Simulation of aquifer-peatland-river interactions under climate change

M. A. Bourgault, M. Larocque and M. Roy

ABSTRACT

Wetlands play an important role in preventing extreme low flows in rivers and groundwater level drawdowns during drought periods. This hydrological function could become increasingly important under a warmer climate. Links between peatlands, aquifers, and rivers remain inadequately understood. The objective of this study was to evaluate the hydrologic functions of the Lanoraie peatland complex in southern Quebec, Canada, under different climate conditions. This peatland complex has developed in the beds of former fluvial channels during the final stages of the last deglaciation. The peatland covers a surface area of ~76 km^2 and feeds five rivers. Numerical simulations were performed using a steady-state groundwater flow model. Results show that the peatland contributes on average to 77% of the mean annual river base flow. The peatland receives 52% of its water from the aquifer. Reduced recharge scenarios (−20 and −50% of current conditions) were used as a surrogate of climate change. With these scenarios, the simulated mean head decreases by 0.6 and 1.6 m in the sand. The mean river base flow decreases by 16 and 41% with the two scenarios. These results strongly underline the importance of aquifer-peatland-river interactions at the regional scale. They also point to the necessity of considering the entire hydrosystem in conservation initiatives.

Key words | aquifer, climate change, Lanoraie (Québec, Canada), peatland, river

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INTRODUCTION

Peatlands comprise over 50% of the world's wetlands (Bragg & Lindsay 2003) and represent over 90% of Canadian wetlands (Tarnocai 1998). They are well recognized for their role in sequestrating atmospheric CO_2 and CH_4 (Roulet 2000; Yli-Petays et al. 2007; Worrall et al. 2011). Peatlands also represent important ecosystems and valuable wildlife habitats, which provide a wide range of benefits to humans, such as limiting floods, sustaining river base flows, and maintaining high groundwater levels over large areas (Dowrick et al. 2006; Querner et al. 2010). Unfortunately, wetland loss and degradation currently represent a major cause of concern for peatland sustainability (Finlayson et al. 1999). Human activities such as urban expansion, agriculture (Poulin et al. 2004), and climate change (Wattendorf et al. 2010) are considered the main causes for worldwide wetland degradation. The growing recognition of the importance of peatlands as ecosystems has led to a recent increase in peatland hydrology studies. Consequently, there has been a growing appreciation of these systems as vital economic and ecological resources, because they contribute to biological, landscape, and cultural diversity (Bragg & Lindsay 2003).

Many peatlands are groundwater-fed by local or regional aquifer systems. Although studies have pointed to the importance of peatlands on the watershed water balance, groundwater recharge, base flows, and river flow variability (e.g. Bullock & Acreman 2003), the mechanisms connecting peatlands to local or regional groundwater flows, or to rivers, remain incompletely understood.

Hydraulic conductivities of the surrounding aquifer, peatland topography (Bradley & Gilvear 2000), the extent of the unsaturated zone in the peat (Reeve et al. 2000),

recharge to the organic deposits (Delin *et al.* 2007), and peat specific storage (Reeve *et al.* 2006) are among the parameters and processes known to influence peatland hydrology. Conceptual models such as the acrotelm-catotelm model (Hilbert *et al.* 2000; Holden & Burt 2003) and the double porosity model (Rossi *et al.* 2012) have been proposed to understand water dynamics within a peatland and its influence at regional scale. Reeve *et al.* (2001) have shown through simulations that groundwater contribution to peatlands can be dominated by a local and subregional flow. Peatland hydrology is also strongly influenced by land uses (drainage, agriculture, groundwater extraction, peat mining) (Foley *et al.* 2005; Candela *et al.* 2009) and climate change (Whittington & Price 2006).

Numerical models have proven effective to better understand peatland hydrology, particularly in characterizing flow processes occurring at the peatland surface (Holden *et al.* 2008) and subsurface flow processes such as aquifer-peatland exchanges (Fraser *et al.* 2001). For example, Kvaerner & Klove (2008) have used hydrological modeling to show that during low flow periods water within rivers originated mainly from peat storage while during high flow streams were feeding the peatland. However, relatively few studies report the use of a hydrogeologic numerical model to understand the influence of peatland on the regional hydrology under climate and human-induced perturbations. One example is the study of Levison *et al.* (2013) who showed that a headwater peatland could switch from an aquifer-fed peatland to an aquifer-recharging peatland under climate change-induced recharge reduction.

The objective of this study was to evaluate the hydrologic functions of a peatland under different climatic conditions. The study site is the Lanoraie peatland complex located in southern Quebec (Canada). This peatland complex is the largest in southern Quebec (76 km^2) and it is the site of an ecological preservation known as the *Réserve écologique des Tourbières-de-Lanoraie* (4.2 km^2). This site has been studied for various aspects over many years (Comtois 1982; Aménatech 1989; Rosa & Larocque 2008; Rosa *et al.* 2009; TechnoREM 2009; Tousignant *et al.* 2010; Lamarre & Pellerin 2011). TechnoREM (2009) has developed a regional-scale groundwater flow model to simulate flows in the superficial aquifer. Although it covers the Lanoraie peatland complex, this model does not represent the organic deposits as a heterogeneous porous media, nor does it simulate aquifer-peatland-river exchanges. In the current study, a tridimensional groundwater flow model is built to simulate specifically these regional aquifer-peatland-river exchanges. The model includes a detailed tridimensional representation of the peatland complex. This model is calibrated for current conditions and it is used to simulate decreasing recharge scenarios resulting from changing climate conditions. Increased pumping of groundwater for irrigation and human consumption is also considered as an additional stress to the hydrosystem.

STUDY SITE AND METHODS

Study area

The Lanoraie peatland complex (45′58″ N, 73′20″ W) is located 40 km northeast of Montreal (Quebec, Canada) (Figure 1(a)). The peatland complex is part of a hydrosystem composed of five catchment areas (Saint-Joseph, Point-du-Jour, Saint-Jean, Saint-Antoine and Bras-sud-ouest rivers) where surface water and groundwater are used for human consumption and agriculture. The average monthly air temperature ranges from −11.4 °C in January to 20.6 °C in July. The average total annual precipitation is approximately 1,019 mm/yr, 20% of which falls as snow (Ministère du Développement durable, de l'Environnement, de la Faune et des Parcs (MDDEFP) 2012). The Lanoraie peatland is mostly composed of minerotrophic peat, but also includes three ombrotrophic areas (Figure 1(a)).

The Lanoraie peatland complex region has a strong agricultural vocation and 84% of the territory is used for agriculture (TechnoREM 2009). The major crops are potatoes, carrots, onions, sweet corns, squashes, cranberries and strawberries. In many locations, irrigation water comes from pumped groundwater or is harvested from small reservoirs excavated at the border of the peatland.

Some areas of the peatland have been completely drained for the construction of small roads, for organic soil production and for agriculture. A vegetation analysis carried out in the peatland complex shows that 'abiotic'
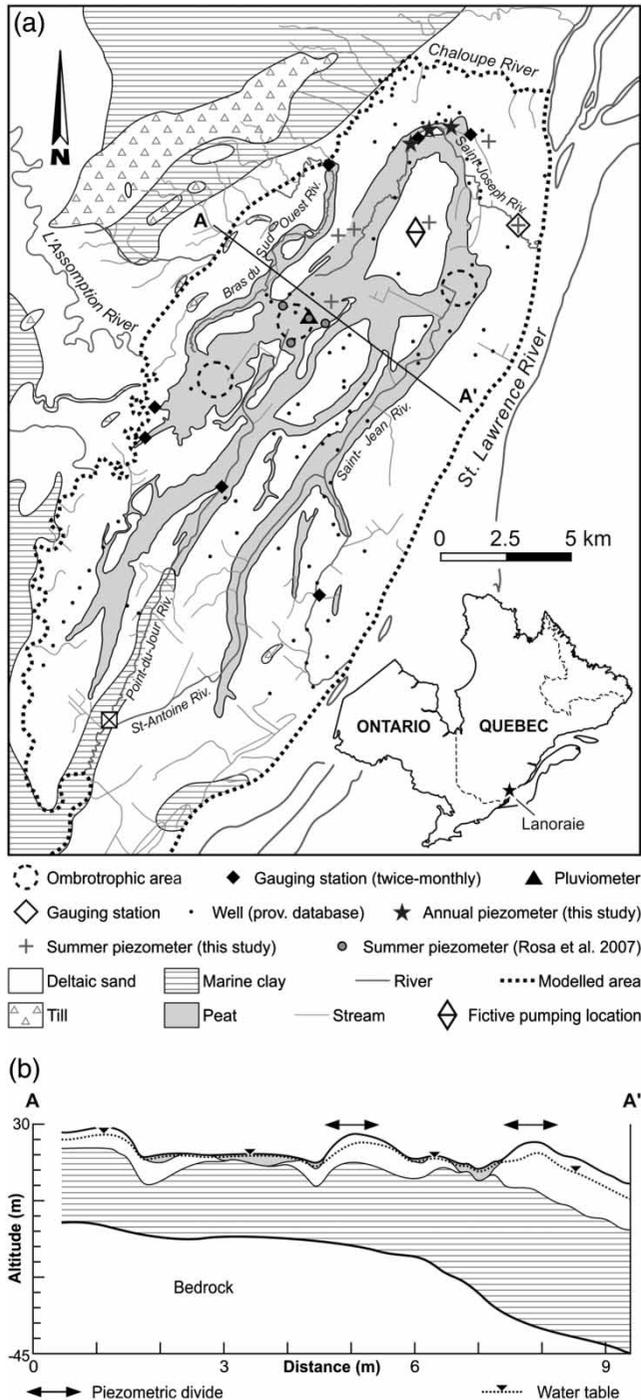
Figure 1 | Location, geology and measurements of the Lanoraie peatland complex (Quebec, Canada): (a) plan view and modeled area (black dash line surrounding the region) and (b) cross-section AA'.

and 'anthropogenic' disturbances in the peatland explain 47 and 24% of the variation in the vegetation composition, respectively (Tousignant *et al.* 2010).

The Lanoraie peatland complex lies on Quaternary glacial sediments that have distinct hydrogeological characteristics. The lowest part of the sedimentary sequences is composed of marine clay and lacustrine silt associated with the postglacial Champlain Sea and the Lampsilis Lake (Occhietti *et al.* 2011), respectively, which invaded the isostatically-depressed terrain immediately following ice retreat. In the model, these two units were combined based on their hydrodynamics properties and called the marine clay aquitard (Bourgault *et al.* 2011). Chronological constraints (radiocarbon, ^{14}C, dating) indicate that this aquitard unit was deposited between 12 ky BP and 9.8 ky BP (Richard & Occhietti 2005). It is a major hydrogeological unit that can be found throughout the St. Lawrence Lowlands up to an altitude of 235 m (Occhietti *et al.* 2011). This aquitard unit is overlain by thick sandy sediments deposited within a large deltaic complex during the regression of the marine waters in response to the glacial isostatic adjustment (rebound) following deglaciation. Continued isostatic rebound drove the shoreline southeastward, near the present position of the St. Lawrence River. The deltaic sands were then subject to fluvial erosion and remobilization. The superficial free water table aquifer used for human consumption and irrigation is located in the sand deposits.

The peatland complex subsequently developed in paleochannels of the St. Lawrence River. The peat deposits started accumulating in low-lying depressions oriented in a SW-NE axis around 6.9 ky BP (Comtois 1979). The organic deposits lay on deltaic sand (aquifer) and lacustrine silt and marine clay (aquitard) deposits, which together provide a hydrogeological environment allowing connections with the regional aquifer (Figure 1(b)). The peatland and the deltaic sand now form the main superficial reservoirs, with mean thicknesses of 2.6 m (varying between 2 and 8.4 m) and 6.5 m (varying between 1 and 19 m), respectively (Rosa *et al.* 2009; Bourgault *et al.* 2011). Bourgault *et al.* (2011) have shown that the bedrock topography rises considerably below the peatland complex (Figure 1(b)), forming high and low terrace areas. The high terrace area surrounding the peatland is characterized by the presence of small sand ridges where piezometric levels are higher than the peatland water table in the peatland itself (Figure 1(b)).

Available data

Gridded climatic data were generated by the Centre d'expertise hydrique du Québec (Poirier *et al.* 2012), an agency from the Quebec Ministry of Environment (Ministère du Développement durable, de l'Environnement, de la Faune et des Parcs – MDDEFP). The spatial interpolation method relies on measured values at climatological stations. These stations, mainly owned by the MDDEFP, are operated by the ministry's branch of atmospheric monitoring activities (Direction du suivi de l'état de l'environnement (DSÉE) – Service de l'information du milieu atmosphérique (SIMAT)) through a climate monitoring program. The interpolation has been performed at a daily time step, using simple isotropic kriging with monthly mean variograms at a 0.1 degree resolution over southern Quebec (see Poirier *et al.* (2012) for more details). The available data cover the 1900–2010 period. This study makes use of kriged data of mean temperature and vertical inflows (*VI*). Vertical inflows correspond to the simulated amount of water available for infiltration based on the snowmelt module in the HYDRO-TEL model (see Poirier *et al.* (2012) for more details).

At the study area, the interannual mean vertical inflows and air temperature from 1960 to 1990 are 941 mm and 5.8 °C. For this period, air temperature was used to calculate potential evapotranspiration (ETP), based on the method outlined in Oudin *et al.* (2005). The average ETP calculated for the 1960–1990 period is 590 mm/yr.

The steady-state groundwater flow model was calibrated using head measurements from 150 boreholes obtained from TechnoREM (2009), Rosa & Larocque (2008), Aménatech (1989) and Terratec (1987) (see Figure 1(a)). This number of heads is sufficient to capture steady state conditions because they were measured during wet and dry seasons. Piezometric heads were monitored hourly (INW-PT2X pressure transducers) at nine piezometer stations installed specifically for this study (three in the peatland and six in the sand aquifer). Of these stations, three were monitored year-round while the others were monitored only during the summers 2011–2012 due to the extensive snow cover that prevails during the winter months. The piezometers consist of 3 cm OD polyvinyl chloride (PVC) pipes, sealed at their base and equipped with 1 m long intakes within sand deposits and 30 cm within peat deposits

(the well screen creating a 50% porosity zone in the lower part of the pipe). Within the peatland, the piezometers were inserted down to 1 m below the peat surface whereas in the sand, they were inserted 1 m below the ground.

Discharge measurements and water levels are available on a daily basis from 2000 to 2005 on the Point-du-Jour River gauging station (no. 052236, hydrometric network operated by the Centre d'expertise hydrique du Québec (CEHQ)) and from 1989 to 2010 on the St. Lawrence River gauging station (no. 000116-CEHQ). The station on the Point-du-Jour River is located 1.5 km upstream of the l'Assomption River and drains a 70.3 km^2 watershed (Figure 1(a)). In the current study, a gauging station was installed for water-level measurements (TrueTrack sensor; rating curve) on the Saint-Joseph River during the 2011 summer. This station is located at 500 m upstream and drains a 40 km^2 watershed. River discharge was also measured every 2 weeks at different locations on the rivers during the summers of 2005 (unpublished data) and 2011 (this study), using a Swoffer 2100 velocimeter (see Figure 1(a)).

Base flows were estimated using the Chapman base flow separation method (Chapman 1999) and are evaluated to be 0.28 ± 0.1 m^3/s and 0.30 ± 0.1 m^3/s for the Saint-Joseph and Point-du-Jour rivers, respectively. The uncertainty on annual base flows was evaluated using a mean error of 25% on the flow data measurements used to calibrate the rating curves. This error value is similar to the one suggested by Di Baldassarre & Montanari (2009).

River flows for the other rivers were estimated using bi-monthly manual measurements (cross-section method based on flow velocities). They range from 0.04 to 1.00 m^3/s for the Saint-Jean River, from 0 to 0.80 m^3/s for the Saint-Antoine River and from 0 to 0.67 m^3/s for the Bras-sud-ouest River. Some of the river flow measurements were made after several days without rain and are a good range for base flow approximations. The absence of discharge found in the Saint-Jean and Saint-Antoine rivers is caused by the presence of man-made dams used to supply agriculture water needs during droughts periods.

Peat hydraulic conductivities (K_{peat}) were estimated by Rosa & Larocque (2008) using the Modified Cubic Method and slug tests. Peat hydraulic conductivities range from 0.1 m/s for the upper part of the peat to 1×10^{-8} m/s for

the lower part of the peat, with a mean vertical anisotropy (Kv/Kh) of 1.3 and a general decreasing pattern with depth. The sand hydraulic conductivities (K_{sand}) range from 5×10^{-4} to 3×10^{-6} m/s, with an average value of 1×10^{-4} m/s and a general vertical decreasing trend proportional to depth (with no more than one order magnitude variation) (Rosa 2007; TechnoREM 2009). The sand hydraulic conductivities generally increase towards the south in association with the delta morphology. This reflects the fact that coarser particles tend to be deposited close to former shorelines, as well as on the periphery of the delta, in response to the severe changes in transport dynamic associated with a delta.

Elevation data were obtained from the Quebec Ministry of natural resources (Ministère des Ressources naturelles (MRN)) as well as from differential global positioning system (GPS) surveys (513 points) measured by Techno-REM (2009), Polygéo (2008), Rosa (2007), Aménatech (1989), Terratec (1987) and during this study (mean error 2.5 cm). Using these data, a digital elevation model was built and forced on river bed elevations based on 30 differential GPS measurements. In the study area, the elevation ranges from 7 to 32 m. Errors on topography vary between −4.1 and 5.2 m with a mean value of 0.02 m, a standard deviation of 1.23 m and an absolute error of 0.50 m in the upper unconfined sandy aquifer. Using a 95% confidence interval, all cells containing head measurements that were used for model calibration have a maximum error on topography of ±15 cm.

Model development

Numerical model

Groundwater flow is simulated in steady-state using the groundwater flow module of the Mike SHE model (Thompson *et al.* 2004; Danish Hydraulic Institute (DHI) 2011). The model covers an area of 364 km^2 discretized in 250 m × 250 m grid cells. No-flow boundaries limit groundwater flow at the base and periphery of the model. This no-flow boundary in the north-west part of the model is justified by the fact that both the Chaloupe and l'Assomption rivers are flowing on marine clay sediment, hence intercepting completely the upper unconfined sandy deltaic aquifer.

The southernmost limit is represented with a fixed head boundary (Figure 2(a)). The use of a fixed head boundary to represent the St. Lawrence River is justified by its limited water level variations (≈3 m in the last 22 years at gauging station no. 000116) due to strong controls from a series of dams.

Rivers are represented as head-controlled flux while river base flows are controlled by leakage coefficients (L_c). Drains and natural streams are represented in the model as drains located 1 m below the surface. In reality, most of these drains are minor ditches and creeks too small to be represented as a head-controlled flux. Some
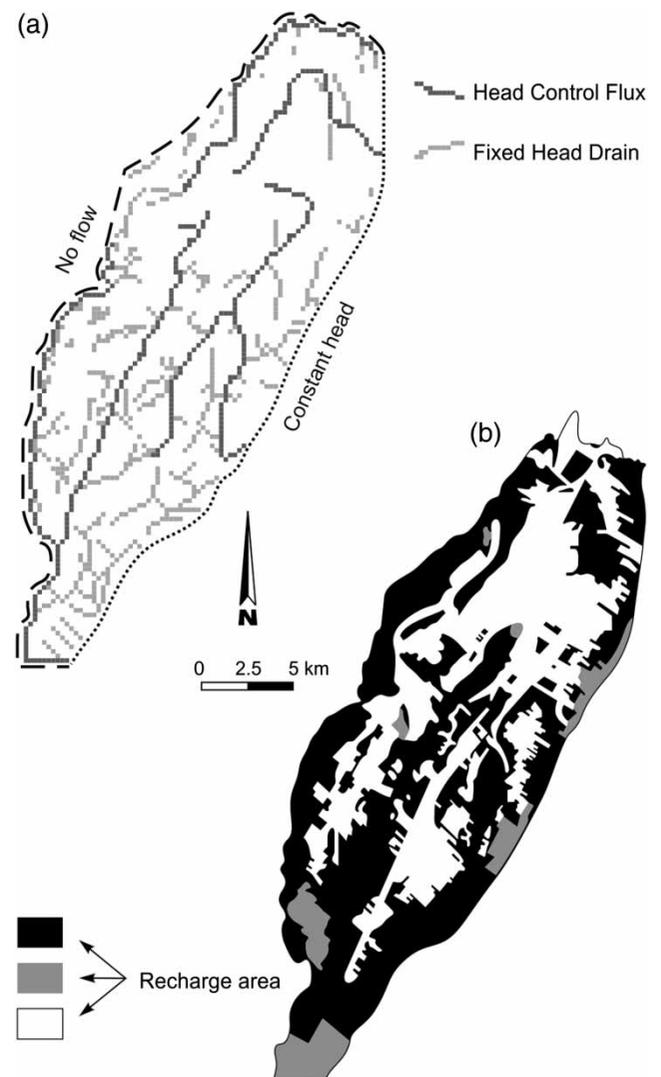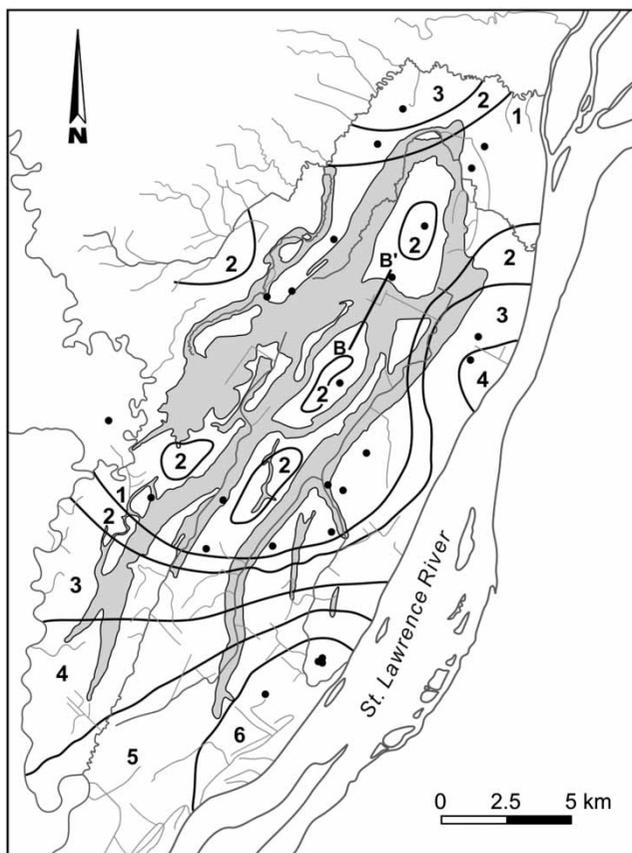

Figure 2 | Conceptual groundwater flow model (a) boundary conditions (b) recharge zones (modified from TechnoREM (2009) and aerial photography analysis).

drains are found within the peatland where the organic deposits have been perturbed for the construction of small roads. Others are found on the edge of the peatland where small reservoirs are excavated to store water for the growing season.

Three recharge zones are used (Figure 2(b)), based on the spatial discretization from TechnoREM (2009): zone 1 corresponds to the sand aquifer; zone 2 corresponds to urban and more densely paved areas; and zone 3 corresponds to the peatland. According to TechnoREM (2009), recharge ranges between 71 and 389 mm/yr with a regional mean value of 230 mm/yr.
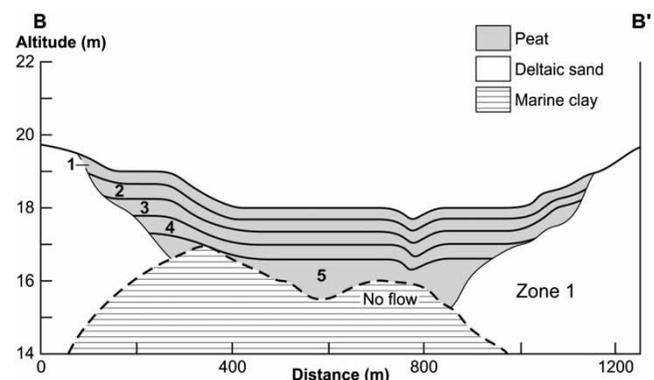
Hydraulic conductivities of the sand aquifer are discretized into six zones, based on field measurements from different sources (Aménatech 1989; TechnoREM 2009; Bourgault *et al.* 2011) (Figure 3). This zonation, based on simple

kriging, can be correlated to different sedimentary facies associated with the deltaic depositional processes. Large particles (zone 3 to zone 6) tend to accumulate on the periphery of the delta forming high hydraulic conductivity regions, as observed in others studies (Kostic *et al.* 2005; Ouellon *et al.* 2008). The choice to use a single layer for the sand aquifer is based on fact that most of the aquifer-peatland interactions are located within the first meter of the saturated zone where sand hydraulic conductivities vary by less than one order of magnitude (Rosa 2007; TechnoREM 2009). Peat hydraulic conductivities are discretized vertically into five different layers because of the large vertical variations reported for this peatland (Rosa & Larocque 2008). A thickness of 0.5 m is used for each of the four upper layers and the bottom layer has a variable thickness where the total peat thickness exceeds 2 m (Figure 4). The peat hydraulic conductivity is considered homogeneous horizontally.

The model was calibrated using groundwater levels in 150 wells (see Figure 1(a)), as well as river base flows from the two gauging stations located on the Point-du-Jour and Saint-Joseph rivers. The manual river-flow measurements were also used to calibrate the model, which are considered to provide a reliable approximation of river base flow during dry periods. Hydraulic conductivities of the sand aquifer K-zones (zone reflecting spatial horizontal hydraulic conductivity variations related to delta morphology) and of the organic deposits K-layers (layer reflecting vertical variations of horizontal hydraulic conductivities related to peat forming environment) were

Figure 3 │ Hydraulic conductivity zones (numbers 1 to 6 refer to sand K-zones, see Table 3 for values, and black lines represent zone limits) and sand hydraulic conductivity measurements (black dots represent location of hydraulic tests and slug tests from Bourgault *et al.* (2011), TechnoREM (2009) and Aménatech (1989)). BB′ refers to the cross section illustrated in Figure 4.

Figure 4 │ Vertical discretization of peat hydraulic conductivities. Numbers 1 to 5 refer to calibrated peat K-layers (see Table 3 for values).

subjected to calibration, along with zonal recharge values and leakage coefficients.

Average relative sensitivity coefficients (S_r) (McCuen 1973) were calculated using Equation (1). Model sensitivity was computed for all the calibrated parameters (K_{sand}, K_{peat} for layers 1 and 2, mean recharge and leakage coefficients) and the analysis focused on the effect of varying these parameters on heads and base flows.

$$S_r = (\Delta F/F_{ref})/(\Delta X/X_{ref}) \tag{1}$$

where S_r is the relative sensitivity coefficient, F is the result being considered (heads and base flows) and X is the modified parameter. F_{ref} corresponds to the model result obtained with the calibrated parameter X_{ref}.

Climate change scenarios

Changes in regional temperature and precipitation can affect recharge considerably (Eckhardt & Ulbrich 2003). In this study, global climate models (GCM) were used to outline different recharge scenarios (Pacific Climate Impacts Consortium (PCIS) 2012). Six projections were selected based on two criteria: (1) maximum temperature increases during recharge periods and (2) maximum decrease in predicted precipitation. All the selected simulations are from the GCM3 model (third generation coupled global climate model developed by the Canadian Center for Climate Modelling and Analysis) for the climate of the 2040–2069 period.

They are based on the delta method, which consists of perturbing baseline meteorological data (here the 1960–1990 period) with monthly variations derived from the difference between future climate scenarios and the reference period. One B1, three A1B and two A2 scenarios were selected representing low, medium, and high CO_2 scenarios, respectively (Green *et al.* 2011).

These criteria were chosen to understand the hydrological function of the peatland in connection with the regional aquifer and the river network within the context of changing climate conditions. It is not intended to study the complete possible range of precipitation and temperature effect associated with climate change on the recharge. Possible increases in recharge reported in some studies (e.g. Jyrkama & Sykes 2007; Levison *et al.* 2013) were deliberately put aside.

The selected GCM runs project summer temperatures to increase between 2.0 °C (CGCM3 A1B-run3) and 3.2 °C (CGCM3_T63 A1B-run1). Winter temperatures are projected to increase between 3.0 °C (CGCM3 B1-run5) and 4.4 °C (CGCM3_T63 A1B-run1). These increases far exceed the temperature increase of $\approx$1 °C observed in the Lanoraie region for the 1960 to 2005 period (Yagouti *et al.* 2006). Annual precipitation changes are projected to vary between a decrease of 10% in summer (CGCM3 A2 run-3) and an increase of 44% during winter and fall (CGCM3 A1B) (see Table 1).
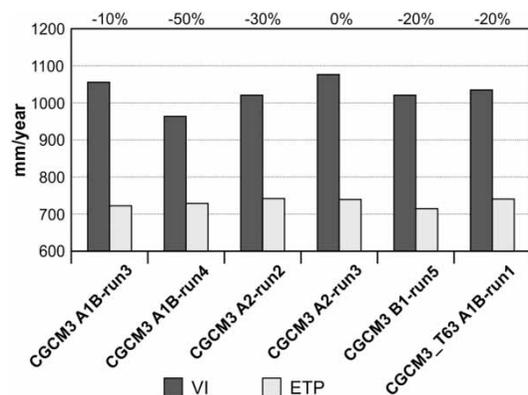
Estimated ETP values for the range of temperature changes vary from 722 mm/yr (CGCM3 A1B-run3) to

Table 1 │ Seasonal temperature (°C) and precipitation (percentage of vertical input) changes for the six selected Canadian GCM in the 2040–2069 horizon (PCIS 2012)

Temperature (°c)	CGC3 A1B-run3	CGCM3 A1B-run4	CGCM3 A2-run2	CGCM3 A2-run3	CM3 B1-run5	CGCM3_T 63 A1B-run1
Winter	3.4	3.4	4.2	4.0	3.0	4.4
Spring	2.7	2.9	3.2	3.0	2.4	3.0
Summer	2.0	2.8	3.0	2.9	2.3	3.2
Fall	2.5	2.9	3.3	3.0	2.5	2.9
Precipitation (%)	**CGCM3 A1B-run3**	**CGCM3 A1B-run4**	**CGCM3 A2-run2**	**CGCM3 A2-run3**	**CM3 B1-run5**	**CGCM3_T 63 A1B-run1**
Winter	44	20	30	31	22	28
Spring	28	10	17	27	30	21
Summer	− 5	− 4	− 10	− 4	− 5	− 10
Fall	44	20	30	31	22	28

743 mm/yr (CGCM3 A2-run2) and are considerably higher than the ETP for the 1960 to 1990 reference period (590 mm/yr). ETP for the climate scenarios was calculated using the Oudin *et al.* (2005) formula with the predicted air temperature derived from the monthly temperature changes for the 2040–2069 horizon. Predicted monthly precipitation changes for the 2040–2069 horizon were applied to the vertical inflow data from the 1960–1990 reference period. Future recharge was estimated for each scenario by applying the net precipitation recharge reduction to the calibrated recharge values. This is based on the hypothesis that overland flow will decrease in the same proportion as recharge in a changing climate. Recharge is estimated to remain the same in one scenario (CGCM3 A2-run3) and to decrease for the other five scenarios between 10 and 50% (Figure 5). Most of the literature-based studies on climate-induced recharge reductions in Canadian settings show a range of possible increases and decreases of recharge (Jyrkama & Sykes 2007; Scibek & Allen 2006; Croteau *et al.* 2010; Levison *et al.* 2013). The recharge decreases are consistent with those obtained here. To facilitate the simulations, two recharge scenarios representing a reasonable range of predicted recharge considered in this work were simulated, i.e., 20% decrease and 50% decrease.

These scenarios undoubtedly represent crude simplifications, especially considering that climate change may impact water resources on time scales shorter than 1 year (Maxwell & Kollet 2008) and never reach a complete steady-state.

Nonetheless, this approach provides a sensitivity analysis that brings valuable information on the influence of a peatland on the regional aquifer and river network in a climate change environment.

RESULTS AND DISCUSSION

Actual peatland and aquifer groundwater dynamics

A piezometric map of the Lanoraie region (Figure 6) was drawn using simple kriging based on 1550 available heads
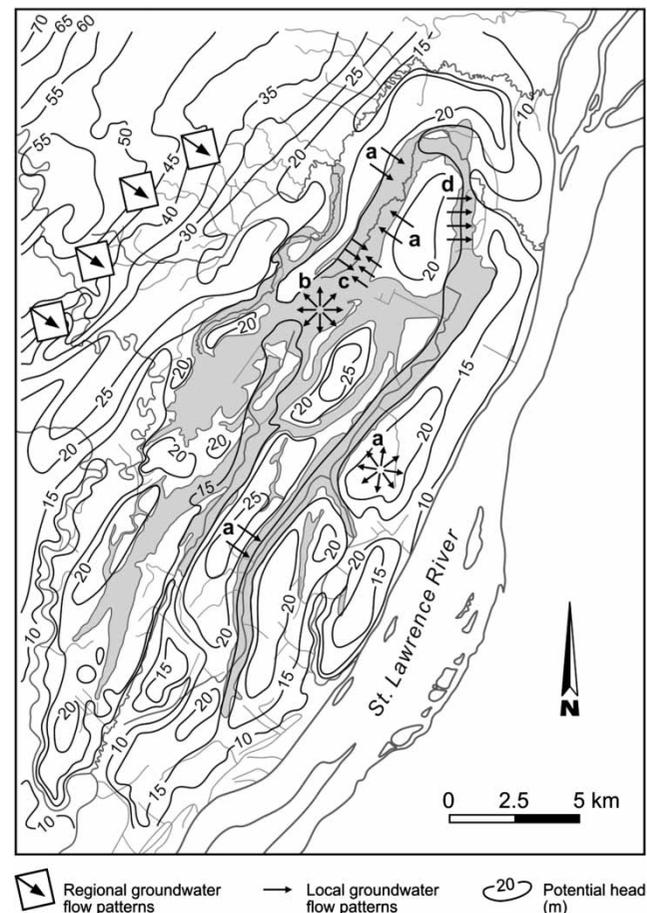

Figure 5 | Effect of recharge scenarios on vertical inflows (*VI*) and ETP (% numbers stand for recharge variations based on a given climate change scenario). 0% change scenario corresponds to the baseline calibrated model.

Figure 6 | Interpolated piezometric map with regional and local groundwater flow directions (arrows are drawn as examples of flow directions): (a) flow following topography from the deltaic aquifer to the surrounding minerotrophic zone; (b) centered radial flow along the peatland topography from ombrotrophic zone to minerotrophic zone; (c) flow along the elongated axis of the peatland feeding the surrounding river network; and d) unidirectional flow from the peatland to the deltaic aquifer.

(as reported by Bourgault *et al.* (2011)). Thirty differential GPS river water level measurements (this study) were used to constrain the piezometric map. Heads within the simulated area vary from 5 to 30 m.a.s.l. Regional groundwater flow directions are oriented NW-SE, thus perpendicular to the elongated axis of the peatland (Figure 6). The NW part of the aquifer appears to be disconnected from the Lanoraie peatland, as previously mentioned. This area is drained by the l'Assomption and Chaloupe Rivers (Figure 1). Four local groundwater flow patterns were documented on the piezometric map: (a) a flow following topography from the deltaic aquifer to the surrounding minerotrophic zone; (b) a centered radial flow along the peatland topography from ombrotrophic zone to minerotrophic zone; (c) a flow along the elongated axis of the peatland feeding the surrounding river network; and (d) a unidirectional flow from the peatland to the deltaic aquifer. The Lanoraie peatland complex is fed primarily by a local groundwater flow system, as well as by precipitation. Because of this setting, the peatland complex is probably sensitive to natural- and human-induced hydrologic changes.

Monitoring of water levels in the organic deposits shows that groundwater levels within the peatland are relatively stable through time. A severe drought period occurred in the summer 2012 resulting in 261 mm of precipitation compared to 369 mm in 2011. Water table depths within the peatland were located on average 15 cm below the peat surface (i.e. within the acrotelm layer) in 2011 and 22 cm in 2012. For peatland piezometers, head fluctuations (i.e. max level minus min level) are on average 12 cm in 2011 and 19 cm in 2012. The summer 2012 drought therefore did not have a significant effect on water levels within the peatland. Monitoring in the sand piezometers shows that water table depths were on average 180 cm below the surface in 2011 and 204 cm in 2012. For sand piezometers, head fluctuations were on average 51 cm in 2011 and 59 cm in 2012. As for the peatland, the dry conditions of summer 2012 did not have a large impact on groundwater levels in the sand aquifer. Heads in the sand aquifer are always higher than groundwater levels in the peatland, suggesting a constant unidirectional flow coming from the sand aquifer to the peatland except for the NE part of the peatland which has been intensively drained for agriculture (see Figure 6 local groundwater flow patterns d).

Model calibration

Sensitivity analysis and calibration method

The model was calibrated manually in steady-state by adjusting leakage coefficient, sand K-zones, peat K-layers and recharge. At the start of the calibration process, no spatial heterogeneity was considered and values from available data were used for sand hydraulic conductivity (1×10^{-4} m/s), peat hydraulic conductivity (1×10^{-2} m/s) and recharge (230 mm/yr). Leakage coefficients were taken from the literature (1×10^{-8}/s). Calibration parameters (except leakage coefficients) were then zoned (K-zones, K-layers and recharge) based on field measurements (for hydraulic conductivities) and aerial photography (for recharge). Finally, river leakage coefficients were independently calibrated to minimize errors on head measurement and annual river base flow.

Results from the sensitivity analysis (Table 2) show that K-sand has the largest effect on heads while the leakage coefficient has the largest effect on base flows. However, the S_r values are sufficiently similar to indicate that errors on estimating hydraulic conductivities or recharge have a similar impact on the model results. This is with the exception of K-peat for layer 2, which has a very limited influence on both heads and base flows. This reflects the fact that the model simulates flows predominantly in the upper peat layer.

Calibration results

Calibrated horizontal hydraulic conductivities (Kh) for the peat and sand layers are shown in Table 3. Sand hydraulic conductivities range horizontally from 1×10^{-5} to 6×10^{-4} m/s. These values are within the range of available

Table 2 │ Average relative sensitivity coefficients

Calibration parameter	Interval	S_r (head)	S_r (river base flow)
K-sand	$0.0003 - 0.00008$ (m/s)	0.61	0.54
K-peat Layer 1	$0.045 - 0.005$ (m/s)	0.10	0.30
K-peat Layer 2	$0.001 - 0.00001$ (m/s)	0.001	0.004
Recharge	$165 - 345$ (mm/yr)	0.17	0.67
Lc	$3 \times 10^{-8} - 1 \times 10^{-8}$ (S^{-1})	0.30	0.71

Table 3 | Calibrated sand and peat horizontal hydraulic conductivities. Vertical hydraulic conductivities are equal to 10% Kh

Sand K-zones	Kh (m/s)
1	1×10^{-5}–8×10^{-5}
2	8×10^{-5}–1×10^{-4}
3	1×10^{-4}–2×10^{-4}
4	2×10^{-4}–3×10^{-4}
5	3×10^{-4}–4×10^{-4}
6	4×10^{-4}–6×10^{-4}
Peat K-layers	**Kh (m/s)**
1	3×10^{-2}
2	1×10^{-4}
3	7×10^{-6}
4	1×10^{-6}
5	1×10^{-8}

hydraulic conductivities and the observed increasing trend of K towards the St. Lawrence River. The vertical anisotropy ratio was calibrated to be 10.

Calibrated horizontal hydraulic conductivities for the organic deposits vary from 1×10^{-8} m/s (layer 5) to 3×10^{-2} m/s (layer 1), i.e. decreasing considerably with depth (Table 3). This is consistent with field-based values from Rosa & Larocque (2008) at this site and with values from other peatland studies (e.g. Ronkanen & Klove 2008). The vertical anisotropy ratio was calibrated to be 10. This ratio is higher than the one reported by Rosa & Larocque (2008), but these authors did not measure the acrotelm vertical hydraulic conductivity. This calibration reflects the acrotelm-catotelm model comprising an upper active peat layer with a high hydraulic conductivity and less active saturated layer with a lower hydraulic conductivity. It suggests that horizontal flow may be the principal component of peatland hydrology, especially in the top layers of organic deposits.

The calibrated recharge in zone 1 is 293 mm/yr. This zone corresponds to high permeability sand where overland flow is negligible. Recharge in zone 2 (urban and more densely paved areas) is 196 mm/yr and recharge in zone 3 (peatland) is 213 mm/yr. The use of a moderate recharge in zone 3 is justified by the fact that the potential recharge from spring snowmelt is removed by overland flow within the peatland, due to a complete saturation of the organic

deposits (Holden *et al.* 2008). The average calibrated recharge for the study area is 245 mm/yr (i.e. on average 26% of the total vertical inflow), which is similar to the mean value of 230 mm/yr used by TechnoREM (2009) (cf. Figure 2(b)). This simple three zones recharge model depicts the influence of vegetation and soil on recharge, as suggested by de Vries & Simmers (2002).

The calibrated leakage coefficients necessary for best reproduction of river low flows vary from 2×10^{-8} to 1×10^{-8}/s. In Mike SHE, leakage coefficients are related to riverbed hydraulic conductivities, to the wetted perimeter of river cross sections, to the average flow length (distance from grid node to the middle of the river bank), as well as to the vertical surface available for exchange flow (DHI 2011). Although leakage coefficients can be dynamic through time and space (Engeler *et al.* 2011), they were considered here to be constant in order to limit undue complexity of the model. The calibrated leakage coefficients are consistent with literature values (e.g. Doppler *et al.* 2007).

Figures 7(a) and (b) show that the steady-state groundwater flow model simulates relatively well the available heads (mean error −0.07 m, mean absolute error 1.5 m and root mean square error 1.81 m). Using a 95% interval confidence, error on simulated heads (difference between simulated and measured heads) is ±47 cm in the peat and ±41 cm in the sand. The lower heads are underestimated by the model while the higher heads are overestimated. However, this calibration may be considered satisfying in the context of a study on the potential of aquifer-peatland-river interaction since error on simulated peat (±47 cm) and sand (±41 cm) is less than the smallest model cell thickness (50 cm).

The effects of peatland perturbation and horizontal zonation (minerotrophic and ombrotrophic) on hydraulic conductivities have not been considered in the model. Considering vertically homogeneous sand hydraulic conductivities could also induce calibration errors. The inaccuracies in head measurements caused by topography (±15 cm) and the observed head variations during the dry 2012 year in the peat (19 cm) and in the sand (59 cm) likely contribute to the calibration error of the steady-state model but do not represent a major source of error. Overall, the calibrated model simulates reasonably well the general flow direction patterns and the hydraulic gradients.
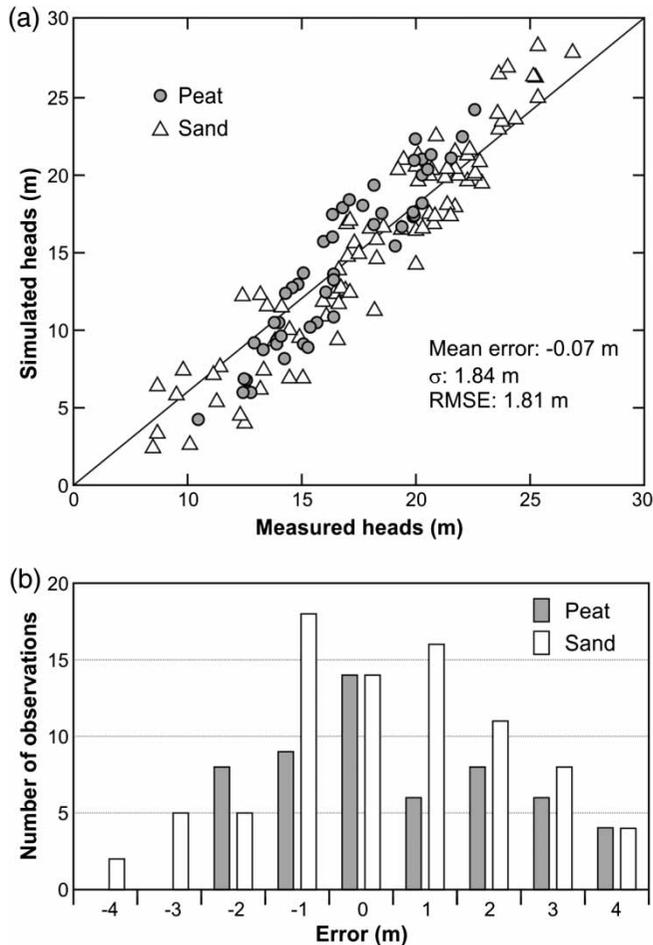
Figure 7 | (a) Measured and simulated heads in the peat and sand deposits, associated mean error, mean absolute error and root mean square error and (b) histogram of simulated errors for the peat and sand water levels.

Figure 8 shows the simulated steady-state base flows of 0.25 and 0.34 m³/s for the Saint-Joseph and Point-du-Jour rivers, respectively. These values are similar to the Chapman-estimated base flows, but are higher than those of TechnoREM (2009) in which a groundwater flow model was used to estimate river base flows on the Saint-Joseph and Point-du-Jour rivers (0.07 and 0.08 m³/s respectively). These differences can be explained by a different representation of rivers in the TechnoREM (2009) model (fixed head boundaries). The simulated base flows for Saint-Jean, Saint-Antoine and Bras-sud-ouest rivers are equal to 0.30, 0.14 and 0.09 m³/s, respectively (Table 4). These values fall within the range of bi-monthly manual measurements. However, daily base flows can vary significantly around the mean throughout the year. This variability is explained
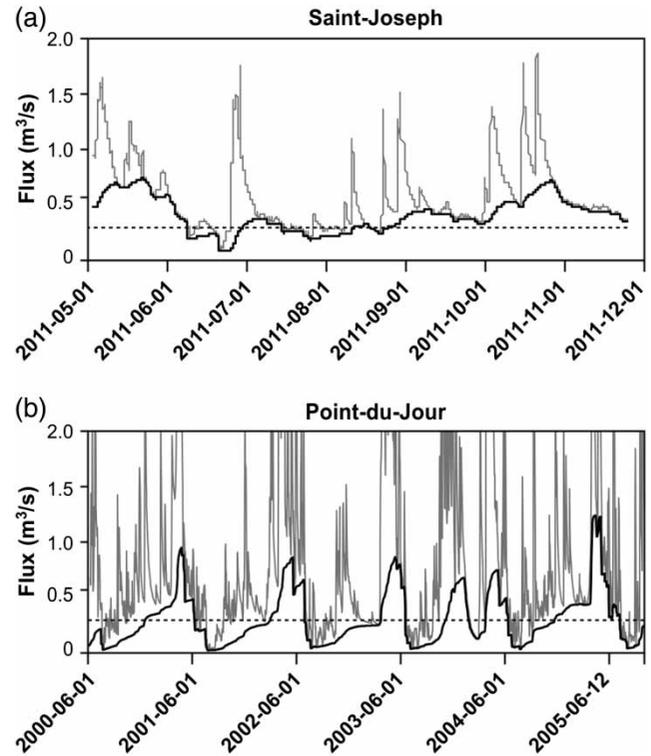
Figure 8 | Total river flow rates, Chapman-estimated base flows and simulated base flows for (a) Saint-Joseph river and (b) Point-du-Jour river.

Table 4 | Average total simulated river base flow and contribution from the peatland to river base flow

River	Average total river base flow (m³/s)	Peatland contribution to river base flow (m³/s)
Saint-Joseph	0.25	0.19
Point-du-Jour	0.34	0.14
Saint-Jean	0.31	0.22
Saint-Antoine	0.14	0.13
Bras-sud- Quest	0.09	0.09

by the fact that groundwater-river exchanges vary with river water levels, as well as with adjacent groundwater levels (Doppler *et al.* 2007). Given these uncertainties, it is considered that the model calibration for the volumes of water drained by the five rivers is reasonably good.

Peatland hydrology

The model was used to quantify aquifer-peatland-river exchanges at the regional scale. These flows can vary

considerably in direction and quantity due to human-induced and natural hydrologic modification. For example, Holden *et al.* (2006) showed that peat drainage can significantly modify river hydrograms by increasing the sensitivity of river response to rainfall and shortening river response time. In addition, Levison *et al.* (2013) demonstrated that aquifer-peatland interaction can experience flow reversals under climate change-induced recharge reductions.

The model domain was separated into different water budget zones. The peatland contribution to the annual total river base flows at the peat-sand transition and at the mouth of each river is quantified in Table 4. For example, the groundwater contribution to the total Saint-Joseph annual river base flow coming from the peatland is equal to 0.19 m^3/s, whereas the total annual river base flow is evaluated to 0.25 m^3/s. This is interpreted as if the peatland annually contributes 76% of the annual total Saint-Joseph river base flow. The peatland contribution to simulated river base flows are 41% for the Point-du-Jour river, 71% for the Saint-Jean river, 93% for the Saint-Antoine river and 100% for the Bras-sud-ouest river. Here, the 93 and 100% values are unrealistic since neither the Saint-Antoine nor the Bras-sud-ouest rivers flow exclusively on peat sediments. However, since these rivers flow on peat sediments over extensive portions of their reaches, the peatland contribution is probably relatively high. These base flow contributions are much higher than results from Levison *et al.* (2013) who have shown that a headwater peatland can sustain 4–7% of its outlets base flows. However in that case, the rivers did not flow through the peat sediments.

The peatland-related base flows obtained here are controlled by leakage coefficients and riverbed sediment hydraulic conductivities, and therefore present a certain amount of uncertainty. The occurrence of exfiltration from the underlying sandy aquifer through the low permeability peat layer to the upper peat (Rossi *et al.* 2012) and to the river/drainage network (Simpson *et al.* 2011), cannot be excluded. Simpson *et al.* (2011) used drain coefficients at the local scale to quantify drainage ditch-aquifer interaction using MODFLOW. These interactions were not included in the Mike SHE model because of the complexity involved in characterizing them in a regional-scale groundwater flow

model. However, peatland-river interactions are included in the model using head-controlled flux boundary where calibrated leakage coefficients control the exchanged fluxes between peatland and rivers. Nonetheless, these simulated fluxes support the concept of an important link between groundwater and surface water in the Lanoraie peatland environment.

The calibrated model was used to evaluate the contribution of the aquifer to the Lanoraie peatland complex. This was quantified by analyzing the water balance of all the cells located within the peatland. The total flow from the aquifer to the peatland is equal to 0.60 m^3/s (Table 5). Simulated hydraulic gradients are relatively constant all around the peatland. This indicates that the simulated aquifer-peatland inflow is distributed uniformly all around the peatland, except for the NE part of the region where the peatland is drained by the aquifer (see local groundwater flow patterns d on Figure 6). Recharge from precipitation is equal to 0.55 m^3/s (i.e. equivalent to the calibrated 230 mm/yr). This means that a significant portion of the water feeding the peatland (52%) comes from the aquifer. Other studies have found that groundwater inflow to a minerotrophic peatland can reach 88% (Drexler *et al.* 1999) or even 95% (Gilvear *et al.* 1993) of the total water input.

For the entire simulated area, the recharge is equivalent to 2.58 m^3/s. The majority of the water that is recharging the peatland is exported by the rivers (0.84 m^3/s or 72%) and the drainage network (0.32 m^3/s or 28%). When considering the entire study area, water outflows through the rivers (1.42 m^3/s or 55%), fixed head boundaries (0.35 m^3/s or 14%), and through the drains (0.81 m^3/s or

Table 5 | Peatland and total region water balance

	Input flow (m³/s)	Output flow (m³/s)
Peatland (76 km^2)	Aquifer 0.60 (52%)	River 0.84 (72%)
	Recharge 0.55 (48%)	Drains 0.32 (28%)
Simulated area (364 km^2)	Recharge 2.58 (100%)	River 1.42 (55%)
		Fixed head 0.35 (14%)
		Drains 0.81 (31%)

31%). Consequently, drainage plays a significant role in both groundwater levels in the sand aquifer and in the peatland. This is an indication that drainage should be managed carefully to conserve the current water balance of the hydrosystem and to ensure water flows to the peatland.

Climate change and pumping scenario

Figure 9 illustrates variations in aquifer heads, aquifer-peatland exchanges, and river base flow changes resulting from the two recharge scenarios (20 and 50% decreases). Recharge decreases of 20 and 50% resulted in mean head reductions of 0.60 and 1.60 m for the sand aquifer, and 0.54 and 1.39 m for the peatland.

The model simulates mean changes of river base flows for the five different surrounding rivers of -0.03 and $-0.09\,\text{m}^3/\text{s}$ (i.e. -16 and -41%) for the entire study area with the two climate change-related recharge reductions (i.e. 20 and 50% decrease) (see negative black bars in Figure 9). Under these scenarios, a diminution of aquifer-peatland exchange from 0.60 to 0.49 m^3/s and 0.31 m^3/s is documented for the 20 and 50% recharge decrease scenarios, respectively. This is equivalent to 18 and 48% decreases in the peatland water input from the aquifer.

These results indicate a moderate sensitivity of groundwater inflow to the peatland and of river base flows to recharge variations. Nonetheless, input fluxes from the

aquifer can play an important role in the ecological function of a peatland. Small changes in the volume of groundwater discharge in the peatland may be sufficient to significantly affect vegetation (Siegel & Glaser 1987), carbon absorption capacities (Gorham 1991), and peatland hydrologic regional functions. This should be taken into account when dealing with peatland conservation. Water management limiting human-induced recharge reductions, water pumping and peatland drainage to maintain river base flows and peatland hydrologic functions represents a real challenge. It is important to keep in mind that the climate change-induced recharge scenarios selected in this study represent extreme projections. The simulated head drawdowns and river base flow decreases might not be representative of future groundwater exchange conditions but they nevertheless illustrate the system response to extreme conditions.

A fictive pumping station (see Figure 1) was introduced in a local topographic high (26 m) to quantify the effect of water withdrawal for agricultural uses and human consumption. The fictive pumping station fully penetrates the sand aquifer (thickness 11 m at this location). Prior to pumping, heads in this area are at 23 m and groundwater flows towards the peatland (see Figure 6). A pumping rate of 0.03 m^3/s generates 9 m drawdown in the grid cell where the fictive well is located (no cell refinement was used) and a reversal of flow directions towards the aquifer up to $\approx 1{,}200$ m from the well, and reaching the peatland. At this pumping rate, the peatland feeds the sand aquifer and the well. This drawdown is larger than the one observed with a 50% decrease recharge equivalent to a mean 1.6 m and a maximum 3.6 m drawdown for the sand aquifer. Based on the average Canadian daily domestic use of fresh water (329 l/person) (Environment Canada 2012), this withdrawal could meet the needs of 1,080 people, which represents approximately 25% of the Lanoraie population. This does not take into account the use of groundwater by activities related to agriculture equivalent to $\approx 0.065\,\text{m}^3/\text{s}$ within the peatland surrounding area (TechnoREM 2009). It is expected that the combined effects of increased pumping and decreased recharge would have a significant impact on the entire Lanoraie hydrosystem. This pumping simulation emphasizes the importance of water use management in this thin aquifer
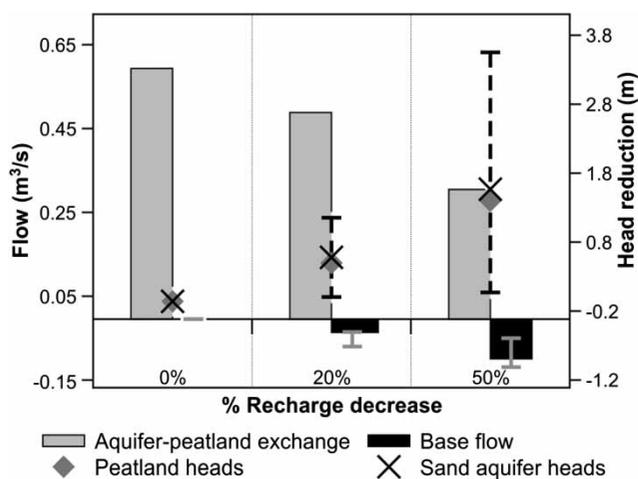

Figure 9 | Simulated aquifer-peatland exchanges, base flows and mean head variations in the peat and in the sand aquifer for two recharge reduction scenarios. Error bars were calculated based on maximum and minimum values.

environment to preserve both the peatland and the groundwater resources.

CONCLUSION

The steady-state groundwater flow model developed here has proven to be adequate to simulate current groundwater flow conditions in the Lanoraie peatland complex and delta aquifer hydrosystem. This work provides important insights on aquifer-peatland-river exchanges for the St. Lawrence Lowlands climate and geological setting. The numerical model shows that: (1) groundwater flows mainly through horizontal flow within the organic deposits; (2) 52% of the inflow to the peatland comes from the sand aquifer; and (3) river base flows are predominantly (41 to 100%) supplied by the peatland. Under climate change scenarios, this study shows that the Lanoraie peatland complex plays a determinant role on the hydrosystem. The organic deposits prevent drastic drawdown of the surrounding sand and peat aquifer while limiting river base flow decreases.

The extreme recharge decrease scenarios simulated here clearly show that climate change could cause significant impacts on the Lanoraie hydrosystem. It is understood that these recharge conditions might not occur. Nevertheless, this work points to the vulnerability of recharge reductions or increased pumping on the water sustainability of the peatland complex studied. Similar results are expected in other low-topography sand aquifers hosting extensive peatlands in humid and cold climates. This work also suggests that an effective peatland management should consider the surrounding aquifer and other conservation actions at the regional scale.

This study underlines the advantages of using a model to quantify the effects of various water uses at regional scale. Such model outputs could provide guidelines in water management plans involving agricultural, other human-related activities and climate related perturbations. Additional multidisciplinary research involving hydrologists and urban and territory planners are undoubtedly required to better protect the important water resources associated with peatlands and other wetlands. This is especially true in a context of increasing environmental pressures induced by urban development and a changing climate.

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