UNIVERSITÉ DU QUÉBEC À MONTRÉAL

INFLUENCE DES PROPRIÉTÉS HYDRODYNAMIQUES, DES VARIATIONS MÉTÉOROLOGIQUES ET DES CONTEXTES HYDROGÉOLOGIQUES SUR L'HYDROLOGIE DE SEPT TOURBIÈRES DE LA VALLÉE DU SAINT-LAURENT, QUÉBEC, CANADA.

THÈSE

PRÉSENTÉE

COMME EXIGENCE PARTIELLE

DU DOCTORAT EN SCIENCES DE LA TERRE ET DE L'ATMOSPHÈRE

PAR

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MAI 2018

REMERCIEMENTS

Bien qu'à plusieurs reprises la solitude vous envahira, celui ou celle qui s'aventure dans un doctorat ne le fera pas seul. Cette aventure laisse des marques qui sont indélébiles, qui nous font prendre conscience que la stabilité n'existe pas. Tout se transforme. Une chose est certaine, les gens qui vous entourent seront indispensables à votre bien-être et à la réussite de votre doctorat.

Tout d'abord, je tiens à remercier mes directrices Marie Larocque et Michelle Garneau qui m'ont non seulement accompagné avec rigueur tout au long de cette démarche scientifique, mais qui ont aussi fait de cette thèse une expérience humaine, qui mériterait à être davantage soulignée et encouragée dans le monde de la recherche. Je remercie également Joseph Holden, André St-Hilaire et Étienne Boucher d'avoir accepté d'être sur mon jury de thèse.

Un gros merci à toute l'équipe d'hydrogéologie de l'UQAM qui ont été à la fois des ami-e-s et des collègues. Merci, Marjolaine Roux pour ces nombreuses heures passées sur le terrain avec moi. Ta force et ton endurance m'ont toujours beaucoup impressionné. Merci Sylvain Gagné et Lysandre Tremblay pour ces discussions méthodologiques sur le coin de la maquette et surtout pour m'avoir accompagné lors de mes premières visites de tourbières, il y a maintenant sept ans. Merci, Olivier Ferland et Félix Turgeon pour avoir pris part à une réflexion générale sur la modélisation numérique. Merci, Karine Lefebvre et Léonora Fleurent, votre persévérance m'a toujours beaucoup inspiré. Merci, Marie Arnoux pour ces moments de détente autour d'une bière.

Un gros merci à l'équipe des Tourbeux et Tourbeuses de l'UQAM qui ont su être ouvert au partage d'idées et de réflexions, et sans qui la dimension paléo-écologique des tourbières resterait encore un égnime. Merci, Anne Quillet, Steve Pratte, Gabriel Magnan, Simon Van Bellen, Julien Beaudet et Julien Minville. Un gros merci à Stéphanie Pellerin, et Salomé Pasquet qui m'ont permis de mieux saisir la dimension écologique des tourbières.

À travers mon doctorat, j'ai aussi eu la chance d'encadrer Marjolaine Roux, Steven St-Aubin et Alexandre Rouleau pour leur projet de fin de baccalauréat. Un gros merci pour m'avoir permis d'avancer plus rapidement dans la collecte des données.

De plus, durant mon doctorat, j'ai réalisé deux stages à l'étranger, dont un en Finlande et un en Angleterre. Ces stages m'ont permis de consolider mes réflexions sur l'hydrologie des tourbières au sein deux deux équipes de recherche extraordinaires.

En Finlande, je voudrais remercier Bjorn Klove, Pekka Rossi, Hannu Marttila, Anna-Kaisa Ronkanen et Meseret Menburu. Un gros gros gros merci aussi à Pertti Ala-Aho, qui en plus d'être un collègue avec qui j'ai pu réfléchir à haute voix, est un super partenaire de badminton, de sauna, de pêche et de ski de fond. Un gros merci à Romain Sarremejane sans qui mes deux séjours en Finlande n'auraient jamais été aussi agréables.

En Angleterre, je voudrais remercier Joseph Holden, Antony Blundell et Kathryn Smith pour m'avoir donné accès à d'incroyables séries temporelles. Un gros merci à Andy Baird, Graeme Swindles, Paul Moris, Dylan Young et Elizabeth Watson pour les riches discussions auxquelles j'ai pu participer dans le cadre des fameux *PEAT MEET*. Un énorme merci à Anne Quillet pour avoir partagé des réflexions sociales et politiques concernant la gouvernance des universités. Un gros merci à Julia Martin-Ortega, Rosalind Bark et Olivia Rendon pour ces nombreux soupers coréens sous le ciel nuageux de l'Angleterre. Un merci particulier à Francisco Carvalho Diniz, Fernanda Coelho, Julia, Jess Barker, Adriane Esquivei Muelbert, Nikée Groot, Bruno Barçante Ladvocar, Phil Hannam et Sarah Batterman pour avoir partagé avec moi d'agréables moments de plein-air, de courses et d'expériences socioculturelles du quotidien en Angletterre.

Je tiens à remercier mes amis-es proches, Geneviève Dauphin, Maxime Vignola, Simon Marcotte, Guillaume Poulin, Charles Montbriand, Maxime St-Denis, Félix Télénis, Nina Sakar et Miori Lacerte qui ont participé à plusieurs reprises directement à la réalisation de cette recherche en plus de travailler quotidiennement dans l'ombre pour rendre ma vie agréable et su me supporter dans les moments les plus difficiles. Je tiens à remercier Léa-Maude Gobeille, Stéphanie Palmer et Camille Ouellet pour toutes les heures passées pour la relecture de cette thèse.

Un très grand merci à ma famille directe Sylvie Létourneau, Rock Bourgault, Jean-François Bourgault et tous les membres de la famille proche et éloignée d'avoir été présents inconditionnellement dans les moments où tout peut basculer.

Cette thèse a été possible grâce au soutien financier du Fonds de recherche du Québec – nature et technologie (FQRNT, 192287), du programme de financement MITACS – Accélération en partenariat avec Conservation de la Nature Canada et la compagnie de consultation en hydrogéologie environnementale Richelieu Hydrogéologie inc., ainsi que par les financements de recherche de Marie Larocque obtenus dans le cadre du Programme d'acquisition de connaissance sur les eaux souterraines (PACES) du Ministère du Développement Durable, de l'Environnement et de la Lutte contre les changements climatiques (MDDELCC).

AVANT PROPOS

Cette thèse est composée de trois articles, rédigés en anglais, formant chacun un chapitre. Le reste de la thèse est rédigé en français selon les exigences de l'Université du Québec à Montréal. Le premier article, qui s'intitule *Quantification of peatland water storage capacity using the water table fluctuation method* a été accepté pour publication dans la revue *Hydrological Processes*. Mes directrices de thèse, Marie Larocque et Michelle Garneau, sont deuxième et troisième auteures respectivement. Le deuxième article qui s'intitule *Quantifying peat hydrodynamic properties and their influence on water table depths in peatlands of southern Québec (Canada)* a été accepté pour publication dans la revue *Ecohydrology*. Pour cet article, mes directrices, Marie Larocque et Michelle Garneau sont aussi deuxième et troisième auteures. Le troisième article *Controls on water table depths and fluctuations in peatlands : a balance between meteorological conditions and hydrogeological settings* a été soumis à la revue *Journal of Hydrology*. Cet article a également été rédigé avec mes directrices Marie Larocque et Michelle Garneau. Chaque article a été conservé dans leur intégralité. Ce choix entraîne des répétitions dans la description des sites d'étude et la méthodologie. Pour chacun des chapitres, je suis le principal responsable de la collecte des données, des analyses de laboratoire, de l'interprétation des résultats ainsi que la rédaction des contenus des trois articles scientifiques. La thèse se termine par une conclusion générale mettant de l'avant son originalité et ses principales contributions.

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LISTE DES ABRÉVIATIONS ET ACRONYMES

ρ_{dry}	Dry density
^{14}C	Radiocarbone
Δh	Variation de niveau de nappe
$\Delta h_{drawdown}$	Différence entre les niveaux de nappe maximum et minimum
Δh_{rise}	Augmentation maximale du niveau de nappe suite à une précipitation
ΔS	Variation de l'emmagasinement
A	Aire
ANOVA	Analyse de la variance
cal BP	Années calibrées avant aujourd'hui
C_k	Covariance au pas de temps k
CH	Tourbière de Covey Hill
DE	Débit entrant
dh	Variation de niveau de nappe
DS	Débit sortant

ET	Évapotranspiration
ETP	Évapotranspiration potentielle
GDE	« Groundwater dependent ecosystems » (écosystème dépendant des eaux souterraines)
GDP	« Groundwater dependent peatland » (tourbière dépendante des eaux souterraines)
GIP	« Groundwater independant peatland » (tourbière indépendante des eaux souterraines)
h	Charge mesurée au temps t
H	Charge statique avant le *slug* test
H_o	Charge induite par le *slug* (t=0)
HPM	Holocene peat model
HSD	« Honest Significant Difference » (différence significative honnête)
i	Gradient hydraulique
ISO	Tourbière de la ville d'Issoudun
k	Pas de temps
K	Hydraulic conductivity
K_{sat}	« Saturated hydraulic conductivity » (conductivité hydraulique saturée)
L	Longueur de la crépine

LCY	Tourbière du Lac Cyprès
LTF	Tourbière « Large Tea Field »
m.a.s.l.	« Meter above sea level » (mètres au-dessus du niveau marin)
max_{prec}	« Maximum precipitation » (précipitation maximum)
min_{prec}	« Minimum precipitation » (précipitation minimum)
MCD	« Monthly cumulate decreases » (diminution cumulée mensuelle)
MCM	« Modified cube method » (méthode des cubes modifiée)
MCI	« Monthly cumulate increases » (augmentation cumulée mensuelle)
N	Nombre d'observations
P	Précipitation
P_{event}	Précipitation enregistrée pour chaque événement
P_{month}	Précipitation moyenne mensuelle
Q	Débit
r	Rayon du puit
r(k)	Coefficient d'autocorrélation
$r_{xy}(k)$	Coefficient corrélation croisée
RSSE	« Residual sum of squared errors » (somme résiduelle des erreurs au carré)
S	Emmagasinement

SU	Flux d'eau de surface
SO	Flux d'eau souterraine
sp.	« Specie (singulier) » (espèce au singulier)
spp.	« Species (pluriel) » (espèces au pluriel)
Ss	Emmagasinement spécifique
Sy	Specific yield
Sy_{cube}	Specific yield calculated using the cube method
Sy_{tank}	Specific yield calculated using the experimental tank method
Sy_{WTF}	Specific yield calculated using the water table fluctuation method
SSE	Tourbière de la ville de Sainte-Séraphine
t	Temps
t_o	Temps initial (t=0)
$Time_{int}$	Time interval
T_{month}	Températures moyennes mensuelles
μ_x	Moyenne de la série x_t
σ_x	Écart type de la série x_t
V	Volume
V_d	« Drained water volume » (volume d'eau drainé)

VIC	Tourbière de la ville de Victoriaville
VR	Tourbière de la ville de Villeroy
W	Masse
WTD	« Water table depth » (profondeur de la nappe)
WTF	« Water table fluctuation » (fluctuations du niveau de la nappe)
x_t	Série temporelle x_t
y_t	Série temporelle y_t

RÉSUMÉ

Les tourbières sont des écosystèmes saturés en eau souvent connectés aux aquifères. Leur intégrité hydrologique et le maintien de leurs fonctions hydrologiques reposent sur leurs capacités à maintenir leurs niveaux de nappe près de la surface. La compréhension des processus qui contribuent à maintenir les niveaux est donc indispensable pour les protéger. L'objectif principal de cette thèse est de comprendre l'influence des propriétés hydrodynamiques, des variations météorologiques et des contextes hydrogéologiques sur le niveau d'eau de sept complexes tourbeux de la vallée du Saint-Laurent, Québec, Canada. Pour ce faire, sept tourbières ont été échantillonnées et instrumentées en tenant compte de la diversité des contextes hydrogéologiques dans lesquels elles se sont développées. Pour chacune des tourbières, trois zones (amont, intermédiaire, aval) ont été identifiées le long d'une ligne d'écoulement, et une zone de recharge de l'aquifère a été identifiée. Deux zones supplémentaires (minérotrophe et d'alimentation) ont été identifiées pour les tourbières qui étaient ceinturées d'une zone pouvant être alimentée par un aquifère. Pour chacune des tourbières, des carottes de tourbe de 1 m ont été prélevées dans les zones amont, intermédiaire et aval. Des travaux de laboratoire réalisés sur ces carottes ont permis de quantifier les conductivités hydrauliques, les coefficients d'emmagasinements et la densité apparente sèche des dépôts tourbeux. Toutes les zones étudiées sur chaque site (dans la tourbière et dans l'aquifère) ont été instrumentées de puits d'observation et de piézomètres munis de sondes pour le suivi automatique des niveaux d'eau qui ont été en opération de mai 2014 à juin 2016. Les séries temporelles et les données de laboratoire ont été analysées à l'aide d'analyse de variance, de fonctions d'autocorrélation, de corrélations linéaires, semi-

logarithmiques et logarithmiques, ainsi que par l'analyse des variations des niveaux de nappe liées aux événements pluvieux et aux récessions. Toutes les analyses ont été réalisées avec le logiciel R.

Le premier chapitre de la thèse a permis d'adapter, tester et valider la méthode *Water Table Fluctuation* permettant de quantifier les coefficients d'emmagasinement des tourbières. Des coefficients d'emmagasinement entre 0.13 et 0.99 variant sur 20 cm ont été calculés. Les valeurs les plus élevées correspondent au niveau maximal de la nappe et diminuent rapidement avec la profondeur, suivant une équation logarithmique. Une différence significative des capacités d'emmagasinement a été observée entre les sites. Cette différence suit un gradient géographique régional du sud-ouest vers le nord-est, ce qui concorde avec le gradient des degré jour de croissance entre les sept tourbières.

Le deuxième chapitre a permis de quantifier l'influence des propriétés hydrodynamiques des dépôts organiques comme facteurs explicatifs des variations des profondeurs de nappe. Pour tous les sites, les densités sèches apparentes varient entre 0.02 et 0.22 g/cm^3 et les conductivités hydrauliques varient entre 1.4 cm/s et $3.0*10^{-6}$ cm/s. Aucune variation significative des propriétés hydrodynamiques n'a été identifiée intra- et inter-sites. Cependant, les niveaux de nappe montrent des différences significatives d'un site à l'autre. Ceci est une indication que les propriétés hydrodynamiques ne sont pas le seul facteur qui contrôle le niveau des nappes et que les contextes météorologiques et hydrogéologiques pourraient être des facteurs explicatifs importants. Trois relations mathématiques ont été développées liant les coefficients d'emmagasinement à la profondeur, à la densité apparente sèche et à la conductivité hydraulique des dépôts tourbeux. Ces équations permettront aux modélisateurs de quantifier de manière plus fiable les propriétés hydrodynamiques de la tourbe dans des modèles éco-hydrologiques.

Le troisième chapitre a permis de mieux comprendre l'influence des conditions météorologiques et des contextes hydrogéologiques sur les niveaux de nappe et leurs fluctuations dans les tourbières. Les conductivités hydrauliques des zones de recharge varient entre $1.4*10^{-7}$ et $8.5*10^{-3}$ cm/s et sont fortement corrélées au niveau annuel de la nappe dans les tourbières. Les augmentations mensuelles des niveaux de nappe des tourbières sont fortement corrélées aux précipitations mensuelles. De manière similaire, les diminutions mensuelles des niveaux de nappe sont fortement corrélées aux températures moyennes mensuelles. Les résultats ont permis d'identifier qu'une baisse de 1 mm/mois dans les précipitations peut entraîner une baisse de 2 mm de la nappe de la tourbière, tandis qu'une augmentation de température de 1 °C/mois peut entraîner une baisse de 1 cm du niveau de nappe. L'application de cette méthode sur d'autres tourbières localisées dans des contextes climatiques différents permettra de mieux comprendre la vulnérabilité des tourbières aux changements climatiques. De plus, les analyses d'autocorrélation et de corrélation croisée ont permis de confirmer la présence d'un équilibre hydrique entre la zone ombrotrophe des tourbières et leurs contextes hydrogéologiques. Cela concorde avec le contrôle qu'exercent les zones de recharge sur les niveaux de nappe des tourbières démontré par la présence d'une forte corrélation entre la conductivité hydraulique des zones de recharge et les niveaux de nappe des tourbières. En ce sens, on distingue les tourbières dépendantes des eaux souterraines, ou fortement connectées, par une fluctuation accentuée de leur niveau d'eau et les tourbières indépendantes des eaux souterraines, ou faiblement connectées, par des variations limitées de leur niveau d'eau. Jusqu'ici, aucune étude n'avait encore démontré l'importance des conditions météorologiques et des contextes hydrogéologiques sur l'hydrologie des tourbières.

Cette thèse apporte de nouvelles données, une meilleure compréhension et un nouvel éclairage du contrôle des facteurs externes sur les niveaux d'eau des tourbières. Les résultats de cette thèse pourront être utilisés pour quantifier les fonctions hydrologiques des tourbières et leur connectivité avec les aquifères, et pour évaluer la vulnérabilité des tourbières aux pressions apportées par les changements climatiques.

INTRODUCTION

0.1 PROBLÉMATIQUE GÉNÉRALE

À l'échelle de la planète, les tourbières occupent environ 3 % de la superficie terrestre (Charman, 2002). Au Canada, ces écosystèmes occupent environ 12 % du territoire et jouent un rôle important dans le cycle de l'eau et le cycle du carbone (Tarnocai, 2009). Les tourbières sont des écosystèmes saturés en eau très souvent connectés aux aquifères. Elles sont caractérisées par une accumulation de la matière organique qui excède la décomposition. Leur intégrité hydrologique et écologique dépend fortement du maintien des niveaux de nappe près de la surface (Holden *et al.*, 2006). Une baisse des niveaux de nappe dans les aquifères superficiels voisins (ex. pompage pour l'irrigation ou l'alimentation en eau), les changements dans l'occupation du territoire (aménagement d'infrastructures routières, exploitation des ressources minières et pétrolières, développement de l'agriculture), et les changements climatiques (Davidson et Janssens, 2006) représentent des pressions importantes pour la pérennité de ces écosystèmes. La conservation des tourbières est donc indissociable d'une gestion durable des ressources en eau sur le territoire.

Il y a plus de vingt-cinq ans, Gorham (1991) estimait que 50 % de la superficie des tourbières dans le monde avait été détruite. Au Québec, dans la vallée du Saint-Laurent, il est estimé que depuis la colonisation, entre 40 et 80 % de la superficie totale des tourbières aurait disparu (Pellerin et Poulin, 2013) et que 65 % des superficies actuelles seraient perturbées par des activités anthropiques telles que le drainage, l'exploitation forestière, l'aménagement du réseau hydro-électrique, la construction de routes, l'exploitation de tourbe et l'agriculture (Joly *et al.*, 2008). S'il est vrai que l'exploitation et la conversion des tourbières en terres agricoles participent au développement socio-économique du Québec, l'importance de reconnaître que la dégradation des tourbières a largement modifié leurs fonctions hydrologiques (MDDEP, 2012) est sans équivoque. À titre d'exemple, leur capacité à réduire les inondations (Acreman et Holden, 2013), à maintenir les débits de base des rivières (Bourgault, Larocque et Roy, 2014) et les niveaux de nappe des aquifères (McLaughlin, Kaplan et Cohen, 2014) est transformée, ce qui peut engendrer des coûts substantiels pour la société (Fournier *et al.*, 2013).

0.2 ÉTAT DES CONNAISSANCES

0.2.1 Définitions

Selon Rydin et Jeglum (2006), un milieu humide est défini par la présence d'eau dans le sol, permanente ou temporaire, en surface ou à faible profondeur. Les milieux humides occupent souvent une position de transition entre les milieux terrestres et aquatiques, concordant avec la présence de sols hydromorphes et d'une végétation composée de plantes hygrophiles capables de tolérer des inondations périodiques.

Les milieux humides se présentent sous diverses formes : tourbières ombrotrophes (*bogs*), tourbières minérotrophes (*fens*), tourbières boisées, marécages, marais, étangs, prairies humides et eaux peu profondes (National Wetlands Working Group-NWWG, 1997). De façon générale, on distingue l'ensemble de ces milieux non seulement en tenant compte des variations de fréquence et d'amplitude des niveaux de nappe (hydropériodes), mais aussi par une combinaison de facteurs pédologiques, biologiques et géochimiques qui résultent des conditions hydrologiques, hydrogéologiques et géomorphologiques (Mitsch et Gosselink, 2007 ; Reddy et DeLaune, 2008), sur lesquelles se base le système de classification canadien des milieux humides (National Wetlands Working Group-NWWG, 1997).

Des méthodes de classification récentes, par exemple le *Ontario Wetland Evaluation System* (Ontario Ministry of Natural Ressources (MNR), 2013) et le *Wetland Ecosystem Services Protocol for the United States* (Adamus, 2011), permettent de classer les milieux humides de manière à identifier leurs fonctions hydrogéologiques, géochimiques et écologiques en tenant compte d'un ensemble de critères biotiques et abiotiques comptabilisés et pondérés sous la forme d'un pointage. Cependant, la plupart de ces méthodes ne caractérisent que partiellement les différentes fonctions des tourbières et ne permettent pas de différencier adéquatement leurs fonctions hydrologiques, une tâche qui exige des travaux de caractérisation et de suivi hydrologique approfondis.

0.2.2 Formation des tourbières

Les tourbières (ombrotrophes, minérotrophes et boisées) sont associées à trois processus de formation : le comblement, la paludification et la formation primaire de tourbe (Rydin et Jeglum, 2006). Le comblement fait référence à l'entourbement d'un lac ou d'un plan d'eau, la paludification à l'entourbement d'un sol minéral peu humide et la formation primaire à l'entourbement d'un sol minéral préalablement humide. Sur les territoires post-glaciaires comme au Québec, les tourbières se sont surtout formées par paludification alors qu'une proportion moindre s'est développée à partir du comblement de petites dépressions (Payette et Rochefort, 2001). Une fois le processus d'accumulation initié, la tourbière se développe en favorisant des changements de végétation et de microtopographie transformant, à différentes échelles ($1\text{-}10^1$ m à $10^2\text{-}10^3$ m) leur morphologie. Ces transformations ont pour effet de modifier l'hydrologie (écoulement de surface et écoulement souterrain) et les fonctions hydrologiques de ces écosystèmes. Cependant, les mécanismes exacts qui contrôlent et modifient la dynamique de formation et développement des tourbières comme la composition du substrat minéral et les variations d'emmagasinement de l'eau restent encore mal compris (Belyea, 2013).

0.2.3 Hydrologie des tourbières

La dynamique hydrique des tourbières est influencée par une variété de facteurs internes (les propriétés physiques de la tourbe telles que la conductivité hydraulique, le coefficient d'emmagasinement, la composition de la tourbe, la densité, et en degré de décomposition, ou encore la végétation de surface et la géomorphologie locale) et externes (le climat, le contexte hydrogéologique et les perturbations anthropiques) qui en déterminent le bilan hydrique tel qu'exprimé ci-bas:

$$P + SO_{DE} + SU_{DE} - ET - SO_{DS} - SU_{DS} = \Delta S \qquad (0.1)$$

où P représente les précipitations [L], DE les débits entrants [L], DS les débits sortants [L], SU les flux d'eau de surface [L], SO les flux d'eau souterraine [L] et ET l'évapotranspiration [L].

La conductivité hydraulique est définie par la capacité d'un milieu poreux comme la tourbe à laisser circuler l'eau. Le coefficient d'emmagasinement, souvent estimé par la porosité effective, est défini comme le volume d'eau drainé par unité de surface résultant d'un abaissement unitaire de charge hydraulique (Fetter, 2001).

0.2.4 Acrotelme et catotelme

À partir d'analyses de conductivité hydraulique et de densité de la tourbe des études ont montré que l'hydrologie des tourbières était contrôlée par la conductivité hydraulique des dépôts organiques (Holden et Burt, 2003a ; Lewis *et al.*, 2012). Les conductivités hydrauliques très élevées dans la tourbe non décomposée favorisent un écoulement horizontal rapide dans une zone dite « active » correspondant à l'acrotelme et un écoulement horizontal beaucoup moins rapide dans une zone dite « inerte » correspondant au catotelme (Baird *et al.*, 2016 ; Holden et Burt, 2003b). L'acrotelme est composé majoritairement de sphaignes vivantes ayant une forte porosité effective, une forte conductivité hydraulique et une faible densité pouvant atteindre 90 %, 10 cm/s et ≈ 0,6 g/cm^3 respectivement (Holden, 2009 ; Ronkanen et Klove, 2008 ; Rosa et Larocque, 2008). Le catotelme est caractérisé par la présence de matière organique plus ou moins décomposée et compressée, où la porosité effective et la conductivité hydraulique sont faibles, et où la densité est élevée, ces paramètres pouvant atteindre 10 %, 10^{-5} cm/s et ≈1,1 g/cm^3 respectivement (Lewis *et al.*, 2012 ; Ours, Siegel et Glaser, 1997 ; Rosa et Larocque, 2008). Cependant, les caractéristiques physiques et hydrodynamiques des dépôts tourbeux ne sont pas les seuls facteurs contrôlant l'hydrologie des tourbières (Labadz *et al.*, 2010).

0.2.5 Facteurs internes

Les rétroactions internes limitent les augmentations et les diminutions marquées des niveaux de nappe. Par exemple, en période de sécheresse, plus les niveaux de nappe diminuent, plus l'évapotranspiration diminue, ce qui limite des baisses encore plus importantes de la nappe (Waddington *et al.*, 2015). Les diminutions en profondeur de la conductivité hydraulique et de la porosité effective contribuent à maintenir les niveaux de nappe élevés dans la tourbe (Waddington *et al.*, 2015). Inversement, lorsque les niveaux de nappe augmentent dans les horizons où la conductivité hydraulique et la porosité effective sont plus élevées, un écoulement horizontal rapide est favorisé, ce qui limite les augmentations de niveaux de nappe. Dans ce cas, la porosité effective plus élevée favorise également l'emmagasinement de l'eau et contribue également à limiter les augmentations de niveaux. Par ailleurs, une forte période de sécheresse accompagnée d'une diminution de nappe peut entraîner une perte de pigmentation chez les sphaignes, ce qui entraîne une augmentation de l'albédo et une diminution de l'évapotranspiration (Gerdol *et al.*, 1996).

0.2.6 Facteurs externes

Selon Reeve *et al.* (2001), les directions de l'écoulement dans les tourbières (horizontaux ou verticaux) sont contrôlées par la conductivité hydraulique des sédiments minéraux qui sont en contact avec les dépôts organiques. Ainsi, lorsque la conductivité hydraulique des sédiments minéraux est élevée, un écoulement peut être observé de la tourbière vers l'aquifère ou de l'aquifère vers la tourbière (Ferlatte *et al.*, 2014). Toutefois, lorsque la conductivité hydraulique des sédiments minéraux est faible, l'écoulement se fait essentiellement au sein même de la tourbe par un écoulement de « subsurface » rapide suivant le gradient microtopographique (Van der Ploeg *et al.*, 2011). L'eau circulant dans l'acrotelme rejoint alors rapidement les eaux de surface des cours d'eau (Grayson, Holden et Rose, 2010 ; Labadz *et al.*, 2010) ce qui peut favoriser une réponse rapide des débits de rivière (Holden et Burt, 2003c). Ce phénomène a été particulièrement étudié pour les *blanket bogs* (Holden et Burt, 2003c) surtout présentes en Grande-Bretagne et l'Irlande et (Holden, 2005 ; Holden, Chapman et Labadz, 2004 ; Soulsby *et al.*, 2015)

Les conditions météorologiques (à court terme) et climatiques (à long terme) jouent aussi un rôle important dans l'hydrologie des tourbières. L'augmentation des températures moyennes pendant la saison de croissance entraîne une augmentation de l'évapotranspiration et une diminution des niveaux de nappe (Wu *et al.*, 2010). Une augmentation des précipitations entraîne une augmentation des niveaux de nappe et contrebalance les baisses occasionnées par l'évapotranspiration et l'écoulement. Dans la plupart des tourbières, les précipitations excèdent l'évapotranspiration (Lafleur *et* *al.*, 2005), ce qui contribue à maintenir les niveaux de nappe elevés au sein de la tourbière. À long terme, l'importance du climat sur les niveaux de nappe fait encore l'objet de discussions (Swindles *et al.*, 2012). Pour certains auteurs, les niveaux de nappe des tourbières sont davantage contrôlés par les variations de température annuelles (Payne, 2014). Pour d'autres, des précipitations inférieures à l'évapotranspiration jouent un rôle prédominant dans le contrôle des niveaux de nappe (Charman, 2007). Une étude a même démontrée que les changements hydrologiques des tourbières seraient principalement liés à des événements extrêmes peu fréquents (Swindles *et al.*, 2010). Dans tous les cas, les changements hydrologiques influencent la composition de la végétation et les processus d'accumulation et de décomposition de la tourbe qui, par un ensemble de processus de rétroactions, contribuent à maintenir des niveaux de nappe élevés dans les tourbières.

0.2.7 Emmagasinement en eau

Les variations de l'emmagasinement en eau (ΔS) [L] des dépôts tourbeux sont calculées à partir de la porosité effective (Sy), de l'emmagasinement spécifique (S_s) [L^{-1}], des variations de niveaux de la nappe (Δh) [L] et de l'épaisseur (b) [L] des dépôts organiques :

$$\Delta S = \Delta h * S_y + bS_s \tag{0.2}$$

La porosité effective diminue non linéairement avec la profondeur (Dettmann et Bechtold, 2016 ; Moore, Morris et Waddington, 2015 ; Rosa et Larocque, 2008 ; Vorob'ev, 1963). L'emmagasinement spécifique (S_s) est défini comme le volume d'eau libéré par unité de volume de sol et par unité de variation de la charge hydraulique. Ce paramètre est lié à la contraction et à la dilatation des dépôts tourbeux. À court terme, les variations du niveau altitudinal de la surface résultent de l'infiltration de l'air dans la porosité effective des dépôts tourbeux suite à un abaissement des niveaux de nappe. L'infiltration de l'air augmente le stress effectif (Kennedy et Price, 2004). Une portion du poids est alors transférée résultant en une perte d'altitude de la tourbe. À long terme, les variations des niveaux sont occasionnées par l'oxydation de la matière organique, ce qui favorise la décomposition et modifie les propriétés hydrodynamiques des dépôts tourbeux (Grover et Baldock, 2013).

Le concept de « capacité d'emmagasinement » en eau des tourbières mérite d'être défini puisqu'il se distingue du paramètre intrinsèque de coefficient d'emmagasinement (ou porosité effective) des dépôts organiques. Puisque l'acrotelme favorise la circulation rapide de l'eau (Grayson, Holden et Rose, 2010 ; Labadz *et al.*, 2010), une tourbière où les niveaux de la nappe sont relativement proches de la surface (±10-15 cm), devrait avoir une capacité d'emmagasinement faible, i.e. un volume réduit d'eau pouvant potentiellement être emmagasiné dans la zone non saturée. Lorsque les niveaux de la nappe sont bas (< 40 cm), l'écoulement plus lent se fait dans les couches plus profondes, moins perméables et moins poreuses de la tourbe. Un volume plus important d'eau peut alors être emmagasiné dans la zone non saturée advenant un événement pluvieux important. La « capacité d'emmagasinement » des tourbières augmente donc à mesure que les niveaux de nappe sont bas et le coefficient d'emmagasinement (porosité effective) est faible.

Plusieurs études ont été réalisées pour décrire les capacités l'emmagasinement en eau des tourbières (Moore, Morris et Waddington, 2015 ; Thompson et Waddington, 2013 ; Vorob'ev, 1963) et l'importance des conditions de saturation préalables sur l'emmagasinement (Dettmann et Bechtold, 2016). Cependant, ces études s'en tiennent souvent à une description technique de l'emmagasinement (Rezanezhad *et al.*, 2016) et à la documentation d'un seul site (Carrer *et al.*, 2015), sans tenir compte de la connectivité des tourbières avec les aquifères et des différents contextes hydrogéologiques dans lesquelles elles se sont formées.

0.2.8 Échanges aquifère-tourbière

Les échanges aquifère-tourbière jouent un rôle important sur l'hydrologie des tourbières (Glaser *et al.*, 2006). Ils sont contrôlés par les propriétés hydrodynamiques des aquifères et leur topographie, de même que par les propriétés hydrodynamiques de la tourbe, la morphologie et la microtopographie de surface de la tourbière.

Les tourbières peuvent être alimentées directement par les eaux souterraines. Dans certaines conditions, l'eau souterraine voyage horizontalement ou verticalement depuis l'aquifère voisin ou sous-jacent et alimente les zones périphériques et même centrales de ces écosystèmes (Isokangas *et al.*, 2017). Dans d'autres conditions, l'eau souterraine participe peu au bilan hydrique des tourbières, notamment lorsque celles-ci sont situées en amont hydraulique d'un bassin versant ou lorsqu'elles reposent sur des dépôts peu perméables ou imperméables (Hayashi, van der Kamp et Rudolph, 1998). Les échanges aquifère-tourbière peuvent être horizontaux (Fraser, Roulet et Lafleur, 2001), verticaux (Rossi *et al.*, 2012) ou bidirectionnels (Devito, Waddington et Branfireun, 1997). Les échanges aquifère-tourbière peuvent être sujets à des inversions locales (Devito, Waddington et Branfireun, 1997) résultant d'une inversion des gradients hydrauliques causée par des précipitations importantes ou à une importante transpiration en période de sécheresse. Par ailleurs, même si l'eau souterraine provenant des aquifères périphériques peut atteindre la tourbe en s'écoulant verticalement à partir de la base des dépôts tourbeux dans des zones locales de plus grande conductivité hydraulique (Rossi *et al.*, 2012), les écoulements se font majoritairement de manière horizontale. Ceux-ci peuvent prendre la forme d'écoulement contrôlé par les propriétés hydrodynamiques de la tourbe et de l'aquifère, ou encore de *pipe flow*, ce qui favorise un écoulement rapide vers l'extérieur de la tourbière (Holden et Burt, 2002).

Les tourbières alimentées par les eaux souterraines sont caractérisées par la présence de zones minérotrophes, où l'on retrouve une végétation adaptée à des conditions riches en minéraux et moins acides que dans les tourbières ombrotrophes. Les tourbières minérotrophes peuvent faire partie de complexes tourbeux en étant généralement localisées en bordure des aquifères et au pourtour des tourbières ombrotrophes. D'autres systèmes peuvent être entièrement minérotrophes soit à cause de la configuration du site dans lequel elles se sont développées ou soit encore par le contexte écoclimatique (White et Payette, 2016). Dans la littérature, lorsqu'une tourbière est minérotrophe c'est parce qu'elle est connectée aux eaux souterraines (Kløve *et al.*, 2011) par opposition aux tourbières ombrotrophes qui ne sont alimentées que par les eaux de pluie donc « indépendante des eaux souterraines ».

Les études antérieures ont montré que les échanges aquifère-tourbière peuvent être quantifiés de différentes manières : calculs de flux moyens à l'aide de l'équation de Darcy (Levison *et al.*, 2014), de bilans hydriques (Fournier, 2008), de bilans de masse d'isotopes stables de l'eau (Spence, Guan et Phillips, 2011), d'analyses géochimiques d'ions majeurs (Ferlatte, 2014 ; Price *et al.*, 2005) et de modélisation numérique (Bourgault, Larocque et Roy, 2014 ; Frei *et al.*, 2012 ; Reeve, Siegel et Glaser, 2001 ; Thompson *et al.*, 2004). Ces méthodes exigent une compréhension détaillée, aux échelles locale et régionale, des caractéristiques géomorphologiques (topographie, épaisseur du matériel minéral, stratigraphie), hydrogéologiques (conductivité hydraulique, porosité effective, variation de nappe, débit de base des rivières) et géochimiques des tourbières et des aquifères auxquels elles sont connectées. En outre, des analyses de séries temporelles ont été utilisées pour l'étude des décalages de temps entre les variations de niveaux des tourbières et des rivières (Holden et Burt, 2003c). Ces analyses n'ont toutefois encore jamais été utilisées pour évaluer la connectivité entre les tourbières et les aquifères en tenant compte de l'influence des différents contextes hydrogéologiques.

0.2.9 Contextes hydrogéologiques

Le développement d'une tourbière peut être initié dans différents contextes hydrogéologiques (Brinson, 1993) favorisant la rétention de l'eau des précipitations et des eaux souterraines. Les contextes hydrogéologiques des tourbières sont caractérisés par les conductivités hydrauliques et les contextes géomorphologiques des aquifères (Lukenbach *et al.*, 2015a ; Lukenbach *et al.*, 2015b).

Les tourbières peuvent se former dans des contextes géomorphologiques variés comme dans des dépressions topographiques originant de différents processus (Winter, 2000) où l'eau souterraine fait résurgence, le long des versants d'eskers ou de moraines (Comas, Slater et Reeve, 2005). Elles peuvent aussi se former en amont et en aval des bassins versants. Ces différents contextes géomorphologiques sont associés à des conductivités hydrauliques très variées et déterminent une large gamme de conditions de bilans hydriques des tourbières qui s'y retrouvent (Gilvear et Bradley, 2009). Les tourbières ne sont presque jamais déconnectées des eaux souterraines (Whigham et Jordan, 2003) puisque dans la plupart des cas, elles se sont développées en périphérie d'une large gamme de dépôts géologiques peu perméables (Avard, 2013) à très perméables (Rossi *et al.*, 2012).

La caractérisation du contexte hydrogéologique dans lequel les tourbières se sont développées peut se faire de plusieurs façons. Par exemple, les relevés manuels (sonde, pelle) permettent de caractériser la nature du substrat minéral sur lequel elles se sont développées et en périphérie de celles-ci. L'utilisation de la géophysique par géoradar fournit des profils topographiques en continu des dépôts organiques et des matériaux sous-jacents (Proulx-McInnis *et al.*, 2013a). Les essais de perméabilité *in situ* (Hvorslev, 1951 ; Rosa et Larocque, 2008 ; Surridge, Baird et Heathwaite, 2005) et de drainage (Price, 1996 ; Vorob'ev, 1963) permettent de quantifier les conductivités hydrauliques et les porosités effectives des aquifères et des dépôts tourbeux. Des essais de pompages peuvent également être réalisés pour la quantification des propriétés hydrodynamiques des aquifères (Fetter, 2001 ; Freeze et Cherry, 1979).

0.2.10 Les tourbières du Québec

Au Québec, plusieurs études ont été réalisées pour comprendre l'hydrologie des tourbières. Ces études ont permis de quantifier les propriétés hydrodynamiques des dépôts tourbeux (Rosa et Larocque, 2008 ; Whittington et Price, 2006), de mieux comprendre l'hydrologie des tourbières naturelles (Carrer, 2014 ; Proulx-McInnis *et al.*, 2013b) et restaurées (Ketcheson et Price, 2014), de quantifier l'évapotranspiration (Proulx-McInnis *et al.*, 2014), de quantifier le bilan hydrique dans le contexte du développement des tourbières (Larocque *et al.*, 2013). Ces études ont aussi permis d'adapter des modèles hydrologiques spécifiquement pour les tourbières (Jutras, Rousseau et Clerc, 2009), de commencer à développer une typologie des connexions aquifère-tourbière (Ferlatte *et al.*, 2014) et de développer des indicateurs végétaux et géochimiques pour localiser les apports d'eau souterraine (D'Astous *et al.*, 2013 ; Larocque *et al.*, 2016).

Plusieurs travaux ont aussi été réalisés pour évaluer l'influence des tourbières dans le cycle du carbone (Cliche Trudeau, Garneau et Pelletier, 2014 ; Garneau *et al.*, 2014 ; van Bellen, Garneau et Booth, 2011) en tenant compte de leurs caractéristiques morphologiques (McEnroe *et al.*, 2009 ; Pelletier, Garneau et Moore, 2011 ; Pelletier *et al.*, 2007). Des travaux ont également été réalisés pour développer des techniques de restauration des tourbières (Graf et Rochefort, 2008), pour évaluer les pertes de superficie des tourbières (Pellerin et Poulin, 2013), pour estimer l'effet potentiel des changements climatiques sur les niveaux de nappe (Levison *et al.*, 2014) et pour améliorer la compréhension de l'impact des facteurs internes et externes sur l'évolution des tourbières (Lavoie, Pellerin et Larocque, 2013 ; Magnan, Garneau et Payette, 2014) et les transformations associées avec la végétation (Laberge *et al.*, 2015 ; Pasquet, Pellerin et Poulin, 2015 ; Pellerin *et al.*, 2009).

Les études sur les fonctions hydrologiques des tourbières de la vallée du Saint-Laurent ont permis d'évaluer les contextes hydrogéologiques sous-jacents à leur formation (Larocque *et al.*, 2013). Elles ont aussi permis de quantifier les échanges aquifère-tourbière (Avard, 2013) et leur contribution aux débits de base des rivières (Bourgault, Larocque et Roy, 2014), ainsi que d'évaluer l'influence des tourbières sur les débits de crue (Fournier *et al.*, 2013). Par ailleurs, une étude a été réalisée afin de tester l'utilisation des méthodes de caractérisation *Wetland Ecosystem Services Protcol* (WESP) et *Ontario Wetland Evaluation System* (OWES) dans la quantification des fonctions hydrologiques de tourbières du sud du Québec (Larocque *et al.*, 2015 ; Lefebvre *et al.*, 2015)

Aucune étude n'a toutefois encore été réalisée à l'échelle de la vallée du Saint-Laurent pour comprendre l'effet du contexte hydrogéologique sur la capacité d'emmagasinement en eau des tourbières.

0.3 OBJECTIFS

L'objectif principal de cette thèse est de comprendre l'influence des propriétés hydrodynamique des dépôts tourbeux, des variations météorologiques et des contextes hydrogéologiques sur les niveaux d'eau de sept complexes tourbeux de la vallée du Saint-Laurent, Québec, Canada.

Les objectifs spécifiques sont les suivants :

1. Adapter, tester et valider une méthode *in situ* permettant de quantifier les coefficients d'emmagasinement des tourbières;
2. Quantifier les propriétés hydrodynamiques des dépôts tourbeux comme facteurs explicatifs des variations des profondeurs de nappe des tourbières ;
3. Comprendre l'influence des conditions météorologiques et des contextes hydrogéologiques sur les niveaux de nappe et leurs fluctuations dans les tourbières.

Cette thèse se base sur trois constats: 1) il n'existe encore aucune méthode uniformisée qui permette de quantifier à l'échelle régionale les coefficients d'emmagasinement des dépôts organiques; 2) l'influence des variations spatiales des propriétés hydrodynamiques intra- et inter-sites sur les niveaux de nappe des tourbières est encore mal compris; 3) même si la littérature suggère l'importance des échanges aquifère-tourbière sur l'hydrologie des milieux tourbeux, les processus en jeu n'ont encore jamais été étudiés pour différents contextes hydrogéologiques.

Les hypothèses sous-jacentes à ce projet de doctorat sont les suivantes : 1) la capacité d'emmagasinement en eau des tourbières est limitée par les fortes variations des coefficients d'emmagasinement des dépôts tourbeux; 2) les variations inter-sites des niveaux de nappe à l'échelle annuelle peuvent être expliquées par les différences de propriétés hydrodynamiques des horizons de surface des dépôts tourbeux; 3) les niveaux de nappe des tourbières peuvent être influencés par les niveaux dans les aquifères voisins soit directement (échanges d'eau) ou indirectement (effet de pression), peu importe la nature de l'aquifère.

La thèse se divise en cinq parties incluant une introduction générale, trois chapitres rédigés sous forme d'articles scientifiques (un article publié, un article soumis et un article à soumettre) et une conclusion présentant la contribution scientifique de la thèse à l'avancement des connaissances.

0.4 SITES D'ÉTUDE

Trois régions administratives du Québec méridional localisées dans la vallée du Saint-Laurent et le nord des Appalaches ont été choisies pour l'étude: la Montérégie, le Centre-du-Québec et la région Chaudière-Appalaches. Dans ces trois régions, sept tourbières ont été instrumentées. Les tourbières de Covey Hill (CH) et de Large Tea Field (LTF) sont situées en Montégérie. Les tourbières de Sainte-Séraphine (SSE), du lac aux Cyprès (LCY), de Victoriaville (VIC) et de Villeroy (VR) se situent dans le Centre-du-Québec. La tourbière d'Issoudun (ISO) est située dans la région de Chaudière-Appalaches (voir localisation des sites sur la Figure 0.1).

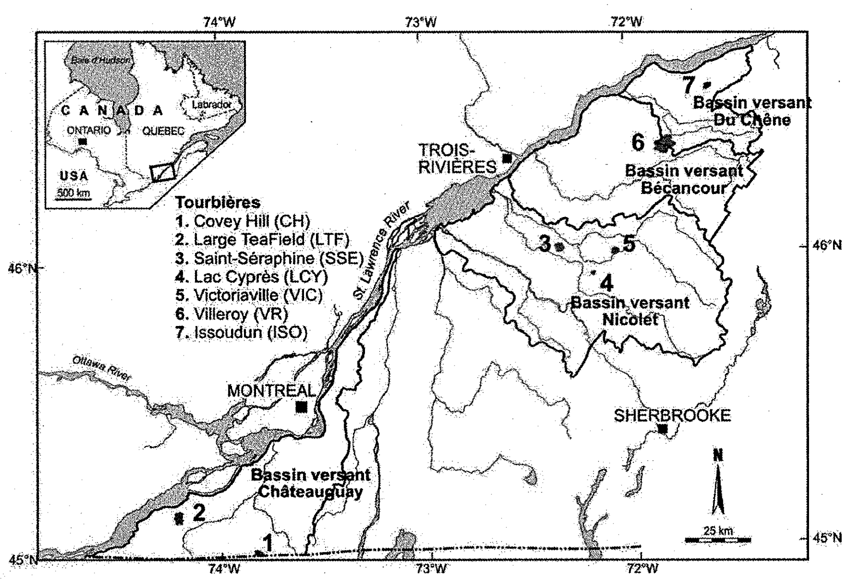

Figure 0.1 Localisation des tourbières étudiées (surfaces vertes) et délimitation des bassins versant dans lesquels elles se situent (traits noirs).

Les tourbières sont localisées dans les bassins versants des rivières Châteauguay (CH et LTF), Nicolet (SSE, LCY et VIC), Bécancour (VR) et du Chêne (VR et ISO). Leurs superficies varient entre 0.5 km^2 et 10.4 km^2 (voir détails au Tableau 0.1). L'épaisseur maximale des dépôts organiques de chaque tourbière varie entre 190 cm (LCY) et 522 cm (SSE). Les sites de CH, LTF et de VR ont déjà fait l'objet d'études afin de mieux comprendre l'hydrologie, l'hydrostratigraphie, la paléoécologie, l'évolution récente de la tourbière et les échanges aquifère-tourbière (Larocque *et al.*, 2013 ; Lavoie et Colpron-Tremblay, 2013 ; Levison *et al.*, 2014).

Tableau 0.1 Description générale des tourbières ombrotrophes étudiées: nom du site, latitude, longitude, altitude par rapport au niveau de la mer, superficie, bassin versant, contexte hydrogéologique, épaisseurs maximales de tourbe et régime nutritif (O pour ombrotrophe et M pour minérotrophe).

Site	Latitude	Longitude	Altitude (m)	Superficie (km^2)	Bassin Versant	Hydrogéologie	Épaisseur maximum de tourbe (cm)	Régime nutritif
CH	45.008	-73.828	310	0.5	Châteauguay	Roc fracturé/ grès fluviatile	322	M+O
LTF	45.132	-74.217	51	6.0	Châteauguay	Argile marine	493	O
SSE	46.042	-72.345	84	4.9	Nicolet	Silt d'origine fluviatile/ diamictons	522	M+O
LCY	45.950	-72.187	106	0.5	Nicolet	Sable éolien/ couche indurée	190	O
VIC	46.023	-72.077	118	2.6	Nicolet	Silt d'exondation marine	360	O
VR	46.376	-71.838	124	10.4	Bécancour/ du Chêne	Sable éolien/ diamictons	491	M+O
ISO	46.579	-71.597	117	2.8	du Chêne	Argile silteuse/ diamictons	454	O

Le choix des sites d'étude a été basé sur la diversité des contextes hydrogéologiques dans lesquels les tourbières se sont développées. Par exemple, la tourbière CH (0.5 km^2; 310 nmm) est caractérisée par une section ombrotrophe et une section minérotrophe alimentée par un aquifère rocheux fracturé composé de grès d'origine fluviatile. La tourbière ombrotrophe LTF (6.0 km^2; 51 nmm) est fortement drainée et s'est développée sur des argiles marines. Le complexe tourbeux SSE (4.9 km^2;

84 nmm) est caractérisé par une section ombrotrophe et une section minérotrophe ceinturées d'un marécage développé sur un dépôt présentant en alternance des silts d'origine fluviatile et des diamictons d'origine glaciaire contenant des silts argileux et des blocs. La tourbière ombrotrophe LCY (0.5 km^2; 106 nmm) s'est développée à partir d'un dépôt sableux remanié par des processus éoliens où l'on trouve sporadiquement de fines couches de sable induré. La tourbière VIC (2.6 km^2; 118 nmm) est une tourbière ombrotrophe qui s'est développée sur des silts d'exondation marine. La tourbière VR (10.4 km^2; 124 nmm) est composée d'une section ombrotrophe ainsi que d'une section minérotrophe et boisée. Elle s'est développée à partir de dépôt sableux remaniés par des processus éoliens alternant avec des diamictons d'origine glaciaire et composés de silts argileux. La tourbière ISO (2.8 km^2; 117 nmm) s'est formée sur des diamictons d'origine glaciaire contenant des argiles silteuses et des cailloutis. À l'exception de LCY, qui s'est formée dans le sillon d'une ancienne dune, CH, LTF, SSE, VIC, VR et ISO se sont développées dans des cuvettes d'érosion fluviatile, juxtaglaciaire ou issue d'érosion postglaciaire. Par ailleurs, des âges au radiocarbone (^{14}C) obtenus sur des macrofossiles végétaux prélevés à la base des dépôts tourbeux de CH et VR indiquent qu'elles se seraient formées entre 13 925 cal BP (CH) (Lavoie, Pellerin et Larocque, 2013) et 10 770 cal BP (VR) (Larocque *et al.*, 2013). Les tourbières de CH, LTF, SSE, VIC, VR et ISO sont localisées en tête de bassin versant et contribuent à l'alimentation des débits des rivières qu'elles alimentent, tandis que celle de LCY ne contient aucun exutoire. Selon Levison *et al.* (2014), la contribution de la tourbière de CH au débit de base des deux rivières qu'elle alimente serait de 4 %. Les résultats de Levison *et al.* (2014) et Larocque *et al.* (2013) montrent que les échanges entre l'eau souterraine et les tourbières de CH et VR correspondent à 9 % et 27 % des apports d'eau annuels respectivement. Toutefois, aucune étude n'a encore été réalisée pour comprendre la connectivité aux eaux souterraines des cinq autres tourbières.

0.5 MÉTHODOLOGIE

Pour répondre aux objectifs de cette thèse, chacun des sites a été caractérisé et instrumenté suivant une méthodologie similaire comprenant : la caractérisation, l'instrumentation, l'échantillonnage et les analyses en laboratoires. Les données récoltées ont été traitée à l'aide du programme statistique R (R environement, 2008).

0.5.1 Caractérisation des sites

Chacun des sites a fait l'objet d'une caractérisation hydrogéologique avant d'être instrumenté. Des sondages manuels ont permis d'estimer les épaisseurs des dépôts tourbeux, d'identifier la nature du substratum sur lequel les tourbières se sont développées et de mesurer les niveaux de nappe le long d'une ligne d'écoulement de l'amont vers l'aval pour chacune des tourbières. Les sondages ont été réalisés sur deux transects perpendiculaires à intervalle de 150 m. Pour les aquifères, des sondages manuels dans les sédiments quaternaires ont permis de valider les informations disponibles sur l'hydrostratigraphie. Des mesures de niveaux de nappe dans les aquifères ont permis d'identifier des zones où les charges hydrauliques étaient inférieures à celles des tourbières, celles-ci étant définies comme des zones de recharge (de l'aquifère). Des zones où les charges hydrauliques dans les aquifères étaient supérieures à celles des tourbières ont également été identifiées et définies comme des zones d'alimentation (de la tourbe). La nomenclature « zone de recharge » a été retenue en regard de la fonction hydrologique de recharge de la tourbière à l'aquifère, tandis « zone d'alimentation » a été retenue pour définir l'alimentation en eau depuis l'aquifère vers les tourbières. Des zones d'alimentation ont été identifiées seulement dans les complexes tourbeux formés de sections minérotrophes et ombrotrophes.

Les tourbières LTF, LCY, VIC et ISO ont été divisées en quatre zones incluant une zone amont, une zone intermédiaire, une zone aval et une zone de recharge (figure 0.2a).

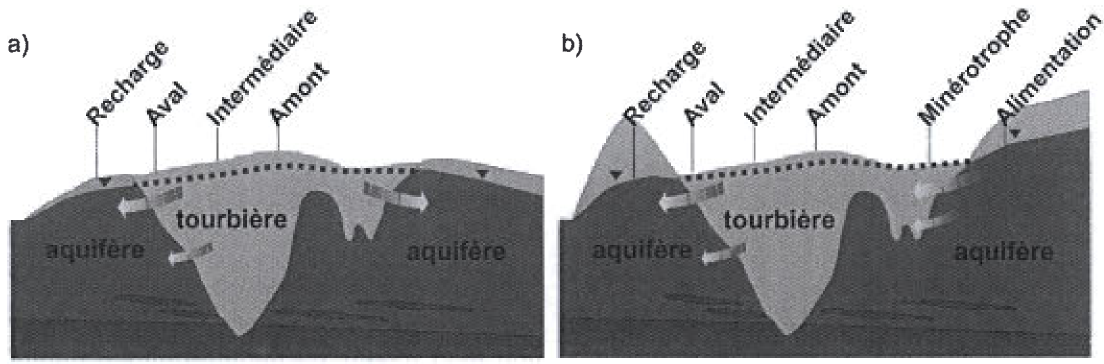

Figure 0.2 Schéma conceptuel montrant les échanges aquifère-tourbière (flèches rouges et jaunes), les niveaux de nappe des tourbières (ligne pointillée) et des aquifères (triangles bleus) et des zones instrumentées pour les tourbières a) qui ne sont pas alimentées par les eaux souterraines et b) qui sont alimentées par les eaux souterraines.

Les tourbières CV, SSE et VR comprennent aussi une zone amont, une zone intermédiaire, une zone aval et une zone de recharge. Elles incluent également une zone minérotrophe et une zone d'alimentation (figure 0.2b). En raison de sa faible superficie, la zone intermédiaire du site LCY n'a pas été instrumentée. Il en va de même de la zone de recharge du site LTF, en raison de sa très faible perméabilité.

0.5.2 Instrumentation des sites

Chaque site a été instrumenté avec un pluviomètre à bascule (*HOBO*) enregistrant séquentiellement les précipitations supérieures à 0,2 mm. Une sonde pour la mesure de la pression atmosphérique (*Solinst* Barologger) a été installée à chacun des sites. Par ailleurs, chaque zone a été instrumentée à l'aide de puits d'observation et de piézomètres. Les puits d'observation ont été utilisés spécifiquement pour les tourbières et ont été fabriqués à l'aide de tuyaux de PVC de 2 m de long et de 2.5 cm de rayon, crépinés sur toute leur longueur. Les puits d'observation ont été insérés dans les dépôts tourbeux à une profondeur de 170 cm, avec une margelle de 30 cm au-dessus de la tourbe. Les piézomètres ont été utilisés spécifiquement pour les aquifères et ont été fabriqués à l'aide de tuyaux d'acier galvanisé de 2.5 cm de rayon et d'une pointe filtrante de type *Solinst*. Les piézomètres, crépinés sur seulement 30 cm à leur base, ont été insérés à des profondeurs variant entre 1 et 5 m en tenant compte des niveaux de nappe dans l'aquifère minéral, tout en s'assurant qu'ils soient le plus près possible de la surface. Tous les puits et les piézomètres ont été instrumentés à l'aide de sondes automatisées (*Solinst* Junior). Les chroniques de niveaux de nappe ont été enregistrées à un pas de temps de 5 minutes de mai 2014 à octobre 2014 et à un pas de temps de 60 minutes d'octobre 2014 à juin 2016. Deux pas de temps ont été utilisés afin d'évaluer la présence de variations de niveaux de nappe à haute fréquence.

0.5.3 Échantillonnage

Dans chaque tourbière, trois carottes de tourbe de 1 m de longueur ont été prélevées le long du transect instrumenté de puits d'observations, dans les zones amont, intermédiaire et aval. Les carottes ont été prélevées à l'aide d'un carottier de type Box (Jeglum, 1991). Au total, 47 carottes ont été prélevées. Un bloc de tourbe de (40 cm x 25 cm x 40 cm) a également été échantillonné sur le site LTF. Sur le terrain, une évaluation sommaire de l'humification de la tourbe de chaque unité stratigraphique a été réalisée à l'aide de la méthode Von Post (Von Post, 1922) permettant de qualifier le niveau de décomposition de la tourbe en dix catégories (H1 à H10).

0.5.4 Analyses en laboratoire

Des analyses de laboratoire ont été réalisées sur l'ensemble des carottes de tourbe. Une carotte par tourbière en zone amont (sept carottes au total) a été utilisée pour la description de la composition de la tourbe (à des intervalles de 8 cm) en plus de mesures de porosité effective (aux mêmes intervalles de 8 cm). La composition de la tourbe a été décrite en laboratoire à l'aide d'un microscope stéréoscopique suivant la méthode Troës-Smith (1955). Quatre grandes catégories ont été retenues, soit *Turfa bryophytica, Turfa lignosa, Turfa herbacea* et *Detritus granosus*. Les porosités effectives ont été mesurées à partir de la méthode de drainage suggérée par Rosa et Larocque (2008) qui consiste à saturer les échantillons de tourbe, à mesurer les volumes d'eau gravitaire à la suite de 24 heures de drainage (V_d) [L^3], et à calculer la porosité effective à l'aide de la formule suivante:

$$S_Y = \frac{V_d}{A * \Delta h} \qquad (0.3)$$

où A [L^2] est égal à l'aire de l'échantillon perpendiculaire à l'écoulement et Δh [L] la variation entre le niveau de nappe initial et le niveau de nappe final.

De plus, 20 carottes (trois par tourbière et deux à LCY) ont été utilisées pour des mesures de densité et 20 autres carottes (trois par tourbière et deux à LCY) ont été utilisées pour mesurer les conductivités hydrauliques. Les mesures de densité ont été réalisées en laboratoire sur des échantillons de 44 cm^3 à partir de la méthode de Dean (1974). Les échantillons ont été séchés et pesés ce qui a permis d'obtenir la densité sèche (ρ_{dry}) selon la formule suivante :

$$\rho_{dry} = \frac{W}{V} \qquad (0.4)$$

Où W est la masse de l'échantillon séché [M] et V son volume [L^3]. La conductivité hydraulique a été mesurée suivant la méthode des cubes modifiés (MCM) (Rosa et Larocque, 2008 ; Surridge, Baird et Heathwaite, 2005). La méthode consiste à inonder des blocs de tourbe (7 cm x 7 cm x 8 cm) préalablement saturés pendant 24 heures, et de calculer, à l'aide de l'équation de Darcy, les débits sortants après stabilisation:

$$K = Q/Ai \tag{0.5}$$

où K est la conductivité hydraulique [L/T] des dépôts tourbeux, Q est le débit [L^3/T], A est l'aire de la section transverse à l'écoulement [L^2] et i est le gradient hydraulique [L/L]. Cette méthode a permis de calculer les conductivités hydrauliques horizontales de la tourbe à des intervalles de 8 cm. Finalement, le bloc de tourbe, récolté au site LTF, a été utilisé pour réaliser des tests de drainage à haute résolution (à des intervalles de 1 cm) sur un plus grand volume de tourbe.

0.5.5 Traitement des données

0.5.5.1 Calcul des conductivités hydrauliques

Des essais de perméabilité à charge variable (injection et retrait) ont été réalisés pour évaluer la conductivité hydraulique des aquifères. Les résultats ont été analysés à l'aide de la méthode de Hvorslev (1951) suivant les formules:

$$K = r^2\left(\frac{\ln(\frac{L}{r})}{2LT_0}\right) \tag{0.6}$$

$$T_0 = \ln\left(\frac{H-h}{H-H_0}\right) \tag{0.7}$$

où K est la conductivité hydraulique [L/T], r est le rayon du puit [L], L est la longueur de la crépine [L], T_o est le temps pour lequel ln(H-h)/(H-H_o))= - 1 [T], H est la charge statique avant le test [L], h [L] est la charge mesurée au temps t et H_o [L] est la charge induite par le *slug* (t=0) [L].

0.5.5.2 Calcul des coefficients d'emmagasinement

Les données piézométriques et pluviométriques ont été utilisées pour calculer la porosité effective (Sy) des dépôts tourbeux en considérant les variations de niveaux piézométriques (dh) [L] et les précipitations enregistrées pour chaque événement ($P_{\text{événement}}$) [L] (Healy et Cook, 2002) :

$$P_{\text{événement}} = dh * S_y \tag{0.8}$$

Cette équation se base sur l'hypothèse que l'ensemble des précipitations participe aux variations des niveaux d'eau mesurées dans les tourbières.

0.5.5.3 Analyses statistiques

Les données piézométriques, pluviométriques et de températures ont été utilisées pour calculer les précipitations mensuelles (P_{mois}) et les températures moyennes mensuelles (T_{mois}) des sites. Des analyses de variance (ANOVA) et des tests de comparaisons multiples (« Tukey's range test ») ont été réalisées sur les données de densité, de conductivité hydraulique, de porosité effective et des niveaux de nappe pour identifier les différences spatiales (intra- et inter-sites) et temporelles (saisonnalité).

L'ANOVA a permis d'évaluer si tous les échantillons suivent une même loi normale. Dans le cas où l'ANOVA est significative, le test de comparaison multiples (« HSD de Tukey,») identifie les couples qui sont distincts. Pour les ANOVA, une valeur p inférieure à 1-α, où α est l'intervalle de confiance, permet de rejeter l'hypothèse nulle et indique que la moyenne d'au moins une variable nominale spatiale ou temporelle est différente. Pour le test « HSD de Tukey », une valeur p inférieure à 1-α permet de rejeter l'hypothèse nulle et indique que les moyennes d'un couple de variables nominales spatiales ou temporelles sont différentes.

0.5.5.4 Analyse des séries temporelles

Les séries temporelles des niveaux de nappe dans les tourbières ont été divisées en deux parties, une partie comprenant les hausses des niveaux de nappe et une autre partie comprenant les baisses des niveaux de nappe. L'isolement des hausses s'est fait à partir d'un script R calculant automatiquement la somme des précipitations pour chaque événement pluvieux ($P_{\text{événement}}$), l'augmentation des niveaux de nappe ($\Delta h_{\text{augmentation}}$) ainsi que les intervalles de temps qui sont associés à $P_{\text{événement}}$ et $\Delta h_{\text{augmentation}}$. Les baisses des niveaux de nappe ($\Delta h_{\text{diminution}}$) ont été isolées en retirant les intervalles de temps associés à $\Delta h_{\text{augmentation}}$ et $P_{\text{événement}}$.

De plus, les séries temporelles des niveaux de nappe dans les tourbières et dans les aquifères ont été utilisées pour le calcul des fonctions d'autocorrélation et de corrélation croisée.

Les autocorrélations quantifient la mémoire temporelle d'un système correspondant au temps de dissipation d'un signal qui est aussi un analogue de l'emmagasinement. Elles sont calculées à l'aide des équations suivantes :

$$r_k = \frac{C_k}{C_0} \tag{0.9}$$

$$C_k = \frac{1}{N}\sum_{t=1}^{N-k}(x_t - \mu_x)(x_{t+k} - \mu_x) \quad (0.10)$$

où r_k est le coefficient d'autocorrélation, C_0 [T] est la variance, C_k [T] est la covariance, k est le pas de temps, N est le nombre d'observations, t est le temps [T] et μ_x est la moyenne de la série x_t.

Les corrélations croisées quantifient le décalage temporelle entre deux séries temporelles où $r_{xy}(k)$ est à son maximum. Elle sont calculées à l'aide des équations suivantes :

$$r_{xy}(\mathrm{k}) = \frac{C_{xy}(k)}{\sigma_x \sigma_y} \quad (0.11)$$

$$C_{xy}(\mathrm{k}) = \frac{1}{N}\sum_{t=1}^{N-k}(x_t - \mu_x)(y_{t+k} - \mu_y) \quad (0.12)$$

où r_{xy} est le coefficient de corrélation croisée, C_{xy} [T] est la covariance, σ_x et σ_y est l'écart type des séries x_t et y_t, k est le pas de temps, N est le nombre d'observations, t est le temps [T] et μ_x et μ_y sont la moyenne des séries temporelles x_t et y_t.

0.5.5.5 Corrélations

Des corrélations linéaires, semi-logarithmiques et logarithmiques (log-log) ont été réalisées à l'aide du programme R (R environement, 2008) sur les données de densité, de conductivité hydraulique, de porosité effective en fonction de la profondeur au sein des dépôts tourbeux. Des coefficients de corrélations (R^2) ont été calculés pour évaluer la force des équations mathématiques dérivées.

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CHAPITRE I

QUANTIFICATION OF PEATLAND WATER STORAGE CAPACITY USING THE WATER TABLE FLUCTUATION METHOD

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Sous presse dans *Hydrological processes* doi : 10.1002/hyp.11116

ABSTRACT

Peat specific yield (Sy) is an important parameter involved in many peatland hydrological functions such as flood attenuation, baseflow contribution to rivers and maintaining groundwater levels in surficial aquifers. However, general knowledge on peatland water storage capacity is still very limited, due in part to the technical difficulties related to *in situ* measurements. The objectives of this study were to quantify vertical Sy variations of water tables in peatlands using the water table fluctuation method (WTF) and to better understand the factors controlling peatland water storage capacity. The method was tested in five ombrotrophic peatlands located in the St. Lawrence Lowlands (southern Québec, Canada). In each peatland, water table wells were installed at three locations (up-gradient, mid-gradient and down-gradient). Near each well, a 1 m long peat core (8 cm x 8 cm) was sampled, and sub-samples were used to determine Sy with standard gravitational drainage method. A larger peat sample (25 cm x 60 cm x 40 cm) was also collected in one peatland to estimate Sy using a laboratory drainage method. In all sites, the mean water table depth ranged from 9 to 49 cm below the peat surface, with annual fluctuations varying between 15 and 29 cm for all locations. The WTF method produced similar results to the gravitational drainage experiments, with values ranging between 0.13 and 0.99 for the WTF method, and between 0.01 and 0.95 for the gravitational drainage experiments. Sy was found to rapidly decrease with depth within 20 cm, independently of the within-site location and the mean annual water table depth. Dominant factors explaining Sy variations were identified using ANOVA and Tukey's range test. The most important factor was peatland site, followed by peat depth and seasonality. Variations in storage capacity considering site and seasonality followed regional effective growing degree days and evapotranspiration patterns. This work provides new data on spatial variations of peatland water storage capacity using an easily implemented method that requires only water table measurements and precipitation data.

Keywords: peatland, water storage, specific yield, water table fluctuation, drainage experiment

1.1 INTRODUCTION

Peatlands play important hydrologic functions by attenuating flooding by storing water during high precipitation events (Acreman et Holden, 2013), contributing to river base flows (Bourgault, Larocque et Roy, 2014) and maintaining groundwater levels in superficial aquifers (McLaughlin *et al.*, 2014). However, enhanced knowledge on quantification of water storage capacity is needed to better understand these peatland hydrological functions. In peatlands, peat storage capacity (S) strongly varies within the first meter and buffers water table fluctuations, flow velocities and evapotranspiration fluxes (White, 1932). For example, when the water table is high, flow velocities and evapotranspiration fluxes increase; the opposite happens during low water table periods.

In mineral aquifers, long-term water storage is also controlled by climatic forcing such as summer water deficits (Yeh *et al.*, 2006), by anthropogenic activities such as groundwater extraction, and to a more limited extent by land drainage which can reduce aquifer recharge (Winter *et al.*, 1998). Short-term changes occur mainly in response to rainfall, pumping, and evapotranspiration fluxes (Geris *et al.*, 2015 ; Healy et Cook, 2002). These processes are also active in peatland ecosystems. They are especially important due to the contrasted values of S between the acrotelm and the catotelm (Ingram et Bragg, 1984). In addition, peat S also changes due to expansion and compression, which is a seasonal effect of water content variation (also named *mire breathing*; Price et Schlotzhauer, 1999), ice expansion in the peat, or a longer time scale effect of organic matter oxidation. Therefore, water table fluctuation does not occur only when air enters the specific yield (Sy) as the water table declines. However, as a first approximation S is usually assimilated to Sy (Price, 1996).

Peat Sy can vary by up to two orders of magnitude (0.01 – 1) within the first top 50 cm (Dettmann et Bechtold, 2016 ; Holden, 2009 ; Vorob'ev, 1963). This buffers peatlands against both inundation and excessive drying (Waddington *et al.*, 2015). Sy has been quantified based on field measurements using porous disk infiltrometers (Holden, 2009 ; Holden, Burt et Cox, 2001), rain-to-rise ratio (Dettmann et Bechtold, 2016 ; Letts, Roulet et Comer, 2000 ; McLaughlin et Cohen, 2014), tracer tests (Ronkanen et Klove, 2008), laboratory drainage experiments (Price, 1996 ; Rosa et Larocque, 2008 ; Vorob'ev, 1963), and pressure chamber measurements (Moore, Morris et Waddington, 2015). The rain-to-rise ratio method is equivalent to the water table fluctuation method (WTF; White, 1932) commonly used in aquifers to quantify groundwater recharge (Healy et Cook, 2002).

The WTF method is a simple alternative to laboratory measurements. It has significant potential as an easily implemented, low-cost method to determine peat Sy. Because peat deposits are heterogeneous (Baird *et al.*, 2016) and compressible media where hysteresis is observed between water table rise and precipitation due to air encapsulation, gas bubble production, and unsaturated pore filling (Barton, Andrews et Kolka, 2006 ; Nachabe, 2002 ; Ramirez *et al.*, 2015), it is hypothesised that the WTF method is more adapted to peatland than conventional laboratory measurements. The use of the WTF method in peatlands, offers an excellent opportunity to upscale the understanding of water storage capacity using widely available data of water table and precipitation.

The objective of this research was to adapt the WTF method to quantify vertical Sy variations in peatlands and better understand the factors controlling their water storage capacity. It is assumed that seasonal expansion and compression-expansion of peat do not influence the short-term rain event-based calculation of Sy. It is also assumed that changes in peat surface topography following a single rain event can be considered negligible. The WTF method was tested in five ombrotrophic peatlands located in the St. Lawrence Lowlands (Quebec, Canada), and results were compared to Sy estimates from laboratory measurements on collected peat samples.

1.2 STUDY SITES

The five studied peatlands (Large Tea Field – LTF, Sainte-Séraphine – SSE, Lac Cyprès – LCY, Victoriaville – VIC, Issoudun – ISO) are located in the southern part of the St. Lawrence Lowlands (Quebec, Canada) in three different watersheds (Châteauguay, Nicolet, and Du Chêne) (Figure 1.1). All sites are headwater peatlands formed in topographic depressions, except LCY, which is located on the flank of fine to medium aeolian sand deposits. All sites are characterized by a hummock and lawn microtopography without any surface pools. Hollows and mud bottom were found only at sites ISO and VIC.

The five sites are set in different geological contexts, characterized by Quaternary surficial sediments (marine clay, fluvial sandy silt, clayey silty till, aeolian fine to medium sand, and regressive marine sand) deposited following the last deglaciation since 12,3 kaBP (Richard et Occhietti, 2004) (Table I). Peat thickness vary between 40 cm and 522 cm with maximum of 190 cm in LCY, 522 cm in SSE, 493 cm in LTF, 345 cm in VIC and 454 cm in ISO. Their surface area ranges between 0.5 and 6.0 km^2 (Table 1.1) and they have developed as complexes with a central ombrotrophic section. Lateral minerotrophic conditions were found only at site SSE.

Mean annual precipitation (reference period: 1981 – 2010) for the Châteauguay (LTF), Nicolet (SSE, LCY, VIC), and du Chêne (Issoudun – ISO) watersheds varies between 965 mm (Châteauguay) and 1114 mm (Nicolet), with the driest conditions recorded in the LTF region specifically. For all sites (Figure 1.2), minimum monthly precipitation occurs during the winter, and maximum monthly precipitation occurs during the summer (MDDELCC, 2015). Mean annual temperature (for the same reference period as for mean annual precipitation) varies between 4.8 °C and 6.7 °C, with the lowest values in the ISO region. For all sites, minimum and maximum temperatures are recorded in January and July respectively (Figure 1.2). Effective growing degree days (GGD>0) (reference period: 1974-2000) varies between 1800 and 2000 for the Châteauguay watershed, between 1600 and 1800 for the Nicolet watershed, and between 1400 and 1600 for the du Chêne watershed (Atlas agroclimatique du Québec, 2012) (Table I).

Vegetation surveys performed at all sites show that *Sphagnum spp.* (*Sph* sp.), *Kalmia angustifolia* (*Kal ang*), and *Eriophorum vaginatum* (*Eri vag*) are the main species. *Andromeda glaucophylla* (*And gla*), *Aulacomnium palustre* (*Aul pal*), *Chamaedaphne calyculata* (*Cha cal*), *Carex spp.* (*Car* sp.), *Rhododendron groenlandicum* (*Rho gro*), and *Polytricum strictum (Pol str)* were also found, albeit sparsely (Larocque *et al.*, 2015; Lefebvre *et al.*, 2015 ; Pasquet, Pellerin et Poulin, 2015). Climatic conditions differ slightly from west to east, in terms of effective growing degree days and ecoregion vegetation assemblages, from the hickory and maple forest (*Carya cordiformis* and *Acer saccharum*) in the western section (LTF), to the lime tree and maple forest (*Tilia americana* and *Acer saccharum*) eastward, which supports the slightly colder and wetter conditions of the ISO site.

1.3 METHODOLOGY

1.3.1 Site instrumentation

Elevation data were obtained for the five sites from a Digital Elevation Model (DEM; 1 m x 1 m resolution) derived from airborne light detection and ranging (LiDAR) surveys. Absolute errors on elevations vary between 5 and 48 cm (Aguilar *et al.*, 2010 ; Hodgson et Bresnahan, 2004), with the smallest errors for open areas. Based on the DEM, three locations were identified in each peatland (up-gradient, mid-gradient, and down-gradient) for the installation of wells (Figure 1.3). Distances between up-gradient and down-gradient wells vary between 123 and 760 m with mean slopes from 0.08 to 0.24% (Table 1.1).

Water table variations were recorded at these three locations within each site using wells constructed from 3 cm OD PVC pipes, with 2 m long intakes perforated with 0.0254 cm slits from top to bottom, and sealed at their base. All wells were inserted into *Sphagnum* lawn microforms. Sites were also equipped with three level loggers (*Solinst*), a barometric logger (*Solinst*), and a rain gauge tipping bucket (*Hobo*). The level loggers and barometric loggers were attached to the well screw tops. Water table variations, barometric pressure, and precipitation were measured every 5 minutes from June 2014 to August 2015 (with the exception of the winter months between November 2014 and April 2015). Sites were also instrumented with a metal bar at down-gradient locations to monitor changes in topography due to peat expansion and contraction. These changes were monitored three times during the study period (spring, summer, and autumn) using a reference level located on the metal bars.

1.3.2 Small cube experiment

Five 1 m long peat cores were sampled using a Box corer (8 x 8 cm) (Jeglum, 1991) at the up-gradient location of each studied peatland. Sampling compression in the acrotelm was 10 cm for LTF, 12 cm for SSE, 20 cm for LCY, 8 cm for VIC, and 2 cm for ISO, and were proportional to the acrotelm thickness. Cores were cut into two 50 cm sections using a sharp knife, wrapped in cellophane, and stored at 4°C. Humification analysis was performed on 5 cm peat slices throughout the whole 5 cores. Sy measurements were performed on 7 x 7 x 8 cm peat samples (14 cores in total; 3 for LTF, 3 for SSE, 2 for LCY, 3 for VIC and 3 for ISO) using gravity drainage experiments assuming that Sy can be assimilated to its drainable porosity (Price, 1996).

Gravity drainage was performed in acrylic cubes (7 x 7 x 8 cm) and used to estimate Sy following Eq. 1.1 (Freeze et Cherry, 1979),

$$S_y = \frac{V_d}{A * \Delta h} \quad (1.1)$$

where V_d is the drained water volume (cm^3), A is the area of the peat sample (7 cm x 7 cm = 49 cm^2), and Δh is the water table fluctuation (cm). Peat samples were resized after 0.5 cm was cut from each side to remove any compression due to transportation. Samples were saturated for 24 hours and drained for an additional 24 hours. Each acrylic cube was connected at the bottom to a 1.3 cm plastic tube attached to an adjustable base support to drain the samples. Each drainage experiment began by decreasing the height of the plastic tube to that of the bottom of the tested sample. Although slightly different from conventional drainage experiments, this method was specifically chosen so as to be comparable to the experimental tank method described in section 1.4.3.

For the less decomposed samples, the errors were proportional to the lost volume due to compression above the water table. Errors were calculated using the ratio between the loss of height and the mean annual water table depth since compression was limited to the unsaturated zone. Since compression was not evenly distributed throughout the core, errors on Sy measurement were only applied to the upper 20 cm.

For the more decomposed samples (below 20 cm; all the sites), rapid outflow was observed, probably due to secondary porosity created during sample insertion into the acrylic cubes. The rapid outflow was measured at the beginning of each experiment and divided by the total volume of the acrylic cubes (7 cm x 7 cm x 8 cm) to quantify the maximum error associated with the method.

1.3.3 Experimental tank

The laboratory method developed by Rosa et Larocque (2008) to estimate Sy was adapted to quantify the fine-scale, empirical relationship between Sy and depth below the peat surface. Laboratory experiments were conducted in a 40 cm long, 25 cm wide, and 36 cm high experimental tank built using 4 mm thick clear acrylic panels (Figure 1.4). The peat sample was retrieved from the LTF peatland at the up-gradient location. The mean water table depth (26 cm) at this site is equivalent to that of the four other studied peatlands, making it representative of all sites for this experiment. No compression was observed during sampling.

In the laboratory, the two sides of the peat sample were supported with perforated stainless steel plates to create two experimental reservoirs. These reservoirs were connected using flexible 5.1 cm PVC tubing, and redirected to a single outlet to control water table elevation within the reservoirs. The tank was filled from the bottom with water collected in the field with 4 L Nalgene bottles. A neon lamp suspended 15 cm above the tank provided 12 h of daylight to maintain living vegetation conditions.

Drainage experiments were performed every centimetre between 0-20 cm, and every 2.5 cm between 20-36 cm. Drainage intervals were increased below 20 cm so as to reduce volumetric error measurements since Sy and drained water decrease with depth below the peat surface. Drainage experiments were performed twice for the upper 20 cm to account for air encapsulation and unsaturated pore filling (Barton, Andrews et Kolka, 2006 ; Nachabe, 2002). No compression or expansion resulting in a change of the peat elevation was observed during the drainage experiments.

Sy estimates were obtained using Eq. 1.1, as defined in section 1.4.2 above, but with an A = 40 cm x 25 cm = 1000 cm^2. However, Sy could not be estimated below 0.08, due to an increase in volumetric error measurements associated with the decreasing water volume released from the drainable porosity and to bottom sedimentation within the two reservoirs.

1.3.4 Water table fluctuation method

Using the WTF method, specific yield (Sy) was calculated as follows:

$$S_y = P/\Delta h \qquad (1.2)$$

where P is the amount of precipitation, and Δh is the water level rise following a precipitation event. Eq. 1.2 assumes that the time lag between the end of each precipitation event and the maximum water level rise is sufficiently short for evapotranspiration, net subsurface flow and water table recession following P events (i.e., water reaching the saturated zone is entirely transferred into storage). The method also assumes that recharge is equal to precipitation (i.e., no runoff), that the static equilibrium water content profile within the unsaturated zone is attained instantaneously following a rain event and that any rain-to-rise ratio deviation from a theoretical model will be due to the presence of a capillarity fringe, air entrapment, peat expansion and contraction, net subsurface flow, water recession following P events and antecedent moisture content of the unsaturated zone.

A computation script written in the R language (R environement, D.C.T, 2008) was developed to identify the precipitation events to be considered and the maximum water table rise following each precipitation event. The program automatically calculated total precipitation during a given event (P), maximum water level rise following this event (Δh), and Sy using three parameters: the time interval ($Time_{int}$), the maximum (max_{prec}) and minimum precipitation (min_{prec}). $Time_{int}$ was used to separate precipitation events. Max_{prec} and min_{prec} were used to determine which precipitation events to include in the Sy calculation. Small precipitation events were excluded based on the assumption that a large proportion of the precipitation never reached the saturated zone during these events. Large precipitation events were also excluded since they induced large Δh with depth approximation error. Measurement errors on Δh were equal to 1 mm whereas P errors are estimated to be as high as 6.4 % of total P for small rain events (Chiah, 2003 ; Hodgkinson, Pepper et Wilson, 2004). Therefore, precipitation events smaller than 1 mm and larger than 35 mm, and those associated with water table variations smaller than 10 mm were excluded, because the relative error on the rain-to-rise ratio (equivalent to Sy) was too large in these cases.

While calibrating the R program, variations with $Time_{int}$ were set between 1 and 10 hours, max_{prec} between 20-100 mm and min_{prec} between 0-10 mm. These intervals were chosen since precipitation events between 10 and 20 mm easily reached the saturated zone and were well constrained vertically. $Time_{int}$, max_{prec}, and min_{prec} were calibrated to minimize the residual sum of squared errors (RSSE) between the model estimation, using Sy obtained from the WTF method, and the individual laboratory Sy values, obtained using the small cube experiment and the experimental tank method, while seeking to retain a maximum number of precipitation events. A minimal value of $Time_{int}$ was used to support the hypothesis that subsurface flow was negligible and that the night-time recession period (4 to 9 hours) was greater than $Time_{int}$. This is based on the observation that the time lag between the end of a precipitation event and the maximum water table increase was less than 3 hours (mean of 2 hours) for all rainfall events.

For all-time series analysis, $Time_{int}$, max_{prec}, and min_{prec} were set to 3 hours, 35 mm and 7 mm, respectively. Time series were resampled at 10, 20, 30, 40, and 60 min, and one day time intervals to identify the maximum time step required to calculate Sy. Modification of the selected time intervals had no effect on Sy calculation, except for the one day time interval. To optimize calculations, the one hour time series interval was used for all Sy calculations.

All Sy calculated using the WTF method (Sy_{WTF}) were compared between sites, depths, location within the peatland, and seasonality, using one-way Analysis of Variance (ANOVA) implemented in R. Significant differences found among these variables were further analyzed using Tukey's Honest Significant difference (HSD), again in R. Finally, all Sy and rates of Sy decrease with depth obtained from the WTF, the experimental tank, and the small cube experiment methods were compared.

1.4 RESULTS

1.4.1 Surface topography, hydrology and peat humification

At all locations in the five studied peatlands, the upper 5 cm was composed of living vegetation while peat was slightly humified between 10 and 20 cm below the surface (H3-H4 (Von Post, 1922). Peat humification increased toward the catotelm, with highly decomposed peat (H7-H8-H9) for sites VIC, LCY, LTF, and SSE, and slightly to moderately decomposed peat (H4-H5) for site ISO.

Throughout the five peatlands, water table depths (WTD) varied between 1 and 60 cm, with a maximum measured variation of 19 cm in LCY, 26 cm in SSE, 24 cm in LTF, 15 cm in VIC, and 19 cm in ISO. With the exception of VIC, WTD decreased from the up-gradient to the down-gradient locations (Figure 1.5). Mean WTD for all sites combined varied between 9 and 49 cm for up-gradient locations, between 12 and 33 cm for mid-gradient locations, and between 6 and 44 cm for down-gradient locations. Mean WTD for all locations in a given site in 2014 and 2015 were 41 cm in LCY, 37 cm in SSE, 26 cm in LTF, 19 cm in VIC, and 9 cm in ISO. Acrotelm thickness varied between 35 and 55 cm (comprising value of humification lower than H5) with mean acrotelm thickness equaled to 55 cm for LCY, 50 cm for SSE, 45 cm for LTF, 30 cm for VIC and 45 cm for ISO.

Changes in peat surface topography throughout the study sites and within each peatland were on average 1.0 cm during the two monitored growing seasons. One extreme value of 5 cm change in peat surface topography was measured at the ISO site where ice was still partly presents following the record-cold winter 2014-2015.

1.4.2 Specific yield estimated using the small cube method experiment and experimental tank measurements

The Sy values estimated using the cube (Sy_{cube}) and the tank (Sy_{tank}) methods varied from 0.01 and 0.95 within the first meter (Sy_{cube} and Sy_{tank} cannot exceed 1.0) (Figure 1.6). The mean Sy_{tank} and Sy_{cube} of the living and slightly humified peat layer comprised within the acrotelm was 0.69 and 0.35 for the two methods respectively. For the cube method, Sy rates decreased with depth, varying between 0.001 and 0.030 cm^{-1}. The upper ~25 cm showed rates of decrease varying from 0.015 cm^{-1} to 0.030 cm^{-1}, whereas the rate of decrease between 25 and 100 cm is indistinguishable from 0 cm^{-1}. The average Sy measurement error for the small cube experiment on the 0-20 cm samples was 0.49 for LCY, 0.32 for SSE, 0.38 for LTF, 0.42 for VIC and 0.22 for ISO, with an overall mean of 0.37. The average Sy measurement error due to this manipulation was estimated to be 0.05 (n=40), with a maximum value of 0.11. For the experimental tank method, the rate of Sy decrease with depth is 0.07 cm^{-1} between 10 and 25 cm, and 0.005 cm^{-1} for the bottom sections (25-30 cm). While modeling Sy_{tank} as a function of depth, Sy tank values between 0 and 10 cm were not considered due to the lack of variation with depth associated with the living vegetation.

Between 0 cm and 20 cm, Sy_{cube} measurements were considerably lower than Sy_{tank}, probably due to peat compression during coring for Sy_{cube} which varied between 2 and 20 cm. No compression was observed during sampling for the tank experiment. Hence, the Sy_{cube} measurements should be considered to represent the lower boundary of the true Sy values. Even if these data should not be used as absolute values, they suggest a non-linear trend of Sy with respect to depth.

Sy_{tank} values for depth between 0 and 10 cm were relatively constant, and differed considerably from the values obtained at greater depth. This is consistent with the greater peat humification below 10 cm, which changed from poorly humified (H1-H2) above 10 cm to slightly humified (H3-H4) below.

Different regression models for the Sy vs depth relationship (i.e., linear, log, and power law) were calculated. Similar to the work of Sherwood *et al.* (2013), the best fit model for both methods were power law models:

$$S_Y = \beta_0 depth^{-\beta_1} \quad (1.3)$$

where $\beta_0 =$ 1.45 and $\beta_1 =$ -0.75, with resulting RSSE = 0.62 for the small cube method, and where $\beta_0 =$ 41.41 and $\beta_1 =$ 1.58, with resulting RSSE = 0.19 for the experimental tank method. These power law models are used henceforth to describe Sy changes with depth. However, the rate of Sy decrease with depth needs to be adjusted for each peatland since the mean water table depth, acrotelm thickness and peat composition can vary between peatlands.

1.4.3 Specific yield estimated using the WTF method

During 2014 and 2015, a total of 1182 precipitation events were recorded, ranging between 1 and 57.2 mm, with a mean of 5 mm, and precipitation intensity varying between 0.2 to 27.6 mm/hour. During this period, Δh values varied from 10 to 178 mm. Following a rain event, the calculated Sy_{WTF} varied between 0.02 and 2, with a mean of 0.59 (Figure 1.7). A total of 99 precipitation events (13%) generated Sy_{WTF} values exceeding 1, 183 (24%) resulted in Sy_{WTF} values between 0.59 and 1, and 465 (63%) resulted in Sy values smaller than 0.59. Values of Sy_{WTF} above 1 were not considered in the analysis since they did not respect the hypothesis that runoff was negligible.

Sy_{WTF} values were highly variable between sites, with values between 0.32 and 0.99 for ISO, 0.18 and 0.99 for VIC, 0.13 and 0.99 for LTF, 0.25 and 0.90 for SSE, and 0.29 and 0.88 for LCY (Figure 1.8). The best fit power law equation for the Sy-depth models used β_0 ranging from 6.69 to 2783.01 and β_1 from -0.94 to -2.23. Modeled rates of Sy decrease with depth varied between 0.008 cm^{-1} and 0.06 cm^{-1} for all sites, with a higher rate of decrease when water table levels were high. The rate of Sy decrease with depth shows similar patterns across all sites.

Results from the ANOVA showed that site, seasonality, within-site location, and depth have a significant effect on Sy. Site ($p < 0.0001$), depth ($p < 0.0001$), and seasonality ($p = 0.007$) were the strongest factors, while location within the peatland was the weakest ($p = 0.05$; Figure 1.9).

Considering site (Figure 1.9a), LCY, VIC, and ISO show no significant difference in their mean Sy, whereas LTF and SSE, differ strongly from LCY, VIC, and ISO (confidence interval of 99%). For depth (Figure 1.9b), groups of 0-5, 5-10, and 10-15 cm show higher calculated Sy than deeper groups. However, there are no systematic significant differences between all depth groups. For seasonality (Figure 1.9c), Sy varies following the seasons and shows no significant difference during the wet periods (May, June, October, and November). Finally, the ANOVA results indicated that within-site location was not a dominant factor since no significant difference was found between the up-gradient, mid-gradient, and down-gradient locations when comparing the different locations in a given peatland or when merging all the sites (Figure 1.9d).

1.5 Discussion

1.5.1 Specific yield measurements

The Sy measurements and rates of decrease obtained in this study were generally consistent with the range of values reported for different types of wetlands (peatland, blanket peat bog, open water, constructed peatland, cutover bog) and using different methods (e.g., gravity drainage, moisture retention measurements, infiltration rate experiment, water table fluctuation method, tracer tests) (Table 1.2). Using the WTF method, Moore *et al.* (2015), McLaughlin et Cohen (2014), and Dettmann et Bechtold (2016) reported Sy values ranging from 0 to 1.1, from 0.13 to 1.05 and 0 to 0.9 within the first 50, 65 and 45 cm respectively. This was equivalent to decreasing rates with depth ranging between ~ 0.007-0.013 cm^{-1} (Moore, Morris et Waddington, 2015), 0.02 cm^{-1} (McLaughlin et Cohen, 2014) and ~ 0 – 0.08 cm^{-1} (Dettmann et Bechtold, 2016). Using pressure chamber experiment measurements as quantitatively equivalent to Sy, Moore *et al.* (2015) found that Sy varied between 0.1 and 0.7, and decreased with depth at a rate ranging between 0.007 and 0.013 cm^{-1}. With infiltration measurements, Holden (2009) found that Sy varied between 0.01 and 1.00 within the upper 20 cm, independently of the surface vegetation (with the exception of *Eriophorum*, where it reached 0.001). This is equivalent to a decrease in Sy with depth between ~ 0.02 and ~ 0.05 cm^{-1}. Finally, using gravity experiments, Vorob'ev

(1963) investigated Sy and the relationship between capillarity fringe and gravitational moisture in unforested low-lying swamps (the term used by the author to designate peatlands), and found that Sy decreased non-linearly with depth, from ~0.09 to ~0.45, at a rate of ~0.04 to 0.06 cm^{-1} (Table II). In this study, Sy varied between 0.13 and 0.99 using the WTF method and between 0.01 and 0.95 using the small cube and tank drainage experiments. These results are strong observational evidence of the sharp decrease of Sy with depth. Moreover, results obtained using the WTF method show almost identical ranges and patterns obtained by Dettmann and Bechtold (2016).

1.5.2 Comparison of methods

In this work, the cube method and the experimental tank were combined to determine the fine scale variations of Sy as a function of depth within the top peat deposit (experimental tank) and the general patterns of Sy as a function of depth throughout the peat column (cube method). The sampling process can induce artificial modifications to the peat. For instance, the use of a box corer to sample peat is an imperfect method, especially in peatlands with a thick acrotelm layer that can be easily compressed. However, the box corer provides the capacity to sample deeper peat cores, thus providing insight into the values of Sy lower within the peat column. Sampling the larger peat volume required for the experimental tank induces minimal peat compression, but addressed only the top peat layer. Moreover, Sy measurements are commonly performed directly in the laboratory on samples that have different volumes or in the field where it is hard to evaluate the scale of the measurements. In fact, strong heterogeneity of hydrodynamic properties are usually encountered at the local scale and are expected to modify measurements and induce a scale effect (Turner *et al.*, 2015). Hence, it is expected that Sy obtained in the laboratory will differ from Sy measurements obtained with *in situ* methods.

Comparing results from the three different methods remains challenging also because they depart slightly from the Sy definition. For example, the drainage experiments (small cubes and tank) measure drainage porosity which is an approximation of Sy. Nevertheless, given the fact that the WTF method provided Sy values similar to those of the cube method and of the experimental tank and that the results obtained in this study are almost identical to the results obtained by Dettmann et Bechtold (2016) using the same method, it is hypothesized that the assumption underlying the use of the WTF method are reasonable. In future research, the WTF method will need to be used in a wide variety of peatlands to fully constrain its validity.

1.5.3 Factors influencing storage capacity variations

Many authors (Holden, 2009 ; Moore, Morris et Waddington, 2015 ; Price, 1996 ; Thompson et Waddington, 2013) have demonstrated that peatlands vary significantly in terms of microtopography (hummock, lawn, hollow, pool), disturbances (fire, drainage), hydrogeological context, and hydroclimatic environment (Geris *et al.*, 2015). These are all factors that have been recognized as affecting storage capacity. Fires have been shown to decrease Sy, which increases the flashiness of water table fluctuations (Sherwood *et al.*, 2013). Sy differ between hummocks and hollows as these tend to dry up more rapidly and retain more water than hummocks (Moore, Morris et Waddington, 2015). Hydrogeological contexts control the connectivity of peatlands to aquifers, limiting water table fluctuations (i.e., minerotrophic peatland), and hydroclimatic conditions modify precipitation regimes, evapotranspiration, and soil moisture dynamics, exerting a control on water storage (Geris *et al.*, 2015).

In this study, observed Sy differences could not be explained by the presence of disturbances or variations in microform, since vegetation assemblages did not show strong evidence of perturbation and microforms did not differ significantly within and between sites. Additionally, the hydrogeological context, which was found to differ strongly from site to site (Table I) could not explain the increasing Sy trend observed in Figure 1.9a. For example, LCY and VIC have both developed on fine to medium sand (high permeability), whereas ISO formed on glacial clayed silt (low permeability), yet no statistical difference was found between their means Sy.

Between site locations, differences in storage capacity are better explained by the decreasing trend in effective growing degree days registered from the south-west to the north-east St. Lawrence Lowlands. Higher numbers of effective growing degree days increase overall evapotranspiration rates. Sites characterized by greater evapotranspiration tend to have water tables closer to their respective minimum annual water table position, where humification is higher. Therefore, under similar precipitation regimes, those sites experiencing higher evapotranspiration rates will have lower Sy_{WTF}. However, their dynamic storage capacity will be higher, since more space is available before reaching a threshold water-table depth.

Large variations in Sy with depth within the peat profile (Figure 1.9b) have also been reported in the literature (Holden, 2009 ; Moore, Morris et Waddington, 2015 ; Vorob'ev, 1963), and correspond to the increasing degree of peat decomposition with depth. For instance, a Sy of greater than 0.13 is equivalent to a Von Post degree of decomposition between H1 and H5, whereas a Sy of less than 0.13 is equivalent to a degree of decomposition between H6 and H9. This link between Sy and degree of decomposition has also been reported by Letts *et al.* (2000), where Sy decreased from 0.66 to 0.13, with peat type changing from fibric to sapric, and by Boelter (1964), also reported Sy as high as 0.80 in undecomposed peat and as low as 0.10 in highly decomposed peat. However, results from the current study show that depth is not a systematic explanatory factor when all sites were considered together. Similar Sy_{WTF} distributions with depth were observed for all sites, independently of the mean annual

WTD of each. For example, at LCY where mean annual WTD is 41 cm, Sy_{WTF} is almost identical to that of ISO, where mean annual WTD is only 9 cm. Therefore, mean annual WTD should not be considered to be a proxy of peatland water storage capacity.

Seasonality is another important control on dynamic storage capacity (Figure 1.9c). Indeed, median Sy_{WTF} is higher during wet periods compared to dry periods. This is explained by the fact that evapotranspiration rates are higher during dry periods compared to wet periods. Moreover, these results are consistent with recent findings by Geris *et al.* (2015), showing that tree cover temporarily increases the dynamic storage capacity during summer due to higher evapotranspiration.

The absence of a within-site location effect on Sy_{WTF} in this study (Figure 1.9d) has strong implications for future research. The absence of spatial variation within the studied sites suggests that a single Sy-depth model could be sufficient to represent a given site. However, more research is needed to better understand the vertical Sy variation of the water table fluctuation layer, due to the various hydrogeological contexts and microforms.

1.5.4 Implications for peatland understanding and management

Results from this study have many hydrological implications in terms of hydrological modelling, evapotranspiration feedback, water table climate linkage, and understanding peatland water storage capacity at the local and global scales. Many authors have studied overland and rapid/slow subsurface flow within peatlands to quantify peatland-surface water interactions (Devito, Waddington et Branfireun, 1997 ; Holden *et al.*, 2008 ; Reeve, Siegel et Glaser, 2000 ; Reeve, Siegel et Glaser, 2001). The WTF method provides a means to quantify the Sy, and therefore to better understand the timing and the transition between overland and subsurface flow within peatlands. Two previously established (McLaughlin et Cohen, 2014) Sy ranges were also observed in this study: greater than 1, and between 0 and 1. Sy values greater than 1 indicate additional water input from uphill or from the redistribution of precipitation within the peatland. When Sy is between 0 and 1, precipitation accumulates within the pore spaces until a threshold, where pore sizes of undecomposed peat are too large to hold more water (Holden, 2009). Somewhat counterintuitively, this can be interpreted as indicating that the water table does not need to reach the surface to be characterized by a Sy_{WTF} greater than 1.

Peatland water storage capacity is an important component of flood mitigation (Acreman et Holden, 2013). The results obtained with the WTF method offer new data that could be very useful for short term transient hydrological/hydrogeological models. A single model of vertical Sy could be used in physically-based models to simulate peatland dynamics (Reeve *et al.*, 2006). This could lead to more accurate estimates of the delay between precipitation and river floods in watersheds containing large peatland coverage. However, using long-term transient hydrological models requires a thorough understanding of the effect of swelling/shrinking peat soils on water storage capacity (Camporese *et al.*, 2006) which is rarely available.

1.6 CONCLUSION

The objective of this study was to adapt the WTF method in order to quantify vertical Sy variations in peatlands and to better understand the factors controlling peatland water storage capacity. This objective was achieved by comparing results from laboratory experiments on small and intermediate-size peat samples with results from the WTF method. The methods were carried out on five peatlands of the St. Lawrence lowlands, at three different locations within each peatland.

Although uncertainties in Sy were identified for the cube samples in the upper peat layers, similar relationships describing vertical variations with depth reported in the literature suggest that results from the WTF are reasonable. Results show that this method is a promising tool to quantify Sy and its vertical variation within the water table fluctuation layer of peatlands. The power law provides the best description of Sy-depth variations.

Moreover, site location and seasonality are dominant controls upon water storage capacity, suggesting that both hydroclimatic context and evapotranspiration are of primary importance to understanding peatland water storage capacity. This research has shown that within-site location plays a minor role in Sy variations, suggesting that the WTF method could be used to quantify water storage capacity using a single dip well. However, further studies are needed to investigate the influence of microforms (i.e., hummocks, hollows and pools) and hydrogeological context on water storage capacity.

The WTF method is non-invasive, inexpensive, and can easily be used in a wide variety of contexts, since hourly precipitation and peatland water table fluctuation data are commonly measured in peatland monitoring projects. This method provides a relatively simple means of improving the available data on peatland water storage capacity in different conditions, thus contributing to better understand peatland hydrological functions.

Acknowledgments

This research was funded by the Quebec Ministry of Environment (Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques), by local municipalities, by a scholarship from MITACS Accelerate and the Nature Conservancy of Canada, and by a scholarship from the Fonds de recherche du Québec Nature et technologies (FRQNT). The authors would like to thank the Nature Conservancy of Canada for providing access to the LTF site and private landowners for making their property available for this study (ISO, LCY, SSE, and VIC). Finally, the authors thank Jill Vandermeerschen, the SCAD-UQAM (Service de consultation en analyse de données), Sylvain Gagné, Diogo Barnetche, Marjolaine Roux, and Guillaume Poulin for their statistical, field work and technical support.

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1.8 TABLES

Tableau 1.1 Site descriptions coordinate, altitude, area, distance, and mean slope between up-gradient and down-gradient location, watershed, lithology, dominant species, annual evapotranspiration (Atlas agroclimatique du Québec, 2012), and difference between P and ETP.

Site	Lat	Long	Altitude (m)	Area (km²)	Distance (m):slope (%)	Watershed	Hydrogeology	Dominant species	Annual ETP (mm)	P-ETP
LTF	45.132	-74.217	51	6.0	697:0.08	Chateauguay	Marine clay	Sph sp, Kal Ang, Eri Vag, Rho Ca, Pol Str, Aul Pal	640 - 710	neg
SSE	46.042	-72.345	84	4.9	760:0.20	Nicolet	Fluvial silt/Glacial clayey silt	Sph sp, Kal Ang, Eri Vag, Cha Cal	575 - 701	pos /neg
LCY	45.950	-72.187	106	0.5	123:0.24	Nicolet	Eolian fine to medium sand	Sph sp, Kal Ang, Cha Cal, Rho Gro	575 - 701	pos /neg
VIC	46.023	-72.077	118	2.6	593:0.16	Nicolet	Marine exondated fine sand	Sph sp, Kal Ang, Eri Vag, Pol Str, Cha Cal, Rho Gro	575 - 701	pos /neg
ISO	46.579	-71.597	117	2.8	454:0.23	du Chene	Glacial clayey silt	Sph sp, Kal Ang, Eri Vag, Car sp, And Gla, Cha Cal	548 - 611	pos

Note. P = precipitation; ETP = evapotranspiration; LTF = large tea field; SSE = Sainte-Séraphine; LCY = Lac Cyprès; VIC = Victoriaville; ISO = Issoudun; Sph sp. = Sphagnum spp.; Kal ang = Kalmia angustifolia; Eri vag = Eriophorum vaginatum; Pol str = Polytricum strictum; Aul pal = Aulacomnium palustre; Cha cal = Chamaedaphne calyculata; Rho gro = Rhododendron groenlandicum; Car sp. = Carex spp.

Tableau 1.2 Specific yield measurements in wetlands as reported in the literature.

Sy	Rate decrease (cm^{-1})	Method	Author	Main objective	Wetland type	Depth (cm)	Year
0 – 0.9	≈ 0 - 0.08	WTF	Dettmann and Bechtold 2016	methological development	peatland	0 - 45	2016
0 - 1.1	0.007 – 0.013	WTF	Moore et al. 2015	site-depth-microforms	peatland	0 - 65	2015
0.1 - 0.7	0.007 – 0.013	Pressure chamber	Moore et al. 2015	site-depth-microforms	peatland	0 - 50	2015
0.13 - 1.05	0.02	WTF	McLaughlin and Cohen 2014	evapotranspiration and groundwater exchange estimation	open water	50 - 0 (above surface)	2014
0.05 - 0.4	NA	WTF	McLaughlin and Cohen 2014	evapotranspiration and groundwater exchange estimation	open water	60 – 0 (above surface)	2014
0 - 0.85	NA	Pressure chamber	Thompson and Waddington 2013	microforms-depth-density-wildfire alteration	peatland	0 - 45	2013
0.01 - 1	0.02-0.05	Infiltrometer	Holden 2009	depth-cover type	upland blanket peat	0 - 20	2009
0.23	NA	Gravity (experimental tank)	Rosa and Larocque 2008	peat hydrological properties	peatland	0 - 40	2009
0.75-0.99	NA	Tracer tests	Ronkanen and Klove 2008	modelling of water treatment wetlands	contructed peatland	NA	2008
0.13 - 0.66	NA	Gravity	Lett et al 2000	depth - humification - modelling WT variation	peatland	0 - 35	2000
0.25 - 0.55	≈ 0.01	Gravity	Price, 1996	effect of peat harvesting on water balance	peatland	0 - 55	1996
0.04-0.06	≈ 0	Gravity	Price, 1996	effect of peat harvesting on water balance	cutover bog	0 - 62	1996
0.1 - 0.55	≈ 0 - 0.015	Gravity	Price 1992	water budget - hydrological processes	blanket bog	0 - 250	1992
0.09 - 0.45	0.04 - 0.06	Gravity	Vorob.ev. 1963	depth-cover type	swamp (peat)	0 - 20	1963

Note. WTF = water table fluctuation

1.9 FIGURES

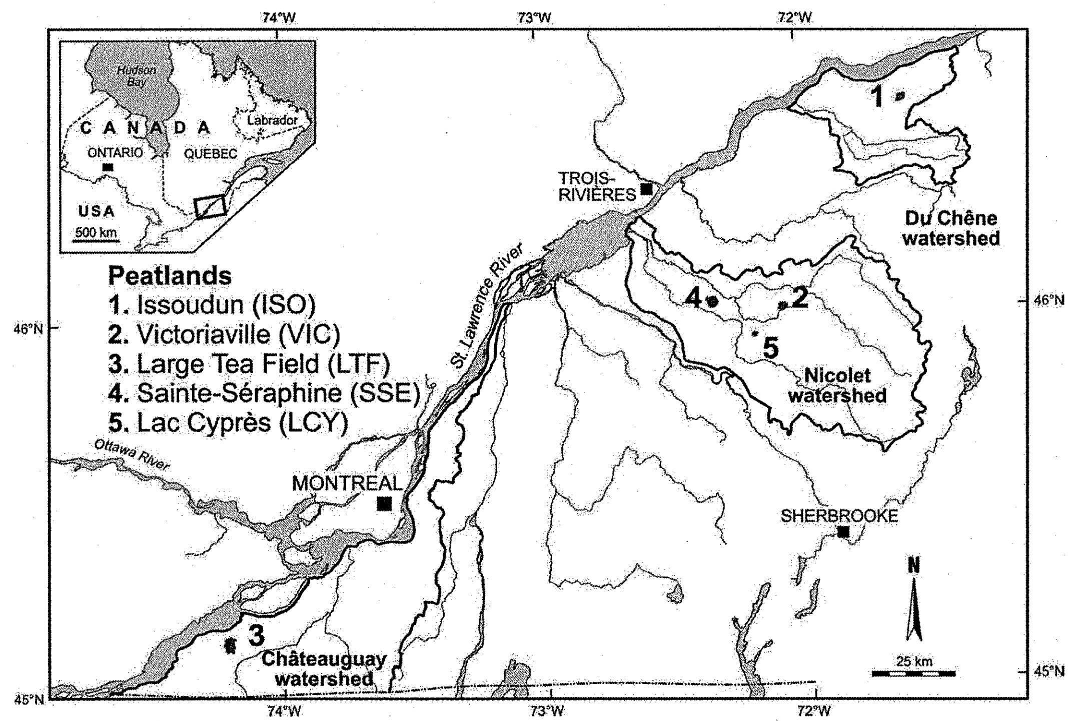


Figure 1.1 Locations of the five studied peatlands in the Châteauguay (LTF), Nicolet (SSE,LCY, and VIC), and du Chêne (ISO) watersheds of southern Québec, Canada.

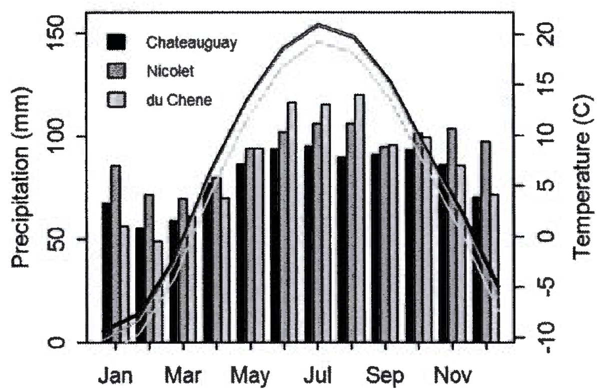


Figure 1.2 Mean monthly precipitation (bars) and temperature (lines) between 1981 and 2010 for Châteauguay (black), Nicolet (grey), and du Chêne (light grey) watersheds. Note that temperature curves for Châteauguay and Nicolet overlap or nearly overlap for much of the year.

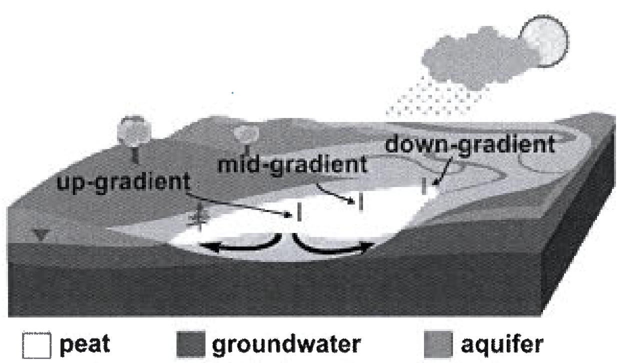


Figure 1.3 Up-gradient, mid-gradient, and down-gradient locations of the instrumented wells in the studied peatlands. Black arrows show general water circulation patterns.

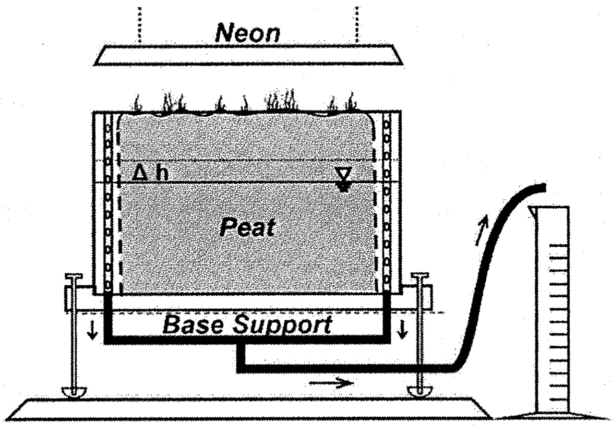
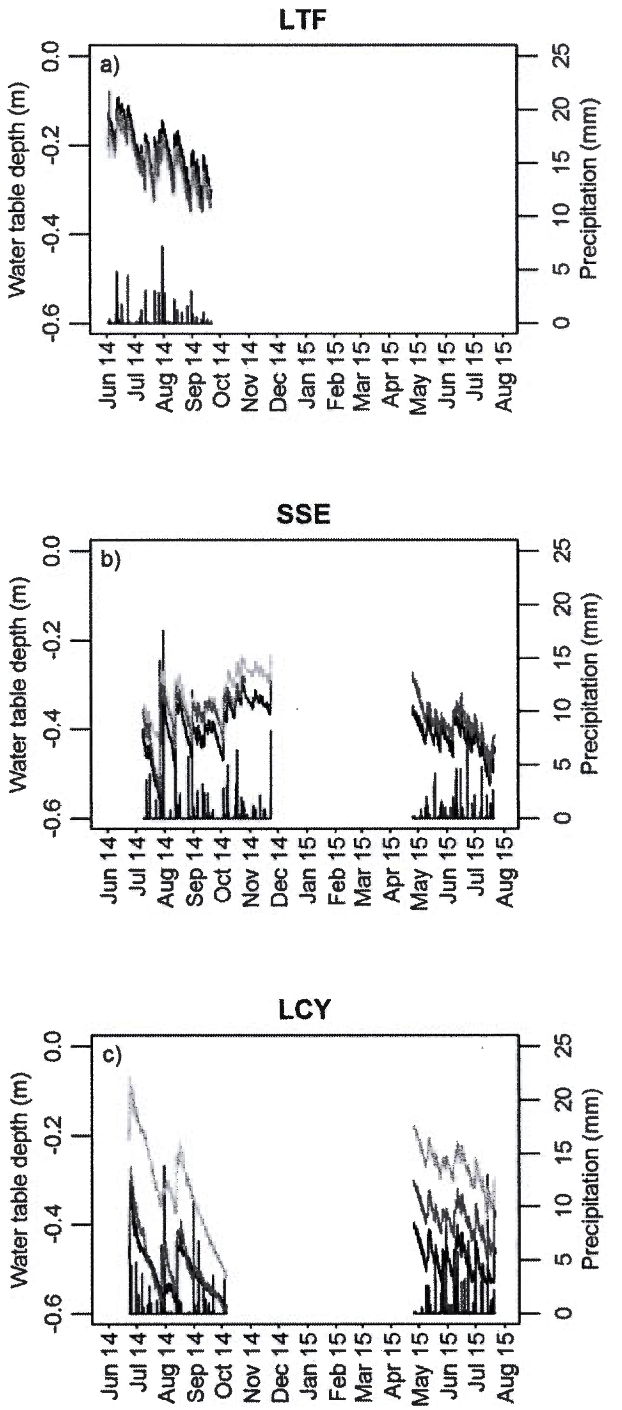
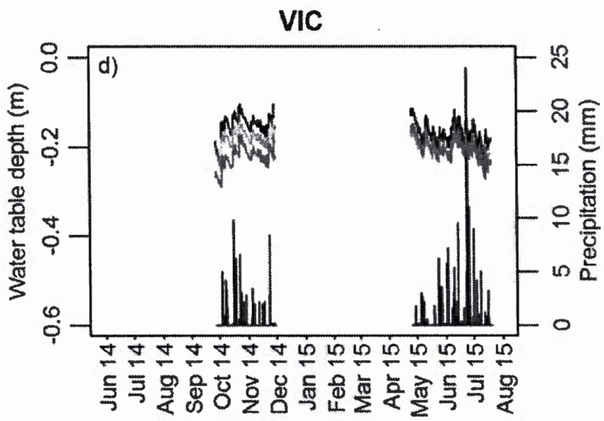


Figure 1.4 Design of the experimental tank with an impermeable base support built for the drainage experiment to calculate specific yield variations with depth (modified from Rosa and Larocque, 2008).


LTF
a)
SSE
b)
LCY
c)
Water table depth (m)
0.0
-0.2
-0.4
-0.6
Precipitation (mm)
25
20
15
10
5
0
Jun 14
Jul 14
Aug 14
Sep 14
Oct 14
Nov 14
Dec 14
Jan 15
Feb 15
Mar 15
Apr 15
May 15
Jun 15
Jul 15
Aug 15



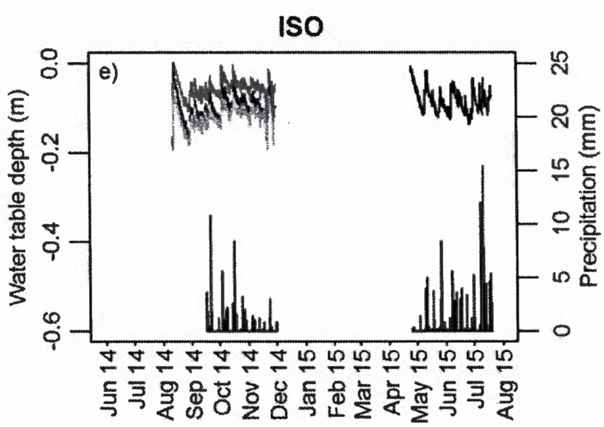


Figure 1.5 Water table depths and precipitation from June 2014 to August 2015 at the up-gradient (black), mid-gradient (grey), and down-gradient (light grey) locations at (a) Large Tea Field (LTF), (b) Sainte-Séraphine (SSE), (c) Lac Cyprès (LCY), (d) Victoriaville (VIC) and (e) Issoudun (ISO). The period without data corresponds to the winter season. The LTF time series is only from June to September 2014 due to technical difficulties with the rain gauge in the summer 2015.

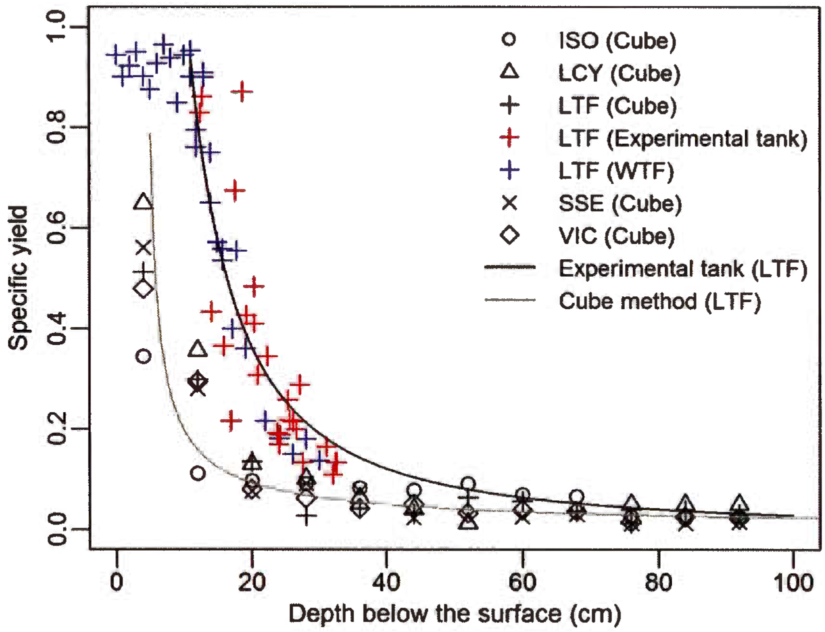


Figure 1.6 Variation in specific yield (Sy) with depth using the small cube (mean values are plotted for each site), experimental tank (LTF only), and WTF (LTF only) methods. The black line shows the Sy–depth relationship using the experimental tank method (LTF), and the grey line shows the logarithmic Sy–depth relationship using the cube method (LTF).

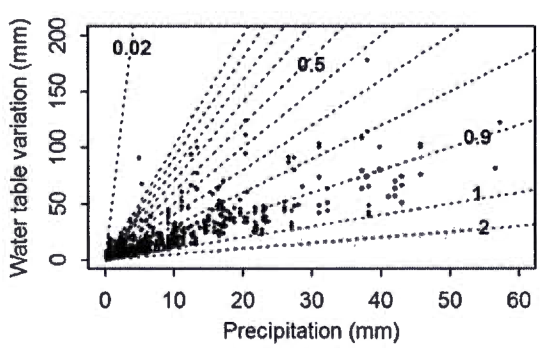


Figure 1.7 Water table variation (Δh) as a function of precipitation (P) for all sites and locations. Each point represents a single precipitation event. Dashed lines and associated value represent the ratio of P/Δh equivalent to Sy.

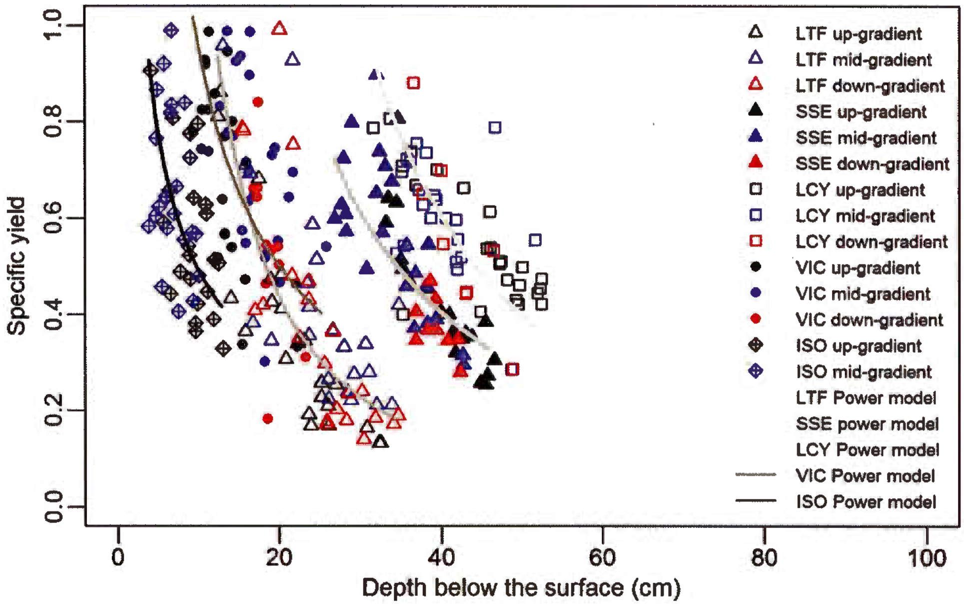


Figure 1.8 **Variation in specific yield estimated using the power law model applied to the WTF method as a function of depth below the surface for all peatlands and all locations (up-gradient, mid-gradient, and down-gradient)**

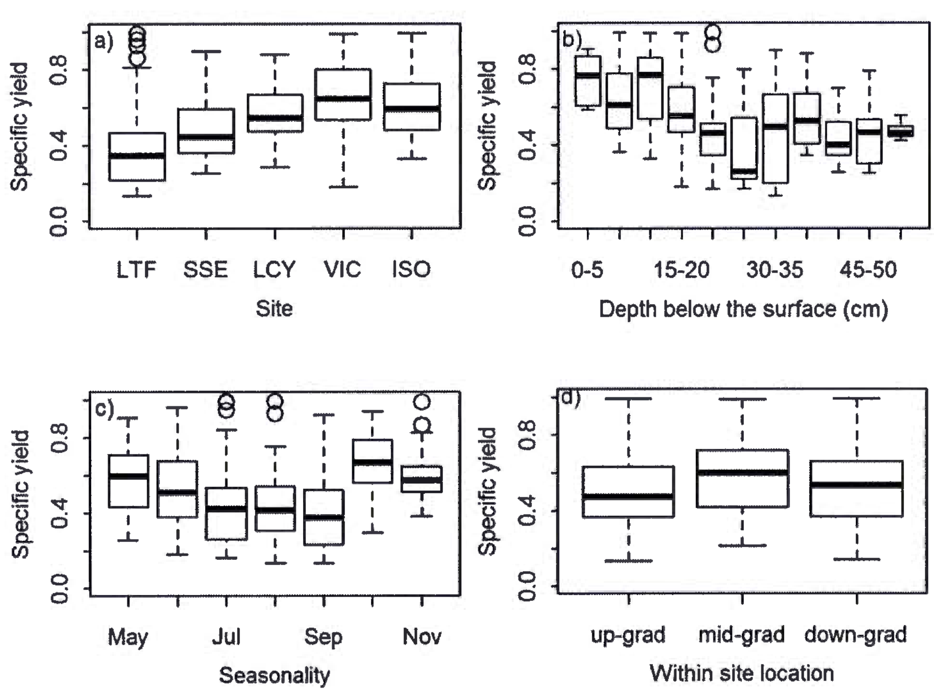


Figure 1.9 Influence of (a) site, (b) depth below the surface, (c) seasonality (May to November), and (d) within-site location on specific yield found using the water table fluctuation method. Each box plot shows the minimum (lower bar), the first quartile (lower portion of the box), the median (bold black line), the third quartile (higher portion of the box), the maximum (upper bar), and the outliers (circles).

CHAPITRE II

QUANTIFYING PEAT HYDRODYNAMIC PROPERTIES AND THEIR INFLUENCE ON WATER TABLE DEPTHS IN PEATLANDS OF SOUTHERN QUEBEC, CANADA

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Sous presse dans *Ecohydrology* Manuscript ID : 10.1002/eco.1976

ABSTRACT

Water table depth in peatlands is strongly linked to physical properties of the peat, such as density (ρ_{dry}), peat composition and humification, hydraulic conductivity (K), and specific yield (Sy). Dry bulk density and peat depth are commonly used as indicators of K in eco-hydrological models. However, no mathematical relationship exists to quantify Sy based on K and ρ_{dry}. As a result, eco-hydrological models cannot explicitly reproduce the strong buffering capacity of peatlands. The objectives of this study were to analyze the literature-reported mathematical link between all the physical properties to develop new mathematical relationships between these parameters, and to evaluate whether variations in the physical properties of the peat control water table depth in peatlands. Seven peatlands located in the St. Lawrence Lowlands (Québec, Canada) were sampled, and 1 m-long peat cores were collected from up-gradient, mid-gradient, and down-gradient zones. All cores were used to measure ρ_{dry}, K, Sy, and to estimate peat composition and humification. Statistically significant correlations were found between: 1) K and Sy (log-log model), 2) K and depth (log-log model), 3) Sy and depth (log-log model), 4) ρ_{dry} and Sy (log model), and 5) ρ_{dry} and K (log model). No significant difference was found in either K or Sy between sites. However, significant differences were found in water table depths. Because they provide a fuller description of the peat properties that control water table depths, these newly developed functions have the potential to improve the capacity of eco-hydrological models to simulate time-varying hydrological conditions.

Keywords: peatland, water table depth, hydraulic conductivity, specific yield, density, ecohydrology

2.1 INTRODUCTION

Peatlands are water-dependent ecosystems often connected to aquifers (Rossi et al., 2012) and rivers (Bourgault et al., 2014), and are characterized by an accumulation of organic matter that exceeds its decomposition. The connectivity of peatlands to aquifers and rivers, referred to as hydro-connectivity, and their capacity to accumulate and store carbon depends on the water table depth (Ise et al., 2008), which is strongly influenced by the physical properties of the peat (i.e., density (ρ_{dry}), peat composition and humification, hydraulic conductivity (K), and specific yield (Kelly et al., 2014).

The parameters ρ_{dry} (Radforth and Brawner, 1977) and depth (Young and Klaiwitter, 1968) are commonly integrated in eco-hydrological models as indicators of K (Frolking et al., 2010) to determine the facility with which water circulates through the organic deposit (Fetter, 2001). However, no mathematical equations are reported in the scientific literature to link ρ_{dry} and K to Sy. Even though Sy is known to vary strongly with depth (Bourgault et al., 2016), this parameter is either not integrated in eco-hydrological models (Frolking et al., 2010), or is considered constant (Morris et al., 2012). Since Sy controls the storage capacity of the peat (Dettmann and Bechtold, 2016) and its water table reactivity to precipitation (Bourgault et al., 2016), eco-hydrological models therefore cannot explicitly reproduce the strong buffering capacity of peatlands (Waddington et al., 2015). This limits their capacity to reproduce water table depths. The limited extent of literature-reported data partially explains the oversimplification in eco-hydrological models. For example, even if a handful of studies have reported measurements of K (Rosa and Larocque, 2008) and Sy (Lapen et al., 2000) across North America (Letts et al., 2000; Quinton et al., 2008) and Europe (Baird, 1997; Baird et al., 2016; Holden and Burt, 2003a), data are still extremely limited in eastern Canada, where peatlands occupy large surface areas..

The objectives of this study were to analyze the literature-reported mathematical link between ρ_{dry}, peat composition, humification, K, and Sy to develop new mathematical relationships between these parameters, and to evaluate whether variations in the physical properties of the peat control water table depths in peatlands. Measurements of ρ_{dry}, peat composition and humification, K and Sy were performed on 47 peat cores in seven peatlands located in the St. Lawrence Lowlands (southern Quebec, Canada). Water table variations were recorded over two summer periods at three locations (up-gradient, mid-gradient, and down-gradient) in all of the peatlands.

2.2 SITE DESCRIPTION

All seven studied peatlands (Covey Hill – CH, Large Tea Field – LTF, Sainte-Séraphine – SSE, Lac Cyprès – LCY, Victoriaville – VIC, Villeroy-VR, and Issoudun – ISO) are located in the St. Lawrence Lowlands, with the exception of CH, which located in the northernmost extension of the Adirondack Mountains (Figure 1). These peatlands are located in the Châteauguay (CH, LTF), Nicolet (SSE, LCY, VIC), Bécancour (VR), and Du Chêne (VR, ISO) watersheds, and are spread over a distance of 250 km in southern Quebec (Canada). Five of the seven studied peatlands (LTF, SSE, LCY, VIC, and ISO) have already been described in Bourgault et al. (2016), including their geological context, micro-topography, peat thickness, vegetation composition, humification, and hydro-climatic contexts.

The peatlands developed in different geological contexts, characterized by a wide variety of quaternary surficial sediments (marine clay, fluvial sandy silt, clayey silty till, aeolian fine to medium sand, and regressive marine sand) (Bourgault et al., 2016). The CH site is an exception, having developed on fractured Cambrian sandstone of the Potsdam Group (Levison et al., 2014).

Six sites (CH, LTF, SSE, VIC, VR, and ISO) are basin peatlands (National Wetlands Working Group-NWWG, 1997) and are set in headwater conditions. LCY is a slope peatland (as defined by NWWG, 1997) that developed on fine to medium sand dune deposits. The peatlands are characterized by a micro-topography of alternating hummocks and lawns. Hollows are only observed at ISO and VIC, while small shallow pools are observed at VR.

Vegetation surveys performed at all sites show that *Sphagnum* spp. (*Sph* sp.), *Kalmia angustifolia* (*Kal ang*), and *Eriophorum vaginatum* (*Eri vag*) were the main species for all sites. *Sphagnum* spp. (*Sph* sp.), *Kalmia angustifolia* (*Kal ang*), and *Rhododendron groenlandicum* (*Rho gro*) were the dominant species on hummocks. On lawns and hollows, *Sphagnum* spp. (*Sph* sp.), *Eriophorum vaginatum* (*Eri vag*), and *Carex* spp (*Car* sp.) were the dominant species. In shallow pools (only observed in VR), *Sphagnum cuspidatum (Sph cus*) was found. In sites CH, SSE and VR, minerotrophic vegetation was found at the margin of the peatlands and used to determine groundwater connectivity (Table 1). *Alnus rugosa* (Aln rug), *Iris versicolor* (Iri ver) and *Sphagnum* spp. (Sph sp.) were the common species of the minerotrophic zones.

All the peatlands began to accumulate following land emersion after the last deglaciation, between ca. 10 770 cal BP (Larocque et al., 2013) in VR, and ca. 13 450 cal BP in CH (Pellerin et al., 2007). Peatland areas range between 0.5 and 10.4 km2, and peat thickness varies between 190 and 522 cm (Table 1). All the peatlands have central ombrotrophic sections, and some have lateral minerotrophic sections (CH, SSE, and VR). Rates of accumulation for the top meter of peat (only available for CH and VR) vary between 0.6 and 1.1 mm.yr-1 for VR (Lavoie and Colpron-Tremblay,

2013) and between 0.01 and 4 mm.yr-1 for CH (Lavoie et al., 2013), and includes the acrotelm, in which peat is partially decomposed.

Mean annual precipitation (1981 – 2010) varies between 929 mm (ISO) and 1114 mm (LTF) (MDDELCC, 2017). For all sites, the minimum monthly precipitation occurs during the winter, and the maximum is recorded during the summer. Mean annual temperature (1981-2010) varies between 4.8 (ISO) and 6.7 °C (LTF). Minimum and maximum temperatures are recorded in January and July respectively for the seven sites.

2.3 METHODS

Field work was carried out between May 2014 and June 2016. Peat sampling sites were located along a transect covering up-gradient, mid-gradient, and down-gradient zones in all the peatlands. The three zones were identified using the digital elevation model (1 x 1 m resolution) derived from airborne light detection and ranging survey (LiDAR). Up-gradient was defined as the highest altitudinal zone, down-gradient the lowest altitudinal zone and mid-gradient an intermediate zone. Distances between up-gradient and down-gradient wells varied between 123 and 760 m with mean slopes from 0.08% to 0.24% (see Bourgault et al. 2016).

The LCY peatland does not include a mid-gradient location because of its small area (0.5 km2). Twenty sampling locations were thus visited, and two 1 m-long peat cores were sampled at each site using a Box corer. One additional peat core was sampled in each of the up-gradient locations, for a total of 47 peat cores. Sampling compression was measured in the field and ranged between 2 and 20 cm for all sites and locations. Mean sampling compression was 4 cm for CH, 5 cm for LTF, 8 cm for SSE, 12 cm for LCY, 6 cm for VIC, and 2 cm for ISO. Peat gaps due to compression were not considered in the analyses. Cores were cut into two 50 cm sections using a sharp knife, wrapped into two half-cylinder PVC pipes (ρ_{dry} measurements) or rectangular plastic casings (K and Sy measurements) for transportation, and stored at 4°C. In the laboratory, one core per sampling location was used for ρ_{dry} measurements, one for K measurements, and one for Sy measurement (Sy measurements were performed only in up-gradient locations). Water table variations were recorded at the three locations within each site using wells constructed from 3 cm OD PVC pipes, with 2 m long intakes perforated with 0.254 mm slits equally spaced by 60 mm from top to bottom, and sealed at their base. All wells were equipped with level loggers (Solinst) that recorded water table variations at hourly intervals from June 2014 to May 2016.

2.3.1 Peat composition and humification

Peat composition and humification of the up-gradient core of each peatland were described. Degree of humification was assessed directly in the field using the standard von Post procedure (Von Post, 1922). In the laboratory, peat composition was describedat 4 cm intervals following the Troels-Smith (1955) method for up-gradient cores only. Peat composition was described using a stereoscopic microscope and classified within four groups, Turfa bryophytica, Turfa lignosa, Turfa herbacea, and Detritus granosus.

2.3.2 Dry bulk density (ρ_{dry})

Twenty 1 m-long peat cores (two for LCY) were used to perform ρ_{dry} measurements (Dean, 1974). To perform this analysis, all cores were frozen for three hours and then cut with a sharp knife at 2 cm intervals, corresponding to a volume of 44 cm3. Each sliced section was weighed, dried overnight at 105 ˚C, and weighed again. ρ_{dry} was calculated using the following equation, where W is the slice weight after drying and V is its volume:

$$\rho_{dry} = \frac{W}{V} \tag{2.1}$$

For all cores, means were calculated at 8 cm intervals so as to be comparable to K and Sy measurements.

2.3.3 Hydraulic conductivity (K)

Twenty 1 m-long peat cores were cut into 343 cm3 (7 cm x 7 cm x 7 cm) samples, for a total of 12 samples per core. In the laboratory, each cube was wrapped in a thin wax film and submerged into liquid paraffin, as required for the Modified Cube Method (MCM) (Surridge et al., 2005). The wax was removed from two sides of the cube to measure horizontal saturated hydraulic conductivity (Kh; equivalent to K_{sat}) and the samples were allowed to saturate overnight. The horizontal saturated hydraulic conductivity (hereafter called K) was measured using a constant head permeameter (Beckwith et al., 2003; Surridge et al., 2005). The waxed samples were placed on a funnel connected to a graduated cylinder, and a thin film of water was maintained on their upper face to produce a hydraulic gradient equal to one. By repeating the experiment on each sample, discharge (Q) from the peat sample was measured three times. Uncertainties between the three experiments were negligible for all samples (less than 2%). Mean K was calculated using Darcy's Law:

$$K = \frac{Q}{Ai} \tag{2.2}$$

where A (49 cm2) is the cross-sectional area and i (cm.cm-1) is the hydraulic gradient (i = 1).

2.3.4 Storage coefficient (Sy)

Bourgault et al. (2016) previously reported Sy variations with depth for five of the studied peatlands (LTF, SSE, LCY, VIC, and ISO). The Sy values for the other two peatlands (CH and VR) are reported here. These cores were cut into 8 cm3 samples for a total of 12 samples per core. Sy measurements were performed on these samples using the same gravity drainage experiments as those described in Bourgault et al. (2016). Gravity drainage was performed in acrylic cubes (8 cm3) and used to estimate Sy following Eq. (2) (Freeze and Cherry, 1979),

$$S_Y = \frac{V_d}{A * \Delta h} \tag{2.3}$$

where Vd is the drained water volume (cm3), A is the area of the peat sample (7 cm x 7 cm = 49 cm2), and Δh is the water table fluctuation (cm). The peat samples were soaked in water for 24 hours prior to the experiment, and then drained for 24 hours. Each acrylic cube was connected at the bottom to a plastic tube with a diameter of 1.3 cm attached to an adjustable base support to drain the samples. Each drainage experiment began by decreasing the height of the plastic tube to that of the bottom of the tested sample. Sy was measured twice on third of the sample to evaluate the experimental errors.

2.3.5 Data analysis

Tukey HSD analyses were performed to identify differences between peatlands and between site locations, using a 99% confidence interval. Linear regression and non-linear regression analyses were performed to identify relationships between K, Sy, ρ_{dry}, depth, and median water table depth. All the mathematical analyses were performed using the R statistical software (R environement, D.C.T, 2008).

2.4 RESULTS

2.4.1 Water table depth

Water table depth for all the sites (CH, LTF, SSE, LCY, VIC, VR, and ISO) and locations (up-gradient, mid-gradient, and down-gradient), including winter months when snow accumulates at the surface, was between +25 cm (above peat surface) and -65 cm (below peat surface). Significant differences were found between sites (Figure 2), with median water table depths equal to -10 m for CH, -30 m for LTF, -35 m for SSE, -41 m for LCY, -16 for VIC, -5 for VR, and -1 for ISO. Two groups could be distinguished. The first group (CH, VIC, VR, and ISO), was characterized by shallow water table depths, and the second group (LTF, SSE, and LCY) was characterized by a deeper water table (Figure 2). However, no significant differences in water table depths were found within each of the seven peatlands (e.g., up-, mid-, and down-gradient).

2.4.2 Vegetation and humification

Acrotelm thickness (up-gradient locations) was 32 cm for CH, 57 cm for LTF, 57 cm for SSE, 56 cm for LCY, 28 cm for VIC, 21 cm for VR, and 24 cm for ISO, and was determined based on the minimum water table depth (Holden and Burt, 2003b) (Figure 3). In all sites, the acrotelm is mainly dominated by Turfa bryophytica, with varying percentages of Turfa lignosa (up to 40%) and/or Turfa herbacea (up to 30%) and/or Detritus granosus (up to 50%) (Figure 3). In the cores from CH, LTF, SSE, LCY, and VIC, a sharp transition from Turfa bryophytica to a highly decomposed Detritus granosus peat was observed. The transitions were characterized by an increase in humification from a non-decomposed Sphagnum-dominated fibric peat (≤ 20 cm) to a highly decomposed sapric peat (≥ 55 cm), which was expected to strongly affect ρ_{dry}, K, and Sy (Letts et al., 2000). The cores from VR and ISO were mainly composed of Turfa bryophytica for the entire sequence, with interspersed layers of Turfa lignosa between 66-74 for VIC and Turfa herbacea between 34-60 cm for VR.

2.4.3 Dry bulk density

ρ_{dry} results varied between 0.02 and 0.22 g/cm3. Variance analysis of ρ_{dry} showed significant difference between sites, with median ρ_{dry} equal to 0.06 g/cm3 for ISO, 0.08 g/cm3 for VR, 0.10 g/cm3 for VIC, 0.10 g/cm3 for CH, 0.11 g/cm3 for LTF, 0.11 g/cm3 for SSE, and 0.14 g/cm3 for LCY (Figure 4). In sites CH, LTF, SSE, LCY and VIC, a transition in slope was observed at a depth of 50 cm for CH, 20 cm for LTF, 35 cm for SSE, 35 for LCY, and 30 cm for VIC, and a maximum ρ_{dry} was reached at the depth of the transition (Figure 5). In VR and ISO, the maximum ρ_{dry} was found at the base of the cores (1 m depth). Two groups were distinguished, the first consisted of sites CH, ISO, and VR, and the second of sites LCY, LTF, and SSE, with the VIC site being between the two groups. No significant differences between site locations (up-gradient, mid-gradient, down-gradient) were recordedwith regards to ρ_{dry}.

2.4.4 Saturated hydraulic conductivity

Hydraulic conductivity results show strong variation in K, over nearly six orders of magnitude between sites (Figure 6). Experimental errors on K were less than 2% and considered negligible. The median K was $6.9*10^{-3}$ cm/s for CH, $5.1*10^{-4}$ cm/s for LTF, $8.0*10^{-5}$ cm/s for SSE, $4.0*10^{-4}$ cm/s for LCY, $6.4*10^{-4}$ cm/s for VIC, $2.3*10^{-3}$ cm/s for VR, and $3.5*10^{-3}$ cm/s for ISO, and show no significant difference between the sites. The highest K value is 1.4 cm/s at site SSE, while the lowest is 0.000003 cm/s at site LCY, with an overall median K value of 0.067 cm/s.

Similar to ρ_{dry}, two distinct rates of K decrease with depth were observed: a rapid decrease observed within the upper part of the acrotelm, and a small decrease corresponding to the catotelm (Figure 7). Regression models were used to represent the decrease in measured K with depth. Models for log (K) – depth (see figure 7; blue lines) and log (K) - log (depth) (see figure 7; black lines) were compared. Results show that the log (K) - depth model best described CH (R^2=0.88) and VR (R^2=0.42), whereas the log (K) - log (depth) model best described LTF (R^2=0.55), SSE (R^2=0.78), LCY (R^2=0.86), VIC (R^2=0.66), and ISO (R^2=0.60). However, the difference in R^2 between the two models for CH and VR is not significant compared to the difference in R^2 between the two models for LTF, SSE, LCY, VIC and ISO. Therefore, all sites are considered best described using log (K) - log (depth) models.

Comparing figure 3 and figure 7, an increase in K is observed in Turfa bryophytica peat layers between 22 and 34 cm and 60 and 82 cm for VR and in Turfa herbacea between 66 and 74 cm for VIC. This pattern was not observed at the other sites. Finally, no significant difference was observed between the different site locations, with the exception of SSE and VR, where the Tukey HSD test (CI = 99%) identified a significant difference for the down-gradient locations.

2.4.5 Storage coefficient (Sy)

Result of Sy using the MCM method varied between 0.01 and 0.82 (Figure 8). Similarly to K, a rapid change in rates of decrease is observed for all peat cores (Figure 9). This rapid decrease is restricted to the acrotelm, with a median Sy of 0.27 for all sites, whereas a slow decrease is observed in the catotelm, with a median Sy of 0.05 for all sites. Median Sy were 0.16 for CH, 0.05 for LTF, 0.03 for SSE, 0.38 for LCY, 0.05 for VIC, 0.06 for VR, and 0.09 for ISO, and showed significant differences only between LCY and ISO. Based on previous results from Bourgault et al. (2016), no significant differences in Sy were observed across locations (i.e., up-gradient, mid-gradient, and down-gradient) in sites LTF, SSE, LCY, VIC, and ISO.

2.4.6 Mathematical relationships between ρ_{dry}, K_{sat}, Sy, and peat depth

Strong correlations were found between median water table depth and ρ_{dry} (Figure 10), K and depth (see figure 11), Sy and depth (see figure 12), K and ρ_{dry} (see figure 13), ρ_{dry} and Sy (see figure 14), and Sy and K (see figure 15). No correlation was found between median water table depth and K (R^2 = -0.05), or median water table depth and Sy (R^2=0.13). K-depth (figure 11), Sy-depth (figure 12), and Sy-K (figure 15) relationships were best modelled using log-log functions:

$$\log(y) = \alpha * \log(x) + \beta \tag{2.4}$$

where y is the dependant variable (e.g. Sy, K), x is the independent variable (e.g. depth, ρ_{dry}) and α and β are constants controlling the curvature of the relationship. Calculated α and β varied respectively from -3.74 to -2.56 and from 1.26 to 3.17 for K-depth relationship (figure 11), from 0.32 to 0.40 and from 0.28 to 0.56 for Sy-depth relationship (figure 12), and from 0.33 to 0.40 and from -0.19 to 0.02 for Sy-K relationship (figure 15). K-ρ_{dry} (figure 13) and Sy- ρ_{dry} (figure 14) were best modelled using semi-log functions:

$$y = \alpha * \log(x) + \beta \tag{2.5}$$

where calculated α and β varied respectively from -33.90 to -25.01 and from 0.57 to 0.29 for K- ρ_{dry} relationship (figure 13) and from -10.20 to -5.87 and from -0.53 to -0.12 for Sy- ρ_{dry} relationship (figure 14). Results from this study were compared to the K- ρ_{dry} relationship developed by Radforth and Brawner (1977) and included in the Holocene peat model (HPM; Frolking et al., 2011) (figure 13), and the model of

K-depth developed by Young (1968), which is included in the Digibog model (Baird et al., 2012) (figure 11).

2.5 DISCUSSION

2.5.1 Functional correlations between K_{sat}, Sy, ρ_{dry}, and depth

K, Sy, and ρ_{dry} values measured in this study were well within the ranges of values reported in the literature. Baird et al. (2016) showed that K can vary between 10-1 cm/s and 10-5 cm/s within the first meter of peat sequences. From their data compilation, Dettmann and Bechtold (2016) have shown that Sy varies between 0.01 and 0.95 within the first 50 cm of peat. Compiled values of ρ_{dry} reported by Loisel et al. (2014) for different types of peatlands around the world vary mainly between 0.05 and 0.20 g/cm3, with a mean value of 0.10 g/cm3.

The strong correlations for the K-depth, Sy-depth, and K-ρ_{dry}, relationships are consistent with the equations used in models (Baird et al., 2012; Frolking et al., 2010) and field data based studies (Bourgault et al., 2016; Dettmann and Bechtold, 2016; Morris et al., 2015). The equation used in the HPM for the K-ρ_{dry} relationship overestimates results from this study (see figure 13). This is explained by the fact that the K-ρ_{dry} relationship used in the model was derived from sites that might not have been located in a similar hydrogeological context. Moreover, because K has been shown to be a sensitive parameter in the HPM (Quillet et al., 2013), it would be advisable to include the possibility for a region-specific or site-specific K-ρ_{dry} relationship to be used. The exponential function of Young (1968), describing the K-depth relationship, underestimates K values of the present study in the top 10 cm and overestimates K values between 20 and 60 cm (see figure 11). This underestimation of surface K could have an important effect on simulated peatland hydrodynamics, since the surface layer controls water table variations, and therefore water flow velocities. Additionally, figure 15 shows a strong positive correlation of Sy as a function of K. This is also important, as it demonstrates a quantitative relationship between these two parameters in peatlands. Finally, a relationship was identified to link Sy and ρ_{dry} (figure 14) that could be included in models using ρ_{dry} as an indicator of K and Sy.

However, higher K at the surface and lower K at the bottom of a peatland is not always observed (see figure 7). As explained by Baird et al. (2016), stratigraphic changes in vegetation assemblages and decomposition, within the catotelm, can modify the peat pore structure and result in K values equal to or exceeding values usually found in shallow, near-surface peat. In the present study, this was observed at VR, with higher K values found between 22 and 34 cm and 60 and 82 cm (see figure 7.f), where peat was less decomposed and dominated by Turfa bryophytica. These conditions can favor local peatland-aquifer connectivity.

Additionally, in VR and SSE, K values were lower in down-gradient locations (i.e., close to the peatland margin; see figure 7.c). This reinforces the results from Lapen et al. (2005), which raised the importance of this lower peatland margin in maintaining an elevated water table within the peat deposits. According to Baird (2016), the finding of significant difference regarding the hydraulic properties between the different locations within the peatlands is crucial because it shows the importance of different-scale features (e.g. micro-topography, patterning, raised bog, margin) in the understanding of peatlands function both hydrologically and ecologically.

Therefore, the quantitative relationships developed in this paper should be used cautiously considering that spatial heterogeneity in peatlands is common. The different functions and their parameters variability could be tested using models. Additionally, the similarity between the relationships developed in this work and the relationships available in the literature suggests that generalization is conceivable. A community effort to assemble existing unpublished data should be considered to validate the newly developed relationships.

2.5.2 Water table depth in peatlands

In modelling studies, peatlands are generally conceptualized with a highly conductive upper layer, corresponding to the acrotelm (high K, high Sy, low ρ_{dry}, and low humification), and a low conductivity bottom layer, corresponding to the catotelm (low K, low Sy, high ρ_{dry}, and high humification) (Baird et al., 2008). In this study, the transition was observed within the top 50 cm of peat, similar to what has been reported in the literature (see figure 11 and figure 12). For many authors, this strong vertical variation in hydrodynamic properties is crucial to understanding differences in water table depth. Peatlands characterized by a more conductive upper layer are expected to have a lower median water table depth and peatlands with a less conductive upper layer is expected to have a higher median water table depth. However, this is not what was observed in this study.

In this study, significant differences in ρ_{dry} and water table depths were found between sites, but no significant differences in K and Sy were observed. Moreover, no correlation was found between the hydrodynamic properties and water table depth. This suggests that factors other than K and Sy of peat (e.g., hydro-connectivity, climate) are probably involved in the control of water table depth. Moreover, since all sites are located in a similar climatic context, it is hypothesized that the connectivity between each peatland and a neighbouring river or superficial aquifer should be considered and included as control factors of water table depth (Winter, 2001).

2.5.3 Implications for eco-hydrological models

As discussed in Baird et al. (2016), a physically based representation of peat hydrology should account for both K and Sy. In indicator-based models, such as the HPM, K is quantified using ρ_{dry} and is used to model the yearly variation in water table depth. However, Sy is not represented. In models solving the Darcy flow equation (e.g., Modflow, Digibog), Ksat is vertically discretized as a function of depth and only Digibog has integrated Sy (constant value). The absence or the simplification of Sy limits the ability of eco-hydrological models to quantify water table fluctuations in peatlands, and therefore to reproduce their daily and monthly hydrodynamics. And, since peat accumulation and decomposition processes are highly dependent on water table depth (Belyea and Clymo, 2001; Blodau and Moore, 2003; Moore and Dalva, 1993), simulating carbon dynamics without adequately describing the vertical changes of Sy with depth poses a challenge. This is especially true when considering that droughts, which occur on a short time scale, can transform a temperate peatland from a carbon sink to a carbon source (Fenner and Freeman, 2011). Moreover, Sy is a necessary component of transient modelling. Therefore, the quantification of Sy should be a priority in any modelling application aiming to downscale eco-hydrological models. Such downscaling is becoming more and more important, because peatlands store large amount of carbon (Fenner and Freeman, 2011) and can be strongly affected by extreme climatic events, such as drought and extreme precipitation.

This work provides new functions that could be included in eco-hydrological models. For example, the HPM, which describes the accumulation and decay of peat with a definition of annual peat layers (Frolking et al., 2010), could integrate the newly developed relationship between Sy and ρ_{dry} (see figure 14). Using this function would allow to the water table depth to be better determined following precipitation, and therefore the model to be temporally downscaled. Users of models based on the groundwater flow equation or Darcy's law, such as Digibog (Baird et al., 2012), could use the new equation describing Sy as a function of depth (see figure 12) to better discretize the vertical variation of Sy within the peat profile. If K values are available, they could be used to estimate unavailable Sy values (see figure 15). The use of these new equations would facilitate model calibration, provide more reliable peatland hydrology models, and contribute to a better understanding of peat accumulation and decomposition on short time scales (Belyea and Clymo, 2001; Blodau and Moore, 2003; Moore and Dalva, 1993).

However, as demonstrated in this study, describing the hydrodynamic properties that control water table fluctuations in peatlands and which are strongly linked to density profiles, is not sufficient to fully understand differences in water table depths between different sites. It is thus crucial to better understand how the connectivity of peatlands with aquifers and rivers can influence peatland hydrology

2.6 CONCLUSION

The objectives of this study were to quantify relationships between ρ_{dry}, depth, K, and Sy, to be used in eco-hydrological models, to develop new functions that could improve eco-hydrological models, and to evaluate whether differences in water table depths of peatlands located in the St. Lawrence lowlands could be linked to vertical variations in hydrodynamic properties. The first and the second objectives were achieved by revisiting two functions (K-ρ_{dry}; K-depth) and developing three new functions (K-Sy; Sy-depth; Sy-ρ_{dry}) that could be integrated in future eco-hydrological models. These functions could lead to better model calibration, and alleviate the necessity for intensive laboratory measurements, while including peatlands in regional models and improving existing steady-state models. Importantly, in eco-hydrological models, these functions could contribute to downscaling models to include processes occurring at smaller time scales and to improving models to better describe flow dynamics within peatlands by including Sy. The third objective was achieved by comparing the statistical relationships between water table depth and ρ_{dry}, depth, K, and Sy, and evaluating the strength of the correlation between all variables. A significant relationship between ρ_{dry} and water table depth was found, but there was no significant difference in K or Sy between the sites. A good linear correlation ($R^2 = 0.57$) was found between ρ_{dry} and water table depth, but this is not the result of a difference in hydrodynamic properties. It is therefore crucial to better understand how the connectivity of peatlands with aquifers and rivers can influence water table depth in peatlands, although considerable improvements to hydrological modelling of peatlands are expected using the current results.

Acknowledgments

This research was funded by the Quebec Ministry of Environment (Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques), by local municipalities, by MITACS Accelerate, by the Nature Conservancy of Canada, and by a scholarship from the Fonds de recherche du Québec Nature et technologies (FRQNT). The authors would like to thank the Nature Conservancy of Canada for providing access to the LTF and CH sites and private landowners for making their properties available for this study (ISO, LCY, SSE, VIC, VR). Finally, the authors thank Anne Quillet, Jill Vandermeerschen, the SCAD-UQAM (Service de consultation en analyse de données), Sylvain Gagné, and Simon Marcotte for their support with scientific results, statistical analyses, and field work.

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2.8 TABLES

Tableau 2.1 Site description: coordinates, altitude, surface area, watershed, hydrogeology, peat thickness, microform, and presence or absence of groundwater input

site	Lat	Long	Altitude (m)	Area (km^2)	Watershed	Hydrogeology	Peat thickness (cm)	Microform	Groundwater fed
CH	45.008	-73.828	310	0.5	Chateauguay	Fractured Cambrian sandstone	322	Hummock/hollow /pools	Yes
LTF	45.132	-74.217	51	6.0	Chateauguay	Marine clay	493	Hummock/lawns	No
SSE	46.042	-72.345	84	4.9	Nicolet	Fluvial silt/Glacial clayey silt	522	Hummock/lawn	Yes
LCY	45.950	-72.187	106	0.5	Nicolet	Eolian fine to medium sand	190	Hummock/lawn	No
VIC	46.023	-72.077	118	2.6	Nicolet	Marine exondated fine sand	360	Hummock/hollow s	No
VR	46.376	-71.838	124	10.4	Becancour/du Chene	Eolian sand/Glacial clayey silt	491	Hummock/hollow /pools	Yes
ISO	46.579	-71.597	117	2.8	du Chene	Glacial clayey silt	454	Hummock/hollow /pools	No

2.9 FIGURES

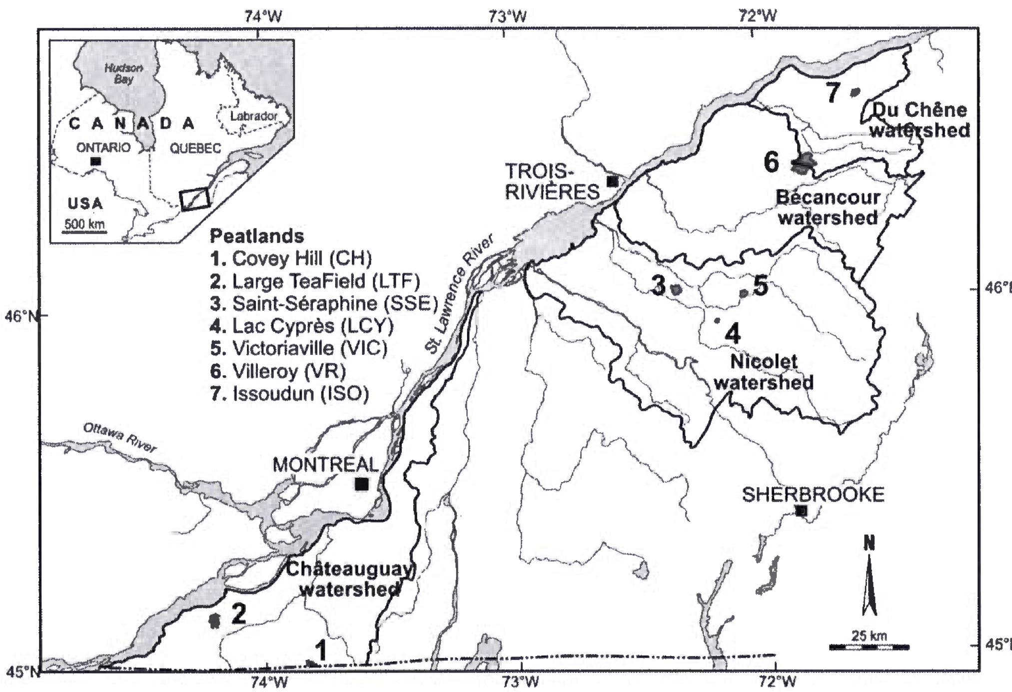


Figure 2.1 Locations of the seven studied peatlands in the Châteauguay (1-CH and 2-LTF), Nicolet (3-SSE, 4-LCY, and 5-VIC), Bécancour (6-VR), and Du Chêne (7-ISO) watersheds of southern Quebec (Canada).

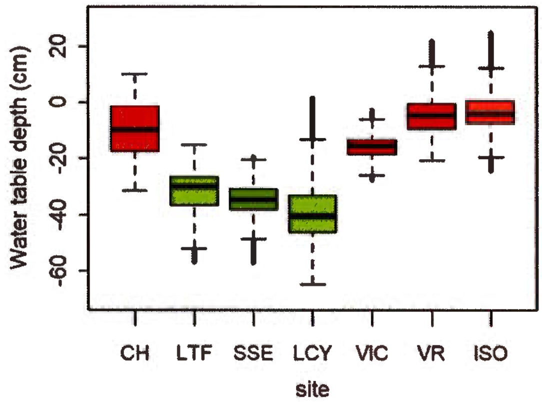


Figure 2.2 Water table depths (WTD) for all locations (up-gradient, mid-gradient, down-gradient) of the seven sites (CH, LTF, SSE, LCY, VIC, VR, and ISO) from June 2014 to May 2016. Colors show significant differences in WTD between the sites. Red boxplots show the significant different group composed of CH, VIC, VR, and ISO whereas green boxplots show the second group composed of LTF, SSE, and LCY.

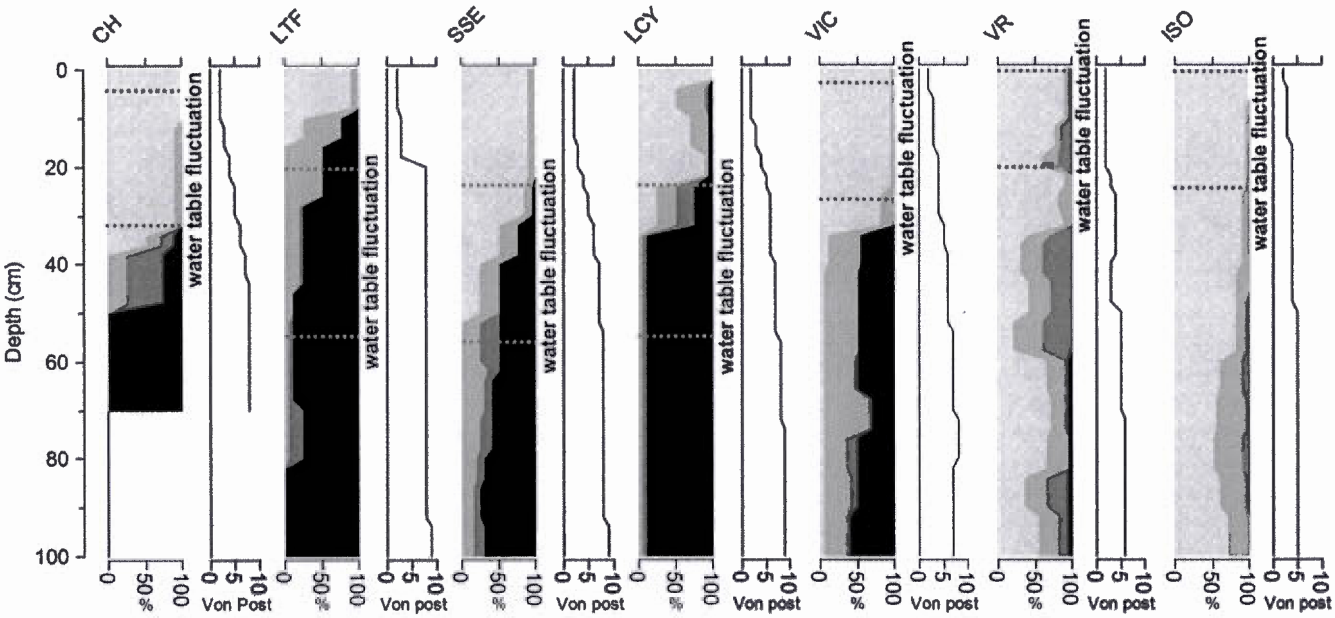


Figure 2.3 **Description of peat composition (shading), peat humification, maximum and minimum water table depths (dark grey dashed lines), and degree of humification(von Post; black line) from one core (up-gradient) of each of the seven sites (CH, LTF, SSE, LCY, VIC, VR, and ISO). Black = *Detritus granosus* ; dark gray = *Turfa herbacea* ; grey = *Turfa lignosa* and light grey = *Turfa bryophytica*.**

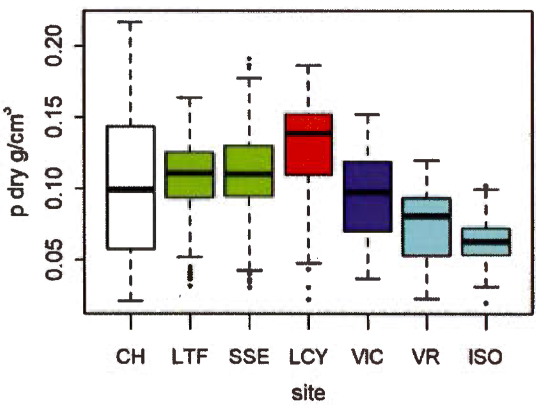


Figure 2.4 Bulk dry density variation for all locations (up-gradient, mid-gradient, down-gradient) of the seven sites (CH, LTF, SSE, LCY, VIC, VR, and ISO). Colors show significant differences in bulk dry density between the sites. Red shows the group with the highest ρ_{dry} and light blue the group with the lowest ρ_{dry}. The group shown in white show both similarities with the green group and the dark blue group.

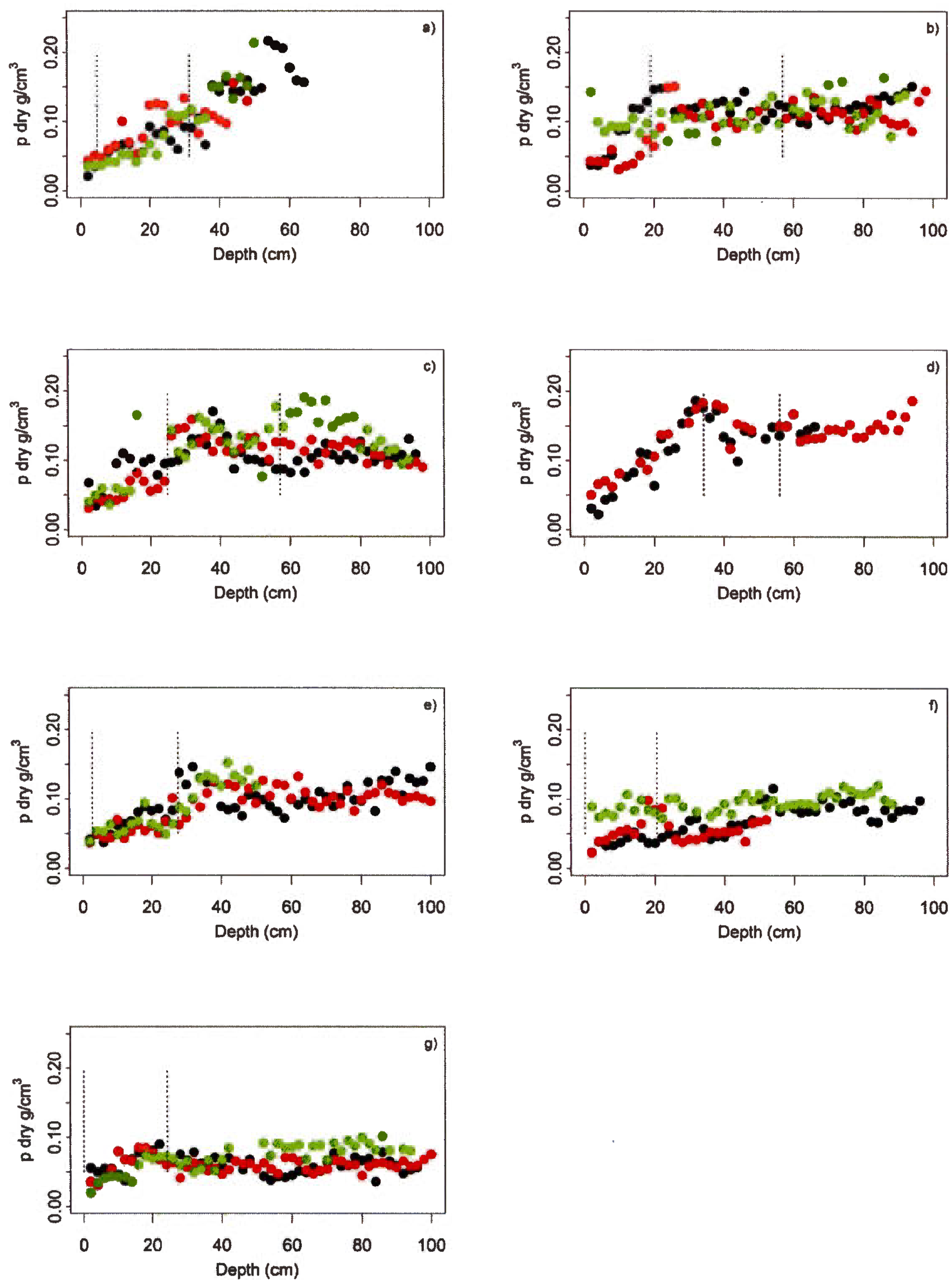

a)
b)
c)
d)
e)
f)
g)
p dry g/cm3
0.00
0.10
0.20
Depth (cm)
0
20
40
60
80
100

Figure 2.5 Variations in dry bulk density (ρ_{dry}) with depth in the up-gradient (black), mid-gradient (red), and down-gradient locations (green) of a) CH, b) LTF, c) SSE, d) LCY, e) VIC, f) VR, and g) ISO. Black vertical dashed lines represent maximum and minimum water table depths in the up-gradient location.

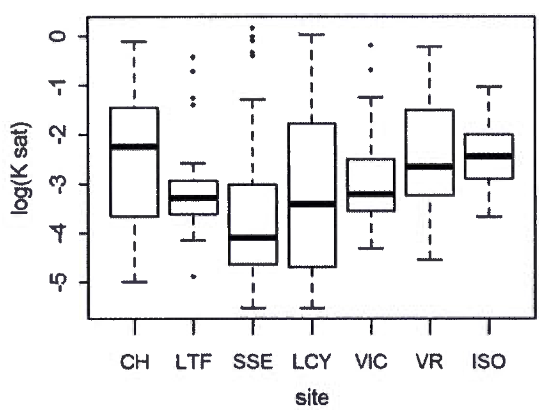
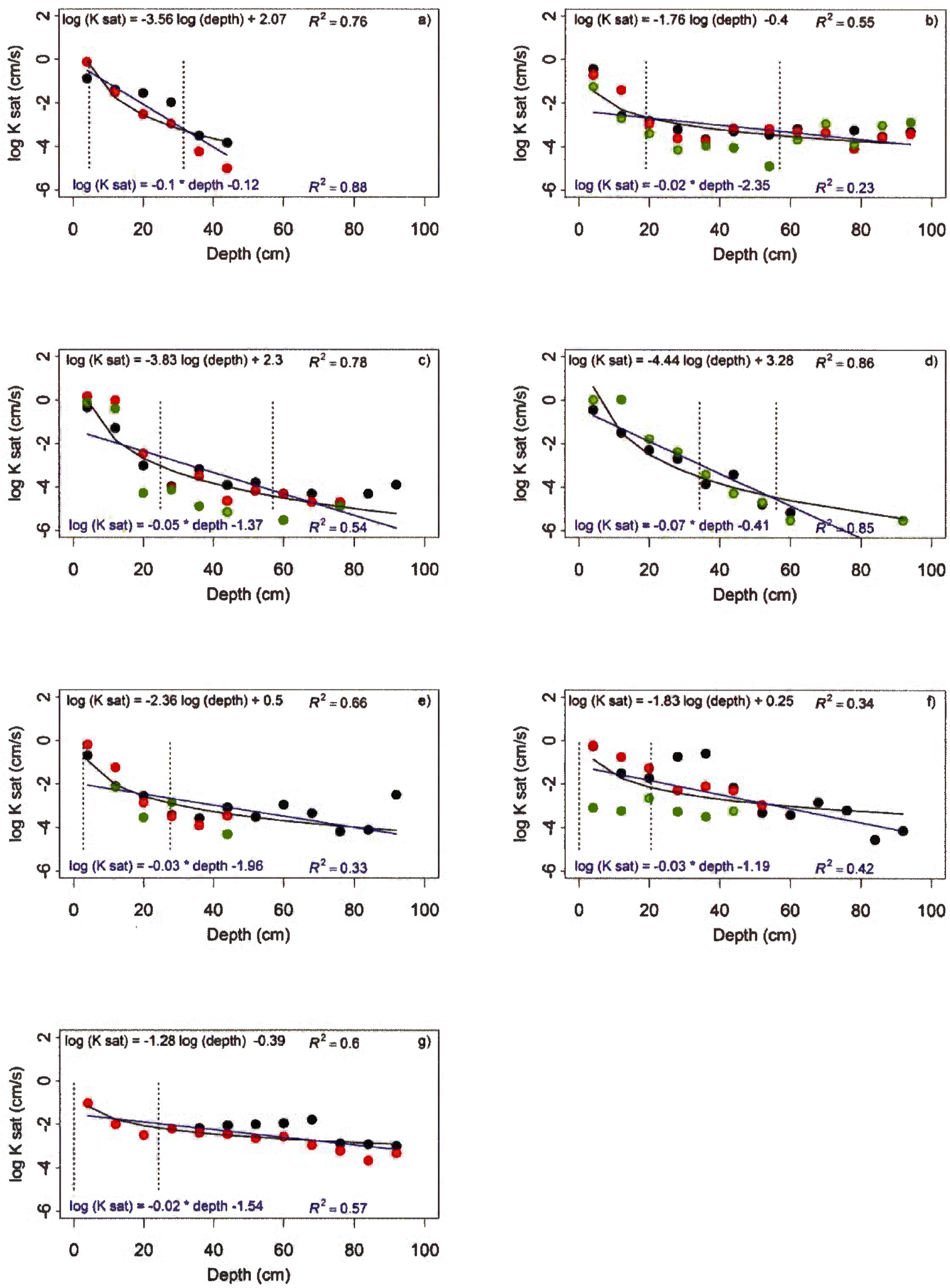


Figure 2.6 Hydraulic conductivity variations for all locations (up-gradient, mid-gradient, down-gradient) of the sites (CH, LTF, SSE, LCY, VIC, VR, and ISO).



log (K sat) = -3.56 log (depth) + 2.07
$R^2 = 0.76$
a)
log (K sat) = -0.1 * depth -0.12
$R^2 = 0.88$
log (K sat) = -1.76 log (depth) -0.4
$R^2 = 0.55$
b)
log (K sat) = -0.02 * depth -2.35
$R^2 = 0.23$
log (K sat) = -3.83 log (depth) + 2.3
$R^2 = 0.78$
c)
log (K sat) = -0.05 * depth -1.37
$R^2 = 0.54$
log (K sat) = -4.44 log (depth) + 3.28
$R^2 = 0.86$
d)
log (K sat) = -0.07 * depth -0.41
$R^2 = 0.85$
log (K sat) = -2.36 log (depth) + 0.5
$R^2 = 0.66$
e)
log (K sat) = -0.03 * depth -1.96
$R^2 = 0.33$
log (K sat) = -1.83 log (depth) + 0.25
$R^2 = 0.34$
f)
log (K sat) = -0.03 * depth -1.19
$R^2 = 0.42$
log (K sat) = -1.28 log (depth) -0.39
$R^2 = 0.6$
g)
log (K sat) = -0.02 * depth -1.54
$R^2 = 0.57$
log K sat (cm/s)
Depth (cm)

Figure 2.7 Log K variation with depth in the up-gradient (black), mid-gradient (red) and down-gradient locations (green) of a) CH, b) LTF, c) SSE, d) LCY, e) VIC, f) VR, and g) ISO, including the log-log model (black line) and the log model (blue line), and the R^2 of each. Black vertical dashed lines represent the maximum and minimum water table depths in the up-gradient locations.

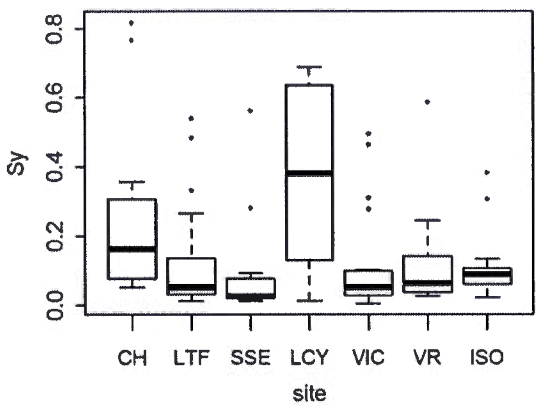
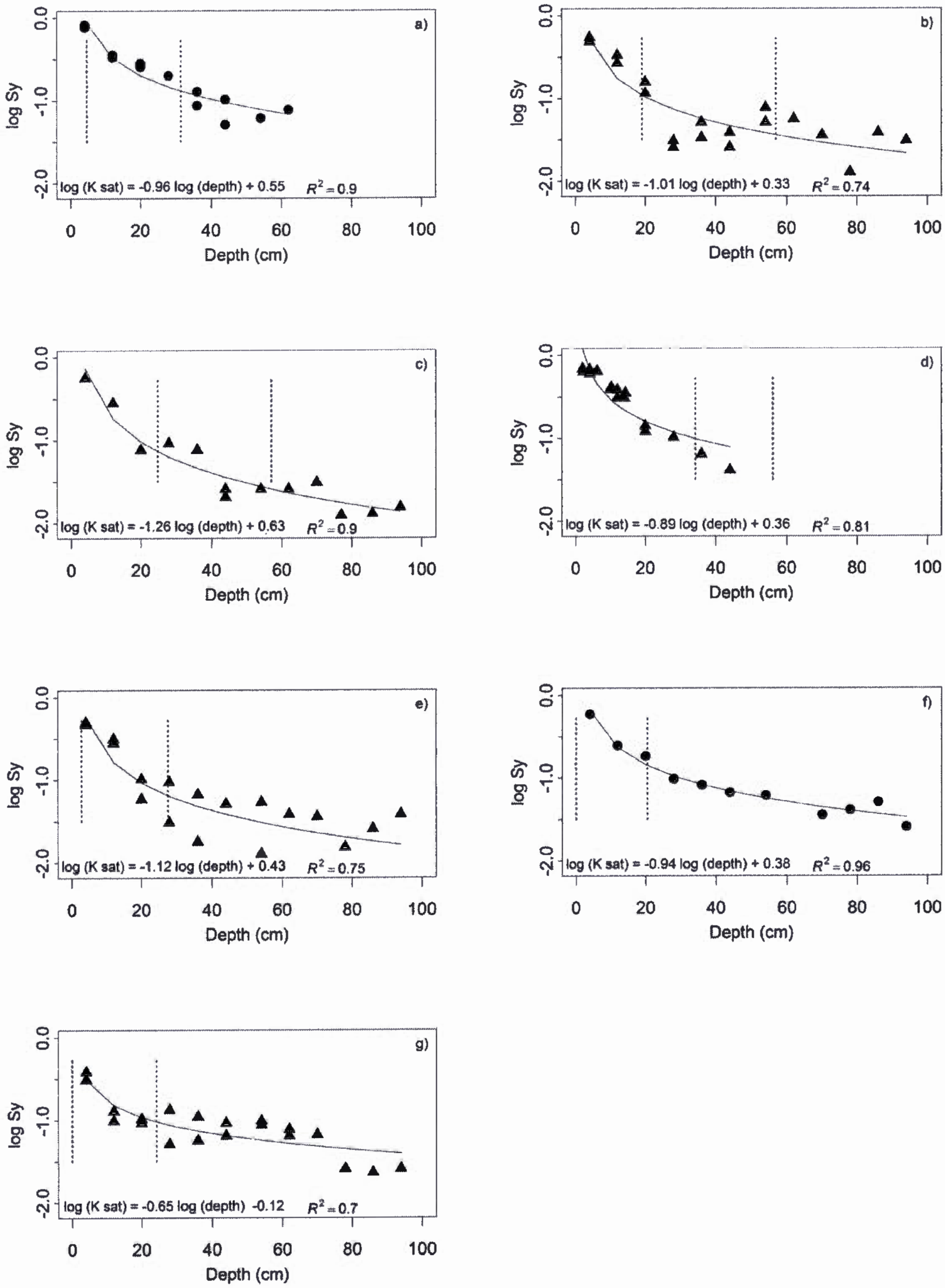


Figure 2.8 Specific yield (S_y) variations for all locations (up-gradient, mid-gradient, down-gradient) of the sites (CH, LTF, SSE, LCY, VIC, VR, and ISO).



a)
log Sy
Depth (cm)
log (K sat) = -0.96 log (depth) + 0.55
R^2 = 0.9
b)
log Sy
Depth (cm)
log (K sat) = -1.01 log (depth) + 0.33
R^2 = 0.74
c)
log Sy
Depth (cm)
log (K sat) = -1.26 log (depth) + 0.63
R^2 = 0.9
d)
log Sy
Depth (cm)
log (K sat) = -0.89 log (depth) + 0.36
R^2 = 0.81
e)
log Sy
Depth (cm)
log (K sat) = -1.12 log (depth) + 0.43
R^2 = 0.75
f)
log Sy
Depth (cm)
log (K sat) = -0.94 log (depth) + 0.38
R^2 = 0.96
g)
log Sy
Depth (cm)
log (K sat) = -0.65 log (depth) -0.12
R^2 = 0.7

Figure 2.9 Log-log model (black line) of Sy variations with depth in the up-gradient (black) location of the seven peatlands . The circles correspond to new data from this study, and the triangles to data from Bourgault *et al.* (2016). Black vertical dashed lines represent the maximum and minimum water table depths in the up-gradient locations.

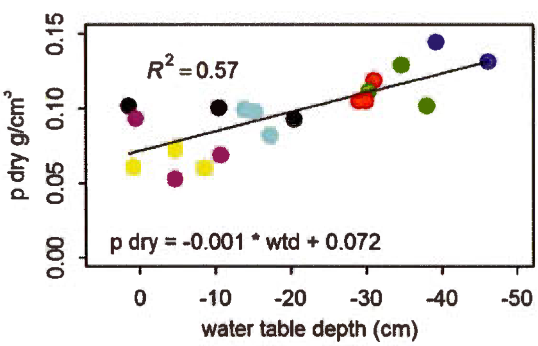


Figure 2.10 **ρ_{dry} as a function of median water table depth from June 2014 to May 2016 for all locations in the seven peatlands. Black = CH, red= LTF, green= SSE, dark blue=LCY, light blue= VIC, pink= VR, and yellow=ISO. The black line shows the linear regression model.**

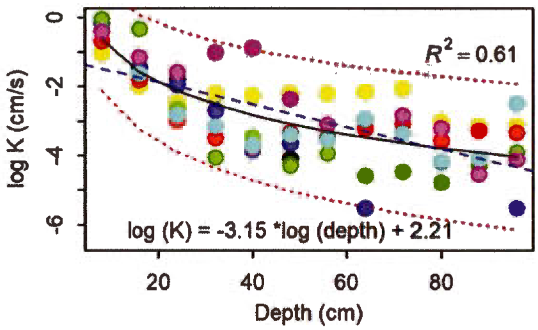


Figure 2.11 log K as a function of depth for all locations in the seven peatlands (Black = CH, red= LTF, green= SSE, dark blue=LCY, light blue= VIC, pink= VR, and yellow=ISO). The black line shows the log-log model developed in this paper, the dashed red lines show the upper and the lower log-log model calculated using a confidence interval of 95% on the parameters α and β, and the dashed blue line shows the semi-log model developed by Young (1968) and used in the Digibog model (Baird *et al.*, 2012).

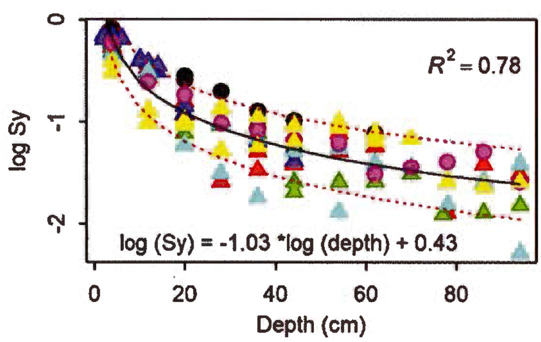


Figure 2.12 Sy as a function of depth for all locations in the seven peatlands (Black = CH, red= LTF, green= SSE, dark blue=LCY, light blue= VIC, pink= VR, and yellow=ISO). The black line shows the model developed in this paper. The dashed red lines show the upper and the lower log-log model calculated using a confidence interval of 95% on the parameters α and β. The circles correspond to new data from this study and the triangles represent data from Bourgault *et al.* (2016).

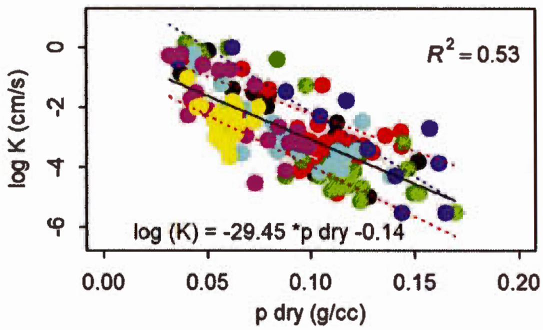


Figure 2.13 Log K as a function of ρ_{dry} for all locations in the seven peatlands. Black = CH, red= LTF, green= SSE, dark blue=LCY, light blue= VIC, pink= VR, and yellow=ISO. The black line shows the semi-log model developed in this paper, the dashed red lines show the upper and the lower log model calculated using a confidence interval of 95% on the parameters α and β, and the dashed blue line shows the semi-log model developed by Radforth and Brawner (1977) and used in the Holocene Peat Model (Frolking et al., 2011).

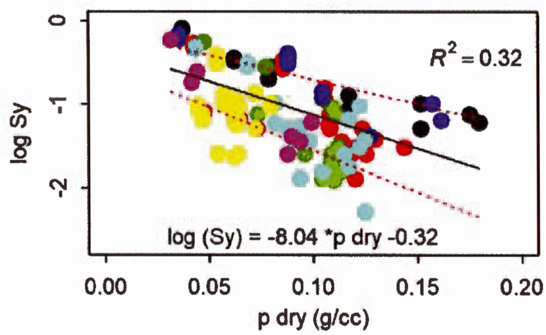


Figure 2.14 Sy as a function ρ $_{dry}$ for all locations in the seven peatlands (Black = CH, red= LTF, green= SSE, dark blue=LCY, light blue= VIC, pink= VR, and yellow=ISO). The black line shows the model developed in this study. The dashed red lines show the upper and the lower log model calculated using a confidence interval of 95% on the parameters α and β.

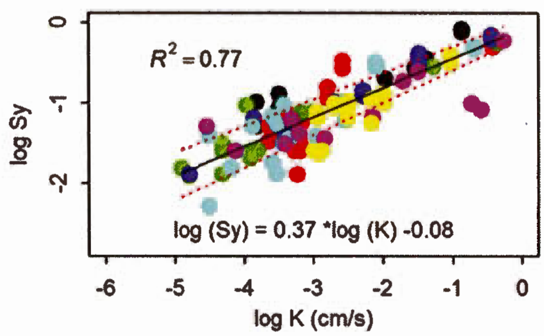


Figure 2.15 Sy as a function K for all locations in the seven peatlands (Black = CH, red= LTF, green= SSE, dark blue=LCY, light blue= VIC, pink= VR, and yellow=ISO). The black line shows the model developed in this study. The dashed red lines show the upper and the lower log-log model calculated using a confidence interval of 95% on the parameters α and β.

CHAPITRE III

CONTROLS ON WATER TABLE DEPTHS AND FLUCTUATIONS IN PEATLANDS: A BALANCE BETWEEN METEOROLOGICAL CONDITIONS AND HYDROGEOLOGICAL SETTINGS

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Article soumis à *Journal of Hydrology* Manuscript ID : HYDROL-S-18-01648

ABSTRACT

Peatlands are wetland ecosystems where net primary production exceeds organic matter decomposition. They are characterized by a near-surface water table controlled by a combination of internal and external processes, influenced by short-term meteorological variations and long-term climate change, among other factors. Site-specific conditions, such as peat hydrodynamic properties, surface vegetation patterns, and hydrogeological setting, are also important controls of water table dynamics. The objective of this paper was to characterize the controls exerted by meteorological conditions and by hydrogeological setting on water table depth (WTD) and water table fluctuation (WTF) in peatlands and in their immediate surroundings. Seven ombrotrophic ecosystems located in or near the St. Lawrence Lowlands (southern Quebec, Canada), which have developed in different hydrogeological settings, were characterized and monitored. Six zones per site were monitored using dipwells and piezometers, with hourly recordings of WTDs: up-gradient, mid-gradient, and down-gradient of the peatland flow, in the peatland minerotrophic zone, as well as in the inflow and outflow zones of the adjacent superficial aquifer. The hydraulic conductivity measurements of the outflow zone ranged between $1.4*10^{-7}$ and $8.5*10^{-3}$ cm/s, whereas the hydraulic conductivity of the inflow zone ranged between $5.6*10^{-7}$ and $3.9*10^{-6}$ cm/s. Evapotranspiration was shown to be the dominant factor controlling cumulative monthly water table decreases (MCD), while precipitation dominated the cumulative monthly water table increases (MCI). Strong correlations were found between mean peatland WTD and the hydraulic conductivity of the outflow zone. Peatlands that were strongly connected with their outflow zone showed the greatest variations in water storage, and cross-correlations between the outflow and the up-gradient zones. This study sheds new light on aquifer-peatland connections, suggesting that WTFs are controlled by meteorological conditions and that hydrogeological setting is an important control for MCI and MCD. Moreover, this work shows that WTD in ombrotrophic peatlands is influenced by the hydraulic conductivity of the outflow zone. This study confirms that peatland-aquifer connectivity influences peatland water storage variations, and therefore peatland vulnerability to disturbances in aquifer groundwater levels.

Keywords: peatland, aquifer, water table depth, water table fluctuation, hydrogeological setting, meteorological conditions

3.1 INTRODUCTION

Peatlands are wetland ecosystems where net primary production exceeds organic matter decomposition. They are characterized by near-surface water tables controlled by many factors, including meteorological conditions (short term), climate (long term) (Schonong et al., 2005; Charman, 2007; Charman et al., 2009), peat hydrodynamic properties (specific yield (Sy) and hydraulic conductivity (K_{sat}); Kelly et al., 2014; Bourgault et al., 2016), hydrogeological setting (Glaser et al., 1997; Lukenbach et al., 2015), and autogenic ecological processes (Belyea and Clymo, 2001; Swindles et al., 2012). Net water balance (precipitation minus evapotranspiration) is recognized to strongly influence short-term water table fluctuation (WTF; Labadz et al., 2010). Reconstruction of past water table depths (WTDs) using testate amoebae has been correlated with mean annual temperature (Schonong et al., 2005; Payne, 2014). Summer moisture deficit has also been shown best explain WTD over the long-term (Charman, 2007). Although the hydrogeological setting in which a peatland developed is also known to influence WTD (Winter, 2001; Lukenbach et al., 2015), few studies have attempted to understand the simultaneous relative influences of current meteorological conditions and hydrogeological setting on peatland water table dynamics.

Peat hydrodynamic properties control the velocity of water circulating through the horizons. It has been shown that peat K_{sat} (Rosa and Larocque, 2008; Morris et al., 2015) and peat Sy (Vorob'ev, 1963; Moore et al., 2015; Bourgault et al., 2018) can markedly decrease within the top meter of peat horizons. This vertical variability exerts a strong control on WTF (Waddington et al., 2015). For instance, as the WTD increases, smaller amounts of rainfall are needed to trigger a water table increase. Inversely, when WTD is high (i.e., shallow), a larger amount of rainfall is needed to raise the water table, until a threshold is reached and additional precipitation cannot be stored. In southern Quebec, Bourgault et al. (2018) have shown that vertical variations in peat Sy and K_{sat} do not differ significantly between peatlands, and thus cannot explain the observed differences in WTD across the studied sites. This suggests that peatland connectivity to an adjacent surficial aquifer, determined by the hydrogeological setting in which the peatland developed, may be an important control of WTD.

The hydrogeological setting of a peatland is defined by the nature of the geological material adjacent to and underlying the organic deposits, and its hydraulic conductivity. Peatlands can be encountered in different geological settings, ranging from highly permeable Quaternary sand deposits (Rossi et al., 2012; Bourgault et al., 2014), to low-permeability sediments, such as silt, clay, or compact till (Ferlatte et al., 2014), to bedrock (Branfireun and Roulet, 1998; Levison et al., 2014). Peatlands can be found in a variety of geomorphic settings (National Wetlands Working Group-NWWG, 1997; Mitsch and Gosselink, 2007), which will influence whether they receive water from an adjacent aquifer (e.g., Ferlatte et al., 2014; Levison et al., 2014), provide water to it (Rossi et al., 2012), or alternate between these two conditions (Devito et al., 1997).

In the literature, the role of hydrogeological setting on peatland hydrology has primarily been considered by identifying aquifer-peatland exchanges using vegetation indicators, the groundwater geochemical signature (Larocque et al., 2016), or numerical flow modelling (Bourgault et al., 2014; McLaughlin et al., 2014). Some peatlands have been found to be groundwater dependent, while others are not (Kløve et al., 2011). Improved understanding of the factors that differentiate groundwater dependent peatlands (GDP) (Kløve et al., 2011) from groundwater independent peatlands (GIP) is crucial, since exchanged flows are expected to be an important control of peatland WTD. Aquifer-peatland connections can also be exerted indirectly through pressure re-equilibration between the organic deposits and the adjacent aquifer. This process has been suggested to be an important mechanism to maintain water levels both in the peatland (Ingram and Bragg, 1984) and in the surrounding aquifer (McLaughlin et al., 2014). Time series analysis is a useful tool to identify pressure-induced connectivity and causal relationships. This method has proven effective in different hydrogeological conditions, including karst aquifers (Larocque et al., 1998; Lee and Lee, 2000; Panagopoulos and Lambrakis, 2006) and alluvial aquifers (Cloutier et al., 2014; Larocque et al., 2016), but has not yet been used in peatlands.

The objective of this paper was to characterize the controls exerted by meteorological conditions and by hydrogeological setting on WTD and WTFs in ombrotrophic peatlands. To attain this objective, precipitation, temperature, and WTD time series were analyzed and compared in seven peatlands located in different hydrogeological settings in or near the St. Lawrence Lowlands (southern Quebec, Canada).

3.2 SITES DESCRIPTION

3.2.1 General information

The seven studied peatlands (Covey Hill (CH), Large Tea Field (LTF), Sainte-Séraphine (SSE), Lac Cyprès (LCY), Victoriaville (VIC), Villeroy (VR), and Issoudun (ISO)) are located in or near the St. Lawrence Lowlands (southern Quebec, Canada; Figure 3.1). They developed in four different watersheds (Châteauguay River, Nicolet River, Bécancour River, and Du Chêne River) and span 250 km on the south shore of the St. Lawrence River. All are set in headwater conditions on sub-watersheds of the main rivers. They are open ombrotrophic systems, with relatively similar vegetation coverage (e.g., *Sphagnum spp.* (*Sph* sp.), *Kalmia angustifolia* (*Kal ang*), and *Eriophorum vaginatum* (*Eri vag*)). They are distinct with regards to their hydrogeological setting, altitude (above mean sea level), surface areas, presence of a minerotrophic zone, acrotelm thickness, maximum peat thickness, physical properties of peat (e.g., dry bulk density (ρ_{dry}), K_{sat}, and S_y), and water storage variation (Table 3.1). Elevation data from the seven sites were obtained from a digital elevation model (DEM; 1 m × 1 m resolution) derived from airborne light detection and ranging surveys (LiDAR; MFFP, 2017).

3.2.2 Meteorological conditions

Mean annual precipitation (reference period 1981 – 2010) for the Châteauguay (CH, LTF), Nicolet (SSE, LCY, VIC), Bécancour (VR), and du Chêne (VR, ISO) watersheds varies between 929 and 1114 mm, with the lowest value recorded in the LTF region. For all sites, minimum monthly precipitation occurs during the winter, and maximum monthly precipitation occurs during the summer (Environment Canada, 2016). Mean annual temperatures (reference period 1981 – 2010) vary between 4.8 and 6.7 °C, with the lowest values occurring in the ISO region. For all sites, minimum and maximum temperatures are recorded in January and July respectively.

For the study period, hourly precipitation and temperature data are available from 2014-04-01 to 2016-06-01. Hourly temperature was retrieved from the closest meteorological stations (MDDELCC, 2017) and hourly precipitation from rain gauge tipping bucket (Hobo) installed at each site. For all the sites, monthly precipitation

(P_{month}) (excluding winter periods, snowfall and months with more than 20% missing value) varied between 24 and 180 mm, with maximum values recorded in June and minimum values recorded in April and September (see complementary material Table 3.2). Monthly temperatures (T_{month}) are similar between the sites, with a minimum of -18.7°C recorded at ISO (April 2015) and a maximum of 32.9 °C at LTF (July 2014; see complementary material Table 3.3). Mean yearly temperature in 2014 was lower than that in 2015 for all sites. For the same period, evapotranspiration (ETP) was calculated using the method of Oudin et al. (2005) (complementary material Table 3.4). Annual potential ETP varied between 607 and 684 mm, with minimum values obtained for site ISO (595 mm in 2014) and maximum values for site LTF (663 mm in 2015). No significant difference in ETP was found between years 2014 and 2015. High ETP occurred during the summer months (June, July, and August), varying between 107 and 137 mm. Low ETP occurred during the spring and autumn months (April, October, and November, varying between 9 and 48 mm; winter months were excluded).

3.2.3 Hydrodynamic properties of the studied peatlands

K_{sat} and S_y were measured by Bourgault *et al.* (2016) in 1 m peat cores retrieved from the present-day surface of each peatland. WTD was measured by Bourgault et al. (2018). K_{sat} varied over nearly six orders of magnitude between sites. The median K_{sat} values were $6.9*10^{-3}$ cm/s for CH, $5.1*10^{-4}$ cm/s for LTF, $8.0*10^{-5}$ cm/s for SSE, $4.0*10^{-4}$ cm/s for LCY, $6.4*10^{-4}$ cm/s for VIC, $2.3*10^{-3}$ cm/s for VR, and $3.5*10^{-3}$ cm/s for ISO, and showed that this between-site difference was not significant. Median S_y was 0.16 for CH, 0.05 for LTF, 0.03 for SSE, 0.38 for LCY, 0.05 for VIC, 0.06 for VR, and 0.09 for ISO, with significant differences revealed between LCY and ISO (Bourgault et al., 2018). For all sites, the S_y varied between 0.01 and 0.82, with a rapid decrease with depth (Bourgault et al., 2016). Power law models were found to best describe S_y versus depth, and were used to quantify maximum storage variations, equal to 74 mm for CH, 192 mm for LTF, 127 mm for SSE, 124 mm for LCY, 133 mm for VIC, 65 mm for VR, and 60 mm for ISO (Bourgault et al., 2016) (see Table 3.1).

3.2.4 Hydrogeological setting

Six of the studied peatlands developed over Quaternary sediments (LTF, SSE, LCY, VIC, VR, and ISO) and one (CH) developed directly over the bedrock. All peatlands have distinct hydrogeological characteristics (Figure 3.2). Site CH (0.5 km^2; 310 m asl) is characterized by a central ombrotrophic section surrounded by a minerotrophic section adjacent to the bedrock (Fournier, 2008; Levison et al., 2014). It has developed in a depression on the Cambrian sandstone of the Potsdam Group (Figure 3.2a). Year-round continuous base flow is provided to its outlet, even during dry periods. These groundwater-surface water exchanges are greater than those of the other ombrotrophic systems in St. Lawrence Lowlands. Site LTF (6.0 km^2; 51 m asl) is an ombrotrophic peatland that developed on marine clay deposits from the postglacial Champlain Sea (Figure 3.2b). Before the peatland was intensively drained, its area was estimated to be 51 km^2 (Payette and Rochefort, 2001), which is more than eight times greater than its current size. Unlike the other sites, site LTF has been subjected to intensive anthropogenic pressures. Site SSE (4.9 km^2; 84 m asl) is a peatland complex composed of a central ombrotrophic section surrounded by a minerotrophic section colonized by a swamp. Site SSE has developed in a geomorphic context of alternating littoral marine sediment (silt sand and clayey silt) and clayey silt diamicton (Figure 3.2c). Site LCY (0.5 km^2; 106 m asl) is an ombrotrophic peatland that developed within a sandy dune swale, where a discontinuous indurated horizon was found at the mineral-organic contact (Figure

3.2d). Site VIC (2.6 km^2; 118 m asl) is an ombrotrophic peatland that developed directly from exondated fine silty marine sediment (Figure 3.2e). Site VR (10.4 km^2; 124 m asl) is a peatland complex composed of a central ombrotrophic section surrounded by a minerotrophic section (Larocque et al., 2015). It has formed on alternating aeolian medium and fine sands, silt, clayey silt, and reworked diamicton from glacial deposits (Figure 3.2f). Finally, site ISO (2.8 km^2; 117 m asl) is an ombrotrophic peatland, which developed over a diamicton dominated by a clayey silt matrix (Figure 3.2g).

3.3 METHODOLOGY

3.3.1 Water level monitoring and hydraulic testing

The peatlands composed of a central ombrotrophic section surrounded by a minerotrophic section (sites CH, SSE, and VR) were separated into six zones: up-gradient (1), mid-gradient (2), and down-gradient (3), minerotrophic (4), as well as inflow (5), and outflow (6). The ombrotrophic peatlands with no minerotrophic section (sites LTF, LCY, VIC, and ISO) were divided into four zones: up-gradient (1), mid-gradient (2), and down-gradient (3) zones, and an outflow zone (4). Within each peatland, up-gradient (highest altitude) and down-gradient (lowest altitude) zones were located along a longitudinal transect, while the mid-gradient zone was located halfway between the two. The up-gradient, mid-gradient, and down-gradient zones were identified using the previously described DEM. The inflow zones were located outside the peatlands. They were characterized by a higher water table than that of the associated peatland. They were found exclusively where minerotrophic zones were present, and therefore were used as a criterion to identify GDPs. The outflow zones were also located outside the peatlands, and were characterized by a lower water table than that of the associated peatland. WTD was not measured in the inflow zone of site CH, because of the technical difficulties related to the fractured bedrock aquifer. At site LTF, the WTD of the outflow zone was not measured, because it was located in impervious clay. At site LCY, the WTD was not measured in the mid-gradient zone, because of the small distance between the up-gradient and down-gradient zones. WTD was therefore measured at six locations at sites SSE and VR, at five locations at site CH, at four locations at sites VIC and ISO, and at three locations at sites LTF and LCY.

The peatland dipwells were constructed from 3 cm outside diameter PVC pipes, with 2 m-long intakes perforated with 0.254 mm slits equally spaced by 60 mm from top to bottom and sealed at the base. In the up-gradient, mid-gradient, and down-gradient zones, the wells were inserted into *Sphagnum* lawn microforms. In the adjacent superficial aquifer, the piezometers were inserted into the mineral deposits 500 m from the peatland border. The piezometers were constructed from 3 cm steel pipes sealed at the base with a 30 cm *Solinst* drive point. Piezometers were driven into the mineral sediments using a Manual Slide Hammer, with the exception of at site CH, where the piezometer was installed in a borehole drilled from a previous study (Levison et al., 2014). All wells and piezometers were instrumented using level loggers (*Solinst*). Water table variations in the peatlands were measured using the dipwells, and head variations in the outflow and inflow zones were measured using the piezometers. All water table depths were measured at an hourly time step, from June 2014 to May 2016. To compare the different sites, water level measurements in the outflows and inflow zones were normalized using the z-scores, and water table variations in the peatlands were reported relative to the surface altitude of their respective locations.

Slug tests were performed to measure the K_{sat} of the mineral deposits in the inflow and outflow zones, using the Hvorslev method (Hvorslev, 1951). A minimum of ten slug tests were performed at each piezometer. In the outflow zones, slug tests were performed at depths of 300 cm for CH, 205 cm for SSE, 193 cm for LCY, 281 cm for VIC, 423 cm for VR, and 161 cm for ISO. These depths were chosen to vary between sites to be close to the maximum WTD observed at each during monitoring of the outflow zones that took place during summer 2013. In the inflow zones, slug tests were performed at a depth of 300 cm for SSE and 220 cm for VR. K_{sat} values for the fractured bedrock at CH are those reported in Levison et al. (2014).

3.3.2 Time series analysis

Every water table increase linked to a single precipitation event, and every water table decrease initiated by ETP and lateral water circulation was isolated using the techniques described in Bourgault et al. (2016). First, a computation script written in the R programming language (R environement D.C.T., 2008) was used to identify the maximum water table rise following each precipitation event. The code calculated total precipitation during the event (P_{event}), the maximum water level rise following the event (Δh_{rise}), and the time interval between P_{event} and Δh_{rise}. Water table decreases were isolated by removing time periods between P_{event} and Δh_{rise} from each water table time series. The difference between the maximum and minimum water table height ($\Delta h_{drawdown}$) was computed. Δh_{rise} and $\Delta h_{drawdown}$ were cumulated monthly, leading to two new variables, the monthly cumulative increase (MCI) and the monthly cumulative decrease (MCD). The data were analyzed to evaluate whether T_{month} and P_{month} could be used as indicators of MCI and MCD. In Dargie et al. (2017), MCI was strongly correlated with P_{month} for WTDs above the peat surface. However, MCI has never been used for peatlands where WTD is below the surface. Likewise, the use of MCD as an indicator of the effect of ETP (considered to be proportional to air temperature) has never been reported in the literature. Linear correlations were performed between T_{month} and MCD, and P_{month} and MCI.

Autocorrelation (r(k)) and cross-correlation ($r_{xy}(k)$) functions were calculated using the hourly-monitored water table measurements over periods of 25 days (600 hours), from June 2014 to June 2016. The autocorrelation functions were calculated both in the ombrotrophic sections of the peatlands and in the outflow zones of the aquifers. The autocorrelation function is useful to differentiate water table reactivity (i.e., a rapid decrease of r(k) over time is associated with a reactive water table). The time lag equivalent to an r(k) value of 0.7 was arbitrarily used to compare the slopes of the autocorrelation functions of the seven sites. The $r_{xy}(k)$ functions were calculated between WTD in the up-gradient zone of the peatland (zone 1 in Figure 3.2) and WTD in the outflow zone of the aquifer (zone 6 in Figure 3.2). The lag time between the two time series is quantified as the maximum value of the cross-correlation.

3.4 RESULTS

3.4.1 Water table depths and water table fluctuations

Results from this study and from data compiled from the previous study of Bourgault et al. (2018), reveal significant differences (Anova test: p value = 10^{-14}, Tukey's test; p value < 10^{-10}) between WTDs at the seven studied peatlands. For all peatlands, WTD varied between -54 cm (at site LCY; below peat surface; Figure 3.3) and 1 cm (at site ISO; above peat surface; Figure 3.3), with WTF varying between 21 cm (site ISO) and 38 cm (site LCY). WTDs were closer to the surface in April and were deeper in August and September (see complementary material Table 3.5).

WTD in the minerotrophic zones of sites CH, SSE, and VR was between 22 cm and -17 cm, and varied between 11 and 22 cm (Figure 3.4). Similar to the levels within the ombrotrophic section of the peatland, water tables in the minerotrophic zone were higher in April and deeper in August and September (see complementary material Table 3.6). No significant differences were found between peatlands.

In the inflow zones, WTD varied between 0 cm (site VR in April 2016) and -131 cm (site SSE in July 2014), while WTF varied between 27 cm (site VR in 2014) and 115 cm (site SSE; see complementary material Table 3.7). Mean annual WTD was -34 cm (SD = 31 cm) for SSE and -48 cm (SD = 23 cm) for site VR. When normalized (standard score; Figure 3.5), WTD at site VR showed stronger variation than at site SSE. No significant difference in WTD was found between the studied peatlands. Similar to the peatlands, the aquifer WTD was closer to the surface in April and deeper in August and September.

In the outflow zones, WTD varied between 0 and -374 cm, while WTF varied between 11 and 95 cm (see complementary material Table 3.8). Mean annual WTD was equal to -78 cm (SD = 14 cm) for site CH, -42 cm (SD = 26 cm) for site SSE, -46 cm (SD = 26 cm) for site LCY, -69 cm (SD = 23 cm) for site VIC, -350 (SD = 20 cm) for site VR, and -13 cm (SD = 4 cm) for site ISO. When normalized (standard score; Figure 3.6), WTD at sites VR and ISO show the largest variations, whereas WTD at site LCY shows the smallest variation of all sites.

3.4.2 Aquifer hydraulic conductivity

The K_{sat} of the outflow zones varied by four orders of magnitude, ranging between $1.4*10^{-7}$ and $8.5*10^{-3}$ cm/s (site LTF was excluded, because K_{sat} of the outflow zone was not measured), whereas the K_{sat} of the inflow zones varied by only one order of magnitude, ranging between $5.6*10^{-7}$ and $3.9*10^{-6}$ cm/s. The median K_{sat} of the outflow zones was $3.6*10^{-4}$ cm/s for site CH (Fournier, 2008) , $5.0*10^{-9}$cm/s for site LTF (Desaulniers and Cherry, 1989), $1.3*10^{-4}$ cm/s for site SSE, $2.9*10^{-3}$

cm/s for sites LCY, $2.6*10^{-5}$ cm/s for site VIC, $1.4*10^{-5}$ cm/s for site VR, and $4.4*10^{-7}$ cm/s for site ISO. The median K_{sat} of the inflow zones was $1.3*10^{-6}$ cm/s for site SSE, and $1*10^{-7}$ cm/s for site VR.

With the exception of site LTF, the K_{sat} of the outflow zones was inversely correlated to the mean WTD at the up-gradient well (zone 1, ombrotrophic section), with an R^2 of 0.7 (Figure 3.7). This suggests that WTD in the ombrotrophic section of the peatlands was closer to the surface when the K_{sat} of the outflow zone was low, and that the WTD decreases as the K_{sat} of the outflow zone increases. No significant correlation was found between the mean WTD of the ombrotrophic section and the K_{sat} measured in the inflow zone (not shown).

3.4.3 Time series analyses

MCI varied between 61 mm (site LCY) and 451 mm (site LTF), with the highest MCI occurring during the highest evaporative period (May to August) and the lowest MCI occurring during low evaporative periods (March, April, and November; Figure 3.8). MCD varied between 44 and 542 mm for all sites, with the highest MCD (at site LTF) occurring during the highest evaporative period (July and August) and the lowest MCD (at site ISO) occurring during the lowest evaporative period (October and November) (Figure 3.9).

MCI and P_{month} were strongly correlated for all sites, with R^2 values of 0.8 for site CH, 0.8 for site LTF, 0.6 for site SSE, 0.8 for site LCY, 0.7 for site VIC, 0.6 for site VR, and 0.8 for site ISO (Figure 3.8). The associated slopes varied between 1.0 and 4.2 mm of MCI per mm of precipitation, with the highest slope for sites LTF (slope = 4.2), LCY (slope = 2.3), and SSE (slope = 2.9), and the lowest slope for sites VR (slope = 1.0) and ISO (slope = 1.4). MCD and T_{month} were also strongly correlated for all sites, with R^2 values of 0.7 for site CH, 0.7 for site LTF, 0.8 for site SSE, 0.9 for site LCY, 0.7 for site VIC, 0.8 for site VR, and 0.8 for site ISO (Figure 3.9). The associated slopes varied between 8 and 18 mm MCD per °C, with the strongest slope calculated for sites LTF (slope = 18 mm/°C), LCY (slope = 15 mm/°C), and SSE (slope = 10 mm/°C), and the weakest slope calculated for sites VR and ISO (slope = 8 mm/°C in both cases). Sites LTF, LCY, and SSE show the strongest variation in both MCI and MCD, whereas sites VR and ISO show the weakest variation in MCI and MCD. WTDs were not significantly correlated to either P_{month} or to T_{month} (not shown).

For the peatlands, r(k) reached a value of 0.7 after 430 h for site CH, 451 h for site LTF, 167 h for site SSE, 135 h for site LCY, 158 h for site VIC, 154 h for site VR, and 485 h for site ISO (Figure 3.10a). The most rapid decrease in r(k)was observed for site LCY, whereas the weakest decrease was observed for site ISO. In the adjacent aquifers, r(k) reaches a value of 0.7 after 245 h for site CH, 492 h for site SSE, 570 h for site LCY, 301 h for site VIC, 326 h for site VR, and 139 h for site ISO (Figure 3.10b). The most rapid decrease in r(k) was observed for site ISO, and the slowest decrease was observed for site LCY.

Cross-correlation functions between the outflow zone and the peatland (up-gradient zone) were calculated for all sites (Figure 3.11), except for site LTF because of its hydrogeological setting. Maximum $r_{xy}(k)$ was 0.62 for site CH, 0.67 for site SSE, 0.65 for site LCY, 0.69 for site VIC, 0.37 for site VR, and 0.30 for site ISO. Time lags were similar for all sites, and were less than 16 hours.

3.5 DISCUSSION

3.5.1 Water table depths and hydraulic conductivity

Results of the WTD measured in the different zones of the peatlands (i.e., up-gradient, mid-gradient, down-gradient, minerotrophic) and of the aquifers (inflow, outflow) (Larocque et al., 2013; Ferlatte et al., 2014; Levison et al., 2014; Larocque et al., 2015; Lefebvre et al., 2015) were similar to values reported in the literature for the St. Lawrence Lowlands.

The K_{sat} of the superficial aquifers surrounding the peatlands corresponds to the ranges previously reported for unconfined aquifers in the St. Lawrence Lowlands. For example, commonly measured K_{sat} of unconsolidated superficial aquifers in the St. Lawrence Lowlands varies between 10^{-2} cm/s and 10^{-4} cm/s for unconfined sandy aquifers and between 10^{-4} cm/s and 10^{-6} cm/s for silty glacial deposits (Larocque et al., 2013; Larocque et al., 2015; Lefebvre et al., 2015).

3.5.2 Groundwater flow dynamics

In the seven studied peatlands, flow dynamics and flow directions were analyzed using water table elevations at the different monitored zones. For sites CH, LTF, SSE, LCY, VIC, VR, and ISO, water flowed from up- to down-gradient zones before reaching the edge of the peatland, where water flowed into the outflow zone of the superficial aquifer. This type of flow was also observed by Ferlatte et al. (2014) at site VR. Site LTF is an exception, since the low K_{sat} of the outflow zone characterizes the superficial deposits as an aquitard. At sites CH, SSE, and VR, water flowed both from the up-gradient zone towards the minerotrophic zone, and from the inflow zone toward the minerotrophic zone. The converging water then flowed within the minerotrophic zone of the peatland toward the surface outlet. This was also previously described by Ferlatte et al. (2014) in some peatlands of the St. Lawrence Lowlands.

In the current study, four distinct relationships between peatland down-gradient WTD and hydrogeological setting were observed. In the first, water converged towards the peatland margin down-gradient and the WTD was closer to the surface than in the corresponding up-gradient zone. This was observed at sites CH, VR, and ISO, and corresponds to peatland margins in contact with lower K_{sat} mineral deposits (Figures 3.2a and 3.2f). The second case, observed at sites CH, SSE, and VR, was characterized by groundwater flowing from the aquifer toward a minerotrophic zone, where the WTD was near the surface and strong variation in aquifer K_{sat} was observed (Figures 3.2a, 3.2c, and 3.2f). The third case corresponds to conditions whereby the WTD in the up-gradient zone was similar to that of the corresponding down-gradient zone. This was observed where peatland margins are in contact with higher K_{sat} sediments (i.e., sites SSE, LCY, and VIC; Figures 3.2c, 3.2d, and 2e). A fourth relationship was also found, whereby down-gradient WTDs were similar to up-gradient WTDs, and the peatland margins were heavily disturbed by intensive human activities (i.e., site LTF; Figure 3.2b).

3.5.3 Meteorological controls of water table depths and fluctuations

The effect of precipitation and temperature on peatland WTF was quantified using MCI and MCD. For the seven peatlands, MCI correlated strongly with P_{month} (Figure 3.8), and MCD correlated strongly with T_{month} (Figure 3.9). Linear regressions were quantified and used to evaluate the vulnerability of the peatlands to changes in precipitation and temperature. According to the definitions given above, when MCI minus MCD is negative, the net monthly water balance is also negative. Successive negative values indicate increased vulnerability of a peatland to dry conditions. Conversely, when MCI minus MCD is positive, the net monthly water balance is also positive and successive positive values favour high water tables and reduce peatland vulnerability to dry conditions.

With the exception of site LTF, which is highly disturbed, it was generally found that sites LCY and SSE (characterized by the strongest changes in MCI and MCD) are deposited on sediment that has the highest K_{sat}. On the other hand, sites VR and ISO (characterized by the weakest changes in MCI and MCD) are deposited on materials that have the lowest K_{sat}. These results are important, because they suggest that peatlands that are weakly connected to a superficial aquifer have smaller WTF and will therefore be less vulnerable to climate change than peatlands that are more strongly connected to aquifers and undergo stronger WTF. Consequently, improved knowledge of the influence of aquifer-peatland connections is needed.

The two newly developed indicators, MCI and MCD, are easily accessible indicators of peatland vulnerability to meteorological conditions in different hydrogeological settings that can be relatively easily implemented. Their usefulness will need to be confirmed on other peatlands and on longer decadal and multi-decadal periods.

3.5.4 Aquifer-peatland connections

Direct aquifer-peatland connections are characterized by water flowing from the peatland toward the aquifer and water flowing from the aquifer toward the peatland. These fluxes can be quantified using Darcy's law. They are expected to be limited to the upper portion of the peat horizons, due to the rapidly decreasing K_{sat} observed below the first meter of depth (Surridge et al., 2005; Rosa and Larocque, 2008; Kelly et al., 2014).

When water flows toward the peatland, groundwater fluxes contribute to maintaining the water table at the surface, and limit WTF in the minerotrophic portion of the peatland. Groundwater fluxes have been estimated to contribute significantly to the total annual water budget of peatlands. For example, Bourgault et al. (2014) quantified that groundwater inflows contributed 50% of the total annual water budget in a peatland (Lanoraie, St. Lawrence Lowlands). Levison et al. (2014) quantified groundwater inflows as contributing more than 60% of the total annual water budget for the CH peatland.

Flows towards the aquifer (Avard, 2013; Levison et al., 2014) are usually relatively small compared to regional recharge values. However, even if the outflow is negligible for the aquifer, results from this study suggest that the aquifer can play an important role in determining peatland WTD. In fact, for all peatlands (except site LTF), the WTD was strongly correlated with the K_{sat} measured in the outflow zones (Figure 3.7). This indicates that high K_{sat} in the aquifer generates a strong peatland-aquifer connectivity (with peatland water flowing toward the aquifer), resulting in a lower mean annual WTD in the peatland. This was not observed at site LTF, because the peatland has been heavily disturbed, and the WTD no longer reflects its natural conditions. When the aquifer K_{sat} is low, peatland-aquifer flow exchanges are limited, and the mean annual peatland WTD is higher.

These results are also confirmed using the auto-correlation and cross-correlation functions. Site LCY is an example of a strongly connected site. At this site, there was a strong cross-correlation between the sandy aquifer and the ombrotrophic portion of the peatland (see Figure 3.11). Simultaneously, while the ombrotrophic zone of site LCY had the most rapid decrease in r(k) (Figure 3.10), its surrounding sandy aquifer had the slowest decrease (see Figure 3.10b). This could indicate that, while WTFs were limited in the aquifer, more reactive WTFs were measured in the up-gradient zone of the peatland, which appears to buffer the aquifer water table.

However, the opposite situation was found for site ISO, which developed on low K_{sat} sediment. A weak cross-correlation between the outflow and the up-gradient zone was found, and, while the ombrotrophic section of site ISO was characterized by the slowest decrease in r(k), the associated aquifer was characterized by the most rapid decrease in r(k). In this case, this could indicate that peatlands deposited on low K_{sat} sediment are weakly connected with the surrounding aquifer, and therefore less reactive WTFs will be observed in the peatlands.

These results are important, since they show that all of the peatlands, with the exception of site LTF, are in equilibrium with their respective hydrogeological setting, and that the underlying mechanism controlling WTD in the peatlands is the K_{sat} of the outflow zone. The results also show that, even if there is no flow from the aquifer toward the peatland, evidenced by the absence of minerotrophic vegetation, pressure-induced connectivity between the peatland and the outflow zone exerts a control on peatland WTD. The definition of GDPs and GIPs should be revisited to include pressure-induced connectivity in addition to exchanged fluxes. The controls exerted by the hydrogeological setting on the long-term water table variation should also be addressed in future work.

3.5.5 Groundwater-dependant and groundwater-independent peatlands

GDPs and GIPs were identified using WTD measurements in the surrounding aquifers. GDPs were characterized by inflow zones, where water tables were higher than those of the peatlands. GIPs were entirely surrounded by outflow zones, where the water tables were lower than those of the peatlands. Sites CH, SSE, and VR were confirmed to be GDPs, as suggested by the presence of a marginal minerotrophic zone surrounding the ombrotrophic zone. However, sites LTF, LCY, VIC, and ISO were identified to be GIPs.

The classification of peatlands as GDPs or GDIs is important, because GDPs, as recognized by the European Water Framework Directive, contribute to maintaining good quality groundwater (Moss, 2008). GDPs are one type of groundwater dependent ecosystem (Kløve et al., 2011), often recognized for their rich biodiversity (Murray et al., 2003). Groundwater dependent ecosystems are increasingly incorporated into water management policies worldwide (Rohde et al., 2017). Lukenbach *et al.* (2015) have shown that GDPs tend to have lower WTDs (Lukenbach et al., 2015) in their ombrotrophic section. This was not observed in the current study, and WTD was not able to distinguish GDPs from GDIs.

In light of the previous results, clarification of the influence of the hydrogeological setting on distinguishing GDPs and GIPs is needed. The hydrogeological setting determines the presence of groundwater inflows, which characterize GDPs (Kløve et al., 2011), for example in eskers (Isokangas et al., 2017) or in sandy deltaic environments (Bourgault et al., 2014). However, GDPs can also be found in association with low K_{sat} sediments, such as glacial deposits (e.g., site VR), marine silts (e.g., site SSE), and in fractured bedrock aquifers (e.g., site CH). GDPs are therefore not restricted to specific geological settings.

As demonstrated by the measurement of WTD in the aquifers surrounding the different peatlands, GDPs are characterized by a zone where hydraulic gradients increase toward the peatland. These zones are associated with higher topographic features that maintain a high water table (inflow zones; Figure 3.2a, 3.2c, and 3.2e). In this study, these zones were located within a maximum of 500 m of the peatland, with an elevation of between 2 and 4 m higher than that of the peatlands. It is therefore suggested that the GDPs could be linked with the surrounding local topography. Inversely, GIPs are surrounded by zones where the hydraulic gradients indicate water flowing out of the peatland. In these cases, the GIPs are the highest topographic features (within 500 m), which makes them easy to identify using high resolution topographic maps.

3.5.6 Implication for future work

Overall, the results of this study have demonstrated that water table increases and decreases in peatlands are controlled by meteorological conditions (e.g., precipitation and temperature). Importantly, the newly derived indicators (MCI and MCD) could be used to evaluate peatland vulnerability. A community effort to assemble existing water table measurements in peatlands so as to quantify the correlation between monthly meteorological conditions and monthly cumulative variations should be considered, and this will help to better understand the resilience of peatlands to future climate change.

This study sheds new light on the connection between aquifers and peatlands in some specific hydrogeological settings. It is the first time that a strong correlation between the hydraulic properties of the outflow zone and the WTD in the ombrotrophic section of a peatland is suggested. These results are important because they indicate that adjacent superficial aquifers play an important role in peatland hydrology, and more precisely on the WTD of ombrotrophic peatlands, which have traditionally been assumed to only be impacted by precipitation. As a result, it is hypothesized that peatlands that develop in highly permeable hydrogeological settings could, throughout their development, be characterized by lower water table levels than peatlands that develop on low K_{sat} mineral material. The former would then be more vulnerable to increases in temperature and decreases in precipitation. In addition, since the outflow zone exerts a control on peatland WTD, it is assumed that any disturbance occurring in the surrounding aquifers are potential threats to the peatland ecosystem, whether the latter are groundwater dependent (i.e., GDP) or groundwater independent (i.e., GDI). Further investigation is needed to delineate zones within surrounding aquifers so as to better protect peatlands.

3.6 CONCLUSION

The objectives of this paper were to quantify the relationship between meteorological variables and WTFs, and to characterize the impact of the connectivity between peatlands and aquifers on WTD in peatlands. This study was performed on seven peatlands and their surrounding aquifers, located in or near the St. Lawrence Lowlands (southern Quebec, Canada). Two new indicators were calculated, monthly cumulative increase (MCI) and monthly cumulative decrease (MCD), and were compared with monthly precipitation (P_{month}) and monthly temperature (T_{month}). Strong correlations quantified the effects of monthly temperature and monthly precipitation changes on WTD. The results show that a 1°C change in monthly temperature imposes a change of between 8 and 18 mm in monthly WTD, and that a 1 mm change in monthly precipitation imposes a change of between 1.3 and 4.3 mm in monthly WTD. This method should be validated in different climatic contexts and hydrogeological settings to further document the vulnerability of peatlands to climate change.

The comparison of monthly WTDs in peatlands and their surrounding aquifers has revealed a significant relationship between the K_{sat} of the outflow zones and the mean annual WTD for all peatlands, with the exception of the heavily impacted LTF site. Sites that are strongly connected with their aquifer show significant differences between MCD and MCI compared to weakly connected sites. Peatlands that were strongly connected with their outflow zone show the strongest cross-correlations and water storage variation, suggesting that the hydrogeological setting does exert some control on peatland WTD and WTF. This mechanism should be further explored to better understand the long-term WTD responses of peatlands to climate and anthropogenic pressures. Because they support new insights regarding peatland hydrology where aquifers play a dominant role, the methods developed in this study need to be further tested under more variable climatic conditions and hydrogeological settings.

Acknowledgments

This research was funded by the Quebec Ministry of Environment (Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques), by local municipalities, by MITACS Accelerate, by the Nature Conservancy of Canada, and by a scholarship from the Fonds de recherche du Québec Nature et technologies (FRQNT). The authors would like to thank the Nature Conservancy of Canada for providing access to the LTF and CH sites, and private landowners for making their properties available for this study (ISO, LCY, SSE, VIC, VR).

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3.8 FIGURES

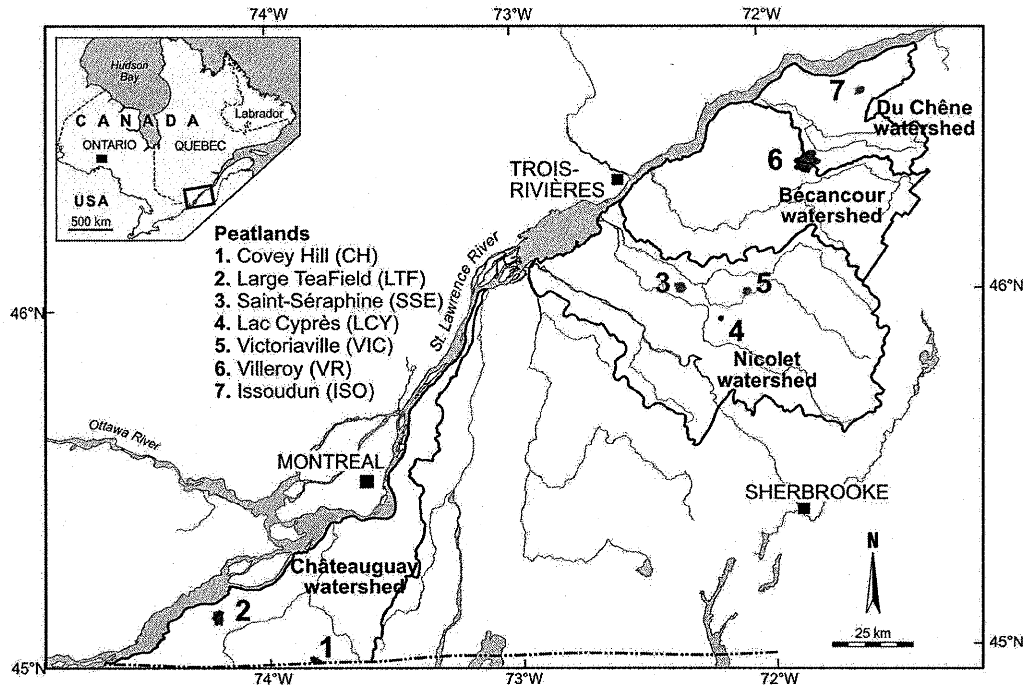


Figure 3.1 Location of the seven studied peatlands (green areas) in the Châteauguay (1-CH and 2-LTF), Nicolet (3-SSE, 4-LCY, and 5-VIC), Bécancour (6-VR), and Du Chêne (7-ISO) watersheds (black lines), including the major rivers (blue lines) in southern Quebec, Canada.

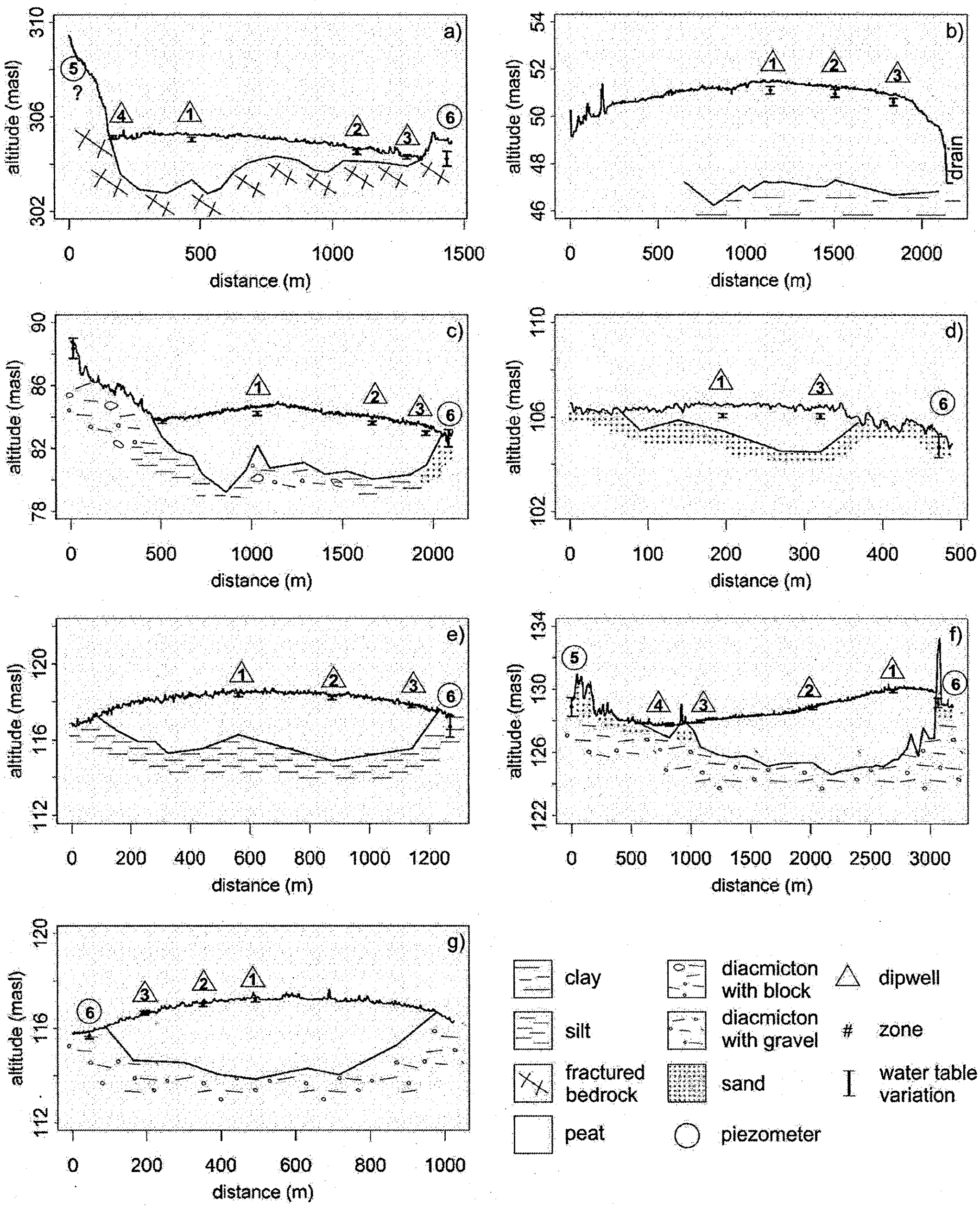


Figure 3.2 Hydrogeological setting for sites a) Covey Hill (CH), b) Large Tea Field (LTF), c) Sainte-Séraphine (SSE), d) Lac Cyprès (LCY), e) Victoriaville (VIC), f) Villeroy (VR), and g) Issoudun (ISO), including

instrumented dipwells and piezometers of all sites. Monitored water table variations are illustrated for the June 2014 to June 2016 period and for all monitored zones (1-up-gradient, 2-mid-gradient, 3-down-gradient, 4-minerotrophic, 5-inflow, and 6-outflow).

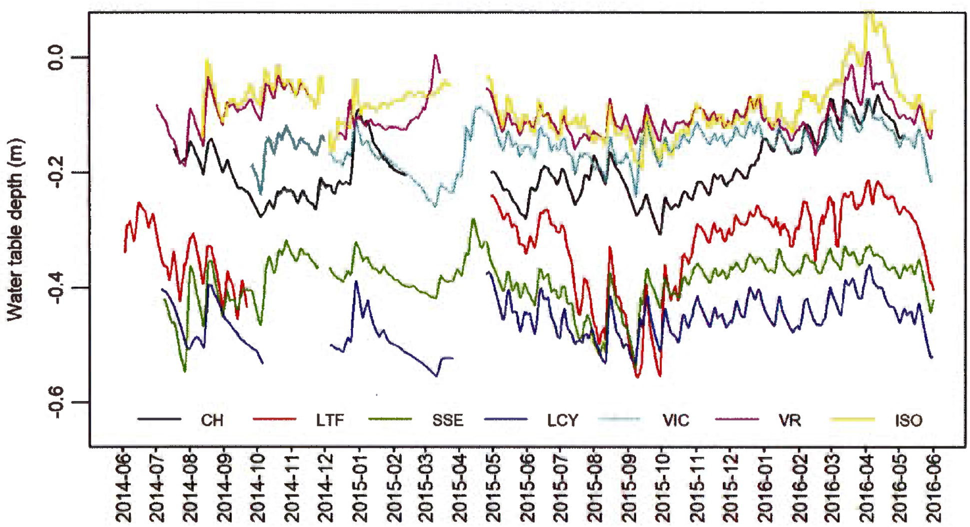


Figure 3.3 Temporal evolution of the water table depth in the up-gradient piezometer (piezometer 1 in Figure 3.2) of each studied peatland, from June 2014 to June 2016.

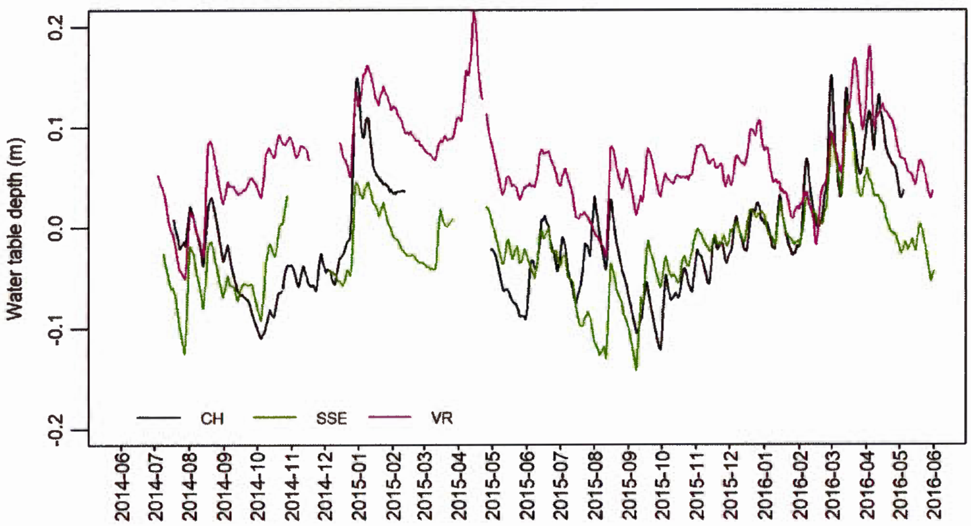


Figure 3.4 Water table depth in the minerotrophic zone (piezometer 4 on Figure 3.2) of the peatland for sites CH, SSE, and VR from June 2014 to June 2016.

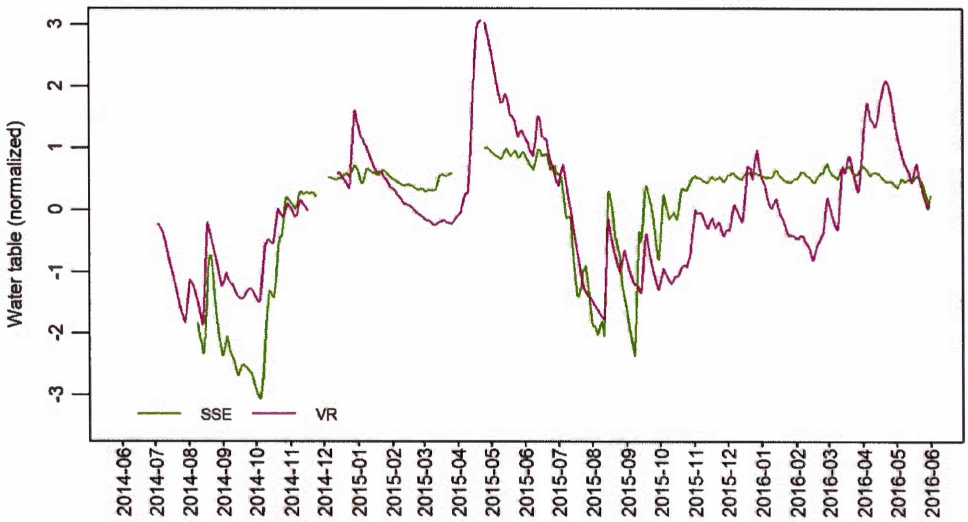


Figure 3.5 Normalized (standard score) water table depth in the inflow zones (piezometer 5 in Figure 3.2) of the aquifer for sites SSE and VR, from June 2014 to June 2016.

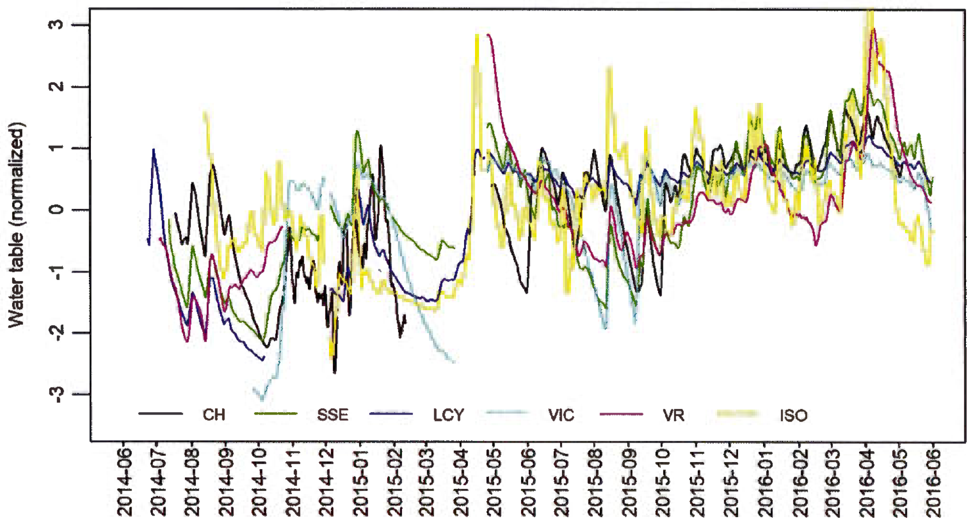


Figure 3.6 **Normalized (standard score) water table depth in the outflow zones (piezometer 6 on Figure 3.2) of the aquifer for sites CH, SSE, LCY, VIC, VR, and ISO, from June 2014 to June 2016.**

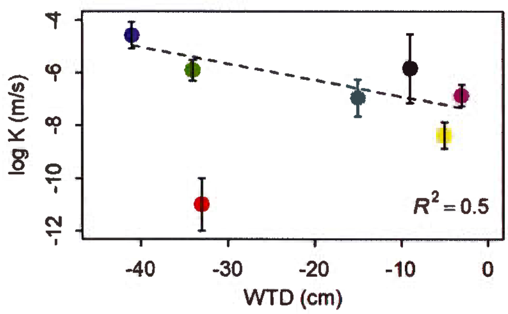


Figure 3.7 Median (point), minimum (lower bar), and maximum (upper bar) hydraulic conductivity of the outflow zone, as a function of the median water table depth in the up-gradient piezometer (zone 1, ombrotrophic section). (Black = CH, red= LTF, green= SSE, dark blue=LCY, light blue= VIC, pink= VR, and yellow=ISO).

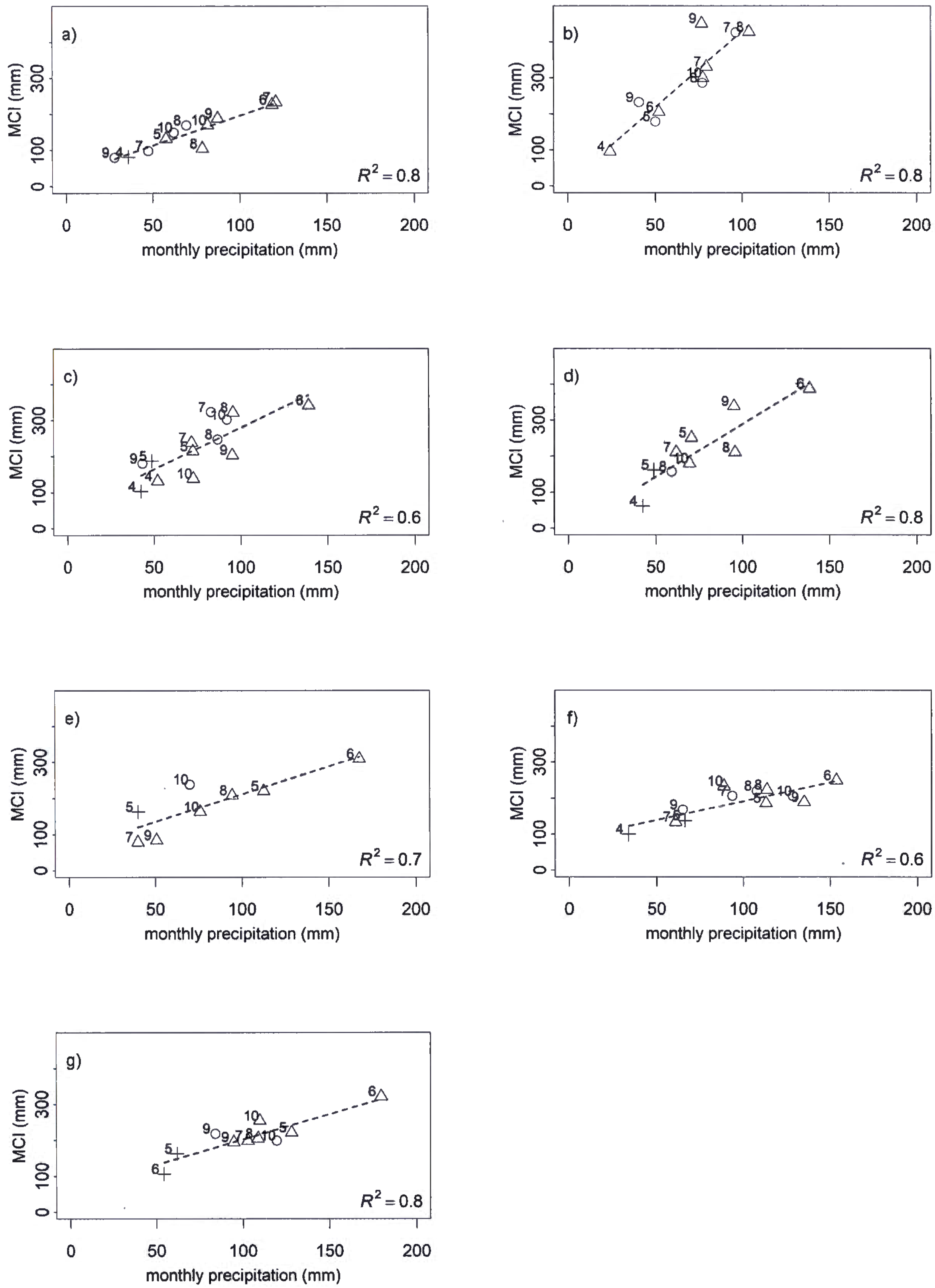

a)
$R^2 = 0.8$
b)
$R^2 = 0.8$
c)
$R^2 = 0.6$
d)
$R^2 = 0.8$
e)
$R^2 = 0.7$
f)
$R^2 = 0.6$
g)
$R^2 = 0.8$
MCI (mm)
0
100
300
monthly precipitation (mm)
0
50
100
150
200

Figure 3.8 Monthly cumulative water table increase (MCI) as a function of monthly precipitation for the seven sites: a) Covey Hill (CH), b) Large Tea Field (LTF), c) Sainte-Séraphine (SSE), d) Lac Cyprès (LCY), e) Victoriaville (VIC), f) Villeroy (VR), and g) Issoudun (ISO). Numbers associated with each point indicate the month for which the MCI was calculated (i.e., 3 = March – 11 = November). Symbols indicate the year for which the MCI was calculated (open circle = 2014, triangle=2015, cross=2016).

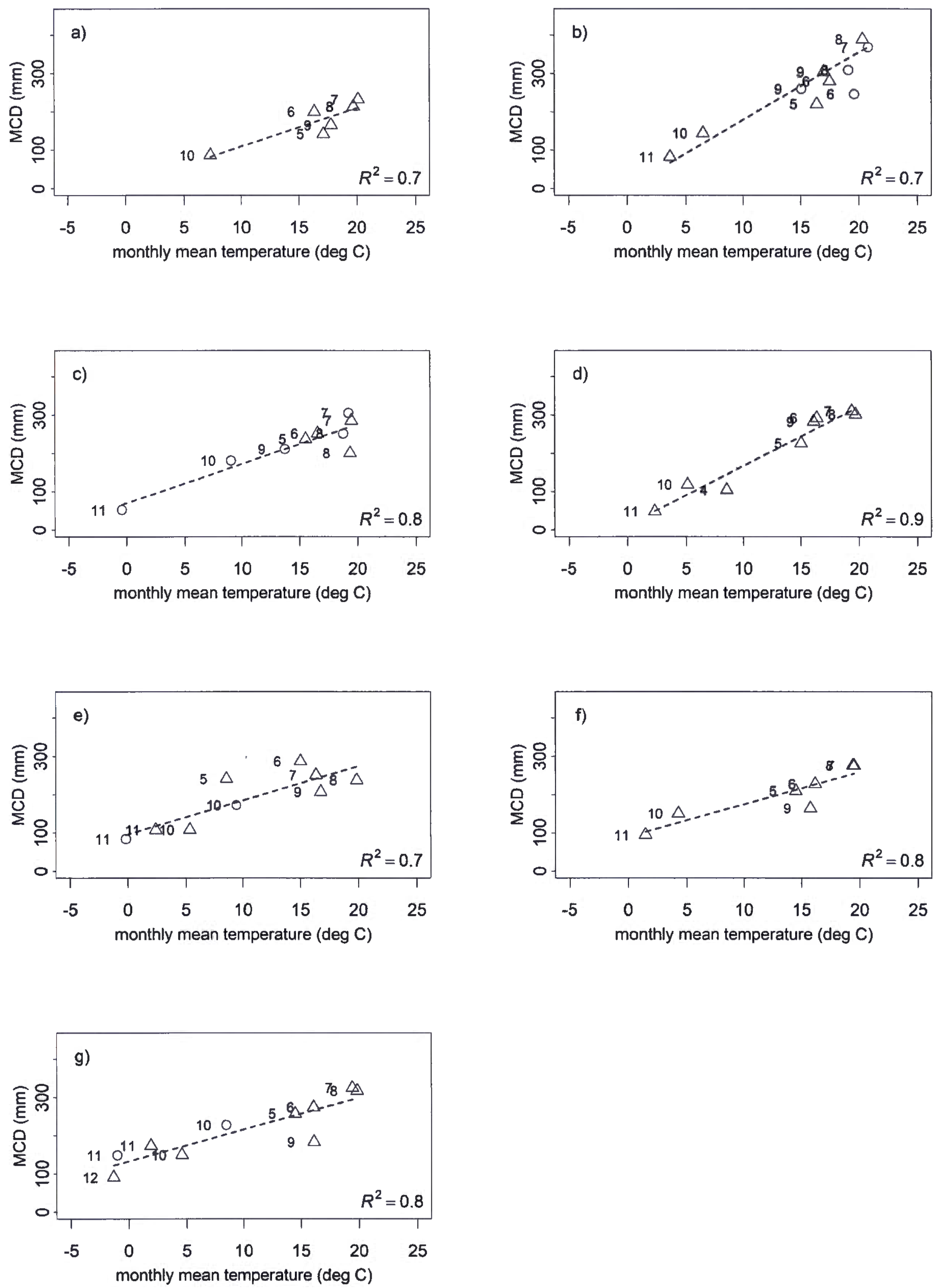
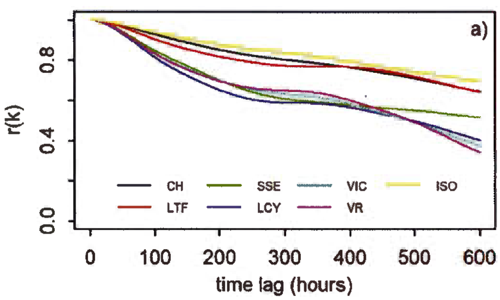

a)
MCD (mm)
monthly mean temperature (deg C)
R² = 0.7
b)
R² = 0.7
c)
R² = 0.8
d)
R² = 0.9
e)
R² = 0.7
f)
R² = 0.8
g)
R² = 0.8

Figure 3.9 Monthly cumulative water table decrease (MCD) as a function monthly mean temperature for the seven sites: a) Covey Hill (CH), b) Large Tea Field (LTF), c) Sainte-Séraphine (SSE), d) Lac Cyprès (LCY), e) Victoriaville (VIC), f) Villeroy (VR), and g) Issoudun (ISO). Numbers associated with each point indicate the month for which the MCD was calculated (i.e., 3 = March – 11 = November). Symbols indicate the year for which the MCI was calculated (open circle = 2014, triangle=2015, cross=2016).



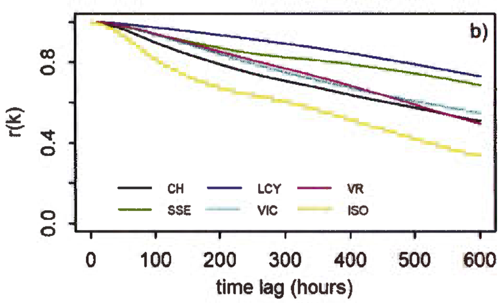


Figure 3.10 Autocorrelation function (r(k)) of water table depth as a function of time lag (hours) a) at the position of the ugradient piezometer (piezometer 1 in Figure 3.2) and b) in the outflow zone (piezometer 5 in Figure 3.2).

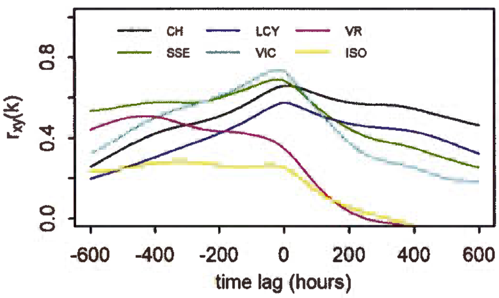


Figure 3.11 Crosscorrelation function ($r_{xy}(k)$) between the piezometer in the up-gradient portion (piezometer 1 in Figure 3.2) and the piezometer in the outflow zone (piezometer 5 in Figure 3.2).

3.9 TABLEAUX

Tableau 3.1 Characteristics of the studied peatlands, including name, latitude, longitude, watershed, altitude, area, maximum peat thickness, hydrogeological setting, acrotelm thickness, presence of minerotrophic zone, mean annual temperature (°C), mean annual precipitation (mm), dry bulk density (ρ_{dry}), hydraulic conductivity (K), storage coefficients (Sy), and storage variation (from Bourgault et al. 2016).

Site	Latitude	Longitude	watershed	Altitude (m)	Area (km²)	Maximum peat thickness (m)	Hydrogeological setting	Acrotelm thickness (cm)	Minerotrophic zone	Mean annual temperature (°C)	Mean annual precipitation (mm)	Median ρ dry (g/cm³) (max, min)	Median K (cm/s) (max, min)	Median Sy (max, min)	Water storage variation (mm)
1-CH	45.008	-73.828	Chateauguay	310	0.5	322	Fractured cambrian sandstone	32	Yes	6.1	929	0.10 (0.02 – 0.22)	$6.9x10^{-3}$ (0.8 – $1x10^{-6}$)	0.16 (0.05 – 0.82)	74
2-LTF	45.132	-74.217	Chateauguay	51	6.0	493	Marine clay	57	No	6.7	965	0.11 (0.03 – 0.16)	$5.1x10^{-4}$ (0.4 – $1x10^{-5}$)	0.05 (0.02 – 0.54)	192
3-SSE	46.042	-72.345	Nicolet	84	4.9	522	Fluvial silt/ glacial clayey silt	57	Yes	6.4	1114	0.11 (0.03 – 0.19)	$8.0x10^{-5}$ (1.4 – $3x10^{-6}$)	0.03 (0.01 – 0.56)	127
4-LCY	45.950	-72.187	Nicolet	106	0.5	190	Eolian sand	56	No	6.4	1114	0.14 (0.02 – 0.19)	$4.0x10^{-4}$ (1.1 – $3x10^{-6}$)	0.38 (0.01 – 0.69)	124
5-VIC	46.023	-72.077	Nicolet	118	2.6	360	Marine exondated silt	28	No	6.0	1114	0.10 (0.04 – 0.15)	$6.4x10^{-4}$ (0.6 – $5x10^{-5}$)	0.05 (0.01 – 0.49)	133
6-VR	46.376	-71.838	Becancour/ du Chene	124	10.4	491	Eolian sand/ glacial clayey silt	21	Yes	5.0	1037	0.08 (0.02 – 0.12)	$2.3x10^{-3}$ (0.6 – $3x10^{-5}$)	0.06 (0.01 – 0.59)	65
7-ISO	46.579	-71.597	du Chene	117	2.8	454	Glacial clayey silt	24	No	4.8	1037	0.06 (0.02 – 0.10)	$3.5x10^{-3}$ (0.1 – $2x10^{-4}$)	0.09 (0.02 – 0.38)	60

3.10 SUPPLEMENTARY MATERIALS

Tableau 3.2 Total monthly precipitation (mm) in the studied peatlands, from April 2014 to June 2016. Precipitation were retrieved from rain gauge tipping buckets (Hobo) installed at each site. Asterix indicate the months with 20% and less missing values.

Site	year	April	May	June	July	August	September	October	November	Total
1-CH	2014	-	-	-	47*	69	28	62	-	206
	2015	-	57	118	121	78	87	81	-	542
	2016	36	-	-	-	-	-	-	-	36
2-LTF	2014	-	-	134	96	77	41	-	-	348
	2015	-	50	143	79	104	77	77	-	530
	2016	24	-	52	-	-	-	-	-	76
3-SSE	2014	-	-	-	83	87	43	92	-	305
	2015	52	72	139	72	96	95	73	-	599
	2016	43	49*	-	-	-	-	-	-	92
4-LCY	2014	-	-	-	-	59	44	-	-	103
	2015	-	71	139	62	96	95	69	-	532
	2016	43	49	-	-	-	-	-	-	92
5-VIC	2014	-	-	-	-	-	-	70	-	70
	2015	-	112	168	40	94	51	76	-	541
	2016	-	47*	-	-	-	-	-	-	47
6-VR	2014	-	-	-	94	108	65	129	-	396
	2015	-	113	154	61	114	135	89	-	666
	2016	34	66	-	-	-	-	-	-	100
7-ISO	2014	-	-	-	95	106	84	119	-	404
	2015	-	128	180	103	109	95	-	-	615
	2016	-	62	54*	-	-	-	-	-	116

Tableau 3.3 Average monthly air temperature (°C) in the studied peatlands, from April 2014 to June 2016, including minimum and maximum in parentheses. For each site, data were retrieved from the closest meteorological station.

Site	year	April	May	June	July	August	September	October	November	Mean
1-CH	2014	2.6 (-6.6-16)	13.5 (2.6-23.9)	17.7 (5.4-30.0)	18.8 (9.1-31)	17.8 (7.2-28.4)	14.4 (-0.7-29.3)	9.6 (-1.8-26.3)	1.4 (-11.6–20.2)	5.4 (-32.2-31.0)
	2015	1.8 (-15.3-12.7)	15.8 (-1.1-29.6)	16.1 (2.9-26.7)	19.7 (6.9-30.9)	18.9 (8.8-31.5)	16.7 (0.5-30.6)	6.6 (-6.6-24.4)	4.0 (-9.5-21.4)	6.2 (-30.1-31.5)
	2016	2.2 (-21.2-21.9)	13.6 (-0.9-31)	17.9 (5.7-31.5)	- -	- -	- -	- -	- -	- -
2-LTF	2014	5.7 (-7.2–27.1)	13.9 (-1.0–30.6)	19.2 (5.2-32.2)	20.4 (9.9-32.9)	19.2 (7.2-29.6)	15.6 (-0.7-30.4)	10.6 (-1.7-26.9)	2.2 (-11.2–20.6)	6.8 (-33.1-32.9)
	2015	6.5 (-9.8–24.7)	16.9 (-0.1-30.5)	17.1 (3.2-27.4)	20.6 (6.6-31.8)	19.6 (7.9–31.4)	16.2 (-0.3-29.6)	6.7 (-6.6-24.4)	4.7 (-8.9-22.0)	6.9 (-29.5-31.8)
	2016	3.7 (-10.3-22.7)	14.0 (-0.4-31.4)	18.3 (5.4-31.7)	- -	- -	- -	- -	- -	- -
3-SSE	2014	5.3 (-8.5-25.5)	13.5 (2.1-28.7)	19.0 (8.3-29.8)	20.4 (11.7-31.9)	19.4 (9.9-29.3)	15.1 (0.0-29.2)	9.7 (0.3-25.1)	0.9 (-10.6-15.4)	6.2 (-29.9-31.9)
	2015	5.1 (-11.9-21.7)	15.8 (0.7-29.6)	16.7 (4.1-26.0)	20.2 (9.1-30.0)	20.2 (11.4-31.3)	17.8 (2.4-30.8)	6.2 (-6.0-23.0)	3.9 (-12.0-20.1)	6.3 (-30.7-31.3)
	2016	3.3 (-11.8-21.3)	13.6 (0.3-30.4)	18.3 (6.7-31.3)	- -	- -	- -	- -	- -	- -
4-LCY	2014	5.3 (-8.5-25.5)	13.5 (2.1-28.7)	19.0 (8.3-29.8)	20.4 (11.7-31.9)	19.4 (9.9-29.3)	15.1 (0.0-29.2)	9.7 (0.3-25.1)	0.9 (-10.6-15.4)	6.2 (-29.9-31.9)
	2015	5.1 (-11.9-21.7)	15.8 (0.7-29.6)	16.7 (4.1-26.0)	20.2 (9.1-30.0)	20.2 (11.4-31.3)	17.8 (2.4-30.8)	6.2 (-6.0-23.0)	3.9 (-12.0-20.1)	6.3 (-30.7-31.3)
	2016	3.3 (-11.8-21.3)	13.6 (0.3-30.4)	18.3 (6.7-31.3)	- -	- -	- -	- -	- -	- -
5-VIC	2014	4.3 (-10.0-23.0)	12.4 (-1.5-27.0)	17.7 (5.1-29.5)	19.4 (9.9-30.4)	18.1 (7.7-28.9)	14.0 (-3.6-28.2)	9.3 (0.0-24.2)	-0.2 (-11.2-15.5)	5.2 (-33.1-30.4)
	2015	3.8 (-13.8-20.1)	14.6 (-0.9-28.1)	15.5 (3.6-25.2)	19.1 (5.0-30.0)	19.2 (9.4-31.0)	16.4 (-0.8-29.4)	5.6 (-6.9-22.8)	-3.1 (-16.1–19.1)	5.3 (-29.2-31.0)
	2016	2.0 (-13.9-19.5)	12.4 (-2.5-28.3)	17 (4.7-30.5)	- -	- -	- -	- -	- -	- -
6-VR	2014	3.7 (-10.8-22.8)	12.3 (-2.1-28.2)	17.9 (4.2-29.7)	19.9 (8.8-31.2)	18.3 (5.5-29.0)	13.9 (-3.2-28.6)	8.8 (-0.4-23.6)	-0.2 (-12.1-15.9)	5.1 (-35.5-31.2)
	2015	3.7 (-14.5-19.5)	14.3 (-1.0-27.6)	15.8 (2.3-25.9)	19.4 (4.5-31.4)	19.5 (8.0-31.7)	16.6 (-1.3-29.9)	5.6 (-6.4-22.5)	2.8 (-16.0-20.9)	5.3 (-30.6-31.7)
	2016	1.9 (-14.2-20.8)	12.4 (-2.7-30.0)	17.0 (4.8-30.2)	- -	- -	- -	- -	- -	- -
7-ISO	2014	2.9 (-12.3-15.7)	11.9 (-0.1-27.8)	17.8 (5.3-29.8)	19.7 (8.6-30.9)	18.4 (8.7-28.9)	13.5 (-1.9-28.1)	8.7 (-1.8-21.0)	-0.3 (-15.3-14.0)	4.8 (-34.8-30.9)
	2015	3.5 (-18.7-18.8)	13.9 (0.0 – 27.1)	15.6 (3.0-25.4)	18.9 (6.2-30.1)	19.5 (10.3-30.1)	16.4 (-0.4-28.4)	5.3 (-7.0-22.0)	2.4 (-12.3-16.7)	5.0 (-32.7-30.1)
	2016	4.1 (-6.9 -19.8)	12.6 (-2.4-29)	17 (5.6-30.5)	- -	- -	- -	- -	- -	- -

Tableau 3.4 Total monthly evapotranspiration (mm) in the studied peatlands, from April 2014 to June 2016, calculated using the Oudin et al (2005) method. For each site, the temperature data used to calculate ETP were retrieved from the closest meteorological station.

Site	year	April	May	June	July	August	September	October	November	Total
1-CH	2014	45	96	126	132	112	75	43	10	639
	2015	47	109	116	135	118	85	34	19	663
	2016	38	98	122	-	-	-	-	-	258
2-LTF	2014	47	96	125	133	113	76	44	14	648
	2015	48	110	116	135	118	83	34	19	663
	2016	37	97	122	-	-	-	-	-	256
3-SSE	2014	45	96	127	137	116	75	43	11	650
	2015	43	108	114	136	119	85	33	17	656
	2016	38	97	124						259
4-LCY	2014	45	96	127	137	116	75	43	11	650
	2015	43	108	114	136	119	85	33	17	656
	2016	38	97	124	-	-	-	-	-	259
5-VIC	2014	40	90	119	130	109	70	41	10	610
	2015	37	99	110	130	116	82	31	16	620
	2016	33	90	116	-	-	-	-	-	238
6-VR	2014	37	88	117	130	107	68	38	9	595
	2015	37	98	107	127	114	79	29	15	606
	2016	31	89	114	-	-	-	-	-	235
7-ISO	2014	37	88	117	130	107	68	38	9	595
	2015	37	98	107	127	114	79	29	15	606
	2016	31	89	114	-	-	-	-	-	235

Tableau 3.5 Average monthly water table depth in the up-gradient zone (piezometer 1 in Figure 3.2) of the studied peatlands, from June 2014 to June 2016, including minimum and maximum values in parentheses.

Site	year	April	May	June	July	August	September	October	November	Annual mean WTD
1-CH	2014	-	-	-	-17	-17	-23	-25	-24	-22
		-	-	-	(-20,-13)	(-21,-13)	(-27,-16)	(-29,-22)	(-28,-19)	(-29,-13)
	2015	-15	-24	-21	-22	-20	-27	-25	-22	-23
		(-20,-8)	(-30,-19)	(-25,-17)	(-27,-15)	(-25,-15)	(-32,-22)	(-28,-20)	(-25,-18)	(-32,-15)
	2016	-10	-14	-20	-	-	-	-	-	-10
		(-16,-5)	(-16,-13)	(-25,-15)	-	-	-	-	-	(-25,-5)
2-LTF	2014	-	-	-28	-36	-36	-41	-	-	-35
		-	-	(-34 -23)	(-46 -28)	(-47 -29)	(-47 -35)	-	-	(-47,-23)
	2015	-24	-29	-29	-39	-44	-50	-37	-30	-37
		(-25,-23)	(-37,-24)	(-35,-24)	(-49,-27)	(-51,-31)	(-57,-33)	(--45,-27)	(--40,-28)	(-57,-23)
	2016	-24	-32	-40	-	-	-	-	-	-29
		(-37,-19)	(-44,-25)	(-47,-30)	-	-	-	-	-	(-47,-19)
3-SSE	2014	-	-	-	-47	-41	-42	-36	-35	-40
		-	-	-	(-56, -34)	(-49, -34)	(-46, -39)	(-48, -30)	(-38, -30)	(-56,-30)
	2015	-33	-40	-40	-45	-46	-43	-39	-38	-41
		(-39,-25)	(-44,-36)	(-45,-34)	(-52,-37)	(-55,-35)	(-57,-34)	(-43,-34)	(-41,-34)	(-57,-25)
	2016	-36	-38	-41	-	-	-	-	-	-37
		(-40,-31)	(-46,-34)	(-41,-40)	-	-	-	-	-	(-46,-31)
4-LCY	2014	-	-	-	-46	-45	-49	-53	-	-47
		-	-	-	(-51, -40)	(-52, -37)	(-52, -46)	(-54, -52)	-	(-54,-37)
	2015	-38	-44	-45	-48	-49	-48	-46	-45	-46
		(-40,-37)	(-50,-38)	(-50,-37)	(-51,-41)	(-54,-39)	(-54,-38)	(-50,-39)	(-48,-42)	(-54,-25)
	2016	-41	-46	-48	-	-	-	-	-	-44
		(-47,-34)	(-53,-42)	(-53,-43)	-	-	-	-	-	(-53,-34)
5-VIC	2014	-	-	-	-	-	-21	-15	-15	-16
		-	-	-	-	-	(-46 -39)	(-25 -11)	(-18 -11)	(-26,-11)
	2015	-12	-15	-15	-17	-18	-17	-14	-14	-15
		(-21,-7)	(-19,-11)	(-19,-10)	(-24,-12)	(-25,-12)	(-28,-8)	(-18,-9)	(-18,-12)	(-28,-7)
	2016	-12	-16	-17	-	-	-	-	-	-14
		(-17,-3)	(-25,-11)	(-24,-13)	-	-	-	-	-	(-25,-3)
6-VR	2014	-	-	-	-14	-10	-9	-6	-6	-9
		-	-	-	(-21 -7)	(-17 -1)	(-11, -6)	(-12, -1)	(-11, -0)	(-21,0)
	2015	-7	-12	-11	-13	-12	-12	-11	-11	-12
		(-9,-4)	(-15,-8)	(-15,-6)	(-18,-8)	(-16,-7)	(-15,-8)	(-15,-8)	(-15,-8)	(-18,-4)
	2016	-6	-11	-	-	-	-	-	-	-8
		(-12,-3)	(-16,-7)	-	-	-	-	-	-	(-16,-3)
7-ISO	2014	-	-	-	-	-7	-7	-6	-6	-6
		-	-	-	-	(-15,-0.2)	(-11 ,-3)	(-9 , 1)	(-15,0)	(-15,0)
	2015	-5	-10	-12	-12	-13	-16	-13	-11	-12
		(-8,-2)	(-14,-4)	(-16,-6)	(-16,-6)	(-17,-4)	(-21,-7)	(-19,-5)	(-14,-7)	(-21,-2)
	2016	-3	-14	-11	-	-	-	-	-	-4
		(-13,0)	(-19,-10)	(-15,-6)	-	-	-	-	-	(-14,0)

Tableau 3.6 Average monthly water table depth in the minerotrophic zone (piezometer 4 in Figure 3.2) of the studied peatlands, from June 2014 to June 2016, including minimum and maximum values in parentheses.

Site	year	April	May	June	July	August	September	October	November	Annual mean WTD
1-CH	2014	-	-	-	0	0	-6	-7	-5	-4
		-	-	-	(-3,3)	(-4,4)	(-11,-0.5)	(-11,-2)	(-7,0)	(-11,0)
	2015	-2	-7	-2	-3	-2	-9	-6	-4	-3
		(-3,1)	(-11,-2)	(-7,4)	(-9,-6)	(-8,-5)	(-13,-3)	(-9,-0.5)	(-7,1)	(-13,4)
	2016	3	-1	-3	-	-	-	-	-	-
		(-4,13)	(-4,1)	(-6,-2)	-	-	-	-	-	-
3-SSE	2014	-	-	-	-7	-4	-6	-2	-	-4
		-	-	-	(-14, 0)	(-10, 0)	(-9, -4)	(-10, -4)	-	(-14,0)
	2015	1	-3	-3	-8	-9	-7	-3	-1	-5
		(-1,4)	(-5,1)	(-7,-3)	(-13,-2)	(-15,-3)	(-17,-0)	(-6,-2)	(-4,2)	(-17,4)
	2016	1	-2	-4	-	-	-	-	-	-
		(-4,6)	(-7,2)	(-4,-3)	-	-	-	-	-	-
6-VR	2014	-	-	-	-6	-2	-1	-2	2	-1
		-	-	-	(-11, 0)	(-9, 4)	(-3, 1)	(-3, 6)	(-2,4)	(-11,6)
	2015	9	-1	1	-3	-2	-1	0	1	0
		(-1,22)	(-3,2)	(-2,4)	(-7,2)	(-10,3)	(-6,-3)	(-2,5)	(-4,4)	(-9,22)
	2016	11	5	-	-	-	-	-	-	-
		(6,24)	(2,7)	-	-	-	-	-	-	-

Tableau 3.7 Average monthly water table depth in the intflow zone (piezometer 5 in Figure 3.2), from June 2014 to June 2016, including minimum and maximum values in parentheses.

Site	year	April	May	June	July	August	September	October	November	Annual mean WTD
1-CH	2014	-	-	-	-82	-80	-95	-102	-94	-91
		-	-	-	(-89,-70)	(-91,-65)	(-108,-76)	(-116,-75)	(-112,-79)	(-116,-65)
	2015	-72	-87	-71	-75	-76	-91	-71	-67	-77
		(-73,-71)	(-99,-72)	(-85,-61)	(-90,-62)	(-91,-63)	(-99,-71)	(-80,-60)	(-73,-60)	(-99,-60)
	2016	-63	-67	-	-	-	-	-	-	-63
		(73,-53)	(-72,-64)	-	-	-	-	-	-	(-73,-53)
3-SSE	2014	-	-	-	-70	-70	-88	-72	-52	-71
		-	-	-	(-85, -46)	(-83, -56)	(-96, -76)	(-97, -51)	(-58, -27)	(-97,-27)
	2015	-8	-23	-37	-61	-68	-60	-47	-30	-46
		(-13,-3)	(-39,-9)	(-53,-11)	(-77,-40)	(-85,-42)	(-85,-23)	(-58,-15)	(-39,-16)	(-85,-3)
	2016	-4	-20	-27	-	-	-	-	-	-12
		(-23,0)	(-39,-4)	(-28,-26)	-	-	-	-	-	(-40,-0)
4-LCY	2014	-	-	-34	-73	-84	-98	-103	-	-82
		-	-	(-62,-16)	(-92, -35)	(-97, -68)	(-104, -86)	(-105,-99)	-	(-105,-16)
	2015	-36	-31	-33	-38	-35	-35	-33	-31	-34
		(-68,-19)	(-36,-27)	(-38,-27)	(-45,-31)	(-46,-26)	(-47,-25)	(-37,-26)	(-34,-28)	(-68,-19)
	2016	-24	-30	-	-	-	-	-	-	-27
		(-31,-15)	(-37,-26)	-	-	-	-	-	-	(-27,-15)
5-VIC	2014	-	-	-	-	-	-145	-116	-61	-92
		-	-	-	-	-	(-147 -143)	(-149 -56)	(-73 -54)	(-149,-54)
	2015	-48	-52	-53	-77	-89	-69	-58	-55	-64
		(-49,-47)	(-59,-46)	(-64,-44)	(-104,-57)	(-121,-57)	(-121,-43)	(-69,-46)	(-60,-50)	(-121,-43)
	2016	-51	-60	-	-	-	-	-	-	-56
		(-59,-42)	(-81,-52)	-	-	-	-	-	-	(-81,-42)
6-VR	2014	-	-	-	-363	-363	-361	-354	-	-361
		-	-	-	(-373 -353)	(-374 -355)	(-364, -357)	(-360, -350)	-	(-374,350)
	2015	-319	-337	-345	-353	-354	-355	-351	-347	-348
		(-323,-316)	(-344,-323)	(-350,-341)	(-358,-346)	(-360,-346)	(-361,-348)	(-353,-345)	(-352,-344)	(-361,-316)
	2016	-324	-343	-	-	-	-	-	-	-333
		(-337,313)	(-348,-336)	-	-	-	-	-	-	(-348,-313)
7-ISO	2014	-	-	-	-	-13	-14	-12	-15	-14
		-	-	-	-	(-18,-6)	(-16 ,-10)	(-16 , -6)	(-23,9)	(-23,-6)
	2015	-10	-13	-13	-13	-9	-12	-11	-10	-11
		(-17,-2)	(-15,-7)	(-15,-8)	(-23,-2)	(-13,0)	(-15,-5)	(-15,-2)	(-13,-6)	(-23,-2)
	2016	-5	-14	-11	-	-	-	-	-	-10
		(-14,0)	(-17,-10)	(-14,-5)	-	-	-	-	-	(-17,0)

Tableau 3.8 Average monthly water table depth in the outflow zone (piezometer 6 in Figure 3.2), from June 2014 to June 2016, including minimum and maximum values in parentheses.

Site	year	April	May	June	July	August	September	October	November	Annual mean WTD
3-SSE	2014	-	-	-	-	-88	-113	-69	-27	-76
		-	-	-	-	(-113, -50)	(-128,-94)	(-131, -26)	(-36, -16)	(-131,-16)
	2015	-4	-6	-10	-59	-68	-55	-28	-19	-35
		(-6,-1)	(-11,-1)	(-22,-2)	(-98,-14)	(-106,-22)	(-113,-18)	(-43,-12)	(-24,-14)	(-113,-1)
	2016	-18	-21	-24	-	-	-	-	-	-20
		(-25,-11)	(-38,-15)	(-24,-23)	-	-	-	-	-	(-38,-11)
6-VR	2014	-	-	-	-74	-73	-79	-58	-48	-68
		-	-	-	(-93 -53)	(-94 -46)	(-84, -71)	(-84, -44)	(-54, -42)	(-94,-42)
	2015	-8	-11	-26	-61	-72	-72	-69	-54	-47
		(-50,0)	(-24,-7)	(-42,-7)	(-84,-27)	(-91,-45)	(-83,-53)	(-78,-43)	(-61,-47)	(-91,0)
	2016	-10	-36	-	-	-	-	-	-	-23
		(-51,0)	(-51,-23)	-	-	-	-	-	-	(-51,0)

CONCLUSION

Principale contribution de la thèse

L'objectif principal de cette thèse était de comprendre l'influence des propriétés hydrodynamiques, des variations météorologiques et des contextes hydrogéologiques sur l'hydrologie de sept complexes tourbeux de la vallée du Saint-Laurent, Québec, Canada. Les objectifs spécifiques étaient 1) d'adapter, de tester et de valider une méthode *in situ* permettant de quantifier les coefficients d'emmagasinement des tourbières, 2) de quantifier les propriétés hydrodynamiques des dépôts tourbeux comme facteurs explicatifs des variations des profondeurs de nappe des tourbières, et 3) de comprendre l'influence des conditions météorologiques et des contextes hydrogéologiques sur les niveaux de nappe et leurs fluctuations dans les tourbières. Pour ce faire, sept tourbières ont été caractérisées et instrumentées. Les sites étudiés sont des complexes tourbeux ombrotrophes, dont trois sont ceinturés d'une zone minérotrophe. Ils ont été sélectionnés en raison de leurs contextes hydrogéologiques, de leurs connectivités avec les eaux souterraines et de leurs niveaux d'eau.

La thèse est composée de trois chapitres rédigés sous la forme d'articles scientifiques. Le premier article (chapitre 1) a déjà été publié dans la revue *Hydrological Processsses* et porte sur le développement d'une méthode permettant de quantifier les coefficients d'emmagasinement des tourbières. Le second article (chapitre 2) a déjà été publié dans la revue *Ecohydrology*. Il présente de nouveaux indicateurs des propriétés hydrodynamiques des tourbières, tels que la densité de la tourbe et la profondeur par rapport à la surface au sein des dépôts organiques. Ces résultats permettront de mieux représenter les conditions *in situ* dans les futurs modèles écohydrologiques. Le troisième chapitre a été soumis pour publication dans la revue *Journal of Hydrolgy*. Il présente de nouvelles connaissances sur l'influence des conditions météorologiques et des contextes hydrogéologiques sur les niveaux d'eau des tourbières.

Les principales contributions scientifiques de la thèse ont été : 1) de démontrer que les propriétés hydrodynamiques jouent un rôle mineur sur le contrôle niveaux de nappe des tourbières à l'échelle annuelle 2) d'évaluer l'influence des conditions météorologiques sur les niveaux de nappe des tourbières à l'échelle mensuelle et 3) de présenter deux processus hydrauliques qui contrôlent les niveaux d'eau des tourbières, ce qui démontre l'importance de documenter l'importance de la connectivité des tourbières et des aquifères. De plus, la thèse a permis d'identifier la présence d'un seuil hydrique qui contrôle les fluctuations maximales des niveaux de nappe des tourbières. En outre, puisqu'aucune distinction n'a pu être identifiée intra- et inter-sites dans l'analyse des propriétés hydrodynamiques des dépôts tourbeux, cette thèse démontre que les niveaux de nappe des tourbières à l'échelle annuelle sont davantage contrôlés par les contextes hydrogéologiques dans lesquels elles se sont formées, que par les propriétés hydrodynamiques de la tourbe.

Originalité et retombées

Quantification des coefficients d'emmagasinement des tourbières

La thèse a aussi permis d'adapter la méthode « *Water Table Fluctuation* » couramment utilisée pour les aquifères et basée sur le calcul des fluctuations de niveaux d'eau, afin d'estimer les coefficients d'emmagasinement en eau des tourbières. La modification de la méthode pour les tourbières représente une contribution originale pour l'étude de l'hydrologie des tourbières. Les résultats montrent que les coefficients d'emmagasinement varient fortement dans les horizons de surface de la tourbe. La saisonnalité des coefficients d'emmagasinement est visible durant les périodes de forte évapotranspiration (juin-juillet-août). Par ailleurs, la méthode développée a permis de quantifier une profondeur de nappe maximale au-delà de laquelle les précipitations ne peuvent plus être emmagasinées et circulent rapidement dans les horizons de surface des tourbières. La méthode est prometteuse et pourra être utilisée dans différents types de tourbières une fois qu'elle aura été testée dans une variété de conditions géo-éco-climatiques. Elle apportera une meilleure compréhension de la fonction hydrologique d'emmagasinement des tourbières qui est encore très peu documentée, bien que particulièrement importante notamment pour l'atténuation des inondations.

Indicateurs des propriétés hydrodynamiques des tourbières

Les résultats de la thèse ont également permis de documenter les variations intra- et inter-sites de la densité sèche apparente, et de la conductivité hydraulique des dépôts organiques des sept tourbières étudiées en support à la compréhension de leur dynamique hydrologique. Les résultats montrent que les profils verticaux de conductivité hydraulique sont très similaires d'une tourbière à l'autre. Il est donc proposé d'utiliser des relations mathématiques décrivant les propriétés hydrodynamiques de la tourbe qui seraient représentatives des tourbières du Québec méridional. Les équations proposées, mettant en relation la densité sèche apparente, la conductivité hydraulique et le coefficient d'emmagasinement avec la profondeur au sein des dépôts tourbeux, pourront être utilisées lorsque les données mesurées *in situ* ne sont pas disponibles. Elles permettront notamment d'améliorer la représentation verticale des propriétés hydrodynamiques dans les modèles numériques hydrologiques et éco-hydrologiques afin de quantifier les niveaux de nappe des tourbières à différentes échelles temporelles.

Influence des conditions météorologiques et des contextes hydrogéologiques sur l'hydrologie des tourbières

La thèse a permis de consolider les connaissances entourant l'effet des conditions météorologiques et des contextes hydrogéologiques sur les niveaux de nappe des tourbières. Les résultats ont permis de quantifier le lien entre une augmentation mensuelle des niveaux de nappe des tourbières et les précipitations totales, et entre une diminution mensuelle des niveaux de nappe et les températures moyennes. Pour les sept tourbières étudiées, une diminution de précipitations entre avril et octobre de 1 mm/mois entraîne une diminution des niveaux de nappe entre 1et 3 mm/mois. De plus, une augmentation des températures mensuelles de 1°C entraîne une diminution entre 7 et 13 mm/mois des niveaux de nappe des tourbières. Ces résultats sont très importants puisqu'ils permettent de mieux anticiper les impacts des changements climatiques sur les tourbières. Les résultats ont aussi permis de démontrer l'importance des contextes hydrogéologiques et des propriétés hydrodynamiques des zones de recharge sur les niveaux de nappe des tourbières. Les résultats suggèrent qu'une tourbière qui s'est développée dans un contexte hydrogéologique perméable pourrait, à travers l'ensemble de son développement, enregistrer des niveaux de nappe plus profonds qu'une tourbière qui se serait développée sur des dépôts peu perméables et où les niveaux seraient plus près de la surface. Les tourbières formées sur des dépôts perméables seraient caractérisées par des dépôts organiques plus décomposés que les tourbières formées sur des dépôts peu perméables, ce qui met en évidence l'importance de considérer les contextes hydrogéologiques dans les échanges gazeux tourbière-atmosphère.

De plus, considérant le contrôle qu'exercent les niveaux de nappe dans les aquifères sur ceux des tourbières, toute perturbation induisant une baisse des niveaux de nappe des aquifères représente un risque pour l'intégrité hydrologique et écologique de celles-ci. Il est donc conseillé de réaliser davantage d'études qui permettront de délimiter des zones au pourtour des tourbières afin d'assurer une protection accrue de ces milieux déjà fortement perturbés dans le Québec méridional.

Ouverture

D'un point de vue scientifique, les résultats de cette thèse apportent un nouvel éclairage au sujet des facteurs qui contrôlent l'hydrologie des tourbières. D'un point de vue pratique, la thèse a permis de développer de nouveaux outils qui permettront de mieux comprendre les fonctions hydrologiques des tourbières et qui pourront éventuellement servir à protéger celles-ci face aux pressions telles que celles induites par les changements dans l'utilisation du territoire et les changements climatiques.

La compréhension de l'hydrologie des tourbières est indispensable à toute étude sur ces écosystèmes, notamment sur leurs fonctions de réduction des inondations, de maintien des niveaux de nappe et de séquestration de carbone dont les processus sont intimement liés à l'hydrologie. Cependant, bien que plusieurs recherches aient démontré la forte capacité des tourbières à maintenir leurs niveaux de nappe près de la surface, les résultats de cette thèse mettent en lumière l'importance d'intégrer l'effet des contextes hydrogéologiques sur la dynamique éco-hydrologique des tourbières. Il est à noter que jusqu'à maintenant, aucun schéma conceptuel intégrant l'influence des contextes hydrogéologiques sur les processus de rétroactions internes des tourbières n'est disponible dans la littérature.

Cette thèse favorise l'ouverture à de nombreuses autres études. Elle offre notamment de nouveaux outils permettant d'analyser des données déjà disponibles afin de mieux intégrer les tourbières dans divers projets qui visent à maintenir les services écosystémiques. Par exemple, l'application de la méthode *Water Table Fluctuation* sur des mesures de niveaux de nappe mesurés dans des tourbières localisées dans divers contextes climatiques, permettrait une compréhension accrue des facteurs qui contrôlent l'emmagasinement en eau des tourbières et par conséquent leur capacité à réduire les inondations. Cette même méthode, par le calcul des coefficients d'emmagasinement, pourrait aussi être utilisée comme critère d'évaluation hydrologique de la réussite d'un projet de restauration. De plus, les résultats de cette thèse pourront, dès maintenant, être utilisés pour établir un réseau de suivi à l'échelle de la vallée du Saint-Laurent et potentiellement à l'échelle du Québec afin de suivre l'évolution hydrique des tourbières dont plusieurs présentent déjà des signes de perturbation hydrologique.

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