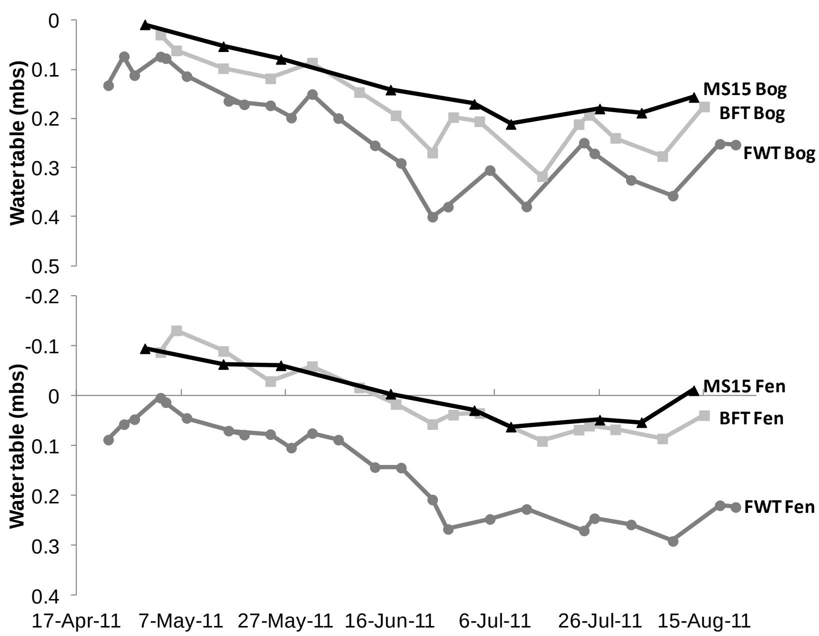


Figure 3-7 –a) average water table levels below the surface in the bog and b) fen landscapes in the two study sites (FWT and BFT) and the non-impacted site (MS15).

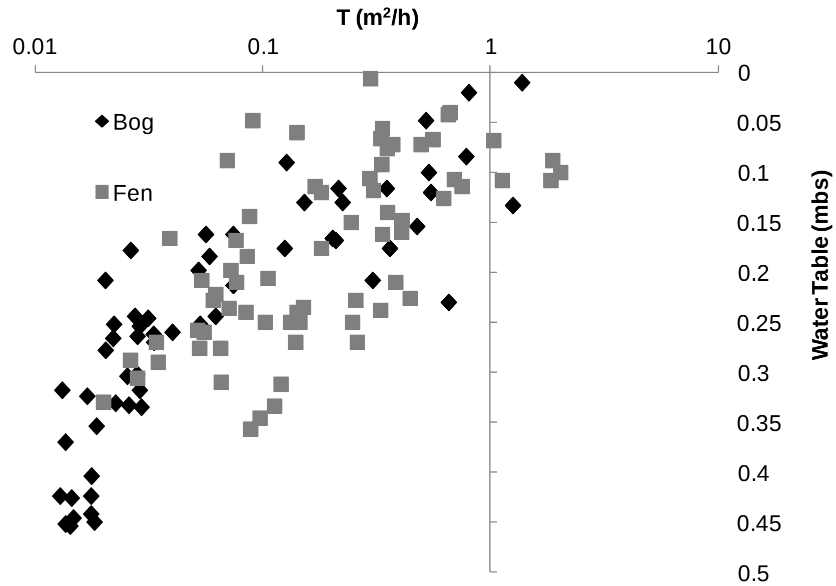


Figure 3-8 – transmissivity at the FWT in the peat profile in bog and fen landscapes at different water table depths.

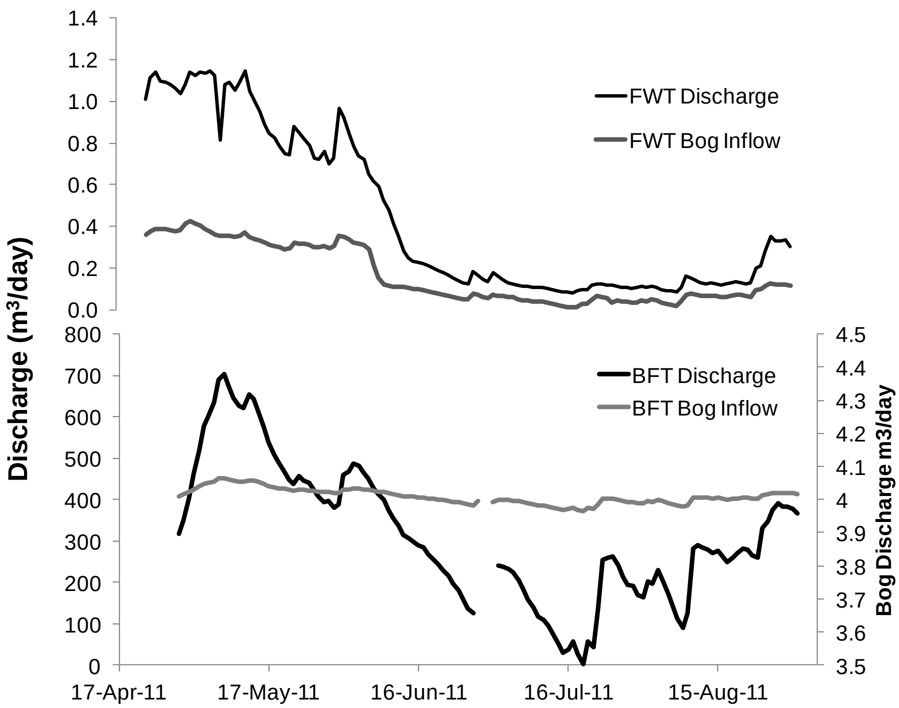


Figure 3-9 – ground water discharge from a) the FWT catchment (black line) during the 2011 season, and the inflow contributions from the surrounding bogs (grey line) and b) the surface runoff from the BFT catchment measured at the flume (black line), and bog inflow at BFT site (grey line); plotted on the second y-axis.

At the BFT site the total discharge in 2011 through the flume was found to be 27 300 m^3 over the entire study period (22.8 mm), the majority of the flow coming off of the domed bog and through the channel fen were captured in this flow (Figure 3-9). Flow data from this system were also restricted for the period following snow melt because during spring melt water went around the sides of the flume, so discharge measurements were unreliable. The domed bog that runs parallel to the fen channel contributed a total of only 410 m^3 (0.34 mm) over the same time period, which is approximately 1.5% of the total discharge that went through the flume. The discharge through the flume from the channel fen contributed from <1-7 % of the total flow discharging from the North Granny Creek watershed at any given time.

3.5.4 Runoff

Over the study season for both years there were 259 mm and 255 mm of rain resulting in 72 mm and 54 mm of runoff from North Granny Creek watershed for 2010 and 2011, respectively. All flows from the FWT and BFT watersheds discharged into the north and south NGC channels. Throughout the summer study season the two sub-catchments supplied from <1-7% of the water discharging through to NGC at the confluence, providing a small contribution to flow.

3.6 Discussion

The dewatering of the De Beers Victor mine has created a cone of depression that radiates out from the open pit. This drawdown provided the circumstance to evaluate how the hydrological connection between bogs and fens function under drier conditions as a result of mine dewatering. As the mine's dewatering continues, the cone of depression extends further into the North Granny Creek watershed; as of 2011 only 14.5 % of the NGC watershed was considered impacted by mine drawdown (Leclair et al., submitted). Figure 3-5 shows an example of the declining average water table in the underlying bedrock aquifer since early mine operations.

After the frost table developed in early winter, the underlying peat and bedrock continued to lose water as a result of mine dewatering; this caused water tables to continuously decline over the winter months. Following the winter months the long term implications of drawdown is shown in the bedrock aquifer where the seasonal recharge peak was lower each year. In the bedrock aquifer, the period of higher water tables decreased from 2009 to 2011 (Figure 3-5). This can be attributed to increased deep seepage resulting from the cone of depression reaching further into the watershed each year. In the bog and fen peat layer seasonal recharge by melt and/or rainwater fully replenished the storage that had been lost over the winter months to deep seepage. This suggests, however, there was less water available for stream flow. Spring snowmelt occurred earlier each year, which was a result of warming temperatures earlier each season and cannot be attributed to mine dewatering. This suggests that the effects of seasonal and annual weather patterns also play a role on the interactions between these peatland systems and how they respond to mine dewatering.

The increased depressurization in the bedrock aquifer, from mine dewatering, caused increasing, and higher than normal vertical gradients in the peatlands (Table 3-1). Downward gradients are expected in undisturbed bog systems (Siegel and Glaser, 2006), but strong downward gradients in undisturbed fens are not (Glaser et al., 2004b). Bogs typically experience downward gradients. However, the gradients measured at the two study sites were an order of magnitude larger than gradients measured in the MS15 non-impacted site (Table 3-1) in this study and gradients of 0.004-0.006 in the downward direction reported by Whittington and Price (2012) also measured at the MS15 site. The vertical gradients measured at the FWT site were all in the downward direction. This indicates that both the bog and fen landscapes were acting as recharge systems. Natural fens generally have upwelling from groundwater discharging into them (Siegel and Glaser, 1987). Increased downward vertical gradients in fens could have negative effects on the hydrological function of the system. Fens rely on the water they receive from groundwater discharge to sustain water tables and dissolved minerals, on which the vegetation community structure depends (Rochefort et al., 2012).

Vertical gradients at the MS15 non-impacted site we not only an order of magnitude smaller than gradients in the mine impacted area, they also displayed less variability, as demonstrated by the lower standard deviations (Table 3-1). This provides further evidence of how the mine dewatering is impacting the overlying peatlands.

The BFT site experienced similar average downward gradients in 2011 as the FWT site in 2010, particularly in the bogs (Table 3-1). The FWT site is located where the deep-aquifer depressurization is greater, compared to that of the BFT site; as of 2011 the FWT was situated over the 6 m drawdown region and the BFT at the 4 m drawdown (Leclair et al., submitted). The 2011 BFT bog gradients were similar to those measured in the FWT in 2010; this is likely a result of the migrating cone of depression. It is probable that the gradients at BFT will lag those at FWT by a year, as a consequence of their position with respect to the migrating cone of depression.

One of the bog nests (+60 m) at the BFT experienced upward gradients in the peat layer for the majority of the season (Figure 3-4). Upwelling at this nest, located +60 m from the channel fen, is likely because this is a margin zone between bog and fen. The upwelling water is from the domed bog, moving to the shallower, higher hydraulic conductivity peat layers to discharge to the fen channel. The horizontal gradients indicate the bog was still supplying water to the fen despite the whole system losing water from the base of its peat layer. The bogs at the FWT and

BFT site did continue to discharge small quantities under dry conditions, where water tables were up to 44 cm below the surface. The low rates are on account of the low transmissivity when the water table was low (Figure 3-8).

Water table depth is a good indicator of the hydrological health of a wetland system (Mitch and Gosselink, 2007). In the spring, water tables were either above the surface or just below, in both study sites as well as at the MS15 non-impacted site. It was not until the season progressed and water tables dropped that the mine drawdown had a noticeable effect on the hydrology of the two sites. The bogs at both the FWT and BFT site dropped up to 20 cm further below the surface than the bog water table at the MS15 non-impacted site (Figure 3-7). The BFT did not experience water tables as low as those at the FWT bogs, given that it was further out from the cone of deep aquifer depressurization, and consequently had lower vertical gradients.

The water tables in the fens at the two sites deviated further from one another as the season progressed and conditions dried. The BFT fen was able to better maintain its water tables compared to the FWT fen. This variation between sites can be explained by their different morphology and function. The FWT, being a water-track type fen relies solely on discharge from the surrounding bog, and has a relatively small catchment. Since this bog area is being negatively impacted by mine dewatering it is less able to supply water to the fen water-track in the dry summer months, resulting in lower than normal water tables. Furthermore, the water table drawdown in the bog during winter (Figure 3-5), enhanced by mine dewatering, captures more snowmelt water during its wetting-up period in the spring, that would otherwise have gone to the fen. In contrast, the BFT fen is a channel fen with a relatively large catchment, compared to FWT, with most of its headwaters in a less impacted area and much of that being up-gradient fen. Water tables in the BFT fen, therefore, are better maintained by recharge and surface runoff from these outlying areas. Even though the bog at the BFT experienced water tables lower than normal, the channel fen relies less on discharge from the adjacent bog and more on water from the non-impacted headwaters.

The longitudinal flows (Q) in the FWT were calculated (see Equation 3-1) based on the flow going through the seasonally variable saturated flow face (i.e. its height changing with water table), according to the longitudinal gradient and the transmissivity (T). Bogs and fens had a trend of decreasing transmissivity as the water table dropped below the surface (Figure 3-8). In the fen water-track the trend was weaker than that observed in the bogs. Price and Maloney (1994) also found that fen water tracks had a weaker relationship than bogs when evaluating hydraulic conductivity at different water table depths. The transmissivity values in the bogs appear to stop with a minimum value approaching 0.01 m^2h^{-1} with water tables below 35 cm. Given that this study area experienced lower than normal water tables, on account of the mine dewatering, provided an opportunity to measure the changes in transmissivity at these extreme lows. At these water tables, and especially if they decline further, connectivity between these bog and fen landscapes will decline sharply.

Regardless of lower water tables and increased vertical gradients, the bogs at both experimental sites were still feeding the fens in the longitudinal direction; the FWT had similar longitudinal flows in 2010 and 2011 indicating that the seasonal variability masks the annual changes over a one-year period. However, as the cone of depression from the mine increases, the longitudinal flow quantities may decrease as a result of increased vertical recharge, and lower water tables especially in the bogs, hence lower horizontal hydraulic gradients.

A bog's function includes storing the water necessary to support its ecological and biogeochemical processes (Quinton et al., 2003), and as shown here, to provide part of the water input to connected fens. Decreasing water tables, which are more exacerbated in bogs than fens (Figure 3-7), means reduced transmissivity (Figure 3-8), hence diminished longitudinal flows that sustain the typically wetter condition in fens. The bog landscapes at the FWT and BFT sites are both showing the impacts of the mine dewatering; this is apparent from the lower water tables and increased hydraulic gradients compared to the non-impacted MS15 site (Table 3-1; Figure 3-7).

The longitudinal flows from the FWT system into North Granny Creek were small (less than 1%) during the post snowmelt study season. Due to the complex orientation of these fen water-track systems and the presence of a frozen ground layer in early spring the discharge during snowmelt was not quantified. When snowmelt occurs in early May, the frost table was still present in most areas and provided a partial confining layer that promoted snowmelt runoff to the fens. During spring the water tables were above or near the surface (Figure 3-7) so the effective hydraulic conductivity, thus transmissivity, of the system would be even higher than presented in Figure 3-8. When water tables recede later in the study season the FWT system conveys small amounts of water to the NGC channel, only 38 and 42 m^3 over the post snowmelt season (Figure 3-9). During this time the bog landscapes surrounding the fen (Figure 3-2) were contributing just over 40% of the flow that was leaving the fen water-track, with the remainder coming from the north end of the watershed where several large pools lie, as well as from direct precipitation. Therefore, after accounting for precipitation and evapotranspiration only about half of the discharge from the FWT cascading off the domed bog comes from the dome, the remainder comes from locally adjacent bogs. During the summer the water tables are an average of 25-41 cm below the peat surface in the fens and bogs at the FWT (Figure 3-7), which is well below the height of the peat ridges. At this time, the water-track system therefore has a long residence time, and water losses from the system are dominated by evaporation (see Chapter 2), rather than from groundwater discharge. Fen water-track systems likely contribute more water to the NGC in the spring when water tables are high and surface connectivity is strong. Taking into consideration the large number of fen water-track systems in the NGC watershed (Figure 3-1), these systems remain important for conveying water to the watershed outlet during the snowmelt period; however, increased water loss by deep seepage, and diminished water input from bogs during the spring and summer, will limit fen water-track connections to the streams, thus compromise baseflow, especially during periods of more intense water-deficit.

At the BFT site the bog adjacent to the channel fen is a much smaller and less developed domed bog than the one the FWT drains (Figure 3-1). However, as a result of a large upstream catchment of the channel fen (i.e. extending upstream well beyond the segment of the channel into which the bog drains, a lower proportion of the total discharge leaving the fen channel is supplied by the bog (~1.5%) compared to the bog-fen relationship in the FWT site (~40%) (Figure 3-9). These wet headwaters supply the channel fen with constant discharge, establishing the channel through which the water runs. The BFT watershed is less likely to be affected by the mine dewatering than the FWT because the headwaters of its watershed are further out of the cone of depression. The fen channel discharges anywhere from less than 1% to 7% of the total flow leaving the North Granny Creek watershed. The large amount of discharge leaving the BFT, and the small amount of recharge from the bog suggests that the BFT catchment may be bigger than depicted in Figure 3-1, and the channel fen is actually getting water from even further into the headwaters and beyond the mine impacted area.

If development in this area continues and dry conditions are maintained, the hydrological function of these two systems will be disrupted. For example, drier conditions in the FWT could promote moss growth into the pools (Strack et al., 2006), reducing the depressional storage of the water-track. In the BFT drier conditions could increase water-table and flow variability through the channel fen, promoting shrub growth within it (Riutta et al., 2007). Both of these scenarios may take longer to generate than the projected mine operation lifetime (9 years, 2017), although infilling of pools was noted by Strack et al. (2006) to occur within 8 years of drainage.

Both the fen water-track and the channel fen systems might not convey a significant amount of water individually, but these landscapes dominate the James Bay Lowland, and collectively are responsible for conveying the bulk of the fresh water to James Bay.

3.7 Conclusion

After evaluating the hydrology of these two systems, the impact from under drainage is apparent in the increased vertical gradients and lower water tables. Vertical gradients were found to be, on average, an order of magnitude larger than those measured at the non-impacted site. Due to these increased vertical gradients water tables in the bogs dropped over 20 cm lower than the non-impacted bog studied. Since these bogs act as storage units, when their water tables drop they are less likely to recharge water to the fen systems which rely on recharge to help maintain water tables and nutrients. It is evident that the fen systems experience a larger change in their gradients than the bogs, given their reversed gradients. When assessing the fen water-track system in particular it received half of its discharge from the adjacent bog landscapes. Less inflow from bogs as a result of lower water tables and increased downward gradients are bound to have negative effects on the hydrology of these fen water-track systems. The channel fen was better able to maintain its water tables due to the non-impacted headwaters, masking the effects of the drawdown. However, if dry conditions are brought on by climate change as opposed to development there will not be a “non-impacted” region to maintain water levels. This is concerning, given fen’s importance to transporting fresh water. These fens are still currently functional as conveyors of water, but as development and potentially climate change continues the hydrology, chemistry and ecology of these systems will change. The current change at the study site is small relative to the size of the James Bay Lowland, but the changes are indicative of possible declining water tables in response to a warming climate (Roulet et al., 1992).

4 Conclusions

It is evident that mine dewatering is having a negative impact on the hydrology of the surrounding peatlands. At the end of this study only 14.5% of the North Granny Creek watershed was within the mine impacted region. This area experienced lower evapotranspiration rates and increased deep seepage compared to the nearby none impacted sites that were studied. One of the main functions of these peatlands is to provide recharge to the regional stream networks to sustain biological activity. Over the three study years the impacts of mine dewatering on runoff were masked by varying weather conditions. Therefore, when assessing the total watershed, inter-annual weather conditions had a larger effect on the annual water balance than the impacts measured in the mine-impacted portion.

When evaluating the bog and fen interacts they both experienced the varying effects of drawdown. The bogs experienced larger then natural vertical gradients, resulting in water tables over 20 cm lower than those measured at the non-impacted site despite seasonal weather conditions. Since bogs are known to function as storage units, increased vertical gradients and lower water tables would result in the bogs recharging less water to the surrounding fens. The fens, acting as recharge zones and conveyors of water rely on inputs from the surrounding environments to sustain water tables. Both fen systems studied were experiencing mainly downward gradients, the opposite of what would be expected in a natural fen system. The fen water-track system relies heavily on the inputs from the adjacent bogs and as a result experienced water tables up to 17 cm further below the surface than the fen at the non-impacted site. On the contrary, the channel fen system was better able to maintain its water tables because it relied less on the input from the adjacent bogs and more on surface flows from the headwaters of the watershed, which were less impacted by dewatering.

When evaluating both chapters the bogs were experiencing larger downward fluxes, gradients and lower water tables, implying that they were more impacted by mine dewatering. However, the fens were experiencing reverse flows, completely reversing their hydrological function, implying that the fens may be more impacted by mine dewatering. This ties in to the importance of the connectivity of these bog-fen systems, they are connected and thus the impact on one impacts the other. If these systems were impacted by climate change, lowering water tables, the whole James Bay Lowland will be impacted and there would not be a non-impacted region to help sustain water tables and runoff. If water tables drop on a regional scale bogs will hold back water from the fens which will then have less to discharge to the regional stream networks. Peatlands make up the majority of the James Bay Lowland which supplies fresh water to James Bay. That is why evaluating how these systems function, how they are connected and how they are reacting to drier conditions are so important for the future of the James Bay Lowland.

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