Dynamics of a headwater system and peatland under current conditions and with climate change

Journal:	*Hydrological Processes*
Manuscript ID:	HYP-12-0676.R1
Wiley - Manuscript type:	Research Article
Date Submitted by the Author:	n/a
Complete List of Authors:	Levison, Jana; Guelph University, School of Engineering Larocque, Marie; University of Quebec at Montreal, Earth and atmospheric Sciences Véronique, Fournier; Université du Québec à Montréal, Sciences de la Terre et de l'atmosphère Gagné, Sylvain; Université du Québec à Montréal, Sciences de la Terre et de l'atmosphère Pellerin, Stéphanie; Université de Montréal, Biologie Ouellet, Marie-Audray; Université du Québec à Montréal, Sciences de la Terre et de l'atmosphère
Keywords:	Peatland, Headwater system, Climate change, Groundwater flow modeling, Covey Hill (Quebec, Canada)

DYNAMICS OF A HEADWATER SYSTEM AND PEATLAND UNDER CURRENT CONDITIONS AND WITH CLIMATE CHANGE

J. Levison[1,3], M. Larocque[1*], V. Fournier[1], S. Gagné[1], S. Pellerin[2] and M.A. Ouellet[1]

[1] Centre de recherche pour l'étude et la simulation du climat à l'échelle régionale, Département des sciences de la Terre et de l'atmosphère – Université du Québec à Montréal, C.P. 8888, succ. Centre-Ville, Montréal (QC), Canada ; tel : 514-987-3000 ext. 1515 ; fax : 514-987-7749; larocque.marie@uqam.ca

[2] Institut de recherche en biologie végétale, Université de Montréal, Jardin botanique de Montréal, 4101 rue Sherbrooke est, H1X 2B2, Montréal, Québec, Canada; stephanie.pellerin.1@umontreal.ca

[3] Current address: School of Engineering, University of Guelph, Richards Building, N1G 2W1, Guelph, Ontario, Canada, jlevison@uoguelph.ca,

* Corresponding author

ABSTRACT

Interactions between headwater aquifers and peatlands have received limited scientific attention. Hydrological stresses, including those related to climate change, may adversely impact these interactions. In this study, the dynamics of a southern Quebec headwater system where a peatland is present is simulated under current conditions and with climate change. The model is calibrated in steady-state on field-measured data and provides satisfactory results for transient state conditions. Under current conditions, simulations confirm that the peatland is fed by the fractured bedrock aquifer year round and provides continuous baseflow to its outlets. Climate change is simulated through its impact on groundwater recharge. Predicted precipitation and temperature data from a suite of Regional Climate Model scenarios provide a net precipitation variation range from +10% to -30% for the 2041-2070 horizon. Calibrated recharge is modified within this range to perform a sensitivity analysis of the headwater model to recharge variations (+10%, -15% and -30%). Total contribution from the aquifer to rivers and streams varies from +14% to -44% of the baseline for +10% to -30% recharge changes from spring 2010 data, for example. With higher recharge, the peatland receives more groundwater, which could significantly change its vegetation pattern and eventually ecosystem functions. For -30% recharge, the peatland becomes perched above the aquifer during the summer, fall and winter. Recharge reductions also induce sharp declines in groundwater levels and drying streams.

KEYWORDS

Peatland; headwater system; climate change; groundwater flow modeling; Covey Hill; southern Quebec Canada

1. INTRODUCTION

In Canada, peatlands cover up to 14% of the land area and comprise over 90% of present wetlands (Waddington et al., 2009). They are the most prevalent wetland type in the southern part of the province of Quebec (Ducks Unlimited Canada, 2006). Peatlands play an important ecological role in maintaining fragile habitats (e.g. Calmé et al., 2002). They contribute uniquely to both physical and chemical hydrologic processes including streamflow, evapotranspiration and water storage (Waddington et al., 2009). In eastern Canada, as in other parts of the world, peatlands are under threat from human activities, particularly urban expansion and agriculture (Poulin et al., 2004), and potentially climate change (Moore, 2002; Tarnocai, 2006). In general, very little is known about peatland hydrological dynamics and linkages to local or regional groundwater flow systems. This is especially true for headwater peatlands which can be significant hydrological reservoirs in environments where bedrock hydraulic conductivity is low and surrounding soils can be thin or nonexistent (Winter, 2000).

Numerical modeling of groundwater flow through the peat and in the adjacent aquifer can be used to better understand peatland-aquifer flow dynamics (Ackerman et al., 2009; Baird et al., 2011). In regional scale groundwater flow models, surface water features such as lakes and peatlands are typically represented using constant heads. This boundary condition overly constrains groundwater flow around the peatland and prevents any consideration of temporal variations of peatland-aquifer exchanges. For some peatland-specific studies, modeling simplifications such as two-dimensional representations and steady-state flow regimes (Lapen et al., 2005) limit the results about regional scale and seasonal hydrological processes. The modeling work of Reeve et al. (2001) is a notable exception to the constant head peatland representation or peatland-specific modeling simplifications. Using a regional groundwater flow model and an explicit representation of flow processes between the peatlands and the aquifer, they showed that in the lowland Lake Agassiz area, groundwater flow within the peatlands is driven by local flow systems.

Nevertheless, the scientific literature holds few such examples of regional scale peatland-groundwater interaction models. Simulating groundwater flow in fractured bedrock aquifers itself is challenging because of the heterogeneous distribution of conductive fractures (Cook, 2003). This can be further complicated by large vertical gradients present in fractured bedrock headwater basins. Using an explicit representation of a peatland in a model to accurately simulate transient fractured bedrock aquifer-peatland interactions in a complex headwater context has not, to our knowledge, been previously investigated.

Climate change impacts on groundwater resources at a regional scale are increasingly studied (e.g. Jyrkama and Sykes, 2007; Scibek et al., 2007). Results from these studies in different locations show the possibility of increases and decreases in groundwater recharge, depending on the topography, geology and climate, leading to a variety of trends in groundwater levels. It is recognized that headwater streams in small catchments are more likely to be vulnerable to low-flow impacts than larger river systems (Winter, 2007). In headwater catchments with shallow bedrock aquifers, groundwater is probably also highly vulnerable to climate variations because of slopes and limited (or no) surficial material overlying formations with low permeability which leads to greater runoff and less infiltration (Kosugi et al., 2006). Investigations of climate change effects on peatlands have focused on peat interactions with the atmosphere, notably carbon exchanges (Strack et al., 2004; Belyea and Malmer, 2004), and on hydrologic processes occurring within the organic deposits (e.g. Whittington and Price, 2006). Recently the impact of climate change on wetland interaction with the surrounding aquifer has been studied (e.g. Ackerman et al., 2009; Herrera-Pantoja et al., 2011), finding in particular a vulnerability with declining groundwater levels. Changes in peatland-aquifer connectivity can impact stream and wetland biogeochemistry (Devito, 1995; Brassard et al., 2000) which can induce vegetation changes (e.g. Salinas et al., 2000) and lead to a flashier response to rainfall events (Greyson et al., 2010). However, the amount of hydrological change a headwater system and its ecosystem can sustain before adverse impacts are observed is not well understood. In particular, the function of peatlands in the hydrological and ecosystem resilience of headwater systems is mostly unknown. This lack of knowledge limits the development and application of adaptation strategies such as land and water resources management (e.g. protecting peatlands, reducing groundwater withdrawal, and limiting deforestation and urban development) in headwater systems where peatlands are present.

This research was initiated at the request of Nature Conservancy of Canada to better understand the hydrological function of a headwater peatland recently identified for conservation. The goal of this long term study is to determine if the peatland plays a role in maintaining groundwater levels, as well as river baseflows, streams and springs which form habitats for endangered salamander species (Larocque et al., 2006). Climate change was identified as the most eminent threat to the low development Covey Hill area where the targeted headwater peatland is located. This paper addresses these questions by using a numerical groundwater flow model to simulate the dynamics of the headwater system under current conditions and with climate change-induced recharge variations. Specifically, a groundwater flow model developed in MODFLOW (Harbaugh, 2005) is used to simulate regional flows for the headwater system as well as local aquifer-peatland interactions under current conditions and with a range of recharge scenarios derived from Regional Climate Models.

2. Study area

The Covey Hill peatland is located within the Covey Hill Natural Laboratory (Larocque et al., 2006), 74°00'W, 45°00'N, near the Canada-USA border in the Chateauguay River watershed (Figure 1). Covey Hill is the most northward extension of the Adirondack Mountains. The highest point on the hill is located 345 m above sea level. Covey Hill comprises Cambrian sandstone of the Potsdam Group (Covey Hill Formation), deformed and fractured during the Appalachian orogeny (Globensky, 1986). Groundwater flows in the fractured sandstone. This bedrock aquifer is used by local residents for potable water supply.

The absence of surface deposits on large areas near the hilltop and south of the international border shows the importance of erosion during the last ice advance (12 ky). In other areas, the hill is covered by the thin, permeable and sandy Saint-Jacques till (Lasalle, 1981). Glaciolacustrine sediments are found locally below 220 m above sea level (masl) (Parent and Occhietti, 1988). Sandy beach deposits are located at the foot of the hill, between 80 and 100 masl (Tremblay et al., 2010). Littoral sediments from the erosion of the rock substrate by the Champlain Sea and till are abundant at the base of Covey Hill (see cross-section, Figure 1b). These sediments, composed of highly permeable sands and gravels, are mostly located on the northern side of the hill. The sandstone aquifer is generally unconfined over the study area. The till, silt and clay sediments in the north are less permeable than the sandy deposits at the base of the hill. Groundwater flow through the sandstone aquifer occurs in laterally-extensive sub-horizontal bedding planes, connected by sub-vertical fractures and joints (Nastev et al., 2008). Covey Hill is considered an important recharge area for the 2500 km^2 Chateauguay aquifer (Croteau et al., 2010). Near the end of the last glaciation, the breakout of paleo-lake Iroquois through an outlet near Covey Hill created a relatively impervious sandstone pavement (also called Flat Rock) that extends from below the peatland approximately 30 km southeastward into the Champlain Valley in the United States (Franzi et al., 2002). The Blueberry and Gouffre lakes are remnants of this catastrophic event and form deep reservoirs which store significant volumes of water along the Allen River (Barrington et al., 1992).

The Covey Hill peatland is one of the few remaining undisturbed peatlands in southern Quebec and one of the oldest known in the province. Basal peat ^{14}C dating shows that organic matter started accumulating 13 250 years B.P., probably soon after the breakout of paleo-lake Iroquois

(Pellerin et al., 2007). The peatland covers an area of approximately 0.51 km^2 near the hilltop. The peat averages 1.4 m deep and reaches 3.2 m in some areas (Rosa et al., 2008; see Figure 1b). To the west, the peatland feeds the Outardes River and to the east it discharges in the Allen River. Fournier (2008) used hydraulic gradients and a water budget to demonstrate that groundwater flows year round from the surrounding bedrock aquifer into the peatland. A vegetation study also identified a minerotrophic transition zone (lagg) between the forests located on the bedrock and the central peatland ombrotrophic sector (Pellerin et al. 2009). Surface water input to the peatland from runoff has not been observed since the start of the peatland monitoring and is considered negligible. Based on the piezometric map of Covey Hill the area contributing groundwater to the peatland is estimated to be 1.7 km^2.

2. EXPERIMENTAL ANALYSIS

2.1 Available data

Precipitation and temperature data are available from the Hemmingford weather station located 11 km from the peatland (Environment Canada, 2010). From 2007 to 2010, the annual average precipitation was 1064 mm and the average annual temperature was 6.8ºC. Snow usually falls between November and March. Potential evapotranspiration (PET) is calculated with the Oudin et al. (2005) equation. This equation provides PET estimates based on mean daily air temperature and on extraterrestrial radiation which is estimated following Morton (1983). The seasonal net precipitation (precipitation - PET) is estimated for three-month periods between 2007 and 2010 (Table 1). It varies from a negative net precipitation in summer to a winter maximum of 285 mm. A negative net precipitation indicates seasons where potential evapotranspiration could not be met by precipitation. Because of the sub-zero temperatures, the winter net precipitation accumulates on the ground as snow and becomes available only during spring snowmelt. The average annual PET calculated with the Oudin equation from 2007 to 2010 was 664 mm y^{-1}. The average net precipitation is therefore 400 mm y^{-1} for this period and varies from 323 to 567 mm y^{-1}.

Figure 1a shows the location of gauging stations and their contributing watersheds in the Covey Hill Natural Laboratory where water levels have been recorded hourly since 2007 (*Trutrack* level loggers) on the Allen River (29 km^2 watershed) and the Outardes River (26 km^2 watershed) as well as on the Schulman stream (2.7 km^2 watershed). For all gauging stations, rating curves were constructed by measuring flow rates manually (*Swoffer2100* velocimeter). Flows were estimated during the frost free period of May to October from 2007 to 2010 (2007 to 2009 for the Schulman stream). The Chapman (1999) digital filter was used on the flow rate time series to separate baseflows from total flows (see Table 1). Without field calibration it is difficult to determine the baseflow recession constant k, which describes the rate of baseflow decay. Here, a k value of 0.99 was used to represent the relatively low groundwater contribution to river flows (cf. Gagné, 2010). Total flows and baseflows are similar for the Allen and Outardes rivers and are an order of magnitude smaller for the Schulman stream, as expected when comparing watershed sizes (see Figure 1). On average, the estimated baseflows represent 39, 27 and 29% of the total flows for the Allen River, the Outardes River and the Schulman stream respectively. These proportions are relatively small, but typical of values found in headwater streams (e.g. Croteau et al., 2010). The proportionately larger baseflows on the Allen River can be explained by the presence of deep lakes along its course that intercept significant volumes of groundwater and smooth the impact of rain events.

Groundwater levels were measured in two bedrock piezometers located near the peatland (4.5 and 15 m depth), in nine private monitoring wells, and in three observation wells owned by the Geological Survey of Canada (*Solinst* level loggers; hourly measurements year round). A total of 371 heads are also available from a provincial water well database, the Système d'informations hydrogéologiques (SIH) (Ministère du Développement durable, de l'Environnement, de la Faune et des Parcs-MDDEFP, 2010). Six piezometers (approximately 0.5 m depth) are located directly in the peatland to monitor groundwater levels in the organic deposits (*INW-PT2X* level loggers; hourly measurements during the frost free period of May to October). Several of these piezometers and the shallow bedrock observation well are depicted in Figure 1b. The bedrock water table is located near the surface (between 2 and 15 m depth). Groundwater flows generally in a radial direction from the hilltop, in the laterally-extensive fractures and dissolution joints rather than in the sandstone porosity (Nastev et al., 2008). Heads in the peatland are lower than in the surrounding bedrock aquifer, indicating lateral groundwater input from the aquifer to the peatland (Fournier, 2008).

Hydraulic conductivity (K) values for the fractured bedrock are available from pumping tests and packer tests reported in previous studies (Barrington et al., 1992; Lavigne et al., 2010a) and from slug tests performed in the two bedrock observation wells located near the peatland (Fournier, 2008). Available data for bedrock K range from 4×10^{-10} to 1×10^{-4} m s^{-1}. These highly variable values correspond to a wide range of fracture apertures and connectivity, but clearly decrease with depth. Peat hydraulic conductivity was estimated by Fournier (2008). For the top 0.3 m, it was estimated using an experimental tank reproducing Darcy's experiment (Rosa and Larocque, 2008) and varies between 0.00189 and 0.00725 m s^{-1}. Below this depth and down to 1 m, it was estimated with the Modified Cubic Method (Beckwith et al., 2003a) and varies between 2.1×10^{-8} and 1×10^{-4} m s^{-1}. Hydraulic conductivities show a significant decreasing pattern with depth. Below 1 m, K is expected to be very low and probably significantly restricts flow in the lower peat layers.

2.2 Development of the groundwater flow model

The MODFLOW software (Harbaugh, 2005) was used to simulate groundwater flow in the fractured bedrock and interactions between the aquifer, the peatland and streams, assuming that the unconfined bedrock aquifer behaves as an equivalent porous medium. A digital elevation model was built using elevation data from the Ministère des Ressources Naturelles (MRNF, 2007). The groundwater flow model is discretized in 16 layers for a total thickness of 96 m (layer thickness increases from 0.25 m at the surface to 30 m at the base of the aquifer). The upper eight layers are thin to allow an accurate representation of the peatland stratigraphy: the top two layers (each 0.25 m thick) correspond roughly to the top portion of the acrotelm while the next layers correspond to gradually more humified and less permeable peat layers (reaching the catotelm). A variable head representation of the peatland was used rather than a constant head boundary condition to ensure that simulated flows reflect the hydraulic properties of both the bedrock and the organic deposits in changing hydrological conditions. This representation of the organic deposits is nevertheless simplified and does not include lateral heterogeneity within the peat deposits which can drive groundwater flow (Beckwith et al., 2003b).

The model extends north and east from Covey Hill into the St. Lawrence Lowlands and covers a total area of 173 km^2. It is limited to the northwest by the Outardes River and to the north by the Noire River (Figure 2). A specified head boundary is used to allow groundwater flow to the regional aquifer. A no-flow boundary is used approximately 9 km parallel to and east of the Allen River. This is a flow line based on the piezometric map. The southern and southwestern limit is set on the drainage basins of the Allen and Outardes rivers (i.e., a water-divide, thus a no-flow boundary is used). The bedrock at the base of the model is a no-flow boundary. The model consists of 9698 cells of 135 m x 135 m. Cells are refined over and around the peatland (67.5 m x 67.5 m) to ensure a good representation of head variations. Figure 3 presents a three-dimensional depiction of the model, with a vertical exaggeration of 10 times.

The Outardes and Allen rivers are represented using MODFLOW's River package in the top two layers. The Blueberry Lake and the Gouffre Lake, as well as a marsh area in the USA portion of the Allen River are set as constant heads. Small permanent streams and tributaries are represented using MODFLOW's Drain package in the top two layers. Recharge zones are determined according to the slope and type of Quaternary deposits (Figure 2a, Table 2). The study area is divided into four hydraulic conductivity zones (Figure 2b). Zone 1 corresponds to the peatland. The Covey Hill formation is divided into three zones (2, 3 and 4) based on areas of similar elevation and field hydraulic conductivity measurements (Lavigne et al., 2010a).

The model was calibrated in steady-state by manually adjusting the K values of the four hydraulic conductivity zones using a trial and error procedure based on measured K data. Zonal recharge and river and stream exchange coefficients were also calibrated. The storage coefficient for the organic deposits (zone 1) was set to 0.7, based on an estimation from water level increases following precipitation events (Fournier, 2008) and was calibrated for the bedrock hydraulic conductivity zones. The calibration targets are the available head measurements (SIH database, bedrock observation wells, private monitoring wells and peatland piezometers) as well as the baseflows estimated for the three gauging stations (Allen and Outardes rivers, Schulman stream).

In transient-state, the year is divided into four stress periods of 91 days (10 time steps in each period) corresponding to spring, summer, fall and winter. Following a 20 year spin-up period, the transient model was executed to simulate the 2007-2010 flows, the period during which detailed transient hydrological data are available. In MODFLOW, multipliers are used to modify the value of calibrated steady-state recharge for each transient period. These multipliers were calculated for each 91 day season using the ratio of the net precipitation for the season of interest to the average net precipitation for the calibrated steady-state period. This method assumes that seasonal recharge is distributed analogously to the net precipitation ratios. That is, a lower net precipitation will lead to a reduction in both runoff and infiltration. The same multipliers were used for all recharge zones. In the model, the winter recharge is set to zero and transferred to the spring (when net precipitation is therefore usually the highest). For periods where the net precipitation is a negative value (i.e. for some summer periods), the recharge in the model is also set to zero.

2.3 Climate change scenarios

The impact of climate change on groundwater recharge was investigated by considering net precipitation values calculated with future time series of daily precipitation and temperature data. It is assumed that recharge will follow the same pattern as net precipitation, such that a lower net precipitation will lead to an analogous reduction in both runoff and infiltration. This might not hold true if rainfall intensity increases or if there is less snow due to a shorter winter. Predicted PET values were derived from Regional Climate Models (RCMs) future temperature time series used in the Oudin et al. (2005) equation. Although using a daily weather generator and a recharge model might provide more detailed input data for the groundwater flow model (cf. Herrera-Pantoja et al., 2011), it would be much more labor intensive and is beyond the scope of this work.

The climate change scenarios are derived from four RCMs driven by six General Circulation Models (GCMs). This form of dynamic downscaling provides a better representation of both average conditions and extremes than other methods over the study area. Future RCM scenarios were further downscaled using the daily translation bias correction method (Mpelasoka and Chiew, 2009) to remove the biases between simulated and observed temperature and precipitation variables.

Ten projections (Figure 4, Table 3) were selected from the 25 dynamically downscaled simulations available for the Covey Hill area. Most of the simulations are outputs of the Canadian Regional Climate Model (CRCM) (Music and Caya, 2007) and were generated and supplied by the Ouranos Consortium on Regional Climatology and Adaptation to Climate Change. The remaining simulations are from the North American Regional Climate Change Assessment

Program. All projections are for the 2041-2070 climate. The 10 simulations account for 85% of the future climate variability projected for the study site as established by a cluster analysis carried out on the range of available RCM scenarios. The simulations are driven by six different GCMs under the Intergovernmental Panel on Climate Change emissions scenarios A1B and A2 (IPCC, 2000). The A1B emissions scenario corresponds to a medium population growth, rapid gross domestic product growth and a balance of all energy sources. The A2 scenario is based on high population growth, medium gross domestic product growth, high energy use, medium-to-high land-use changes, and slow introduction of more energy efficient technologies. The A2 scenario is one of the most commonly used scenarios (Jackson et al., 2011).

Future RCM scenarios predict annual average air temperatures increasing by 2.4°C (CRCM4.2.3_ECHAM#1) to 3.6 °C (CRCM4.2.3_CGCM3#2) for the 2041-2070 period. These temperature increases far exceed the maximum difference of 1.6°C from the mean annual temperature observed from 1971 to 2000 on Covey Hill. When used in the Oudin et al. (2005) formula, the increased temperatures of the climate scenarios induce 15 to 21% increase in predicted PET compared to the PET value of the reference period. Annual precipitation projections range from a 3% increase (CRCM_CCSM) to a 13% increase (ECP2_GFDL). This range of precipitation variation is small when compared to the -19% to +38% difference from the mean precipitation observed from year to year during the reference period.

Stemming from these changes in temperature and precipitation, net precipitation varies from a 30% decrease (CRCM_CCSM) to a 10% increase (CRCM4.2.3_ECHAM#1). The net precipitation scenarios do not all agree about the sign of change: seven predict a decrease in mean net precipitation and three an increase. The bounds of the bootstrapped 95% confidence interval on the ensemble mean are -21.5% and 2.9%. The sign of change for net precipitation thus remains uncertain. To facilitate simulations, groundwater recharge variations of +10%, -15% and -30% of the calibrated values are used to study the sensitivity of peatland-aquifer interactions under climate change. These percentages are a simplification of the complex multi-scenario possibilities but are considered sufficiently representative to generate informative results. In the literature, recharge variations due to climate change for humid areas are expected to differ significantly depending on topography, geology and climate. The recharge variations used here are similar to those reported in literature: -59 to +15% in the Chateauguay watershed (Croteau et al., 2010), +53% in the Grand River watershed of Ontario, Canada (Jyrkama and Sykes, 2007), +11 to +25% in the Grand Forks aquifer of British Columbia, Canada (Scibek et al., 2007), -40 to +31% for various locations in Great Britain (Herrera-Pantoja and Hiscock, 2008; Jackson et al., 2011). In the semi-arid region of the southern High Plains of Texas, USA, Ng et al. (2010) report climate change induced groundwater recharge variations from -75% to +35%.

3. RESULTS AND DISCUSSION

3.1 Model calibration, measured and simulated baseline conditions

The calibrated Ks in the groundwater model are within the interval of measured values (Barrington et al., 1992; Fournier, 2008; Lavigne et al., 2010a), decreasing with depth as observed with field measured data (Figure 5). The calibrated K in the peatland is high in the top two layers of organic deposits and decreases rapidly below this depth. Below these layers K is set to even lower values to represent gradually more humified and less permeable peat. The K_h/K_v ratio in bedrock layers 1-9 of zones 2 and 3 is set to 1000 and 100 respectively, to represent the predominantly horizontal groundwater flow within the horizontal bedding planes. The K_h/K_v ratio layers 10-12 for zones 1, 2 and 3 are set to 100, and the deeper anisotropy for these zones is set to 10. In zone 4, the K_h/K_v ratio is 10 for all layers. The calibrated conductance for the River nodes is 200 m^2 d^{-1}. This value provides the best estimates of river base flows. Calibrated conductance for the drains is 500 m^2 d^{-1}.

For the steady-state simulation, the maximum possible recharge was limited to the average annual net precipitation for the 2007-2012 period (400 mm y^{-1}). The steady-state calibrated average recharge for the entire domain is 113 mm y^{-1}, i.e. 28% of this average net precipitation. The difference between net precipitation and recharge can be justified by the diversion of net precipitation to streams and evacuated via surface routes (not simulated in this work). Spatially calibrated recharge varies between 0 and 372 mm y^{-1} (Table 2). The maximum value is attributed to the peatland where little runoff occurs. The minimum recharge is calibrated on the northern portion of the study area where compact till, silt and clay sediments are found. Although in reality recharge is rarely nil, this value illustrates the very limited water volumes that can percolate through these low permeability sediments. The calibrated recharge obtained in this study is lower than the values of 162-180 and 227-240 mm y^{-1} previously estimated by Croteau et al. (2010) and Gagné (2010) respectively for the Allen and Outardes watersheds. This difference can be attributed to the fact these authors calibrated recharge using soil reservoir models to reproduce baseflow estimated from hydrograph separation. Because it is very difficult to distinguish between recharge and subsurface runoff with hydrograph separation, this method can overestimate actual recharge to the aquifer.

For the transient state simulations, Table 1 presents the seasonal values of recharge. Seasonal recharge is lowest (almost zero) in summer and largest in the spring due to snowmelt. From 2007 to 2010, the annual recharge varies from 98 to 172 mm y^{-1}. The storage coefficient was calibrated to 0.004 for the bedrock in zone 2, and 0.001 in zones 3 and 4, typical values for fractured bedrock (Anderson and Woessner, 1992).

Figures 6a and b show that the steady-state groundwater flow model simulates the available head data without any systematic overestimation or underestimation of heads in any area of the study domain (mean error 0.4 m, mean absolute error 7.2 m and root mean squared error 9.3 m). The simulated errors can be partially explained by the fractured and probably highly heterogeneous bedrock aquifer, a condition not represented with the equivalent porous media model. The error on the simulated heads could also arise from the inaccuracy of the SIH data, because it is measured over several years, there are variable drilling depths, and the reference topography (which itself is highly varied) is estimated, and from the inaccuracy in the elevation model. Nevertheless, the calibrated model simulates the large head differences observed over this headwater area relatively well.

Figure 7 illustrates measured and simulated heads from 2007 to 2010 for the peatland and three wells located at the top of the hill, at mid-slope, and at the foot of the hill. The heads are plotted relatively (i.e. elevation centered on 0) to remove any errors related to topographical inaccuracies. The simulated groundwater levels compare reasonably with the observation data. For example, the Nash-Sutcliffe efficiency coefficient (Nash and Sutcliffe, 1970), comparing the seasonal bedrock observation well heads to the simulated heads, where E = 1 corresponds to a perfect match, ranges from 0.983 to 0.998 for the illustrated wells and is similar for the additional bedrock monitoring wells. For the peatland piezometers, the efficiency coefficients are similar (e.g. 0.994 as illustrated in Figure 7). Errors in the transient state simulation are expected to be caused in part by the porous media representation of the fractured bedrock aquifer and the imprecision in storage coefficient calibration.

Table 1 shows that the magnitudes of seasonal baseflows are relatively well simulated for the Allen and Outardes rivers, and for the Schulman stream. Model baseflows range from 0.08 to 0.20 m^3/s for the Allen, 0.05 to 0.24 m^3/s for the Outardes and 0.006 to 0.014 m^3/s for the Schulman . However, the simulated values generally vary less from year to year than the Chapman estimated baseflows. This could be due to the modeling methodology in which bulk seasonal recharge values are used on three month stress periods, rather than storm-specific precipitation and recharge extremes encountered in nature. Also, it must be remembered that the Chapman estimated baseflows are only crude estimations of the aquifer contribution to the rivers. Considering the simple representation of the groundwater contribution to rivers, these results are considered satisfactory.

Fournier (2008) has estimated the groundwater flow contribution to the peatland using the Darcy equation with bedrock-peatland head gradients and measured hydraulic conductivities. The same technique was used here on a seasonal basis. The average seasonal hydraulic gradient between the 4.5 m bedrock piezometer located near the peatland and the closest peatland piezometer is used in this calculation. During the 2007-2010 period, this hydraulic gradient was on average slightly higher during the spring (0.0032 m/m), a mid-value during the fall (0.0031 m/m) and lowest during the summer (0.0029 m/m). It is assumed to be constant all along the 5580 m of the aquifer-peatland North and South inflow lengths. The hydraulic conductivity corresponds to the average between 4.5 m bedrock piezometer K (3.54×10^{-5} m/s) and the hydraulic conductivity of the topmost 0.5 m of peat deposits (1.84×10^{-3} m/s). The model simulates groundwater inflows to the peatland (Table 1) similar to the Darcy flux values for the spring (0.0072 for the model vs. 0.0082 m^3/s for Darcy), but lower for the summer (0.0037 vs. 0.0076 m^3/s) and fall (0.0053 vs. 0.0080 m^3/s) seasons. Although relatively small, this groundwater inflow to the peatland is nevertheless important for the hydrological dynamics of the peatland, its ecosystem and habitat diversity. This inflow provides sustained minerals, nutrients and water to maintain rich and diverse plant communities identified in the minerotrophic transition zone (lagg ecotone; Pellerin et al. 2009). The direction of groundwater flow (i.e. always from aquifer to peatland under current climate conditions) is also correctly simulated. Because of the significantly higher hydraulic conductivities in the upper peat layers, the model simulates groundwater movement through the peatland mainly in the topmost 0.5 m. Similar dominating superficial flow within the top layers of a peatland has also been reported in other field studies (e.g. Devito et al., 1996).

The model predicts groundwater outflow from the peatland in the direction of the Allen and Outardes rivers, equivalent to 4 to 7% of the total baseflow to each river. Simulated flows from the peatland to the two rivers are largest during the spring and fall seasons with a total out flow of 0.0157 and 0.0131 m^3/s respectively for the two seasons. Outflows remains non-negligible (under current conditions) throughout the year (minimum 0.0102 m^3/s during the winter) , with highest contributing percentages in summer and winter when river baseflows are the lowest. Other studies (e.g. Devito et al., 1997) have shown that baseflow from a headwater peatland can be interrupted during the dry season in a low permeability headwater bedrock settings. Although the groundwater flow model for Covey Hill does not provide detailed information on river baseflows, the simulations show that the storage-release capacity of the peatland is important to support river low flows. Similarly to other headwater peatlands, the Covey Hill peatland appears to play a significant buffer role in a hydrological system where the soil and surface deposits offer little storage potential to maintain river flows during the dry season.

Twelve percent of the recharge applied to the model domain is discharged from the aquifer to the small streams which are represented by drains. This corresponds to a significant volume of water, of a similar magnitude to the simulated baseflows of the Allen or the Outardes River. Thirty percent of the recharge emerges in the Allen and Outardes rivers as well as in the Schulman stream uptream from the gauging stations (see Figure 1). Twelve percent emerges in the two rivers below their gauging stations where the rivers flow mostly on impervious sediments and have little interaction with the aquifer.

During an average year, the total flow to the regional aquifer through the northern boundary is equivalent to 52 mm y^{-1}. This inter-aquifer flow represents 46% of the average calibrated recharge for the study domain. Covey Hill is a recharge zone but small streams and rivers intercept a significant part of this recharge. The volume of water that actually reaches the regional aquifer is therefore much lower than what reaches the saturated zone. This is rarely taken into consideration when evaluating regional recharge with 1D water budget methods. This proportion of total recharge that reaches the regional aquifer as groundwater flow cannot be verified with field measurements but appears reasonable given the other simulated flows. Comparatively, in a nearby watershed in south-western Quebec, Nastev et al. (2006) found that discharge to secondary streams comprised 37% of the water budget.

3.2 Simulated climate change scenarios

The recharge scenarios investigated in this study are considered a representative range of possible recharge variations for a future climate. Although the 2007-2010 period during which detailed transient hydrological data are available is outside the 1971-2000 reference period for the climate change scenarios, the four recharge scenarios are simulated up to 2010 to facilitate comparison with recent conditions.

Figure 8 illustrates variations in heads, river and stream flows, as well as subsurface outflow through the northern boundary for each of the recharge scenarios relative to the spring 2010 baseline results. Trends are similar for data from other seasons and years. Recharge variations of +10, -15 and -30% induce median head changes of +1.1, -1.9 and -4.2 m respectively. This high sensitivity of groundwater levels to recharge variations is probably a common trait of headwater aquifers and is an argument in favor of management measures that would limit human-induced recharge reductions or wetland drainage in headwater systems. Nevertheless, the headwater system apparently has some resilience, buffering recharge variations to a limited extent. Interestingly, removing the peatland (i.e. zone 1) from the model in steady state, and therefore simulating a major perturbation scenario, produces a reduction in heads similar to a 15% decrease in recharge (results not shown). The water holding capacity of the organic deposits therefore contributes to some extent to maintain high groundwater levels near the top of the Covey Hill headwater system. In the absence of soils and surface deposits, the Blueberry, Gouffre and Forêt Enchantée lakes certainly also contribute to the hydrological resilience of the system. Beyond a certain level of recharge reduction, heads change more significantly (and this change is much more variable in space), the largest changes being observed on the top of the hill. This agrees with results from other studies (e.g. Lavigne et al., 2010b) which have shown that the highest sensitivity of groundwater levels to pumping increases occurs in areas where potentiometric heads are the highest.

Total contribution from the aquifer to the Allen and Outardes rivers, to the Schulman stream and to all the small streams varies from +14% to -22 and -44% of the baseline for the +10%, -15% and -30% recharge scenarios respectively (Figure 8). In the model, the Allen and Outardes rivers never become dry because they are represented using MODFLOW's River package. This is probably realistic since inputs from the peatland and from a series of lakes along their courses provide significant reservoirs to maintain flow throughout the year. The Schulman stream and the smaller streams located on the northern face of the hill simulated with the Drain package can become seasonally isolated from the aquifer due to low piezometric levels, which represents drying. When recharge decreases, small streams and springs dry out. This drying of small streams and springs could have an adverse effect on endangered salamanders species found on Covey Hill (Larocque et al., 2006).

As recharge decreases, the proportion of the recharge flowing to the regional aquifer increases only slightly for the -15% and -30% scenarios respectively. As less water is diverted to surface routes, more (proportionately) can flow to the regional aquifer. This comes from the drying out of small streams that otherwise drain groundwater towards surface streams and rivers. Conversely, a 10% increase in recharge drives more water to rivers and drains and less, percentage wise, to the regional aquifer.

During the 2007-2010 period, the peatland was constantly fed by the aquifer. Groundwater input to the peatland increases with the +10% recharge scenario, leading to an increase in heads and to more water drained by the peatland outlets. When recharge decreases by 15%, water flows from the bedrock aquifer to the peatland on the southern portion and from the peatland to the aquifer on its northern side (Figure 9). Outflows from the peatland are even higher for the -30% recharge scenario. Also, oxidation of peat and vegetation changes could also occur in response to reduced groundwater inflow to the peatland. Extrapolating from a trend line for flow to the peatland from the aquifer, a recharge decrease of 16.5% causes an annual net groundwater contribution to the peatland of zero. Figure 10 shows that with the -30% recharge scenario, flow reversals occur during the summer, fall and winter seasons, and sometimes during the spring. Under these conditions, the flow regime changes and more water flows out of the peatland than into it through most of the year. This could induce water table drawdowns within the peatland that are beyond the threshold of peatland vegetation resilience to groundwater level variations. Significant vegetation changes could result from this situation with tree growth increase and further reduction of the organic matter accumulation within the peatland. Frequent or long term changes of this nature could impair the buffer function of the headwater peatland. Conversely, with higher recharge some areas of the peatland would become totally flooded. This could significantly impact its vegetation favouring for instance the spread of minerotrophic marshes and aquatic plants (Swan and Gill, 1970; Asada et al., 2005).

It is noteworthy to underline the fact that detailed representation of recharge fluxes and changes in the seasonal occurrence of recharge are not included in this study. This is especially true for winter conditions. Under climate change, the RCM scenarios predict higher winter temperatures, with a mean temperature change of +3.1°C, ranging from +2.1°C to +4.2°C. This will lead to a shorter period of below zero temperatures (10 to 14 days), more frequent recharge events during the winter season, reduced snow accumulation and reduced spring recharge. The climate models indicate an increase in rainfall intensity with the 90th percentile of the maximum daily precipitation rising from 63.7 to 72.7 mm. A detailed soil water budget model would have been necessary along with monthly (or shorter) stress periods to illustrate in more details the impact of increased winter recharge or rainfall intensity on local and regional groundwater flow.

For the two recharge reduction scenarios, the peatland groundwater contributing area is mostly located at the southwest of the peatland and is reduced from 1.7 km^2 to 1.2 and 1.1 km^2 respectively. As mentioned above, the peatland watershed is relatively small and influenced only by local groundwater flow. In this respect, the Covey Hill peatland is probably typical of peatlands located in headwater systems where undulating topography limits the area contributing to groundwater flow. This situation makes it particularly sensitive to hydrological changes in rainfall and recharge.

4. CONCLUSION

This work provides insights into the hydrological functions of a headwater system and peatland in regulating groundwater levels and river baseflows. Under current conditions, this work confirms that the Covey Hill peatland is fed by the fractured bedrock aquifer year round and provides continuous baseflow to its outlets. A peatland located in a headwater system where surface deposits are scarce is expected to play an important role as a water reservoir, helping to regulate the impacts of climate variability. A suite of Regional Climate Model scenarios have provided a net precipitation variation range from -30% to +10% for the 2041-2070 horizon. This range was used to modify calibrated recharge values. Over the studied headwater system, recharge reductions induce sharp declines in groundwater levels and drying streams. Recharge variations of +10, -15 and -30% induce median head changes of +1.1, -1.9 and -4.2 m respectively. Close to the peatland and within the organic deposits, hydraulic gradients change and the peatland becomes perched above the aquifer during the summer, fall and winter. Although the climate change induced recharge scenarios tested in this work are hypothetical, results from this study indicate that a headwater system can be highly vulnerable to recharge variations, both in terms of heads and fluxes. Although the knowledge exists to link these trends to ecosystem changes, more work is needed to establish specific thresholds and quantifiable ecological responses.

The MODFLOW model has proven to be adequate to simulate current groundwater flow conditions in both steady and transient states in the Covey Hill headwater bedrock aquifer as well as to simulate interactions between aquifer and peatland. This was achieved in spite of the inevitable simplifications necessary to represent a regional aquifer, namely using an equivalent porous media representation for the fractured bedrock and deriving recharge from net precipitation values. Representing the peatland explicitly and not overly constraining it using, for example, a constant head boundary condition, was necessary to study the peatland-aquifer interactions. In further research based on additional field characterization, using a fully coupled model could allow the simulation of runoff and infiltration as specific processes, as well as the simulation of surface flow to rivers.

In this study, recharge variations were related to climate change. Other human-induced recharge variations can result from increased urbanization or groundwater level decreases due to groundwater abstraction to meet agricultural or urban needs. The hydrogeological impact of these variations could be magnified if combined with climate change induced recharge reductions. Under these conditions, current management practices might not be sufficient to ensure the long term hydrological and ecosystem functions of a headwater system. More research is necessary to include these considerations into management practices to develop adaptation strategies in the anticipation of climate change and population growth.

ACKNOWLEDGEMENTS

This project was funded by the climate change consortium Ouranos as part of the "Fonds vert" for the implementation of the Quebec Government Action Plan 2006-2012 on climate change (grant #554007 – 107). The authors would like to thank Nature Conservancy of Canada for its logistic contribution and for providing access to its property on Covey Hill. We also thank the landowners for making their properties accessible for the study.

REFERENCES

Ackerman MC, Blake JR, Booker DJ, Harding RJ, Reynard N, Mountford JO, Stratford CJ. 2009. A simple framework for evaluating regional wetland ecohydrological response to climate change with case studies from Great Britain. *Ecohydrology* doi:10.1002/eco.37.

Anderson MP, Woessner WW. 1992. Applied groundwater modeling: simulation of flow and advective transport. *Academic Press, Inc.,* San Diego, California, 381 p.

Asada T, Warner BG, Schiff SL. 2005. Effects of shallow flooding on vegetation and carbon pools in boreal peatlands. *Applied Vegetation Science* **8**:199–208.

Baird AJ, Morris PJ, Belyea LR. 2011. The DigiBog peatland development model 1: rationale, conceptual model, and hydrological analysis. *Ecohydrology* doi:10.1002/eco.230.

Barrington S, Philion H, Bonin J. 1992. An evaluation of the water reserve potentials : the ecological region of the Covey Hill « Gulf ». Agricultural Engineering report, Faculty of Agriculture and Environmental Sciences, *McGill University*, McDonald campus, 53 p.

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

Beckwith CW, Baird AJ, Heatwaite AL. 2003b. Anisotropy and depth-related heterogeneity of hydraulic conductivity in a bog peat. II: modeling the effects on groundwater flow. *Hydrological Processes* **17**:103-113.

Belyea LR, Malmer N. 2004. Carbon sequestration in peatlands: patterns and mechanisms of response to climate change. *Global Change Biology* **10**:1043-1052.

Brassard P, Waddington MJ, Hill AR, Roulet NT. 2000. Modelling groundwater-surface water mixing in a headwater wetland: implication for hydrograph separation. *Hydrological Processes* **14**:2697-2710.

Calmé S, Desrochers A, Savard, JPL. 2002. Regional significance of peatlands for avifaunal diversity in southern Quebec. *Biological Conservation* **107**:273-281.

Chapman, T. 1999. A comparison of algorithms for stream flow recession and baseflow separation. *Hydrological Processes* **13**:01-714.

Cook PG. 2003. A guide to regional groundwater flow in fractured rock aquifers. CSIRO Land and water, Glen Osmond, SA, Australia, 115 p.

Croteau A, Nastev M, Lefebvre R. 2010. Groundwater recharge assessment in the Châteauguay River watershed. *Canadian Water Resourources Journal* **35**(4):451-468.

Devito KJ, Waddington MJ, Branfireun BA. 1997. Flow reversals in peatlands influenced by local groundwater systems. *Hydrological Processes* **11**:103-110.

Devito KJ, Hill AR, Roulet N. 1996. Groundwater-surface water interactions in headwater forested wetlands of the Canadian Shield. *Journal of Hydrology* **181**:127-147.

Devito KJ. 1995. Sulphate mass balances in headwater wetlands of the Canadian Shield: influence of catchment hydrogeology. *Canadian Journal of Fisheries and Aquatic Science* **52**:1750-1760.

Ducks Unlimited Canada. 2006. Plan de conservation des milieux humides et de leurs terres hautes adjacentes de la région administrative du Centre-du-Québec, [http://www.canardsquebec.ca], 55 p.

Environment Canada. 2010. Moyenne climatique de la station Hemmingford Four winds Québec, 1961-2009.http://www.climate.weatheroffice.ec.gc.ca/climateData/dailydata.

Fournier V. 2008. Hydrologie de la tourbière du mont Covey Hill et implications pour la conservation. M.Sc. thesis*, Université du Québec à Montréal*, 84 p.

Franzi D, Rayburn JA, Yansa CH, Knuepfer PLK. 2002. Late glacial water bodies in the Champlain and Hudson lowlands, New York. In: *New York State Geological Association/New England Intercollegiate Geological Conference Joint Annual Meeting Guidebook*, pp. A5 1-23.

Gagné S. 2010. Contribution de l'eau souterraine aux cours d'eau et estimation de la recharge sur le mont Covey Hill. M.Sc. Thesis *Université du Québec à Montréal*, 87 p.

653 Globensky Y. 1986. Géologie de la région de Saint-Chrysostome et de Lachine (sud). Ministère de l'énergie et des ressources.

655 Greyson R, Holdon J, Rose R. 2010. Long-term change in storm hydrographs in response to peatland vegetation change. *Journal of Hydrology* **389**:336-343.

657 Harbaugh AW. 2005. MODFLOW-2005, the U.S. Geological Survey modular ground-water model -- the Ground-Water Flow Process: U.S. Geological Survey Techniques and Methods 6-A16, variously p. http://pubs.usgs.gov/tm/2005/tm6A16/ .

660 Herrera-Pantoja M, Hiscock KM, Boar RR. 2011. The potential impact of climate change on groundwater-fed wetlands in eastern England. *Ecohydrology* doi:10.1002/eco.231.

662 Herrera-Pantoja M, Hiscock KM. 2008. The effects of climate change on potential groundwater recharge in Great Britain. *Hydrological Processes* **22**:73-86.

664 IPCC. 2000. Special report on emissions scenarios (SRES): A special report of working group III of the intergovernmental panel on climate change. *Cambridge University Press,* Cambridge, UK.

667 Jackson CR, Meister R, Prudhomme C. 2011. Modelling the effects of climate change and its uncertainty on UK Chalk groundwater resources from an ensemble of global climate model projections. *Journal of Hydrology* **399**:12-28.

670 Jyrkama MI, Sykes JF. 2007. The impact of climate change on spatially varying groundwater recharge in the Grand River watershed (Ontario). *Journal o Hydrology* **338**:237-250

672 Kosugi K, Katsura S, Katsuyama M, Mizuyama T. 2006. Water flow processes in weathered granitic bedrock and their effects on runoff generation in a small headwater catchment. *Water Resources Resesarch,* **42**, W02414, doi:10.1029/2005WR004275.

675 Lapen DR, Price JS, Gilbert R. 2005. Modelling two-dimensional steady-state groundwater flow and flow sensitivity to boundary condition in blanket peat complexes. *Hydrological Processes* **19**:371-386.

Larocque M, Leroux G, Madramootoo C, Lapointe FJ, Pellerin S., Bonin J. 2006. Mise en place d'un laboratoires National sur le mont Covey Hill (Québec, Canada). *VertigO* **7** (1):1-11.

Lasalle P. 1981. Géologie des sédiments meubles de la région de St-Jean-Lachine. *Ministère de l'Énergie et des Ressources du Québec*, Direction générale de l'exploration géologique et minérale, DPV. 780.

Lavigne MA, Nastev M, Lefebvre R. 2010a. Numerical simulation of groundwater flow in the Châteauguay River aquifers. *Canadian Water Resources Journal* **35**(4):469-486.

Lavigne MA, Nastev M, Lefebvre R, Croteau A. 2010b. Regional sustainability of the Châteauguay River aquifers. *Candian Water Resources Journal* **35**(4):487-502.

MDDEFP (Ministère du Développement durable, de l'Environnement, de la Faune et des Parcs – Québec). 2010. www.mddep.gouv.qc.ca/eau/souterraines/sih/index.htm.

Mearns LO, Arritt S, Biner M, Bukovsky S, Sain S, Caya D, Correia Jr J, Flory D, Gutowski W, Takle ES, Jones R, Leung R, Moufouma-Okia W, McDaniel L, Nunes AMB, Qian Y, Roads J, Sloan L, Snyder M. 2012. The North American Regional Climate Change Assessment Program overview of phase I results. *Bulletin of the American Meteorological Society* **93**: 1337-1362.

Moore PD. 2002. The future of cool temperate bogs. *Environmental Conservation* **29**:3-20.

Morton FI. 1983. Operational estimates of areal evapotranspiration and their significance to the science and practice of hydrology. *Journal of Hydrology* **66** (1-4):1-76.

Mpelasoka FS, Chiew FHS. 2009. Influence of rainfall scenario construction methods on runoff projections. *Journal of Hydrometerology* **10**:1168-1183.

MRNF (Ministère des Ressources naturelles – Québec). 2007. Modèle d'élévation numérique (10 m) de la région de St-Jean Chrysostome (1 : 20 000), 31H04-0101. Base de données topographiques du Québec, Québec, Canada.

Music B, Caya D. 2007. Evaluation of the hydrological cycle over the Mississippi River Basin as simulated by the Canadian Regional Climate Model (CRCM). *Journal of Hydrometerology* **8**:969-988.

Nash JE, Sutcliffe J V. 1970. River flow forecasting through conceptual models part I – A discussion of principles. *Journal of Hydrology* **10**(3):282-290.

Nastev M, Morin R, Godin R, Rouleau A. 2008. Developing conceptual hydrological model for Potsdam sandstones in southwestern Quebec, Canada. *Hydrogeology Journal* **16**:373-388.

Nastev M, Lefebvre R, Rivera A, Martel R. 2006. Quantitative assessment of regional rock aquifers, south-western Quebec, Canada. *Water Resources Management* **20**:1-18.

Ng, G-H C, McLaughlin D, Entekhab, D, Scanlon BR. 2010. Probabilistic analysis of the effects of climate change on groundwater recharge. *Water Resources Research* 46 W07502, doi:10.1029/2009WR007904.

Oudin L, Hervieu F, Michel C, Perrin C, Andreassian V, Anctil F, Loumagne C. 2005. Which potential evapotranspiration input for a lumped rainfall-runoff model? Part 2-Towards a simple and efficient potential evapotranspiration model for rainfall-runoff modelling. *Journal of Hydrology* **303**:290-306.

Parent M, Occhietti S. 1988. Late wisconsinian deglaciation and Champlain Sea invasion in the St. Lawrence valley, Québec. *Géographie physique et Quaternaire* **42** :215-246

Pellerin S, Larocque M, Lavoie M, 2007. Rôle hydrologique et écologique régional de la tourbière de Covey Hill. Report presented to the EJLB Foundation, 63 p.

Pellerin S, Lagneau LA, Lavoie M, Larocque M. 2009. Environmental factors explaining the vegetation patterns in a temperate peatland. *C.R. Biologies* **332**:720-731.

Poulin M, Rochefort L, Pellerin S, Thibault J. 2004. Threats and protection for peatlands in Eastern Canada. *Geocarrefour* **79**:331–344.

726 Reeve AS, Warzocha J, Glaser PH, Siegel DI. 2001. Regional ground-water flow modeling of the
727 Glacial Lake Agassiz Peatlands, Minnesota. Journal of Hydrology **243**:91-100.
728 Rosa E, Larocque M, Pellerin S, Gagné S, Fournier B. 2008. Determining the number of manual
729 measurements required to improve peat thickness estimations by ground penetrating radar.
730 *Earth Surface Processes and Landforms* doi:10.1002/esp.1741.
731 Rosa E, Larocque M. 2008. Investigating peat hydrological properties using field and laboratory
732 methods: application to the Lanoraie peatland complex (Southern Québec, Canada).
733 *Hydrological Processes* **22**:1866-1875.
734 Salinas MJ, Blanca G, Romero AT. 2000. Riparian vegetation and water chemistry in a basin
735 under semiarid mediterranean climate, Andarax River, Spain. *Environmental Management*
736 **26**(5):539-552.
737 Scibek J, Allen D, Cannon AJ, Whitfield PH. 2007. Groundwater-surface water interaction under
738 scenarios of climate change using a high-resolution transient groundwater model. *Journal of*
739 *Hydrology* **133**:165-181.
740 Strack M, Waddington MJ, Tuittila ES. 2004. Effect of water table drawdown on northern
741 peatland methane dynamics: Implications for climate change. *Global Biochem. Cy.* **18**:4003-
742 4010.
743 Swan JMA, Gill AM. 1970. The origins, spread, and consolidation of a floating bog in Harvard
744 Pond, Petersham, Massachusetts. *Ecology* **51**:829–840.
745 Tarnocai, C. 2006. The effect of climate change on carbon in Canadian peatlands. *Global*
746 *Planetary Change* **53**(4):222-232.
747 Tremblay T, Nastev M, Lamothe M. 2010. Grid-based hydrostratigraphic 3D modelling of the
748 Quaternary sequence in the Châteauguay River watershed, Quebec. *Canadian Water*
749 *Resources Journal* **35**(4):377-398.
750 Waddington JM, Quinton. WL, Price JS, Lafleur PM. 2009. Advances in Canadian peatland
751 hydrology, 2003-2007. *Canadian Water Resources Journal* **34**(2):139-148.

Whittington PN, Price JS. 2006. The effects of water table draw-down (as a surrogate for climate change) on the hydrology of a fen peatland, Canada. *Hydrological Processes* **20**:3589-3600.

Winter TC. 2000. The vulnerability of wetlands to climate change: a hydrologic landscape perspective. *Journal of the American Water Resources Association* **36**(2):305-311.

Winter TC. 2007. The role of ground water in generating streamflow in headwater areas and in maintaining base flow. *Journal of the American Water Resources Association* **43**(1):15-25.

Table 1. Seasonal net precipitation, recharge, baseflows (for the gauging station locations shown in Figure 1 estimated with Champan, 1999, and simulated) and aquifer-peatland exchanged fluxes (estimated with Darcy and simulated) for the 2007-2010 period

	Spring	Summer	Fall	Winter
Net precipitation (mm)	0-132* (79)**	-66-36 (-31)	102-227 (150)	133-285 (213)
Calibrated recharge for transient state simulation (mm)	40-119 (87)	0-11 (3)	31-69 (46)	0-0*** (0)
Chapman baseflow (m^3/s)				
- Allen River	0.18-0.40 (0.26)	0.05-0.12 (0.09)	0.07-0.17 (0.12)	n.a.
- Outardes River	0.15-0.40 (0.27)	0.02-0.15 (0.07)	0.02-0.18 (0.09)	n.a.
- Schulman stream	0.018-0.024 (0.021)	0.002-0.004 (0.003)	0.001-0.002 (0.002)	n.a.
Simulated baseflow (m^3/s)				
- Allen River	0.12-0.20 (0.16)	0.09-0.10 (0.10)	0.11-0.15 (0.13)	0.08-0.09 (0.09)
- Outardes River	0.11-0.24 (0.19)	0.06-0.07 (0.07)	0.10-0.16 (0.12)	0.05-0.06 (0.06)
- Schulman stream	0.010-0.022 (0.017)	0.007-0.008 (0.007)	0.009-0.014 (0.011)	0.006-0.007 (0.007)
Darcy aquifer-peatland flow (m^3/s)	(0.0082)	(0.0076)	(0.0080)	n.a.
Simulated aquifer-peatland flow (m^3/s)	0.0047-0.0090 (0.0072)	0.0034-0.0041 (0.0037)	0.0046-0.0065 (0.0053)	0.0029-0.0034 (0.0032)

*: minimum and maximum values
**: average value
***: winter recharge is applied in the spring (i.e. when snow melts)
n.a.: data not available

768 **Table 2. Calibrated annual recharge rates for each recharge zone under current conditions**

Zone	Type of surface deposits	Calibrated recharge (mm y^{-1})
1	Peatland	372
2	Till over Flatrock	117
3	Till	219
4	Fractured bedrock	329
5	Shallow till over fractured bedrock	303
6	Fractured bedrock	183
7	Post-glacial littoral sediments	128
8	Compact till, silt and clay sediments	0

769

770

Table 3. RCM runs considered in this study (see Mearns et al. 2012 for model acronym details)

RCM	GCM	Member	Domain	Emissions scenario
CRCM4.2.3	CGCM3	5	AMNO	A2
CRCM4.2.3	CGCM3	2	AMNO	A2
CRCM4.2.3	ECHAM5	1	AMNO	A2
CRCM4.2.3	ECHAM5	2	AMNO	A2
CRCM4.2.3	Arpège UnifS2	--	AMNO	A1B
CRCM4.2.0	CGCM3	4	AMNO.	A2
HRM3	HADCM3	--	QC	A2
CRCM	CCSM	--	N. Amer.	A2
ECP2	GFDL	--	N. Amer.	A2
RCM3	CGCM3	--	N. Amer.	A2

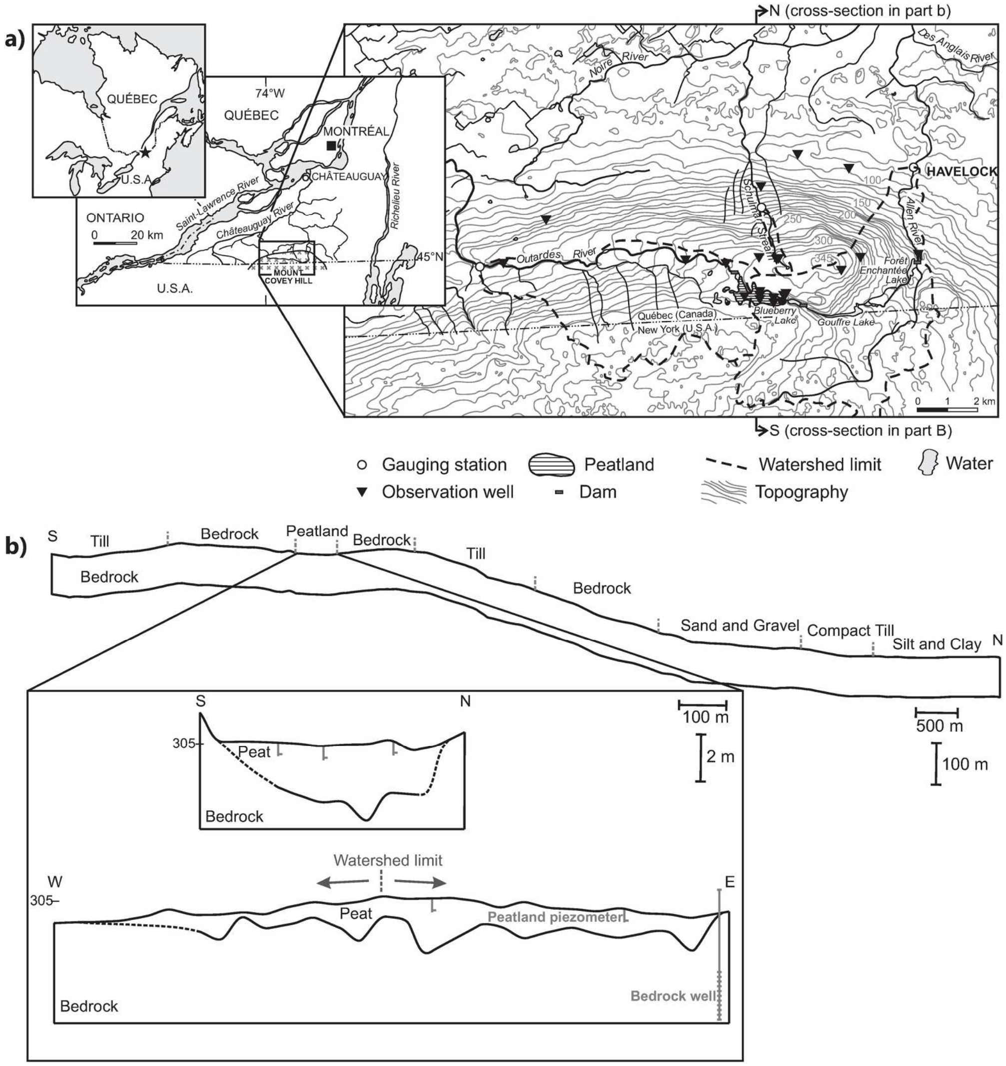
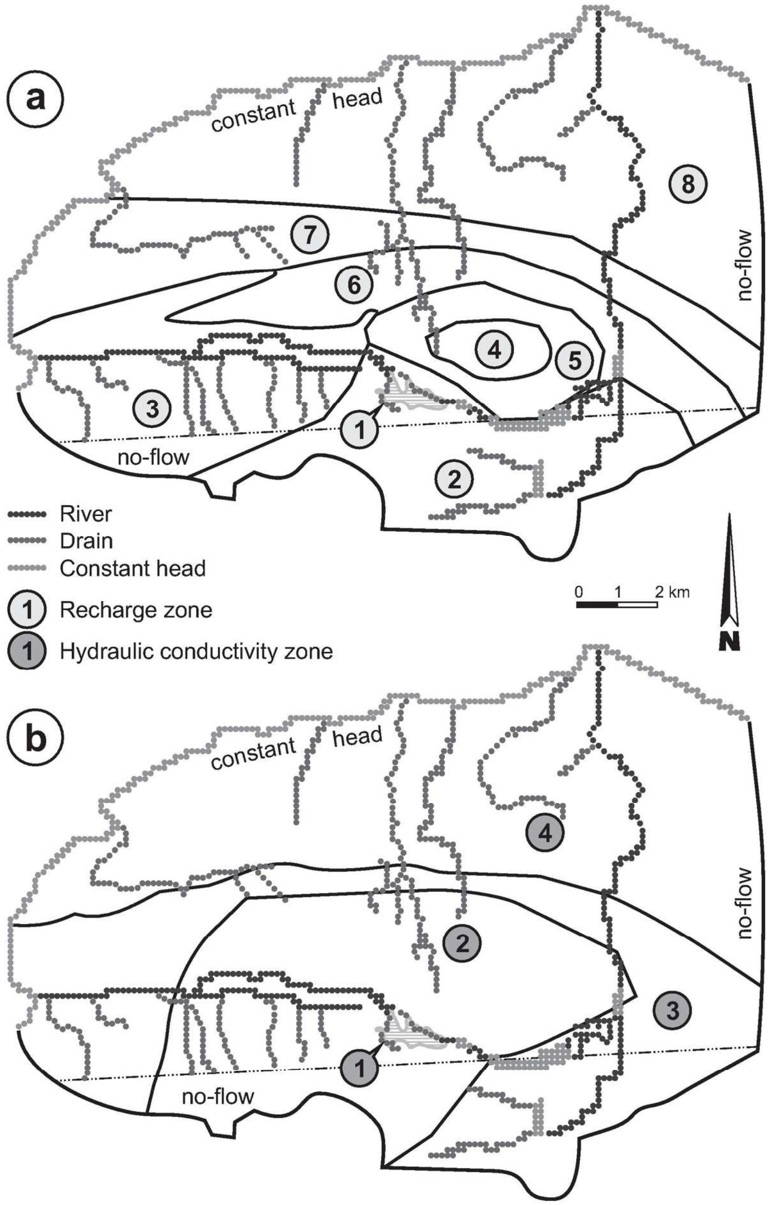
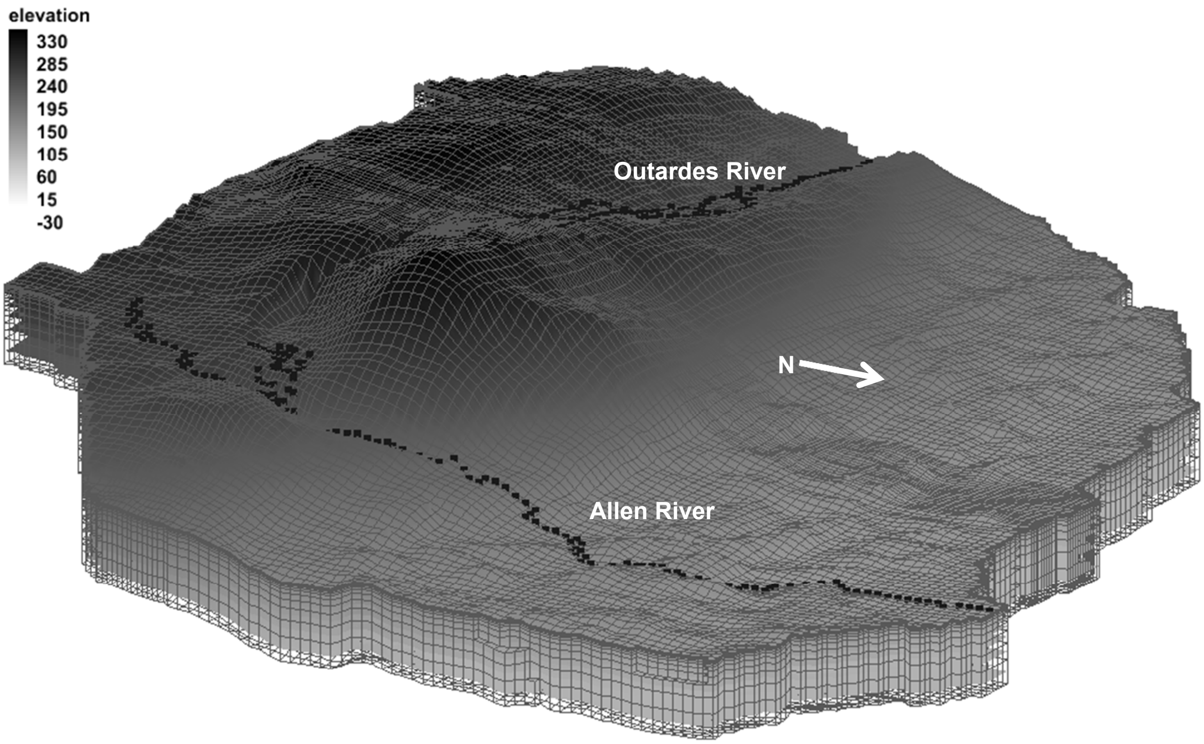
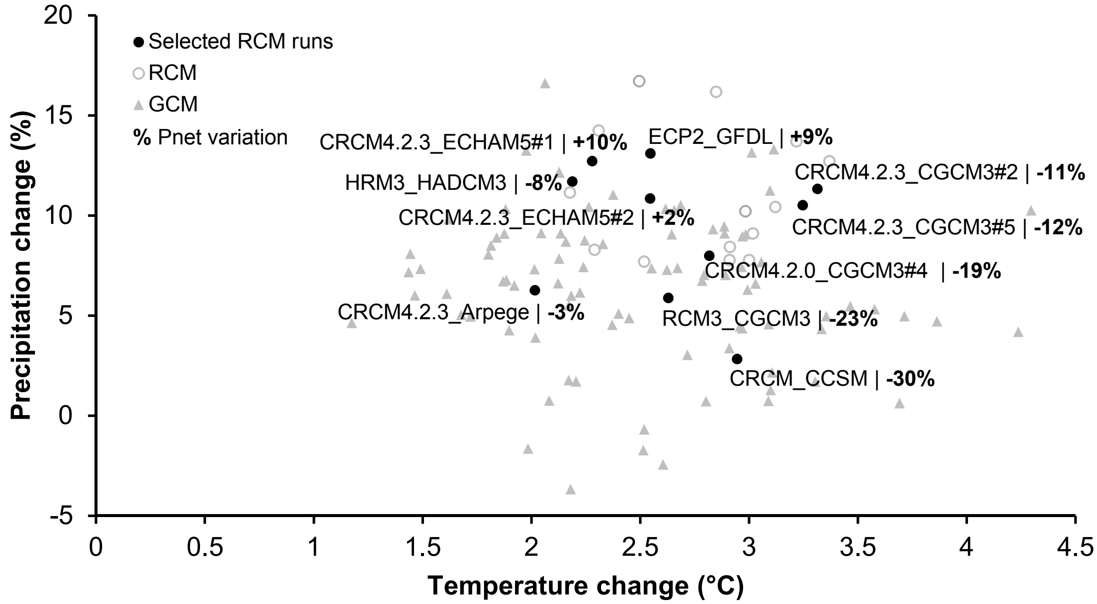


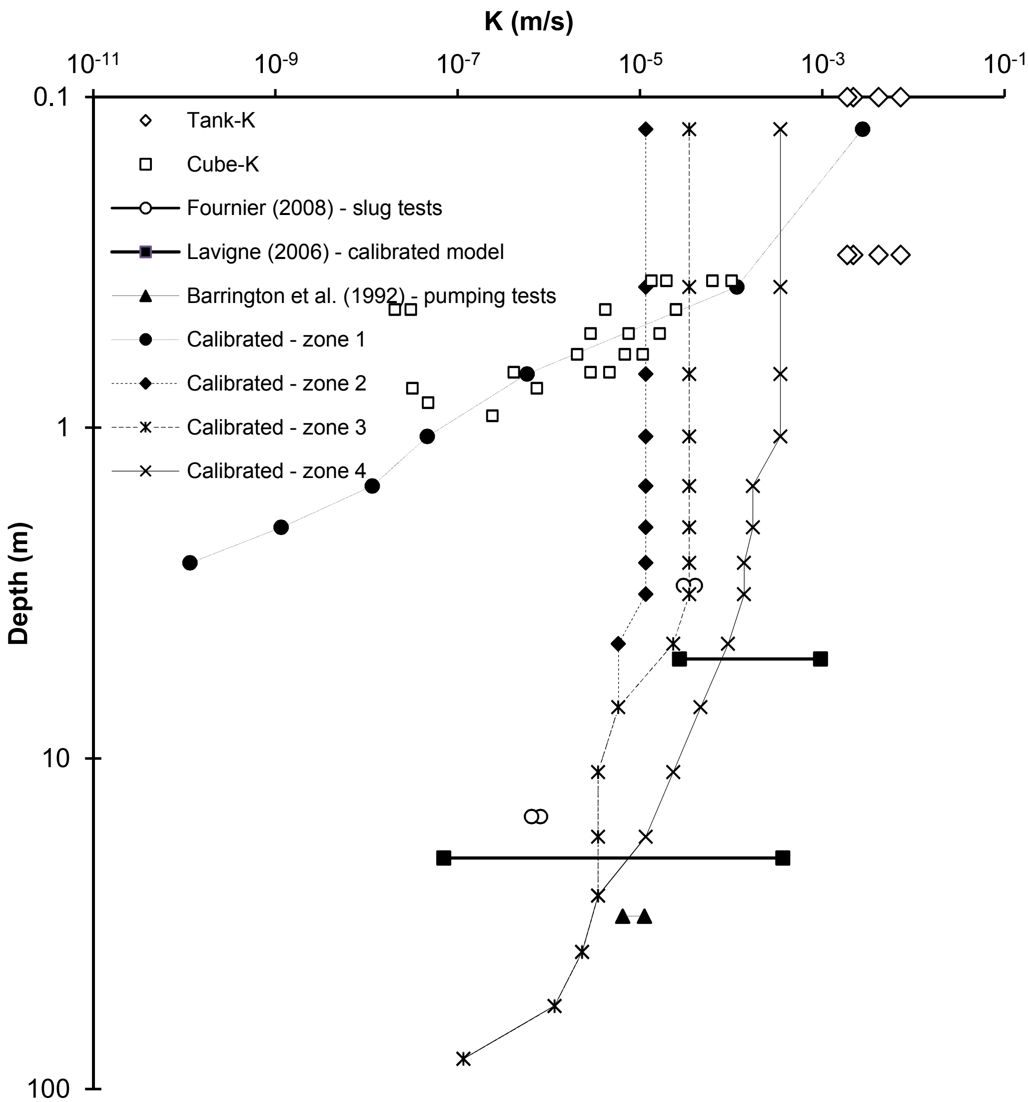
Figure 1. a) location of the Covey Hill Natural Laboratory and b) regional and peatland cross-sections. Note that SIH wells are not represented in this figure. The delineated “watershed limits” correspond to the gauging station watersheds.
188x199mm (300 x 300 DPI)

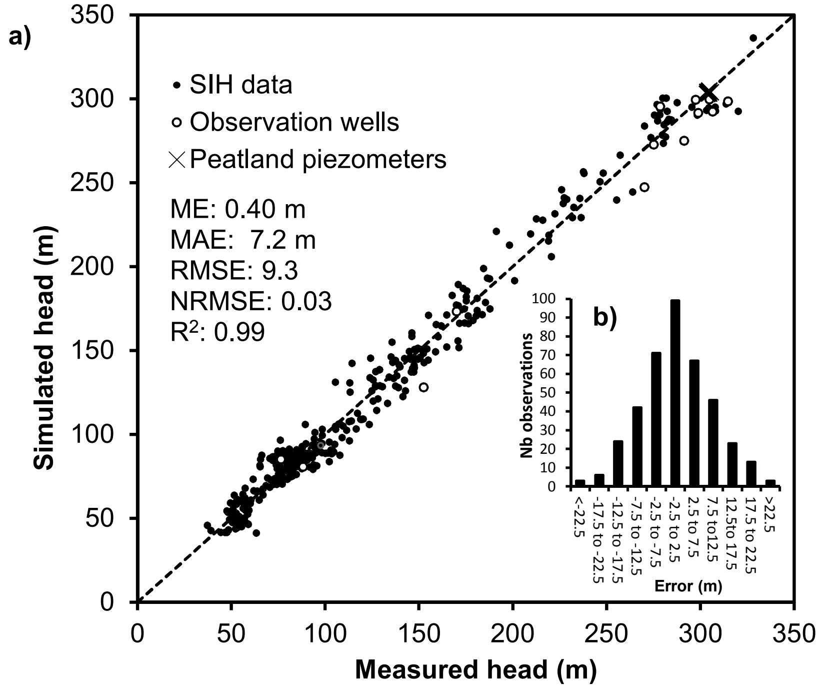


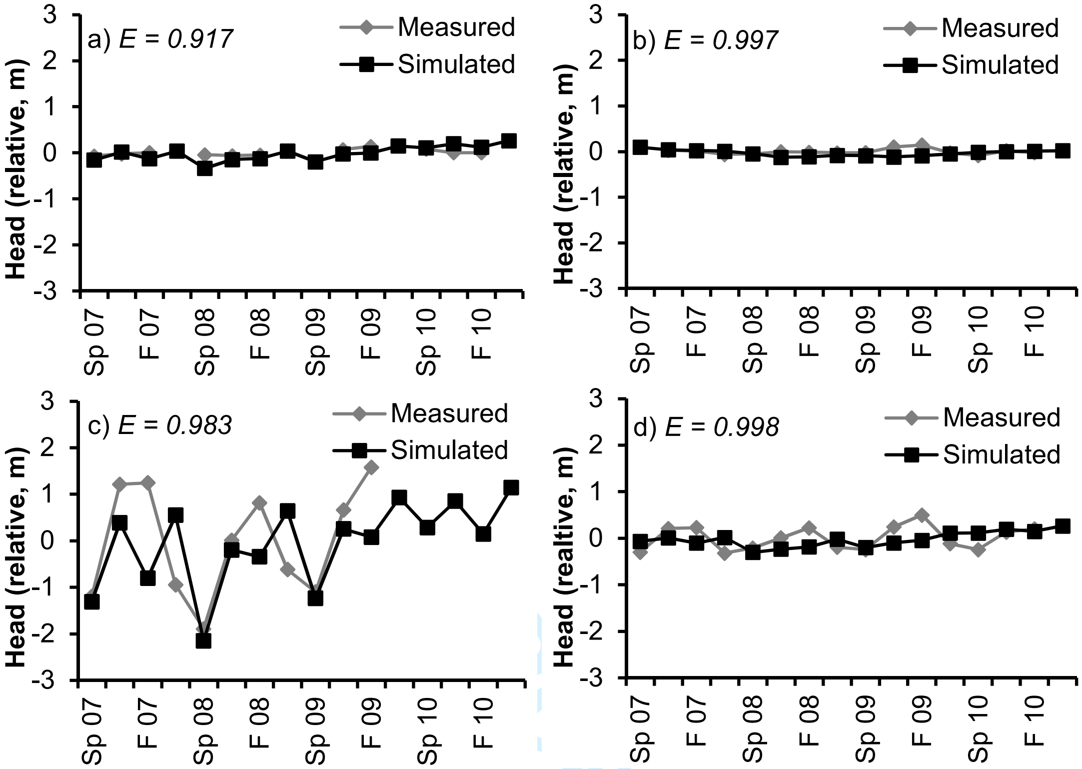
The conceptual groundwater flow model of Covey Hill: a) recharge zones and b) hydraulic conductivity zones
130x205mm (300 x 300 DPI)

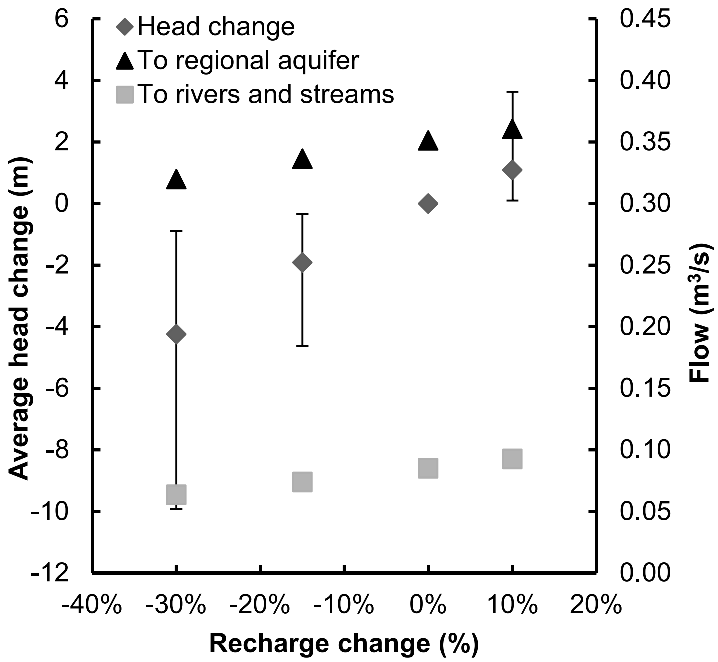

elevation
330
285
240
195
150
105
60
15
-30
Outardes River
N
Allen River

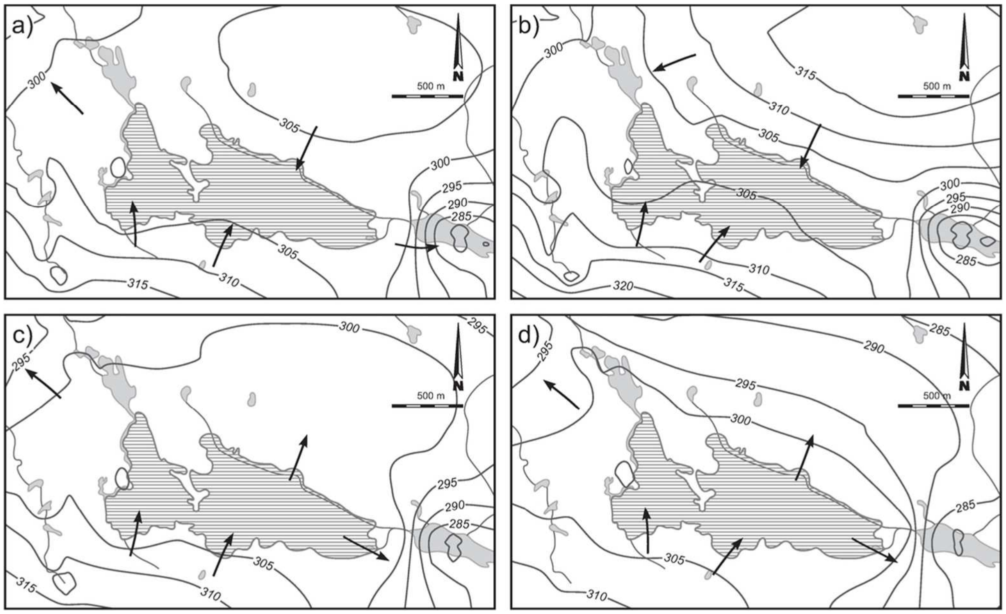

Selected RCM runs
RCM
GCM
% Pnet variation
CRCM4.2.3_ECHAM5#1 | +10%
ECP2_GFDL | +9%
HRM3_HADCM3 | -8%
CRCM4.2.3_CGCM3#2 | -11%
CRCM4.2.3_ECHAM5#2 | +2%
CRCM4.2.3_CGCM3#5 | -12%
CRCM4.2.0_CGCM3#4 | -19%
CRCM4.2.3_Arpege | -3%
RCM3_CGCM3 | -23%
CRCM_CCSM | -30%
Precipitation change (%)
Temperature change (°C)
20
15
10
5
0
-5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5


K (m/s)
10-11
10-9
10-7
10-5
10-3
10-1
0.1
1
10
100
Depth (m)
Tank-K
Cube-K
Fournier (2008) - slug tests
Lavigne (2006) - calibrated model
Barrington et al. (1992) - pumping tests
Calibrated - zone 1
Calibrated - zone 2
Calibrated - zone 3
Calibrated - zone 4

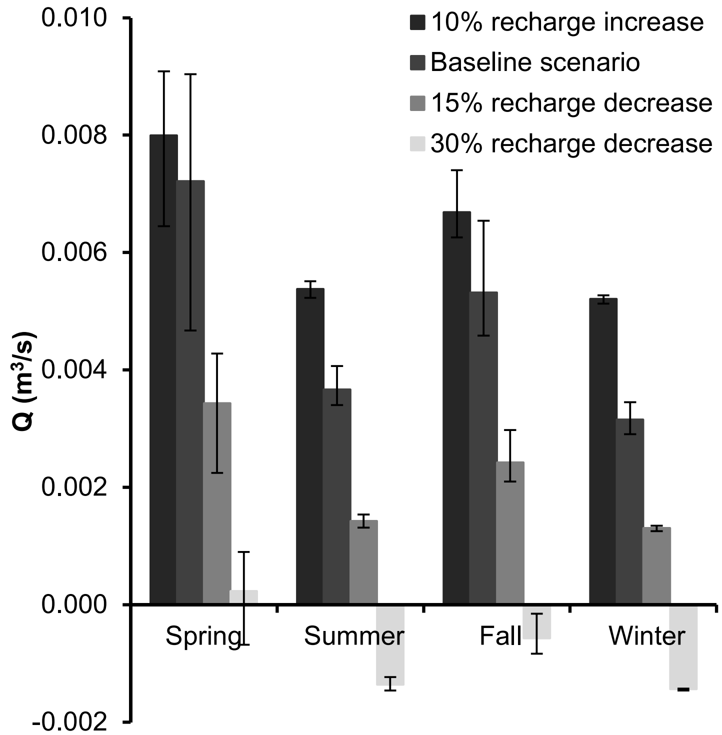

a)
SIH data
Observation wells
Peatland piezometers
ME: 0.40 m
MAE: 7.2 m
RMSE: 9.3
NRMSE: 0.03
R^2: 0.99
Simulated head (m)
Measured head (m)
b)
Nb observations
Error (m)
<-22.5
-17.5 to -22.5
-12.5 to -17.5
-7.5 to -12.5
-2.5 to -7.5
-2.5 to 2.5
2.5 to 7.5
7.5 to12.5
12.5to 17.5
17.5 to 22.5
>22.5


a) *E = 0.917*
b) *E = 0.997*
c) *E = 0.983*
d) *E = 0.998*
Measured
Simulated
Head (relative, m)
Head (realtive, m)
3
2
1
0
-1
-2
-3
Sp 07
F 07
Sp 08
F 08
Sp 09
F 09
Sp 10
F 10


Head change
To regional aquifer
To rivers and streams
Average head change (m)
Flow (m³/s)
Recharge change (%)
6
4
2
0
-2
-4
-6
-8
-10
-12
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
-40%
-30%
-20%
-10%
0%
10%
20%



Simulated flow directions in the peatland contribution area a) for spring 2010, and for the recharge scenarios b) 10% increase, c) 15% decrease and d) 30% decrease
103x62mm (300 x 300 DPI)


0.010
0.008
0.006
0.004
0.002
0.000
-0.002
Q (m³/s)
10% recharge increase
Baseline scenario
15% recharge decrease
30% recharge decrease
Spring
Summer
Fall
Winter