Gestion de l'eau dans la culture de la sphaigne: nouvel indice de stress hydrique et modélisation du mouvement de l'eau dans les bassins de culture

Thèse

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Résumé

La paludiculture sous forme de culture de sphaigne est définie comme la production durable de biomasse de sphaignes sur une base renouvelable et cyclique, souvent dans des tourbières ombrotrophes réaménagées. Il a été établi qu'un meilleur contrôle des paramètres hydrologiques, tels que la tension de l'eau dans la tourbe et la profondeur de la nappe phréatique, était l'un des facteurs clés pour obtenir un taux optimal de croissance des sphaignes. L'objectif du contrôle de ces paramètres hydrologiques est d'assurer un flux d'eau suffisant vers le capitule de la sphaigne pour soutenir sa croissance et son activité photosynthétique, qui est principalement produite dans cette partie de la plante. Cette thèse étudie la gestion de l'eau dans les bassins de production de sphaignes de manière à optimiser l'hydrologie du système de de culture, et en conséquence la croissance des sphaignes. Cette optimisation est notamment obtenue à travers la quantification du stress hydrique lié à la productivité des espèces de sphaigne et la modélisation du mouvement de l'eau dans les bassins de culture.

Une première étape a été d'établir la relation entre la durée et la fréquence des stress hydriques et la croissance de la sphaigne. La compilation de cinq années de culture de sphaigne avec suivi de la croissance des mousses, à la fois dans des systèmes en tourbières réaménagées et dans des mésocosmes en serre, a été utilisée pour construire un ensemble de données couvrant une large variation de profondeurs de la nappe phréatique. Il convient préciser que dans les cultures de sphaigne sur des tourbières restaurées, le terme restauration fait référence à la gestion pour atteindre la ressemblance d'une condition antérieure.

Cette étude appuie le constat que plus le stress hydrique est élevé, plus la productivité des espèces de sphaigne est faible. Dans le cadre de cette étude, le terme stress hydrique ou stress osmotique désigne le stress abiotique subi par une plante de sorte que le taux d'humidité des tissus végétaux est réduit à des niveaux sous-optimaux pour la photosynthèse. Avant de quantifier le stress hydrique, il faut connaître les profondeurs seuils de la nappe phréatique provoquant ces stress. Ces seuils changent entre les sous-genres d'espèces de sphaigne, étant plus élevé pour des espèces du sous-genre Acutifolia (*Sphagnum flavicomans*, *Sphagnum fuscum* et *Sphagnum rubellum*), suivi par le sous-genre Sphagnum (*Sphagnum medium* et *Sphagnum papillosum*) et ensuite par le sous-genre Cuspidata (*Sphagnum fallax*). Pour les systèmes de culture de sphaigne analysés, les profondeurs seuils de la nappe phréatique fluctuent entre 7 et 20 cm. Ces valeurs correspondent à des nappes plus élevées que celle rapportée dans la littérature pour la recolonisation des tourbières de sphaigne lors de projets de restauration, qui est de 40 cm, et ceci parce que dans la culture de sphaigne l'objectif est de maximiser la productivité, et pas seulement la survie des mousses à travers le temps.

Une deuxième étude de ce projet de doctorat a été de quantifier le stress hydrique. Les indicateurs identifiés pour la quantification sont la somme des nappes journalières sous la profondeur de la nappe seuil identifiée (SEW) et nombre de jours où la nappe phréatique est sous la profondeur de la nappe seuil (NDW). Le SEW

considère l'amplitude de la variation de la nappe phréatique et le NDW contemple la fréquence à laquelle la nappe phréatique se trouvait sous des profondeurs critiques pour la productivité des sphaignes. Toutefois, chacun de ces indicateurs nécessite des relevés quotidiens de la profondeur de la nappe phréatique. Cela étant dit, il est essentiel de disposer de relevés quotidiens de la nappe phréatique, ce qui n'est généralement pas le cas. Malgré cela, deux sources d'information sont utiles pour estimer la profondeur journalière : les relevés journaliers des puits de référence situés sur le même site, et les relevés manuelles disponibles qui sont collectées de façon hebdomadaire ou bimensuel pour tous les puits répartis sur le système de culture de sphaigne. Afin d'obtenir les valeurs quotidiennes de la nappe phréatique à partir de ces informations disponibles, des méthodes d'apprentissage automatique ont été identifiées et elles sont couramment utilisées dans ce type d'application. Ces méthodes permettent d'obtenir une erreur d'estimation allant jusqu'à 4.6 cm, ce qui, pour cette application, est une erreur majeure. Pour cette raison, il a également été décidé de développer une nouvelle méthode basée sur la décomposition des séries temporelles, et elle est la plus performante parmi toutes les méthodes utilisées avec une erreur d'estimation de moins de 3 cm et un coefficient de détermination de 0,95. L'un des grands avantages de cette méthode de décomposition des séries temporelles est qu'elle ne nécessite ni entraînement ni estimation des paramètres de calibration, ce qui permet une application facile non seulement dans la culture de sphaignes mais aussi dans les projets de tourbières remouillées. Cette étude a également permis d'évaluer la fréquence des mesures dans les puits manuels et son influence sur l'erreur d'estimation. La réduction de la fréquence des mesures d'une fréquence bimensuelle à une fréquence hebdomadaire entraîne une diminution de l'erreur de 16 % et l'augmentation à une fréquence mensuelle augmente l'erreur de 13 %. Autrement dit, par rapport aux mesures hebdomadaires, la fréquence mensuelle augmente l'erreur de 29 %.

Le troisième focus de cette étude a été d'analyser les fluctuations de la nappe phréatique en fonction des caractéristiques physiques et hydrauliques du système et de l'écoulement souterrain estimé. À cette fin, un modèle a été développé sur la base de l'équation de Boussinesq et qui considère la stratification du milieu, tel que le profil de tourbe où la culture de la sphaigne est aménagée. La performance du modèle, qui prédit 91 % de la variation observée du niveau de la nappe phréatique, est le résultat de la combinaison de la mesure continue du niveau d'eau dans les canaux d'irrigation, les mesures sur place des précipitations, l'approximation de l'évapotranspiration par un modèle utilisant des mesures de la température et de la radiation extraterrestre, ainsi que les mesures *in-situ* de la conductivité hydraulique saturée par la méthode de la tarière manuelle en milieu stratifié. Un résultat important de ce chapitre est l'exploration de micro-canaux d'irrigation creusés dans un bassin déjà établie afin d'améliorer son hydrologie. Ces canaux de section rectangulaire de 20 cm x 20 cm, espacés de 10 m et reliés au canal périphérique principal, ont permis une amélioration du réseau hydraulique des canaux d'irrigation en réduisant l'espacement entre les canaux, qui était initialement de 20 m entre canaux périphériques.

En somme, en plus de répondre spécifiquement à trois défis de la gestion de l'eau en culture de sphaigne, cette thèse fournit une compréhension améliorée du stress hydrique saisonnier chez les espèces de sphaigne, et une vision plus claire du mouvement des eaux souterraines dans les tourbières ombrotrophes réaménagées. Plusieurs des résultats illustrés dans cette thèse sont déjà appliqués dans les systèmes de culture de sphaigne de l'est du Canada.

Abstract

Sphagnum farming or *Sphagnum* cultivation is defined as the sustainable production of *Sphagnum* biomass on a renewable and cyclical basis, often in restored ombrotrophic peatlands. Improved control of hydrological parameters, such as peat water tension and water table depth, has been identified as key factors in achieving optimal *Sphagnum* growth rates. The objective of controlling those hydrological parameters is to ensure sufficient water flow to the *Sphagnum* capitula to support its growth and photosynthetic activity, which is primarily occurring in this part of the plant. This thesis studies water management in *Sphagnum* production systems to optimize the hydrology of the cultivation basins, and consequently of *Sphagnum* growth. This optimization is achieved through the quantification of water stress related to the productivity of *Sphagnum* species and the modeling of the water movement in the cultivation basins.

A first part of this study addresses the relationship between duration and frequency of water stress and *Sphagnum* growth. The data compilation of five years of *Sphagnum* farming monitoring the growth of the mosses, both in managed peatland systems and in greenhouses mesocosms, was used to construct a data set covering a wide variation in water table depths. It is worth pointing out that in the context of *Sphagnum* cultivation on restored peatlands, the term *restored* refers the practices to achieve the resemblance of a previous condition.

This study reinforces the idea that the higher the water stress, the lower the productivity of *Sphagnum* species. In this study, the term water stress or osmotic stress refers to abiotic stress experienced by a plant and its tissue moisture content is reduced to suboptimal levels for photosynthesis. Before quantifying water stress, it is necessary to know the water table depth thresholds causing water stress. These thresholds depths of water table vary between subgenera of *Sphagnum* species, being highest for species tested within subgenus Acutifolia (*Sphagnum flavicomans*, *Sphagnum fuscum* et *Sphagnum rubellum*), followed by subgenus Sphagnum (*Sphagnum medium* and *Sphagnum papillosum*) and then by subgenus Cuspidata (*Sphagnum fallax*). For the *Sphagnum* farming systems analyzed, the thresholds depths of water table fluctuate between 7 and 20 cm. These values correspond to higher water tables than the ones reported in the literature for allowing good recovery of restored of bogs, which is 40 cm, and this is because in *Sphagnum* farming the objective is to maximize productivity, not just the survival of the mosses through time.

A second area of study in this doctoral thesis was to quantify water stress. The indicators identified for quantification are the sum of daily water tables below the identified threshold depth of water table (SDW), and the number of days the water table is below the threshold depth (NDW). The SWE considers the magnitude of water table variation and the NDW contemplates frequency of water table being below the critical depths for *Sphagnum* productivity. However, each of these indicators requires daily water table depth records. Hence, the prerequisite of daily water table depths, which is generally not available. Despite of this, tow sources of

information are useful for estimating daily depth: daily readings from reference wells located on the same site, and available manual readings that are collected on a weekly or bi-weekly basis for all wells distributed over the sphagnum growing system. To obtain daily water table depths from this available information, machine learning methods have been identified. These methods allow to obtain an estimation error up to 4.6 cm, which for this application we consider to be a major error. For this reason, it was also decided to develop a new method based on time series decomposition. This last method was the one that shown the best performance among the methods used with an estimation error of less than 3 cm and a coefficient of determination of 0.95. A major advantage of the new method is that it does not require training or estimation of calibration parameters, which allows easy application not only in *Sphagnum* farming but also in rewetted peatland initiatives. This study also evaluated the influence of the frequency of measuring the water table depth in the wells to be estimated on the estimation error. Reducing the measurement frequency from bimonthly to weekly results in a 16% decrease in error and increasing to monthly increases the error by 13%. In other words, compared to weekly measurements, monthly frequency increases the error by 29%.

The third focus of this study was to analyze the fluctuations of the water table depth as a function of the physical and hydraulic characteristics of the system and the estimated groundwater flow. For this purpose, a model was developed based on the Boussinesq equation and which considers the stratification of the media, such as the peat profile where *Sphagnum* moss is grown. The performance of the model, which predicts 91% of the observed variation of the water table, is the result of the combination of continuous measurement of the water level in the irrigation canals, on-site measurements of precipitation, approximation of evapotranspiration by a model using field measurements of temperature and extraterrestrial radiation, and *in-situ* measurements of saturated hydraulic conductivity by using the auger hole method in stratified media. An important outcome of this chapter is the implementation of micro irrigation channels dug in an already established *Sphagnum* farming basin to improve its hydrology. These micro shallow channels, with a rectangular cross-section of 20 cm x 20 cm were spaced 10 m apart and connected to the main peripheral channel. These have allowed and improvement of the hydraulic network of irrigation channels by reducing the spacing between channels, which was initially 20 m apart.

In short, in addition to specifically addressing three water management challenges in *Sphagnum* culture, this thesis provides an improved understanding of seasonal water stress in *Sphagnum* species, and a clearer understanding of groundwater movement in rehabilitated ombrotrophic peatlands. Many of the results illustrated in this thesis are already being applied in *Sphagnum* farming systems in eastern Canada.

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À mes anges gardiens

No es la muerte la que se lleva a los que amamos. Al contrario, los guarda y los fija en su juventud adorable. No es la muerte la que disuelve el amor, es la vida la que disuelve el amor.

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Avant-propos

Cette thèse inclut cinq sections, dont l'introduction générale (première section) et la conclusion (dernière section). Les trois autres chapitres sont écrits sous forme d'article scientifique, dont je suis le premier auteur. Pour l'élaboration de chacun des articles, j'ai défini les objectifs et les hypothèses de recherche, développé les méthodologies proposées, compilé les bases de données nécessaires, effectué les analyses statistiques, produit les figures et les supports visuels pour illustrer les résultats, et rédigé les manuscrits. Pour l'article concentré du chapitre 1, les coauteurs sont Robert Lagacé, Sandrine Hogue-Hugron, Stéphane Godbout et Line Rochefort. Les coauteurs m'ont guidé dans l'élaboration du plan expérimental, ils ont aidé à l'interprétation critique des résultats et ils ont collaboré à la révision du manuscrit. Robert Lagacé et Sandrine Hogue-Hugron ont également pris part de la conceptualisation et de la sélection des méthodes d'estimation utilisées. Le chapitre 1 a été publié dans le numéro spécial *Advance in Time Series Modelling for Water Resources Management* de la revue scientifique *Sustainability* en avril 2021. Pour l'article scientifique présenté au chapitre 2, les coauteurs sont Robert Lagacé, Mélina Guêné-Nanchen, Sandrine Hogue-Hugron, Stéphane Godbout et Line Rochefort. Robert Lagacé, Mélina Guêné-Nanchen et Sandrine Hogue-Hugron ont contribué à l'analyse des résultats et à la révision du manuscrit. Stéphane Godbout et Line Rochefort ont joué un rôle important dans l'obtention du financement de cet article. Le chapitre 2 a été soumis à la revue scientifique *Mires and Peat* dans un format diffèrent de celle présentée dans cette thèse. Finalement, pour le dernier article exposé au chapitre 3, les coauteurs sont les mêmes que ceux mentionnés au chapitre 2. Ils ont pris part à chacune des étapes de préparation des manuscrits. Une grande partie du chapitre 3 a été présenté à la conférence *International Peatland Congress* qui a eu lieu en 2021 de façon virtuelle.

Chapitre 1 (publié le 13 mai 2021) : Gutierrez Pacheco, S., R. Lagacé, S. Hugron, S. Godbout et L. Rochefort. Estimation of Daily Water Table Level with Bimonthly Measurements in Restored Ombrotrophic Peatlands. Sustainability, 13, 5474; doi : 10.3390/su13105474.

Chapitre 2 : Gutierrez Pacheco, S., R. Lagacé, M. Guéné-Nanchen, S. Hugron, S. Godbout et L. Rochefort. Seasonal indicators as a key descriptors of water stress in *Sphagnum* farming systems.

Chapitre 3 : Gutierrez Pacheco, S., R. Lagacé, M. Guéné-Nanchen, S. Hugron, S. Godbout et L. Rochefort. Adaptation and validation of the Boussinesq model to stratified peat profiles for modeling water table evolution in rewetted bogs.

Introduction

La tourbe à sphaigne qui est utilisée comme substrat horticole (Pellerin et Poulin 2013; Jobin et coll. 2014) représente un volet important dans l'économie canadienne. La tourbe récoltée au Canada contribue à la production de produits horticoles évalués à 568 millions de dollars et contribue au PIB du Canada d'environ 152 millions de dollars par an (CSPMA 2014, 2020; CBBC 2014). Cette industrie joue donc un rôle important en termes économiques et sociaux, en particulier pour le Québec et le Nouveau-Brunswick où se trouve la majorité des tourbières utilisées pour la récolte de la tourbe (CSPMA 2020).

Cependant, l'activité d'extraction de tourbe est examinée (dans une certaine mesure) par les clients et la société en général, qui réclament une réduction de l'impact sur les tourbières naturelles. Le problème ne concerne pas la carence de ce milieu humide, comme c'est le cas dans des pays d'Europe occidentale et centrale où les stocks de tourbe blonde (tourbe de sphaigne légèrement humifiée) sont presque épuisés (Joosten 2012). Au Québec, il existe une vaste superficie de tourbières, la plupart concentrées dans la forêt boréale autour de la baie de James ainsi qu'au Labrador (Tarnocai et coll. 2011). Alors le vrai problème concerne le décalage entre la répartition géographique des écosystèmes tourbeux et l'importance de leur utilisation (Rochefort 2001).

Dans le contexte de restauration de milieux perturbés, l'industrie et la communauté académique ont développé des méthodes de restauration écologique afin de ramener dans le court terme les communautés végétales à fort potentiel d'accumulation de tourbe, et de rétablir les fonctions écologiques des tourbières après l'extraction de tourbe à long terme (Rochefort et coll. 2003; Graf et coll. 2008). Dans ces fonctions écologiques, il est commun de parler de l'accumulation de la tourbe et le stockage du carbone (Waddington et coll. 2009; Nugent et coll. 2018, 2019). Par conséquent, afin de contrecarrer l'effet observé de l'activité d'extraction, principalement en générant des émissions atmosphériques de CO_2 (Petrone et coll. 2001; Waddington et coll. 2002), toute action en matière de restauration doit être entreprise pour diminuer les émissions et obtenir l'acceptabilité sociale de l'extraction de ces écosystèmes.

L'industrie de la tourbe, en plus de s'efforcer de réduire l'empreinte carbone, est confrontée à un défi majeur à relever : de mettre sur le marché des produits plus durables et à valeurs ajoutées. Ainsi, la paludiculture sous forme de culture de sphaigne est définie comme la production durable de biomasse de sphaignes sur une base renouvelable et cyclique (Pouliot et coll. 2015; Gaudig et coll. 2017) et se développe souvent dans des tourbières remouillées (Gaudig et coll. 2018; Hugron et Rochefort 2018; Gutierrez Pacheco et coll. 2021). La culture de sphaigne offre une option d'utilisation durable des tourbières drainées et permet l'utilisation des tourbières tout en conservant les horizons restants de tourbe (Wichtmann et coll. 2016). La culture de sphaigne peut être considérée comme une option intéressante de remise en état des tourbières perturbées non seulement pour la production de fibres non décomposées utilisées dans les mélanges des milieux de cultures, mais aussi pour la création de pépinières de diaspores pour de futurs projets de restauration écologique (Reinikainen et coll. 2012; Jobin et coll. 2014; Pouliot et coll. 2015; Hugron et Rochefort 2018).

Bien que la production de fibres de sphaigne se fasse présentement de façon expérimentale et en petites quantités, elle montre déjà des résultats intéressants. Hugron et Rochefort (2018) affirment que la récolte de fibres de sphaigne non décomposées peut être possible en peu de temps (3 à 4 ans) lorsque l'hydrologie est optimisée. Alors, la culture de sphaigne peut être particulièrement intéressante dans les pays où les sites donneurs sont rares en raison du manque de tourbières naturelles ou de protection juridique.

Transformer la culture de sphaigne en une culture à grande échelle nécessite des connaissances approfondies englobant la séquence de production (Gaudig et coll. 2018; Ludwig 2019). Les quantités de fibres de sphaigne actuellement produites sont loin d'être suffisantes pour satisfaire les besoins, particulièrement de l'industrie des substrats de culture (Ludwig 2019). Pour franchir cette étape, il faut une approche systémique en particulier dans l'étape de production dans les tourbières après l'extraction de la tourbe.

Approche systémique : continuum sphaigne – tourbe – flux d'eau – climat

L'approche systémique, inspirée par le modèle Soil-Water-Atmosphere-Plant (SWAP) (Schouwenaars et Gosen 2007) permet de décrire la réaction de la culture à la modification de l'état hydrique, dénommée fonction de forçage (en anglais, forcing function, Jørgensen 2012; Nielsen et coll. 2020b).

La première composante du système de culture est **la sphaigne**. Elle est une plante poikilohydrique (Weston et coll. 2015), c'est-à-dire qu'elle ne peut pas contrôler activement la perte d'eau de ses tissus en raison de l'absence de racines et de stomates foliaires ainsi que d'un système de transport de l'eau dans les tiges (McCarter et Price 2014). En effet, les sphaignes, qui sont des plantes non vasculaires de l'embranchement des bryophytes (mousses), utilisent la remontée capillaire pour le transport de l'eau et des nutriments.

Pour maintenir l'activité photosynthétique des sphaignes et pour compenser l'eau perdu par évaporation, un flux entrant dans le système doit être établi soit par la pluie, soit par la remontée capillaire de l'eau provenant de la tourbe en dessous (Harley et coll. 1989; Murray et coll. 1989; Schipperges et Rydin 1998; Price et coll. 2009). Le flux de la remontée capillaire, compte tenu de la loi de Darcy (Darcy 1856; Price et Whittington 2010), est proportionnel à la conductivité hydraulique capillaire de la sphaigne et au gradient hydraulique entre le capitule et la tourbe en dessous.

La conductivité hydraulique des sphaignes vivantes est élevée lorsque ses pores sont saturés. Ses valeurs oscillent entre 1,3 et 57,6 m h^{-1} (Price et coll. 2008) et par la suite, la valeur de la conductivité hydraulique diminue rapidement à mesure que la teneur en humidité de la sphaigne diminue (Lagacé 2016, Golubev & Whittington 2018). Quant au gradient hydraulique, il est égal à la différence entre la succion exercée par la sphaigne et la succion de rétention de la tourbe en dessous. Cette dernière valeur est associée à la profondeur de la nappe phréatique (Price et Whitehead 2001).

L'écoulement vers le capitule de sphaigne associé à la remontée capillaire est insuffisant lorsque la nappe phréatique s'éloigne de la surface, car la conductivité hydraulique de la sphaigne diminue, en raison d'une diminution de la teneur en eau, et le gradient hydraulique diminue aussi puisqu'il est inversement proportionnel à la distance entre le capitule et la nappe phréatique. Le flux insuffisant vers le capitule entraîne la dessiccation de la sphaigne.

La sphaigne étant l'ingénieur des tourbières, crée ce flux de remontée capillaire au moyen du réseau formé par les espaces entre les feuilles, et entre la tige et les branches (Rydin et Jeglum 2013). Il a été démontré que la porosité capillaire varie selon les espèces de sphaigne, ce qui représente une hauteur d'ascension de l'eau qui diffère entre les espèces. Hayward et Clymo (1982) suggèrent des valeurs de hauteur d'ascension de 5 cm pour les espèces du sous-genre Acutifolia et même des valeurs de 1,5 cm pour les espèces du sous-genre Sphagnum. Les mêmes auteurs affirment que cette succion capillaire exercée par les sphaignes est relativement faible par rapport aux plantes vasculaires. Ils ont utilisé la Loi de Jurin afin d'estimer la hauteur d'ascension de l'eau en fonction du rayon moyen des espaces poreux créés par l'entremêlement des feuilles, des tiges et des branches. Dans leur travail, ils ont trouvé que les espèces du sous-genre Acutifolia ont un rayon moyen inférieur à celui des espèces du sous-genre Sphagnum. Ils ont enregistré que 50 % des pores avaient un rayon inférieur à 300 µm pour Sphagnum capillifollium (sous-genre Acutifolia). Pour Sphagnum papillosum (sous-genre Sphagnum), cette proportion n'était que de 30 %. Cela explique en partie pourquoi il est courant de trouver les espèces du sous-genre Acutifolia sur les buttes (les parties supérieures de la topographie) alors que les espèces du sous-genre Cuspidata se retrouvent dans les creux ou dépressions. Cette distribution répond au gradient écologique connu sous le nom de gradient butte-dépression, décrit par Campbell et Rochefort (2001).

Comme indiqué ci-dessus, l'une des conditions clés pour la croissance de la sphaigne est le flux d'eau vers le capitule de la sphaigne et en conséquence la succion exercée par la tourbe pour retenir l'eau. Cette notion amène à décrire la deuxième composante de ce continuum : **la tourbe**. La plupart des expériences de culture de sphaigne ont été réalisées dans des tourbières dont la tourbe avait été extraite soit par coupe par blocs (Campeau et coll. 2004; Pouliot et coll. 2015; Brown et coll. 2017; Guêné-Nanchen et coll. 2017) ou soit par aspiration (Kumar 2017; Gaudig et coll. 2018; Hugron et Rochefort 2018) ainsi que sur d'anciennes prairies de tourbières drainées pour l'agriculture (Muster et coll. 2015; Gaudig et coll. 2017), et dans des serres (Pouliot et coll. 2011; Gaudig et coll. 2014).

La matrice de tourbe est normalement représentée par une structure diplotelmique. Ces deux couches de la matrice de tourbières naturelles ombrotrophes ont des caractéristiques différentes. D'une part, l'acrotelme au niveau supérieur, est la zone où la nappe phréatique fluctue, et où il y a une alternance de conditions aérobies et anaérobies. Souvent, l'acrotelme est appelée la couche vivante vu que c'est la couche où les plantes croissent. D'autre part, le catotelme est la couche inférieure en permanence sous la nappe phréatique. Elle est une couche de tourbe compacte dans laquelle le carbone s'emmagasine (Ingram 1978).

Après avoir retiré l'acrotelme et une partie du catotelme (Lavoie et coll. 2003), l'extraction de tourbe est effectuée jusqu'au substrat utilisable, c'est-à-dire, la couche ayant un von Post de H1-H3 pour les substrats de culture et la couche ayant un von Post de H4-H7 pour faire du terreau lorsque mélangé à du sol minéral (Parent 2001). Ainsi, l'horizon restant, soit pour la restauration soit pour la culture de sphaigne, est une partie du catotelme plus décomposée et plus compactée (Clymo et coll. 1998). Lorsque les tourbières sont drainées et exploitées, les conditions deviennent aérobies et le taux de minéralisation de la tourbe dépasse le taux d'accumulation dans cet horizon à caractéristiques hydrophysiques dynamiques (Parent 2001). Alors, les pores sont de plus petite taille, la conductivité hydraulique saturée est plus faible (Van Seters 1999), la capacité de rétention en eau plus élevée (Schlotzhauer et Price 1999), et même la densité apparente peut augmenter après le drainage, ce qui diminue les espaces interstitiels (Price 1997). Ce sont des conditions qui ne sont pas favorables à l'établissement de la sphaigne, précisément parce que le flux d'eau vers le capitule est restreint. Alors, dans ces conditions d'horizon plus compact, la hauteur de succion que la sphaigne doit exercer pour satisfaire à ses processus bioénergétiques est plus grande et la sphaigne est soumise à des stress hydriques. De plus, le régime hydrologique est affecté par l'excavation des fossés de drainage, ce qui augmente l'amplitude des fluctuations de la nappe phréatique (Van Seters et Price 2001; Price et coll. 2003).

Bien que les propriétés structurelles et hydrauliques semblent défavorables à l'établissement de la sphaigne, il a été quand même possible d'obtenir une productivité de sphaigne viable (Wichmann et coll. 2020). Pour ce faire, Gauthier et coll. (2018) suggère d'améliorer la connectivité hydraulique entre la sphaigne et la tourbe résiduelle, et cela implique l'analyse de la composante suivante du continuum : l'eau. En particulier, l'analyse doit se concentrer sur **le réseau hydraulique aménagé** pour l'alimentation de la nappe phréatique établie.

Le régime hydrologique après le drainage est totalement différent du régime observé dans les sites naturels (Price 2001). La nappe phréatique reste élevée après la fonte des neiges et le début du printemps, mais elle peut descendre à des profondeurs pouvant aller jusqu'à 40 cm. Alors, pour restaurer le bilan hydrique à un état comparable à celui d'une tourbière ombrotrophe non perturbée, le blocage de fossés de drainage a été rapporté comme l'une des mesures pour la réussite de la restauration hydrologique (Holden et coll. 2011). Aussi, l'utilisation d'un couvert protecteur peut être utilisée comme mesure palliative (p.ex., paillis de paille, Price et coll. 1998; Quinty et Rochefort 2003).

L'utilisation de canaux d'irrigation superficiels a été rapportée pour le maintien du niveau de la nappe (LaRose et coll. 1997; Pouliot et coll. 2015; Gaudig et coll. 2018). Son utilisation est conseillée en culture de sphaigne afin de compenser le besoin en eau pendant la période estivale (Brust et coll. 2018). Dans les sites de culture de sphaignes, il est courant de trouver des dispositifs d'irrigation qui bordent le bassin (canaux périphériques) ou qui traversent les bassins (canaux centraux). Ces canaux ou fossés sont alimentés par un système d'irrigation qui prélève l'eau de drainage des sites d'extraction voisins ou également des plans d'eau proches (par exemple des lacs). D'un point de vue hydraulique, la hauteur d'eau dans ces canaux doit être supérieur au niveau prévu dans les bassins de culture afin de créer un gradient hydraulique entre le niveau d'eau du canal et le niveau phréatique du bassin pour provoquer le mouvement de l'eau du canal vers le bassin.

Selon les expériences de culture de sphaigne en Allemagne, en Lettonie et au Canada (Lake and Peatland Research Centre 2016; Gaudig et coll. 2018) la disposition du réseau des canaux d'irrigation est en fonction de l'état de décomposition du catotelme résiduel. L'écartement de dispositifs d'irrigation doit tenir compte des conditions du site et il est recommandé un écartement de 5 m dans des zones de tourbe fortement humifiée (Gaudig et coll. 2017) ou 10 – 20 m dans des zones légèrement humifiées (Gaudig et coll. 2014; Brown et coll. 2017). Ces recommandations ont été établies en fonction de critères empiriques, mais aucun critère technique n'a été signalé dans la littérature sur la culture de sphaigne.

Il y a un dernier élément qui doit être inclus dans l'analyse : **le climat**. Le continuum sphaigne-tourbe-eau a besoin d'être ouvert pour vivre. L'équilibre thermodynamique dans le continuum nécessite un apport d'énergie et de matière provenant de l'atmosphère (Nielsen et coll. 2020a). Afin d'organiser les relations écohydrologiques nécessaires à l'optimisation de la culture, il est essentiel de considérer le continuum sphaigne-tourbe-eau comme un système ouvert. Un système en s'isolant consomme ses ressources, atteignant une grande augmentation de son entropie interne et, à la fin, à sa sénescence (Nielsen et coll. 2020a).

À la frontière du continuum avec l'atmosphère, deux flux d'eau sont considérés en tant que flux majeurs d'une tourbière ombrotrophe (Waddington et Price 2000; Petrone et coll. 2001) : un flux entrant représenté par les précipitations et un flux sortant résultant de l'évapotranspiration. Bien que la composante de la transpiration soit négligeable dans la sphaigne, les modèles hydrologiques utilisent souvent le terme évapotranspiration. Dans les tourbières, il y a en effet des plantes vasculaires pour lesquelles la transpiration est une composante importante (Nichols et Brown 1980).

Bien que l'analyse du continuum sphaigne-tourbe-flux d'eau doit garantir le flux d'eau vers le capitule favorisé par un niveau élevé et stable de la nappe phréatique (Pouliot et coll. 2015), cela ne signifie pas que les conditions hydrologiques de la tourbière naturelle sont rétablies. La culture de sphaigne utilise les méthodes de restauration écologique consistant à manipuler certains filtres abiotiques et biotiques afin d'arriver à la composition désirée d'espèces de sphaigne.

Une approche basée sur le génie écologique

Les restaurateurs écologiques ne restaurent pas réellement les écosystèmes; au lieu de cela, ils redémarrent, revitalisent, réorientent ou accélèrent les processus inhérents aux processus écologiques (Clewell et Aronson 2013). Cette approche sera utilisée tout au long du présent projet. La culture de sphaignes, tout en tenant compte de l'écologie des tourbières, vise à réorienter l'utilisation des tourbières après l'extraction de la tourbe vers une production de biomasse sur une base cyclique. En ce sens, il ne s'agit pas de reproduire la même hydrologie qu'une tourbière naturelle (McCarter et Price 2014). L'idée est d'analyser les conditions après le drainage et l'extraction de tourbe et trouver un moyen pour optimiser le régime hydrologique bénéfique pour la production de fibres de sphaigne (Holden et coll. 2004, 2011).

L'approche de génie écologique (Mitsch et Jørgensen 2003) permet d'accorder les relations écohydrologiques ayant le plus d'impact sur la croissance des sphaignes. Cette approche a été utilisée pour des problèmes similaires tels que le traitement des eaux usées, l'atténuation des effets sur les milieux humides et la réhabilitation des terres perturbées (Kangas 2003).

Dans cette optique, un autre concept sera adopté : les seuils écologiques (Ecological Thresholds, Groffman et coll. 2006). Normalement, le but en culture de sphaigne et en restauration hydrologique est d'avoir une profondeur optimale de la nappe phréatique (associée à un flux garanti pour la végétation et conséquemment une valeur optimale d'humidité ou de succion). Alors, il est proposé de la remplacer par une zone de confort en termes de profondeur de nappe phréatique. En dehors de ces seuils, de petits changements dans le vecteur environnemental (nappe phréatique) produisent des réactions dans l'écosystème (p.ex. diminution de la croissance). Ces seuils de délimitation doivent être cohérents avec les relations écohydrologiques qui sont importantes pour l'optimisation de la culture de sphaigne.

Relations écohydrologiques importantes pour l'optimisation de la croissance des sphaignes

À partir de l'expérience des dernières années en culture de sphaignes dans des bassins expérimentaux, la succion de l'eau dans la tourbe est souvent évoquée comme indicateur des stress hydriques. Il est bien connu que lorsque la succion atteint 100 cm (~100 mbar), les sphaignes ne peuvent plus générer la succion capillaire suffisante (Clymo 1973; Hayward et Clymo 1982), conséquemment leur croissance est affectée. Cependant, cette valeur limite de succion est difficile à mesurer à l'aide des tensiomètres puisque ces équipements ne fonctionnent pas bien dans le milieu poreux comme la sphaigne, dont la porosité peut dépasser 90 % (Boelter 1969; Cornejo et coll. 2005).

Par ailleurs, il a été démontré que le niveau de la nappe phréatique contrôle fortement la succion de l'eau dans la tourbe et donc le stress hydrique sur les sphaignes (Moore et Waddington 2015) au moins pour les 40 premiers cm (Price et Whitehead 2001). C'est pourquoi dans le cas de la restauration de tourbières, et surtout dans la culture de la sphaigne, la nappe phréatique doit être aussi proche de la surface que possible (Clymo 1973; Price et coll. 2003; Taylor et Price 2015). Cela correspond à l'écoulement vertical mentionné ci-dessus selon la loi de Darcy. Une nappe phréatique proche de la surface assure un milieu saturé et un gradient hydraulique suffisant pour assurer un flux d'eau suffisant vers le capitule.

La nappe phréatique est généralement l'indicateur utilisé pour évaluer le remouillage des tourbières drainées (LaRose et coll. 1997; Landry et Rochefort 2012). Nonobstant, l'association de la profondeur moyenne de nappe phréatique à la croissance des sphaignes dans le but d'établir un seuil de stress hydrique ne considère pas l'amplitude des variations de la nappe phréatique ni la fréquence à laquelle elle est restée à des profondeurs critiques pour la croissance des sphaignes (Price et coll. 2002; Pouliot et coll. 2015; Brown et coll. 2017). Brown et coll. (2017) sont d'avis que l'amplitude des oscillations du niveau saisonnier de la nappe phréatique était plus importante que la position moyenne de la nappe phréatique pour l'absorption du CO_2 par les sphaignes. Des conditions sèches répétitives ont entraîné une production primaire nette aérienne généralement plus faible (Weltzin et coll. 2000). Parallèlement, Kim et coll. (2021) ont montré que la fluctuation du niveau de la nappe phréatique inhibait la croissance des sphaignes en raison d'infection fongique.

Parallèlement, malgré l'utilisation d'un système de gestion de l'eau pour le contrôle de la profondeur de la nappe phréatique, cette dernière présente des variations, et par conséquent, le flux d'eau vers le capitule de la sphaigne varie aussi. Peu d'attention a été accordée à un autre type d'approche qui tient compte du stress hydrique dû à l'évolution de la fluctuation de la nappe phréatique et ses effets sur la croissance cumulative des sphaignes.

Dans l'optique de l'optimisation de la croissance des sphaignes, décrit comme un processus cumulatif (Díaz et coll. 2012; Mironov et coll. 2019), il convient d'adopter un indicateur de type cumulatif. Tel est le cas du concept de **stress hydrique saisonnier** dû à des niveaux de nappe phréatique préjudiciables pour la croissance de sphaigne. Ce concept a été utilisé dans la culture du maïs (Kanwar et coll. 1988; Haan et Skaggs 2003; Kuang et coll. 2012), du blé (Malik et coll. 2001) et du soja (Evans et coll. 1990, 1991), et son utilisation permet d'évaluer les effets de l'anaérobiose, causée par un mauvais drainage, sur le rendement des cultures. Le principal indicateur utilisé est la somme des dépassements quotidiens à partir d'une profondeur de 30 cm (SEW30, Smedema 1988). Il quantifie la somme du stress quotidien causé par des conditions de saturation excessive du sol dans la zone des racines pendant la période d'intérêt, généralement la saison de croissance. Le SEW30 a été proposé pour quantifier le stress hydrique qui se produit à différents moments et à différents stades de la culture pendant la saison de croissance (Hiler 1969; Hardjoamidjojo et Skaggs 1982). Howie et coll. (2020) ont fait état d'une première exploration dans le cadre de l'occurrence de la végétation des tourbières. Dans leur travail, ils utilisent la somme des niveaux en-dessous de 0 cm (SEW0).

Pour le calcul de ce type d'indicateur, il est nécessaire de disposer d'enregistrements quotidiens de la nappe phréatique. La nappe phréatique des tourbières naturelles et même des tourbières abandonnées et restaurées présente une variabilité importante (Price et coll. 2002; Holden et coll. 2004; Kennedy et Price 2004). Cette hétérogénéité mérite d'être étudiée et la nécessité d'adapter le programme de surveillance des nappes phréatiques doit être prise en compte (Holden et coll. 2011; Parry et coll. 2013). La résolution spatiale limite souvent le potentiel d'analyse hydrologique puisque la profondeur de la nappe phréatique est mesurée dans quelques puits à une ou deux semaines d'intervalle (Shaffer et coll. 2000).

Hétérogénéité spatio-temporelle du comportement hydrologique de nappes

Récemment, une surveillance continue (quotidiennes ou horaires) dans quelques puits d'observation a été effectuée dans le cadre de projets de culture de sphaigne, afin de compléter les mesures manuelles moins fréquentes (Pouliot et coll. 2015; Brown et coll. 2017). Les relevés quotidiens ou horaires, effectués automatiquement, se font dans un pourcentage minimal de puits d'observation, que l'on peut appeler puits de référence. La fluctuation observée dans ces puits de référence est associée aux fluctuations régionales qui sont en grande partie dues aux échanges avec l'atmosphère (précipitations et évapotranspiration). D'autre part, les relevés recueillies manuellement dans les autres puits sur une base hebdomadaire ou bimensuelle et qui captent une grande partie de la variation locale de la nappe phréatique, peuvent être complétées par les relevés provenant des puits de référence afin d'estimer la nappe phréatique journalière là où il n'y a pas d'enregistrement à cette fréquence. L'absence d'informations quotidiennes sur la nappe phréatique a été enregistrée comme un handicap à l'analyse de l'hydrologie des tourbières (Holden et coll. 2011, 2014; Parry et coll. 2013; Brown et coll. 2017).

Certaines méthodologies peuvent être utilisées pour estimer les valeurs quotidiennes de profondeur de nappe phréatique dans les puits avec des mesures hebdomadaires ou bimensuelles à partir des enregistrements journaliers de quelques puits, naturellement avec un registre journalier de la nappe phréatique. Les modèles empiriques basés sur des données (en anglais, data driven methodologies) sont susceptibles de fournir des résultats utiles sans nécessiter de temps d'étalonnage coûteux (Daliakopoulos et coll. 2005). La régression linéaire et les méthodes d'apprentissage machine (en anglais, machine learning methods) font partie des modèles empiriques pour l'analyse et la prévision hydrologiques. Elles sont populaires en raison de leur capacité à identifier des relations non linéaires complexes. Quelques résultats satisfaisants dans la prédiction de la dynamique non linéaire du régime de la nappe phréatique ont été mis en évidence (Coulibaly et coll. 2001; Choubin et Malekian 2017), en ayant des erreurs de prévision de moins de 10 % (Ghose et coll. 2010).

L'estimation des valeurs journalières de la nappe phréatique permet de quantifier le stress hydrique sur une saison de croissance à l'aide d'indicateurs tels que le SEW30. La disponibilité de la profondeur de la nappe phréatique sur une base quotidienne est une exigence pour de tels indicateurs cumulatifs et le détail des méthodologies d'estimation des valeurs journalières de la profondeur de la nappe phréatique sera approfondi au long du chapitre 2 de cette thèse.

Analyse hydrologique du réseau d'approvisionnement en eau

Dans des systèmes de production agricole, la gestion optimisée des nappes phréatiques à l'aide du bilan hydrique représente un facteur important pour optimiser le rendement des cultures et l'utilisation de l'eau (Evans et coll. 1991). La culture de la sphaigne ne devrait pas faire exception. Par conséquent, la prévision de la profondeur de la nappe phréatique devient un moyen important pour permettre la planification et la gestion en temps réel des ressources (Kuang et coll. 2012). Le bilan hydrique a été quantifié au moyen de formulations mathématiques et certaines relations écohydrologiques ont été représentées dans une certaine mesure permettant de comprendre le remouillage de tourbières (Kennedy et Price 2004, 2005; Schouwenaars et Gosen 2007), le développement de la sphaigne en fonction des conditions climatiques (Golubev et Whittington 2018; Jassey et Signarbieux 2019) et même le stockage du carbone en fonction de l'hydrologie des tourbières drainées et restaurées (Dimitrov et coll. 2010; Susilo et coll. 2012; Brust et coll. 2018). L'interprétation du bilan hydrique permet de répondre aux questions concernant a) la quantité d'eau nécessaire pour maintenir la nappe phréatique à la profondeur désirée pour la croissance de la sphaigne, tout au long de la période de croissance, et b) l'identification des périodes où se produisent les excès et les déficits d'eau.

Toutefois, peu de travaux ont été présentés dans la littérature scientifique sur une approche d'intégration au moyen d'un bilan hydrique des interactions décrites ci-dessus du continuum sphaigne-tourbe-eau (Price 2003; Kennedy et Price 2004; Brust et coll. 2018). La plupart de ces recherches associées à la modélisation de l'écoulement souterrain dans le continuum sphaigne-tourbe-eau utilisent l'équation de Darcy, ainsi que les modèles de Richards (1931) et l'équation de Boussinesq (1877). L'équation de Richards (Eq 1) est utilisée afin de représenter le flux dans la zone non saturée (flux vertical). Dans la zone saturée (en dessous de la nappe phréatique), le mouvement d'eau est représenté par l'équation de Boussinesq (Eq 2), et il est assumé que celui-ci est majoritairement horizontal.

$$\frac{d\theta}{d\Psi}\frac{d\Psi}{dt} = \frac{d}{dz}\left(K(\Psi)\ \left(\frac{d\Psi}{dz} + 1\right)\right) \quad (1)$$

$$\mu\frac{dh}{dt} = \frac{d}{dx}(q_x h) \quad (2)$$

Où *h* représente la hauteur de la nappe phréatique, *Ψ* représente la pression, *K* correspond à la conductivité hydraulique en fonction de la hauteur de la nappe phréatique, *dθ/dΨ* est l'inverse de *μ* est la porosité effective, et q_x est le flux unitaire dans la direction *x*.

La représentation du mouvement de l'eau dans les tourbières après l'extraction de la tourbe (Ballard et coll. 2011; Susilo et coll. 2012) et dans un contexte de culture de sphaigne (Taylor et Price 2015; Brust et coll. 2018) a été signalée comme un défi scientifique. Par exemple, Dimitrov et coll. (2010) soulignent l'importance de différencier la porosité présente dans la tourbe car les horizons typiquement présents (fibrique, mésique et humique) ont des différences importantes qui impliquent des effets significatifs sur la réponse hydrologique. Alors, le modèle à utiliser doit être adapté aux milieux stratifiés.

D'autre part, les modèles numériques s'appuient fortement sur des mesures de la conductivité hydraulique des tourbières. Il est prouvé que la conductivité hydraulique des sols tourbeux peut varier de plusieurs ordres de grandeur sur quelques mètres seulement, verticalement ou horizontalement (Holden et Burt 2003; Taylor et Price 2015). Cela rend difficile la modélisation de la position des nappes phréatiques présentes dans les milieux tourbeux, surtout si des maillages d'éléments finis sont utilisés. La taille des cellules de calcul est généralement supérieure à l'échelle à laquelle se produit une variabilité significative des paramètres hydrauliques (Bromley et Robinson 1995).

En guise de solution à ces inconvénients, l'équation de Darcy est adaptée pour la simulation de la nappe phréatique en considérant le milieu stratifié (Dimitrov et coll. 2010). L'écoulement total dans un milieu stratifié est la somme des flux dans chacune des couches identifiées.

$$q_x = \sum_{i=1}^{m}(\zeta_i - \zeta_{i-1})\ k_i\frac{dh}{dx} \quad (3)$$

Où *m* est le nombre de strates ou horizon différenciés, *h* représente la hauteur de la nappe phréatique, ζi est l'élévation de la strate ou horizon *i*, et k_i correspond à la conductivité hydraulique saturée de la strate ou horizon.

Défis de nature technique et scientifique

À l'heure actuelle, trois défis majeurs se posent pour l'optimisation hydrologique des bassins de production de biomasse de sphaigne :

1) L'absence de relation claire rapportée entre la croissance des différentes espèces de sphaignes et le stress hydrique dû aux variations de la nappe phréatique. L'indice de stress hydrique basé sur la somme des profondeurs de nappes phréatiques quotidiennes sous un certain seuil pourrait aider à établir cette relation. Compte tenu des types d'architecture des communautés de sphaignes démontrées par Rydin (1985), Schipperges et Rydin (1998) et McCarter et Price (2014), la profondeur de nappe phréatique seuil pourrait être différente pour chacune des espèces utilisées en culture de sphaignes;

2) L'absence de programmes de surveillance capables de saisir toute l'hétérogénéité spatiale et temporelle du comportement hydrologique dans les tourbières remouillées (Holden et coll. 2004, 2011; Parry et coll. 2013). Les mesures de la profondeur de la nappe phréatique à proximité des sites de mesures de la croissance de la sphaigne sont effectuées chaque semaine ou toutes les deux semaines (Shaffer et coll. 2000; McCarter et Price 2013; Pouliot et coll. 2015; Hawes 2018), ce qui ne permet pas de calculer un indice de stress hydrique journalier. Une solution immédiate et sans investissement important en matériel est l'utilisation des modèles empiriques basés sur des données (en anglais, data-driven methods). Ces méthodes peuvent être utilisées pour estimer les valeurs quotidiennes à partir des enregistrements moins fréquents de la nappe phréatique, cependant, sans aucun doute, la solution pour saisir l'hétérogénéité spatiale est d'installer autant d'équipements d'enregistrement automatique que possible;

3) L'absence de schéma clair pour la conception et l'évaluation du réseau d'approvisionnement en eau pour les bassins expérimentaux. Dans la culture de sphaigne, il ne suffit pas de bloquer le réseau de drainage créé lors de l'extraction de la tourbe, comme c'est le cas dans la restauration. Un système d'irrigation est nécessaire pour répondre aux besoins en eau, notamment en période estivale. Le flux qui sert à alimenter le capitule doit être compensé par un flux provenant de la nappe phréatique, soit par les précipitations, soit par le système d'irrigation. Le flux horizontal faisant varier la profondeur de la nappe phréatique qui alimente le flux vertical peut être simulé avec l'équation de Boussinesq utilisant l'équation de Darcy qui tient compte de la stratification du milieu tourbeux. Ainsi, la configuration des réseaux hydrauliques pourrait être optimisée en tenant compte des propriétés physiques des horizons du profil de tourbe.

Cette thèse se penchera sur ces trois défis dont chacun abordera l'interaction entre la sphaigne, la tourbe, l'eau et le climat, dans un système de culture de sphaigne. Pour cela, ce projet utilisera des données historiques des sept dernières années des sites expérimentaux de culture de sphaigne dans l'est du Canada. Ces données sont reliées à la croissance de sphaignes, le suivi hydrologique, les données climatologiques et les propriétés de la tourbe après l'extraction. Le pilier de cette thèse sera la méthodologie utilisée pour définir et quantifier le stress hydrique saisonnier qui affecte la croissance et la production accumulé de biomasse de sphaigne. En même temps, il est proposé de remplacer l'approche d'une nappe phréatique optimale ciblée par une zone de confort hydrique, délimité par l'indicateur de stress hydrique saisonnier. En dehors de la zone de confort hydrique, de petits changements dans le vecteur environnemental (nappe phréatique) produisent des réactions dans l'écosystème (p.ex. diminution de la croissance).

Questions de recherche

Cette thèse vise à répondre à la question : en culture de sphaigne, comment gérer l'eau dans une perspective d'augmenter la productivité de la sphaigne ? Cette question sera abordée en utilisant le concept de stress hydrique saisonnier, et aussi l'approche systémique sphaigne-tourbe-flux d'eau.

Cette thèse comprend deux objectifs spécifiques orientés vers différentes interactions des composantes de la culture de sphaigne. Le premier objectif est d'évaluer la relation entre le stress hydrique saisonnier et la productivité de la sphaigne, afin de déterminer les seuils de stress hydrique pour les espèces utilisées en culture de sphaigne. Le deuxième objectif utilise les résultats du premier objectif et vise à développer un modèle mathématique pour caractériser le régime de la nappe phréatique dans un milieu tourbeux, en utilisant les informations liées à la gestion de gestion d'eau et les conditions météorologiques. Chaque objectif est à son tour divisé en sous-objectifs plus spécifiques auxquels sont associées les hypothèses de recherche.

Le **premier objectif** se concentre sur l'effet du stress hydrique saisonnier sur la productivité de la sphaigne (Figure 0.1). Les questions spécifiques abordées sont les suivantes : Existe-il un indicateur pour représenter la fluctuation de la nappe phréatique dans les bassins en lien avec la productivité de la sphaigne ? Est-il possible estimer les fluctuations journalières de la nappe à partir de relevés manuels hebdomadaires ? Les communautés de sphaignes répondent-elles de façon identique aux fluctuations de la nappe phréatique ?

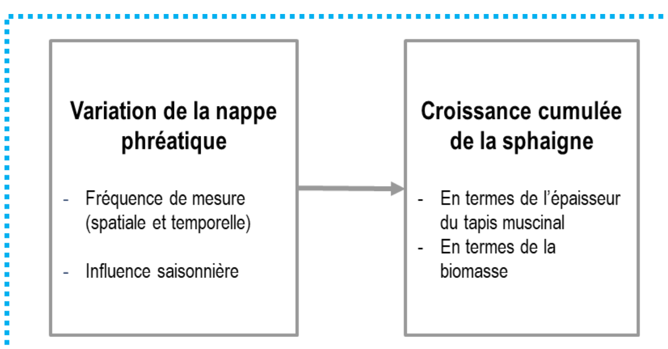

Figure 0.1. Cadre conceptuel du chapitre 1 et 2 sur l'effet du stress saisonnier sur la productivité de la sphaigne.

Les chapitres 2 et 3 se pencheront sur cet objectif qui sera abordé dans le cadre de trois sous-objectifs :

- Identifier la meilleure méthodologie pour l'estimation de la profondeur journalière de la nappe phréatique basée sur des enregistrements occasionnels et des enregistrements quotidiens dans des puits de référence (Chapitre 1). Profondeur de la nappe phréatique sur le puits de référence.

- Identifier des indicateurs de stress hydrique saisonnier en lien avec la productivité de la sphaigne (Chapitre 2).

Pour cela, trois hypothèses sont retenues :

- La valeur journalière de la profondeur de la nappe phréatique dans un puits d'observation peut être estimée à partir des relevés occasionnels, à condition qu'il existe un autre puits à proximité qui a le même régime hydrique et pour lequel des données journalières de la nappe phréatique sont connues.

- Une profondeur élevée et stable de la nappe phréatique favorise une augmentation de la productivité de la sphaigne en termes de biomasse ou de poids sec, ainsi que de l'épaisseur du tapis muscinal, se traduisant par une faible valeur de l'indicateur de stress hydrique saisonnier. Si cet indicateur est significativement corrélé avec la productivité de la sphaigne, il peut être utilisé pour évaluer le stress hydrique saisonnier dans la culture de la sphaigne.

- La productivité de chaque espèce de sphaigne variera en fonction de son adaptation au stress hydrique qui sera corrélé à un indicateur de stress hydrique saisonnier. Cela permettra de déterminer les seuils de stress hydrique optimaux pour les espèces de sphaigne étudiées. Ces seuils sont définis sur la base d'une profondeur cible de la nappe phréatique.

Le **deuxième objectif** étudie le régime de la nappe phréatique en fonction de la gestion de l'eau dans les bassins de culture de sphaigne (Figure 0.2). Il vise à répondre aux questions spécifiques suivantes : La nappe phréatique dans les bassins fluctue-elle en fonction des niveaux d'eau dans les canaux d'irrigation ? Quelle est l'influence des propriétés de la tourbe résiduelle après l'extraction et de l'aménagement des bassins sur le comportement de la nappe phréatique ? Est-il possible de simuler la fluctuation de la nappe phréatique pour les cas où les précipitations et/ou l'évapotranspiration sont importantes ? Le chapitre 3 porte sur ce dernier objectif.

Cet objectif sera abordé dans le cadre de trois sous-objectifs :

- Valider le modèle d'écoulement de Boussinesq adapté aux milieux stratifiés dans les bassins de culture de sphaigne.

- Simuler la fluctuation de la nappe phréatique en tenant compte des scénarios d'irrigation et de drainage, ainsi que les flux d'eau dus aux précipitations et à l'évapotranspiration.

Pour cela, une hypothèse est retenue :

- En considérant une tourbière aménagée comme un milieu stratifié, le flux horizontal total d'eau peut être représenté par l'équation de Boussinesq qui représente le flux d'eau comme la somme des flux horizontaux pour chaque horizon saturé sous la nappe phréatique.

- En utilisant un modèle conceptuel adapté pour tenir compte de la gestion de l'irrigation et des conditions météorologiques, il est possible de décrire les variations de la nappe phréatique dans le temps.

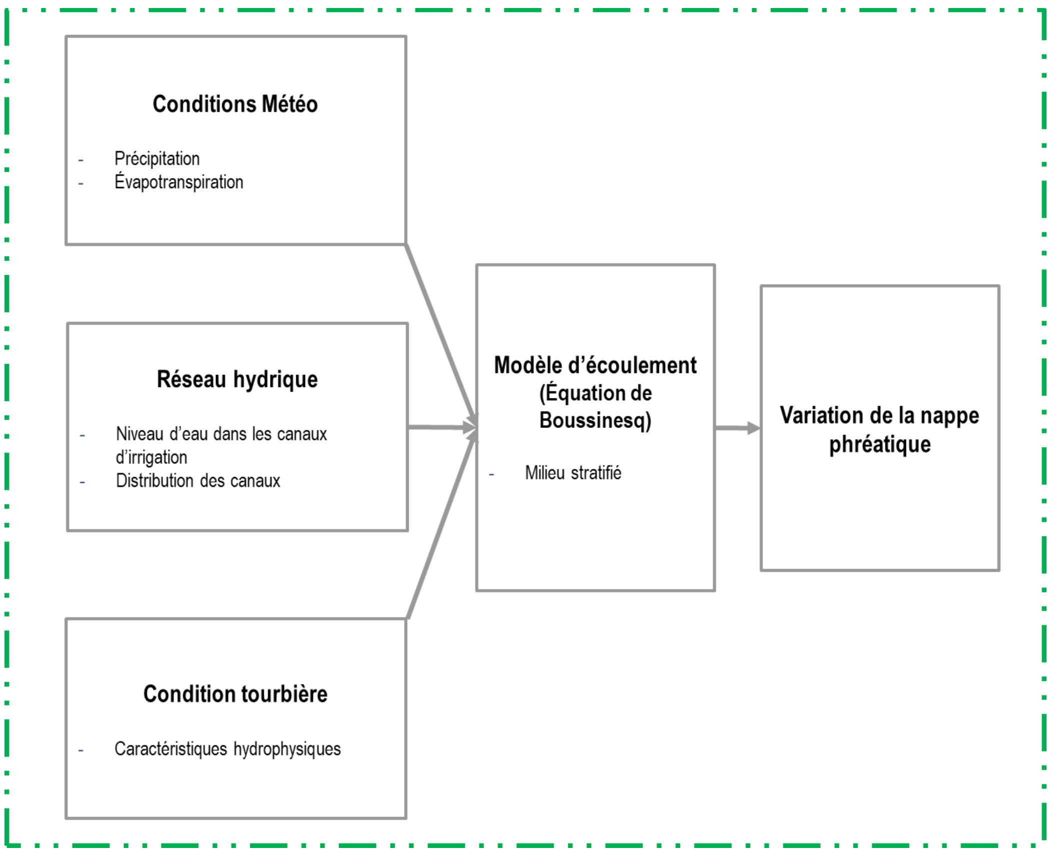

Figure 0.2. Cadre conceptuel du chapitre 3 sur le régime de la nappe phréatique en fonction de la gestion de l'eau dans les bassins de culture de sphaigne.

Finalement, les contributions générales, les suggestions de travaux futurs et les limitations dans les chapitres de la thèse seront considérées dans une conclusion générale, correspondant à la dernière section. Notamment, le dernier chapitre aborde les valeurs cibles de la profondeur de la nappe phréatique pour quantifier le stress hydrique affectant la croissance des espèces de sphaigne, ainsi qu'un résumé des résultats de la modélisation numérique d'un modèle prenant en compte la stratification de la tourbe dans une culture de la sphaigne.

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Chapitre 1 : Estimation of daily water table level with bimonthly measurements in restored ombrotrophic peatland

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1.1 Résumé

Des mesures quotidiennes de la profondeur de la nappe phréatique sont parfois nécessaires pour évaluer l'influence du stress hydrique saisonnier sur la recolonisation des sphaignes dans les tourbières ombrotrophes restaurées. Cependant, les mesures continues de la profondeur de la nappe phréatique sont souvent rares en raison de leur coût élevé et, par conséquent, la profondeur de la nappe phréatique est plus souvent mesurée manuellement à toutes les deux semaines. En plus de ces mesures, des relevés quotidiens de certains puits de référence sont effectués avec des enregistreurs de niveau. Une revue de la littérature a identifié six méthodes potentielles pour estimer la profondeur quotidienne de la nappe phréatique à partir d'enregistrements bimensuels et de mesures quotidiennes dans un puits de référence. Une nouvelle méthode d'estimation basée sur la décomposition des séries temporelles (*tsd*) est également présentée. La méthode *tsd* et les six méthodes identifiées ont été comparées aux enregistrements de la profondeur de la nappe phréatique d'une tourbière expérimentale à régime de nappe phréatique contrôlé, situé dans l'est du Canada. La méthode *tsd* a été la méthode la plus performante (R^2 = 0,95, RMSE = 2,48 cm et le plus faible AIC), suivie de la méthode linéaire générale (R^2 = 0,92, RMSE = 3,10 cm) et de la méthode des machines à vecteurs de support (R^2 = 0,91, RMSE = 3,24 cm). Pour estimer les valeurs quotidiennes, la méthode *tsd*, comme les six méthodes traditionnelles, nécessite des données quotidiennes provenant d'un puits de référence. Cependant, la méthode *tsd* ne nécessite ni entraînement ni estimation des paramètres. Pour la méthode *tsd*, la réduction de la fréquence des mesures à une fréquence hebdomadaire entraîne une diminution de la RMSE de 16 % (2,08 cm) et l'augmentation à une fréquence mensuelle augmente la RMSE de 13 % (2,80 cm).

1.2 Abstract

Daily measurements of the water table depth are sometimes needed to evaluate the influence of seasonal water stress on *Sphagnum* recolonization in restored ombrotrophic peatlands. However, continuous water table measurements are often scarce due to high cost and, as a result, water table depth is more commonly measured manually bimonthly with daily logs in few reference wells. A literature review identified six potential methods to estimate daily water table depth with bimonthly records and daily measurements from a reference well. A new estimation method based on the time series decomposition (*tsd*) is also presented. *tsd* and the six identified

methods were compared with the water table records of an experimental peatland site with controlled water table regime located in Eastern Canada. The *tsd* method was the best performing method (R^2 = 0.95, RMSE = 2.48 cm and the lowest AIC), followed by the *general linear method* (R^2 = 0.92, RMSE = 3.10 cm) and *support vector machines* method (R^2 = 0.91, RMSE = 3.24 cm). To estimate daily values, the *tsd* method, like the six traditional methods, requires daily data from a reference well. However, the *tsd* method does not require training nor parameter estimation. For the *tsd* method, changing the measurement frequency to weekly measurements decreases the RMSE by 16% (2.08 cm) and to monthly increases the RMSE by 13% (2.80 cm).

1.3 Introduction

Hydrological monitoring in ombrotrophic peatlands is used to understand the effect of the water table depth fluctuation on vegetation structure (Rydin & Jeglum 2013), which is mostly composed by *Sphagnum* species. Spatial changes in the water table depth, which is associated with water availability, drive changes in the species composition of biotic assemblages (Campbell & Rochefort 2001). Water table fluctuation also influences decomposition, microbial activity (Andersen et al. 2009), and greenhouse gas emissions (Wilson et al. 2016). Water availability is a valuable information for peatland management because it influences gas diffusion rates, redox status, nutrient availability and cycling and species composition and diversity (Van Seters & Price 2001; Holden 2005a; Ju et al. 2006; McCarter & Price 2013; Taylor et al. 2016); and it is important for water resource management, flooding, and stream water quality (Holden 2005b). There is evidence that demonstrates its potential use in predicting primary production and surface vegetation growth, mainly *Sphagnum*, for moss cultivation (Brown et al. 2017), even in a forestry or peatland post-extraction context (Landry & Rochefort 2012; Graf et al. 2012).

The presence of water in ombrotrophic peatland influences peat hydrophysical properties such as water storage capacity (LaRose et al. 1997), hydraulic conductivity due to the surface subsidence (Price et al. 2003; Rydin & Jeglum 2013), and drainable porosity (Price 1996; Price et al. 2003). It is then a domino effect since any alteration of the hydrological regime can significantly affect peatland vegetation (Breeuwer et al. 2009; González & Rochefort 2014).

In natural ombrotrophic peatland conditions, water table level is heterogeneous due to the effective porosity (larger than 0.5 mm) that allows groundwater to flow. This porosity changes both spatially and temporally because of biological processes (e.g., microbial decomposition, Siegel & Glaser 2006). Also, it should be noted that in ombrotrophic peatlands, the local water table depth follows the domed profile of the terrain. There is an ecological gradient between the center and the edges of a peat bog. This gradient is mainly due to the distribution pattern of trees and shrubs that can locally lower the water table depth because of root water uptake for transpiration demand (Pellerin et al. 2009; Paradis et al. 2015), a phenomenon known as biological drainage

(Jutras, Hökkä, et al. 2006; Jutras, Plamondon, et al. 2006). At the edges of a bog, the number and size of trees (e.g., spruce and larch) commonly increase, which can lead to the formation of a forested lagg (Paradis et al. 2015). The water table depth is, on average, lower and more fluctuating near the bog edges due to the changing topography.

When any of the components of peat bog (e.g., soil structure, vegetation composition, groundwater) are altered, the hydrological regime is changed. Particularly when a drainage system is built, the regime observed is different compared to the natural systems (Price 2001). Anthropogenic activities can result in an increased heterogeneity of water availability, e.g., deforestation (Ireland & Booth 2012; Pinceloup et al. 2020), drainage (Holden et al. 2011; Landry & Rochefort 2012; Haapalehto et al. 2014) and peat extraction (Van Seters & Price 2001; Mioduszewski et al. 2013).

Because the ecosystem functions of ombrotrophic peatlands, e.g., carbon sink, Waddington et al. (2010), fauna and flora habitat, Pinceloup et al. (2020), are becoming progressively valued, interest in conserving and restoring ombrotrophic peatlands is growing. Ecological restauration after peat extraction aims at allowing the progressive return of ecohydraulic characteristics of peatlands mainly through blocking the ditches. Rewetting, especially in combination with other actions such as *Sphagnum* reintroduction benefits the establishment of typical vegetation of peatlands and decreases the abundance of non-desirable plants (Landry & Rochefort 2012).

The commonly used indicator to evaluate hydrological restoration is the water table depth that should be stable and close to the surface (LaRose et al. 1997; Price et al. 2003; Holden et al. 2004) if possible, during the growing season. In restored peatland sites of Canada, the water table depth generally remains high (~ -10 cm from surface) after snowmelt and early spring, but it lowers gradually as temperature increases and can reach depths of up to 40 cm (McCarter & Price 2013). Several studies on restored peatlands in Canada confirm the spatial and temporal variability of water table depth (Price & Whitehead 2001; Taylor & Price 2015; Taylor et al. 2016), even when water table control systems such as irrigation systems are in place (Brown et al. 2017; Guêné-Nanchen et al. 2017).

The spatial and temporal variation of water availability deserves to be studied and the adjustment of the water table monitoring protocol must be considered (Holden et al. 2011, 2014; Parry et al. 2013). The spatial resolution often limits the potential for hydrological analysis since the depth of the water table depth is measured weekly (or bimonthly) in a few selected wells (Shaffer et al. 2000). It has been suggested that the number of wells depends on the objectives of the study, the peatland size and type, logistical arrangements (e.g., available personnel), site complexity, and spatial variability of the water table depth (BWSR 2013). No suggestion is made as to the number of wells to observe the water table regime in post-extraction ombrotrophic peatlands. The need for daily monitoring has been reported in contexts such as peatland drainage (Holden et al. 2011), peatland restoration (Parry et al. 2013; Brown et al. 2017) and peatland hydrology reconstruction (Holden et al. 2014). The main disadvantage of monitoring programs based on infrequently measurements is that they are not able of capturing the full spatial and temporal heterogeneity of hydrological behaviour in bogs (Holden et al. 2004).

At many undisturbed and peat post-harvest sites, measurements of the water table depth are carried out weekly or bimonthly (McCarter & Price 2013; Pouliot et al. 2015; Hawes 2018), which does not allow the analysis of the cumulative effect of prolonged drying or flooding on Sphagnum growth. These infrequent water table measurements co-occur generally with daily records in a few selected wells (also known as reference wells). Some methodologies can be used to estimate daily values from the infrequent water table records. Data-driven empirical methods are susceptible to provide useful results without costly calibration time. This article aims to select the best method to estimate daily water table depths based on infrequent observations (e.g., weekly or bimonthly) and daily records from a reference well.

This paper is divided in seven sections allowing to answer our research question: Is it possible to estimate the daily fluctuation of the water table depth from infrequent manual measurements and daily records from a reference well? This paper begins with a brief overview of the methods identified as potentially useful for estimating daily water table depth with bimonthly measurements and daily measurements of some reference wells. With the limitations of the identified methods, a new estimation method based on the time series decomposition (*tsd*) is described in the third section. Section four describes the methodology for the evaluation of the set of estimation methods. Finally, sections 5 to 7 present and discuss the results.

1.4 Methods of water table dept estimation: a review

Estimation methods

The estimation of water table depth in restored peatlands as function of weather data, hydrological characteristics of peatland (e.g., peat decomposition, depth of peat), and even past records of the depth of the water table has remained a difficult topic (Price et al. 2003; Dimitrov et al. 2010; St-Hilaire et al. 2010; McCarter & Price 2013). Due to bimonthly manual measurements of water table depth co-occur generally with daily instrumented measurements in a few selected wells (reference wells), some methods can be used to estimate the daily water table level in wells with infrequent water table records that are close to reference wells with daily records. These methods are classified into two groups: physical-based and data-driven methods. Physically based methods are widely used for the description of hydrological phenomena in peatlands (Frolking et al. 2002; Ju et al. 2006; Dimitrov et al. 2010; St-Hilaire et al. 2010). However, they do have practical limitations (Daliakopoulos et al. 2005). For example, physical-based modelling approach requires an adequate and accurate definition of aquifer parameters to describe the soil subsurface spatial variability (Coppola et al. 2003;

Mohanty et al. 2010; Taormina et al. 2012). Typically, this information is difficult to obtain because of cost and time constraints (Coulibaly et al. 2001; Nayak et al. 2006).

Data-driven empirical methods are susceptible to provide useful results without costly calibration time (Daliakopoulos et al. 2005). The identified data-driven estimation methods are grouped in three types of methods: Linear method, nonlinear methods, and regression trees. The first category includes the general linear model (*glm*). The second category comprises k-nearest neighbours (*knn*) method, which is based on the similarity measure (distance) between data. Finally, for the regression trees, there are four estimation methods: support vector machines (*svm*), decision tree (*tree*), random forest (*rf*), and adaptive boosting (*AdaBoost*). The next sections present summaries of these methods. For all methods, the following terms must be defined a priori: 1) The estimated wells: some occasional measurements (weekly, bimonthly or monthly) were made for those wells and there is an interest in knowing the daily water table values to identify periods of water stress; and the reference well, which has daily or hourly records of the water table level and is normally located near the estimated well. 2) These data-driven methods are calibrated with the infrequent data from the reference well and the estimated well. The method then uses the daily water table data of the reference well to estimate the daily water table values for the estimated well.

General linear model (glm)

It is the most widely used method because of its easy implementation (Freedman & David A 2009). *glm* model assumes a linear relationship between the independent variables (water table depth of reference wells) and the dependent variable (water table depth of estimated well).

Brown et al. (2017) used a linear regression between weekly logged estimated wells and daily logged reference wells to estimate daily water table values obtaining a coefficient of determination (R^2) of 0.55. The dataset was then used to calculate the Optimal Range Days for gross ecosystem productivity calculation.

By employing linear regression, the estimation procedure is simple, and it is easy-to-understand. Authors like Lu et al. (2014) and Choubin & Malekian (2017) argued that linear models are appropriate to model simple systems characterized by linear relationships between the hydrological observations. The use of a linear model (simple or multivariate) assumes that the process in question behaves like a normal distribution. The use of linear regressions is current even if the groundwater flow and most hydrological processes are commonly considered as nonlinear (Wang 2006).

k-nearest neighbours (knn)

Proposed by Cover & Hart (1967), this method does not have any discriminative function from training data but stores the training data set by groupings. It is based on the selected distance measurement and the number of *k* neighbours. The k-nearest neighbours (*knn*) algorithm selects the *k*-nearest samples in the feature space (N-dimensional space, where N is the number of features), each sample is equivalent to one vote and assigns an attribute (labelling) by a majority vote. In the case of having a reference well associated with an estimated well, the observations can be organized in a 2-D space (*x* for the water table depth of the reference well and *y* for the water table depth of the estimated well). The interpolation for xi is made within the range of observed water table depth for the reference well, x_{min} and x_{max}, and the estimated value for $\hat{y}_i$ is the average of the observed values closest to x_i.

The number of *k*-neighbours may be specified a priori in the cross-validation. It is advisable to use the square root of the number of observations in the calibration set (Lall & Sharma 1996). There are two peculiarities of this algorithm: it is a memory-based approach, it is adapted immediately to new training data, and it is sensitive to the local structure of the data (Raschka & Vahid 2017) since the closest neighbors could have more weight on the average calculation. Modaresi & Araghinejad (2014) and Sakizadeh & Mirzaei (2016) report successful cases of groundwater classification, with accuracy above 90%.

Support vector machines (svm)

This algorithm was originally developed for classification problems (Vapnik & Chervonenkis 1964). However, it aroused special interest years after its emergence because despite being a linear machine, it can be implemented on nonlinear class boundaries (Cortes & Vapnik 1995). The objective of the support vector machines (*svm*) method is to construct a hyperplane to classify the data points (data from the reference well and the estimated well) in the feature space (Cortes & Vapnik 1995). The selection criteria to draw the hyperplane is to maximize the margin. The margin is defined as the distance between the hyperplane of separation and the training points that are close to the hyperplane. These points are also called support vectors. *svm* method has been developed to be applied to nonlinear problems using few support vectors (Witten & Frank 2005; Raschka & Vahid 2017). Although authors like Zhao et al. (2020) and Rahman et al. (2020) report satisfactory evaluation statistics (R^2 greater than 0.93) for groundwater level forecasting, its interpretability is low.

Decision-tree-based models: Regression tree (tree) and random forest (rf)

Like the *svm* method, a division of the data set is performed in different and non-overlapping regions with shared characteristics. Decision-tree-based models represent a suitable solution for applications on small-sized datasets (Breiman et al. 1984). Regression tree (*tree*) represents a set of restrictions or conditions which are hierarchically organized, and which are successively applied from root to a terminal node or leaf of the tree (Quinlan 1986; Rokach & Maimon 2015). In practice, this can produce a very deep tree with many nodes, which produces overfitting. A good option is to prune the tree, i.e., adjust its maximum depth (Raschka & Vahid 2017). The induction of decision-tree-based method involves a) selecting optimal splitting of the dependent variable, into binary pieces, where the child nodes are "purer" than the parent node, b) search through all candidate splits to find the optimal split that minimizes the impurity of the resulting tree (Breiman et al. 1984; Quinlan 1986). Decision-tree-based models allow the presentation of more understandable results. They can model nonlinear phenomena and do not need prior statistical assumptions, elimination of outliers or data transformation (Rodriguez-Galiano et al. 2014).

Random Forest (*rf*) method combines multiple decision tree-based models to produce repeated predictions of the same phenomenon (Breiman et al. 1984). *rf* is a relatively new machine learning technique (Ho 1995). The idea behind *rf* is to average multiple blocks to create a more robust model that has better generalization performance, and it is less susceptible to overfitting to their training set (Breiman et al. 1984; Raschka & Vahid 2017). The multiple blocks are also called deep-decision trees, that individually suffer from high variance. *rf* is a popular approach due to its high precision and capability to handle a large amount of input variables (Biau & Scornet 2016; Tyralis & Papacharalampous 2017). The number of trees and the number of features to be used at each split are the parameters to be determined during training (Amaranto et al. 2018). There are also other two parameters to be established for rf training: the random state to control the random number generator used, and the minimum number of observations at the terminal nodes of the tree (Breiman et al. 1984). This methodology reports the best results (R^2 greater than 0.9) in hydrology applications (e.g., groundwater pollution and groundwater forecasting) in comparison to the set of data-driven methods (R^2 between 0.5 and 0.9), explained before (Rodriguez-Galiano et al. 2014; Tyralis & Papacharalampous 2017; Koch et al. 2019; Brédy et al. 2020).

Adaptive Boosting (AdaBoost)

The original idea was formulated by Robert E. Schapire (1990) and it became one of the most used combined sets in the following years (Freund & Schapire 1996; Kégl 2013). The concept behind the boosting is to focus on training samples that are difficult to classify (Xiao et al. 2013), i.e., to let classifiers (called weak classifiers, also weak learners) learn from poorly classified training samples to improve overall performance (Raschka & Vahid 2017). If the performance of each weak classifier is slightly better than random guessing, the final model can be shown to converge to strong learning. *AdaBoost* is adaptive in the sense that subsequent weak classifiers are tweaked in favour of those samples misclassified by previous classifiers. To maximize the predictive accuracy of *AdaBoost*, the following parameters must be defined (Albon 2017): the learning algorithm use to train the weak models (base estimator), the number of models to iteratively train (number of estimators), and the contribution of each model to the weights (learning rate).

Closing considerations about data-driven methods

All the above methods (general linear model-*glm*, k-nearest neighbours-*knn*, support vector machines-*svm*, decision-tree-based methods-*tree*, random forest-*rf*, and Adaptive Boosting-*AdaBoost*), have a common factor. Their performance in modelling groundwater hydrology requires a long-time series of hydrological data to be trained (Zanotti et al. 2019), and these methods present overfitting during the training step (Brédy et al. 2020). Data-driven methods are sensitive to input measurements and all the previous methods used the same approach: The calibration data (infrequent data from the reference well and the estimated well) is split in two datasets, a training and a validation set. Those methods are used to generate estimates, even for the observed data which is counterintuitive. Also, discrepancies in the input data may be attributed to measurement errors, systematic bias, geographical distance between the sampling points, or a combination of the above factors (Amaranto et al. 2020). These uncertainties of observation lead to a decrease in the accuracy of the prediction or even a problematic interpretation of the results. The latter can be even more problematic for models where the interpretability is low. To counteract the precision challenges of the six data-driven methods presented, it is recommended to consider a regional sensitivity analysis (Corzo & Solomatine 2007) and physical background concept (Zhao et al. 2020), where the observed regime types are considered in the estimation.

1.5 Time Series Decomposition (tsd): the new proposed method

Time series decomposition method (*tsd*), the new proposed method, defines the behavior of the water table as the result of a local component (mainly drainage and irrigation) and a regional component (mainly precipitation and evapotranspiration). The intention remains to estimate the daily water table depth, in this case, as the sum of the regional and local components. The local component can be capture by few measurements and the regional component can be capture from daily measurements in few wells. The principle can be shown in Figure 1.1a with real water table observations on restored site with controlled water table in Eastern Canada in 2017. The water table depths in the two wells are different but show similar patterns. If the observed period is spitted in two-week periods (a normal frequency of water table observation), the trend of the water table depth for each period is defined by the water at the beginning and the end of each period (Figure 1.1b). The differences between the two trends are caused by local management, mainly due to drainage and irrigation. For each well, the difference between the observed water table depth and its trend (Figure 1.1c) represents the daily fluctuation of the water table from the trend. Even though, the two wells show different water table depths, the fluctuation from the trend are similar (p-value > 0.1) and represents the influence of precipitation and evapotranspiration which are regional in nature. This decomposition of water table fluctuations corresponds to two components: a deterministic (trend) and irregular component (daily fluctuation from the trend), which also includes the stationary processes (Hyndman & Athanasopoulos 2018). Although this principle has been explored for discrete and continuous description of physical phenomena (Ginzburg 2017), finding the functions that represent these two components remains unclear.

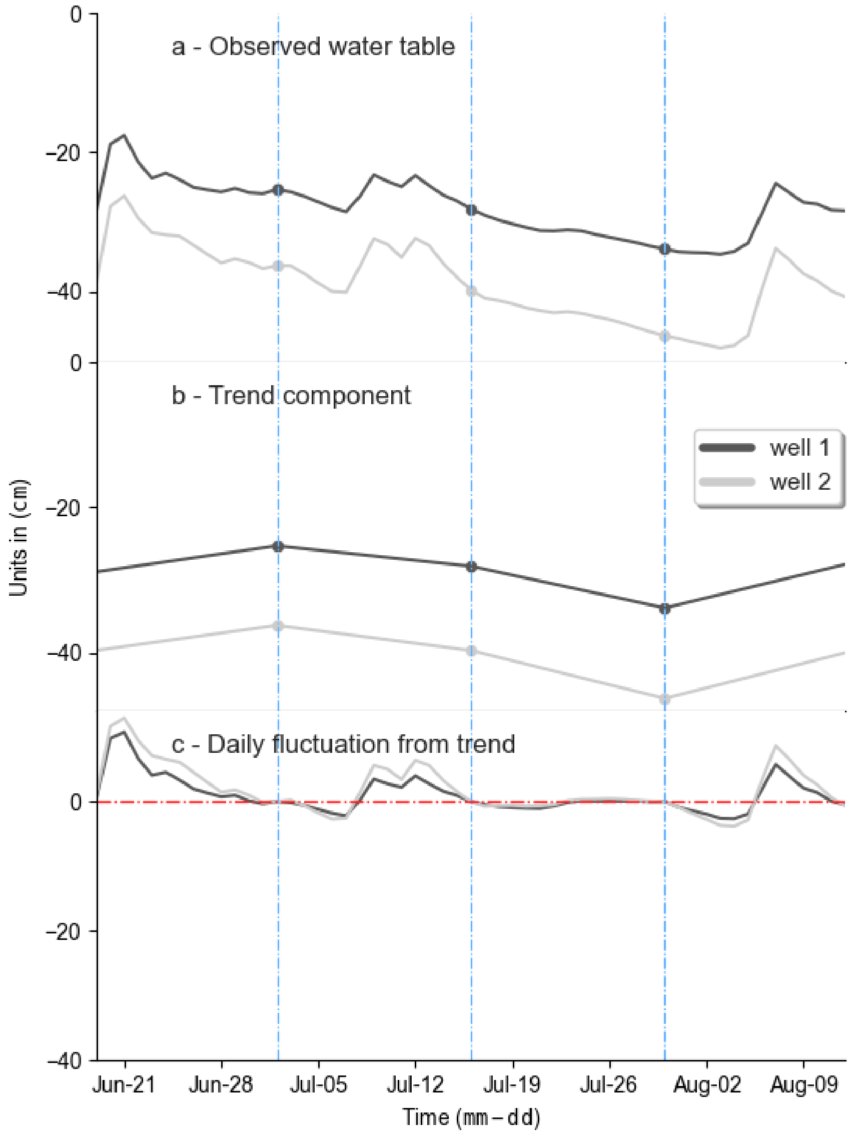

Figure 1.1. Recorded water table depths in two nearby wells at a restored site in Eastern Canada in 2017 and decomposition into two components: the trend (b) and the difference from the trend (c).

Splitting the observed interval in time elements (called periods) and the decomposition of the water table depth in a trend and a fluctuation component are the base of the proposed method. For each period, the daily estimation of the water table depth in a well with infrequent measurements will be the addition of the trend of the water table observed and the daily fluctuation component derived from a reference well, in this case a nearby well with daily observations. As shown in Figure 1.1c, the daily fluctuation from the trend is nearly the same for the estimated well and the reference well. The water table depth of the estimated well can therefore be expressed by Equation 1.1:

$$h^e(t) = \lambda^e(t) + \rho^r(t) \qquad (1.1)$$

where, $h(t)$ is the daily water table depth, $\lambda(t)$ refers to the trend component and $\rho(t)$ is the daily fluctuation from the trend. Superscript *e* and *r* represent the values for the estimated and the reference well, respectively.

The first step for this method is to divide the time scale in periods (time elements), bounded by the infrequent measurements (nodes), such as in finite element method. Then, the method determines the trend component for the estimated and the reference wells. For a period, the trend component (λ) can be described under the shape function of 1-D finite element (Equation 1.2):

$$\lambda^e(t) = h_1^e \psi_1(t) + h_2^e \psi_2(t) \qquad (1.2)$$

where, $\lambda^e(t)$ refers to the trend component for a specific period, h_1 and h_2 are the observed values of the water table depth at the beginning and the end of the period, respectively, and ψ_1 and ψ_2 are called the partitions of unity and are functions of *t*, and they are calculated by Equations 1.3 and 1.4:

$$\psi_1(t) = \frac{t_2 - t}{t_2 - t_1} \qquad (1.3)$$

$$\psi_2(t) = \frac{t - t_1}{t_2 - t_1} \qquad (1.4)$$

where, t_1 and t_2 are the time at the beginning and the end of each period.

For the reference well, the superscript *e* is replaced by superscript *r* in Equation 1.2. Subsequently, the daily fluctuation component (ρ^r) is deducted with Equation 1.5:

$$\rho^r(t) = h^r(t) - \lambda^r(t) \qquad (1.5)$$

where, $h^r(t)$ is the observed water table depth in the reference well.

This procedure described above is computed for each of the observed periods. Figure 1.2 emphasizes the values for period *i*. The estimation of the water table depth in the estimated well ($\hat{h}^e(t)$, solid red line) is equal to the sum of its trend component ($\lambda^e(t)$, dashed red line) and the daily fluctuation component of the reference well ($\rho^r(t)$, gray hatching).

If more than one reference well is available, the estimation of the daily water table depth is made according to the Equation 1.6, as an average of the daily level of the water table in each reference well:

$$h^{e}(t) = \lambda^{e}(t) + \frac{1}{m}\sum \rho^{ri}(t) \qquad (1.6)$$

where *m* is the number of reference wells used for the estimation.

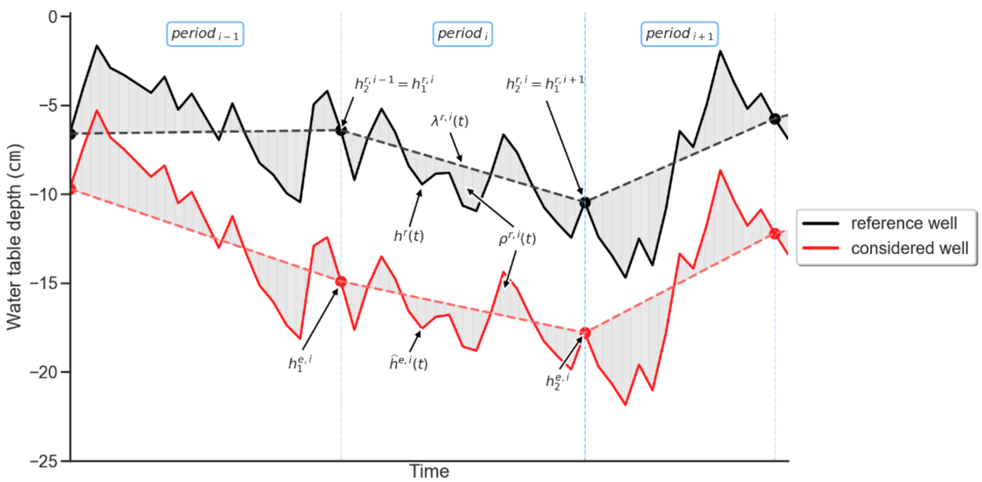

Figure 1.2. Graphical representation for decomposition time series (*tsd*) method.

1.6 Methods

Requirements for testing methods

To test the capacity of previously described methods to estimate the daily water table depth, a site with the largest possible number of wells with daily water table measurements is required. Within the database for this project, the largest number of wells with daily water table depth observations was 30 wells, over a two-year observation period. Each of these wells is considered infrequently sampled, obtaining only bimonthly measurements. For each estimation methods, the estimation model is trained with the bimonthly water table data extracted from each well and the associated reference well. Finally, the daily estimates of the water table depth are made with each method and are then compared with the daily water table observations. The procedure is carried out for each well located on the site.

Study area

Field measurements were conducted in an experimental *Sphagnum* farming peatland site located in Saint-Modeste, Eastern Canada (47°49'55"N 69°27'55"W). A total of five 10 m x 50 m basins (water management systems) were established with controlled water table regime (Figure 1.3). Water table regime was controlled through an automated irrigation installation and each basin was adjusted with different water table management (Table 1.1). *Sphagnum* moss was reintroduced over the five basins in 2013 according to an adaptation of Moss Layer Transfer Technique (Rochefort et al. 2003; Graf et al. 2012).

The basins were located at the edge of an industrial bog on slightly decomposed peat (H3-H5 on the von Post scale, mean peat depth of 1.6 m). The section was in a slight topographic depression, and it was surrounded on the northwest by an adjacent natural peat bog and on the southeast by a peat extraction field. Among the five basins, three had a peripheral channel (PC-NI, PC-20, PC-10) and two had a central channel (CC-10, CC-20). Basins were irrigated with water coming from a sedimentation pond which collected the drainage waters of the surrounding peat extraction fields, except for basin PC-NI which only received rainfall. A pumping system fed the irrigation channels in each basin. The water level in channels was monitored by ultrasonic sensors installed at the dam and, when the water level was lower than the target level, the pumping system was activated to feed the channel. The maximum water level in a channel was controlled by the height of a dam, which was a wooden sluice gate that blocked the water flow and increased the water level upstream of the dam. This increase caused a favourable hydraulic gradient for groundwater flow within the peat for rewetting.

Water table depth monitoring

Water table depth (h) was recorded every hour by a Solinst Level logger ® Edge – Model 3001 (Solinst Canada Ltd., Georgetown, ON, Canada, accuracy: ± 0.1 kPa) during the 2016 and 2017 growing season (May 20th to October 18th). Water table depth was measured in six wells per water management systems (basin) and their locations varied according to the type of basin (Figure 1.3). The data loggers were placed inside the 30 wells of the site to record pressure and temperature simultaneously. The wells were made of 2-in diameter PVC pipe. The wells were installed at a depth of approximately 70 cm using an auger. The wells had nylon stockings on the outer surface to prevent the entry of solids in suspension. All measurements were corrected with the air pressure Barologger Gold – Model 3001 (Solinst Canada Ltd, Georgetown, ON, Canada, accuracy: ± 0.1 kPa) with the Solinst Levelogger Series software.

The daily value of the water table depth was estimated from hourly measurements as the average between the maximum ($h_{max,\,i}$) value and the minimum value ($h_{min,\,i}$) recorded during each day of the growing season (Equation 1.7).

$$h_i = \frac{h_{max,i} + h_{min,i}}{2} \qquad (1.7)$$

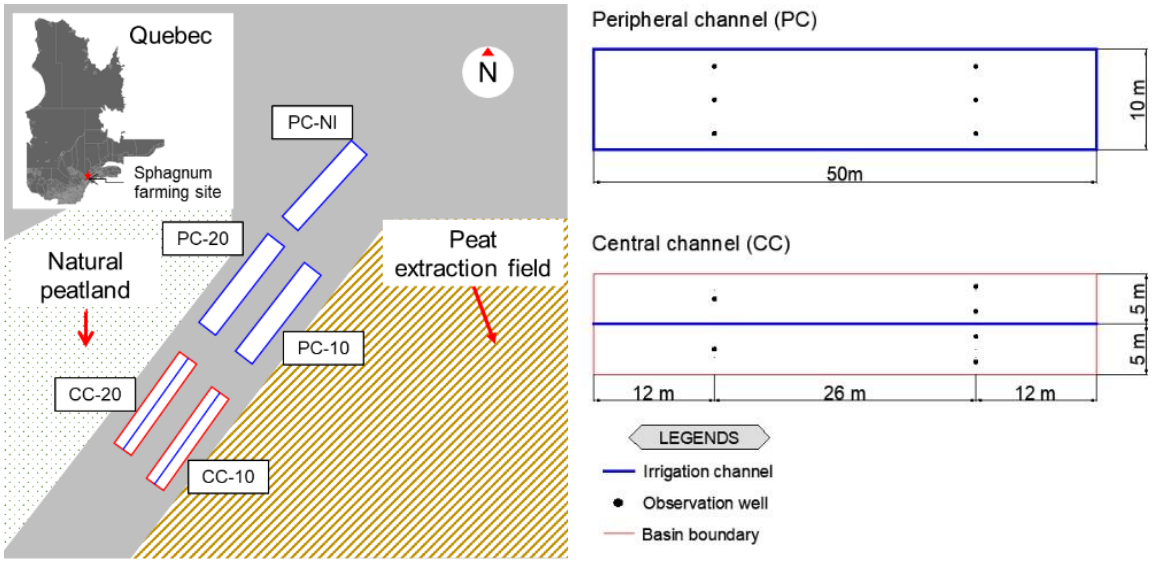

Figure 1.3. Schematic representation of the site with the location of the basins and typical basin configuration.

Table 1.1. Set up description for the five experimental basins for *Sphagnum* farming in Eastern Canada.

Basin ID	Chanel configuration	Target water table level (cm)
PC-NI	Peripheral, non-irrigated	None
CC-20	Central	-20
CC-10	Central	-10
PC-20	Peripheral	-20
PC-10	Peripheral	-10

Bimonthly measurements

Bimonthly measurements were extracted from daily values of water table depth for each well. This time interval was chosen because it was the frequency with which field measurements are normally made. A total of 11 measures were chosen per year, and two years data (2016 and 2017) were used. In other terms, a dataset of 660 bimonthly water table observations were assumed to be taken manually (22 measurements for each well). The water table records from level loggers were verified with the manual measurements taken on outings. The reference of these measurements was the peat surface, which was levelled to obtain zero slopes. The relative position of the wells was recorded with a Prismless Total Station – Model TC905 (Leica Geosystems AG, Heerbrugg, Switzerland). The extracted bimonthly values were considered the infrequent measure of the water table depth. The observed daily values are used to evaluate the performance of estimation methods. For each well, the reference well was chosen as the nearest well, which was generally not further than 3.5 m.

To upsize this dataset of observed bimonthly water table depths used for training, there was the option of using some data augmentation technique, however it was not implemented because time-series data is particularly vulnerable to the transformation of data that occurs while performing data augmentation (Oh et al. 2020).

Estimation methods implementation, calibration and validation

Seven methods were tested: general linear model (*glm*), *k*-nearest neighbours (*knn*), support vector machines (*svm*), decision tree (*tree*), random forest (*rf*), adaptive boosting (*AdaBoost*) and the new method, time series decomposition (*tsd*). The set of seven estimation methods was programmed in Python 3 (Van Rossum & Drake 2009) (version 3.6.9) using the standard scientific libraries (NumPy, SciPy, pandas), statsmodels and scikit-learn packages (Oliphant 2006; McKinney 2010; Seabold & Perktold 2010; Pedregosa et al. 2011; Virtanen et al. 2020). The method architectures of *glm*, *knn*, *svm*, *tree*, *rf*, and *AdaBoost* are shown in Appendix 1.1 and Appendix 1.2.

To avoid model overfit and errors in out-of-sample estimations, the leave-*P*-out cross-validation (Pedregosa et al. 2011) was used to determine method hyperparameters for the *knn*, *svm*, *tree*, *rf* and *AdaBoost* methods. For these cases, *P* was set to 2, so predictions were tested on all distinct samples of size $P = 2$, while the remaining $n - 2$ samples formed the training dataset in each iteration. In calibration, ten resamples of the training dataset were generated for each hyperparameter value to be assessed. A model was fit using each resample data set and used to predict the remaining observations. Minimizing of training and testing root-mean-square error (RMSE, Equation 1.9) was the criterion for the selection of the hyperparameter.

Table 1.2 shows the different hyperparameters used for the training of the methods, the estimated parameters for regression and the number of estimated parameters (*k*). For all methods, except *tsd* which do not require any training, the bimonthly values dataset was divided by the random split function (train_test_split) from scikit-learn python library (Pedregosa et al. 2011). The result of the split was two datasets: a training subset, which contained 80% of data randomly selected and the test subset with the remaining 20%. After the training and calibration of each method, daily estimates were generated and compared with the daily data originally observed. The test dataset was used to assess the generalization ability of the trained model.

Table 1.2. List of hyperparameters used for each method and the number of regression parameters.

Method	Hyperparameters of the method	Estimated parameters for regression	***k***
tsd	No training	0	0
glm	No special consideration	2	a_1, b_1
svm	degree of the polynomial function = 1 linear kernel gamma coefficient automatic	2	w_2, b_2
rf	random state equals zero n_estimators = 2 max depth of the tree = 2	2	f_1, e
knn	n_neighbours = 1 weights based in distance	2	f_1, e
AdaBoost	random state equals zero n_estimators = 1	2	f_1, e
tree	split criteria set by default random state equals zero max depth = 2 min_samples_leaf = 0.3	2	f_1, e

Data analysis and method performance

To quantify the degree of correspondence between the daily estimated and daily observed data, four criteria were considered: Coefficient of determination (R^2), the root-mean-square error (RMSE), the Nash-Sutcliffe Coefficient (NS), and the Akaike information criterion (AIC). These coefficients were calculated according to Equations 2.8 to 2.11.

$$R^2 = 1 - \frac{\sum\left(h_i - \hat{h}_i\right)^2}{\sum h_i^2 - \frac{1}{N}\sum \hat{h}_i^2} \tag{1.8}$$

$$RMSE = \sqrt{\frac{\sum\left(h_i - \hat{h}_i\right)^2}{N}} \tag{1.9}$$

$$NS = 1 - \frac{\sum\left(h_i - \hat{h}_i\right)^2}{\sum\left(h_i - \bar{h}\right)^2} \tag{1.10}$$

$$AIC = N \cdot ln\left(\frac{\sum\left(h_i - \hat{h}_i\right)^2}{N}\right) + 2k \tag{1.11}$$

where h_i are the observed water table depth, $\hat{h}_i$ are the estimated water table depth from each method, $\bar{h}$ is the mean of observed water table depth, N the number of observations, and k is the number of estimated parameters. The best fit between simulated and observed data, the RMSE closer to zero, the AIC lower, the NS and R^2 closer to one. In this study, RMSE and NS statistics are used to measure the method performance for forecasting water table depth, AIC is used to compare the performance of methods regarding accuracy and complexity, whereas R^2 is used to analyze the linear regression goodness of fit between observed and estimated data. Also, for the best fit between simulated and observed data, the intercept and gradient should be close to zero and one respectively to observe over- or under-predictions.

Impact on a practical application: Sum of daily deficit of water table depth

The daily estimates of the water table depth can be used to quantify the annual water stress due to fluctuations of the water table depth in restored bogs. For this publication, the sum of the daily deficit of water table deeper than -15 cm (SDW_{15}) was used to study the error generated by daily estimates from the different methods on the computation of this indicator. This sum is computed for each well as Equation 1.12

$$SDW_{15} = \sum |h_i - (-15)| \quad for\ h_i < -15 \qquad (1.12)$$

SDW_{15} values were computed with the data from the 151 days of observation (May 20th to October 18th) for both years. The SDW_{15} from estimated and observed water table depths were compared using the same performance criteria as in the previous section.

1.7 Results

Water table observations statistics

As expected, the different water management systems (basins) resulted in variability of observed water table conditions (Table 1.3). For basins with a target water table level of -10 cm (PC-10 and CC-10), the water table depth remained close to the surface for both years, with PC-10 having the least variation and a stable level. The basin without any control (PC-NI) was the treatment with the greatest variation in the water table depth. There are significant differences between the water tables observed between basins, except for PC-NI and PC-20.

Methods performance

The results of the method performance evaluation are presented by the Taylor diagram (Figure 1.4), theTable 1.4 and

Appendix 1.3 which show the methods performance. The azimuth angle in the Taylor diagram represents the correlation coefficient (R, dashed lines), the radial distance the standard deviation of estimated water table depth (SD, solid lines), and the semicircles centred at the “Observed” marker the root mean squared error (RMSE, dash-dotted lines). Considering those performance metrics, the seven methods had an overall acceptable performance (R^2 greater than 80%). *tsd* method offers the best performance (R = 0.97, R^2 = 0.95 and RMSE = 2.48 cm). The *glm* and *svm* methods show similar performance (for *glm* R = 0.96, R^2 =0.92 and RMSE = 3.10 cm, for *svm* R = 0.95, R^2 =0.91 and RMSE = 3.24 cm). Finally, *knn*, *rf*, *Adabost* and *tree* were the least performing methods. The inability of a machine learning method to capture the true relationship is called bias. Although this analysis did not focus on the metrics around bias, this study showed that tsd rf and Adaboost methods tend to underestimate while the other methodologies, being glm, svm, knn and tree tend to overestimate (Appendix 1.3).

Table 1.3. Summary of water table depth in the five experimental basins. Number of observations per well (N obs), number of wells per basin (N wells) and descriptive statistics of water table depth: mean, standard deviation (SD), minimum (min) and maximum (max).

Basin ID	N obs	N wells	mean[1]	SD	min	max
			2016			
PC-NI	151	6	-25.33[d]	11.06	-54.25	-0.10
CC-20	151	6	-21.14[c]	7.60	-40.05	0.60
CC-10	151	6	-12.52[b]	6.94	-34.30	1.85
PC-20	151	6	-24.44[d]	8.66	-44.55	-2.25
PC-10	151	6	-9.34[a]	4.75	-25.30	3.50
			2017			
PC-NI	151	6	-26.90[d]	12.48	-51.60	1.40
CC-20	151	6	-21.39[c]	7.45	-44.40	0.45
CC-10	151	6	-11.73[b]	6.27	-35.40	0.50
PC-20	151	6	-24.99[d]	8.24	-43.05	1.40
PC-10	151	6	-5.43[a]	3.30	-21.25	1.40

[1]Means followed by different letters indicate differences, according to Nemenyi (Non-parametric test)

The accuracy and simplicity of the methods is also evaluated using the Akaike information criterion (AIC) which favors models with the lowest RMSE (accuracy) and with the minimum number of estimated parameters (simplicity). The model with the lowest AIC value is privileged which in this case is the *tsd* method, with an AIC of 7628 (Table 1.4).

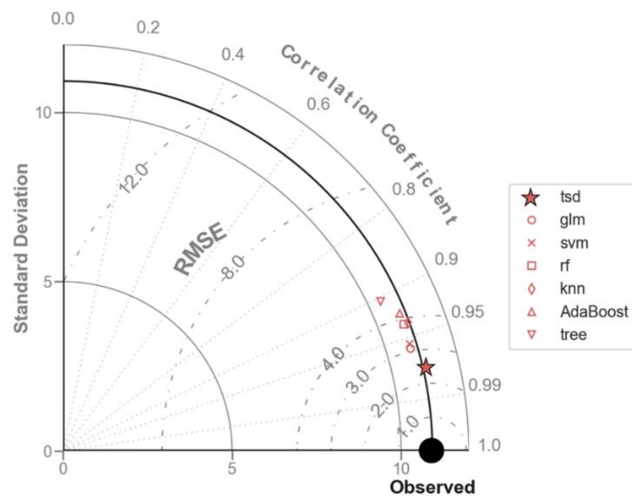

Figure 1.4. Taylor diagram with different statistics (Correlation coefficient – R, standard deviation, Root Mean Squared Error – RMSE and AIC) of the estimated daily water table depth by the seven estimation methods.

Table 1.4. Performance criteria for daily water table depth (cm) estimations by the different methods.

Performance criteria	Methods						
	tsd	***glm***	***svm***	***rf***	***knn***	***AdaBoost***	***tree***
R^2	0.95	0.92	0.91	0.88	0.88	0.86	0.82
RMSE (cm)	2.48	3.10	3.24	3.84	3.87	4.19	4.68
NS	0.95	0.92	0.91	0.88	0.87	0.85	0.82
AIC	7628	10241	10659	12202	12257	12983	13989

The accuracy of *tsd* method, followed by *glm* and *svm* methods for daily water table depth estimation can also observed in specific cases (Figure 1.5). Figure 1.5 (blue lines) presents a near-surface and stable water table depth (basin PC-10, an observation well approximately 1 m from the irrigation channel) and the Figure 1.5 (red lines) also shows more unstable and deeper water table (basin PC-NI, observation well in the middle of the non irrigated basin). In both cases, the estimates with the highest performance in terms of coefficient of determination were those made with the *tsd*, *glm* and *svm* methods. The different water management systems do not affect the order of the best performing methods. When there was larger variation of water table depth, as is the well in basin PC-NI (Figure 1.5, red lines), the estimates were not good for the *AdaBoost*, *tree* and *rf* methods, which show abrupt changes in the depth of water table which do not match the observed values. As evidence of the lower performance, the RMSE for these methods was higher than the other cases (RMSE=7.7 cm for *AdaBoost*, 7.2 cm for *tree* and 4.8 cm for *rf*). When there is a minor variation of water table depth, the model estimates were generally good (RMSE less than 4.5 cm).

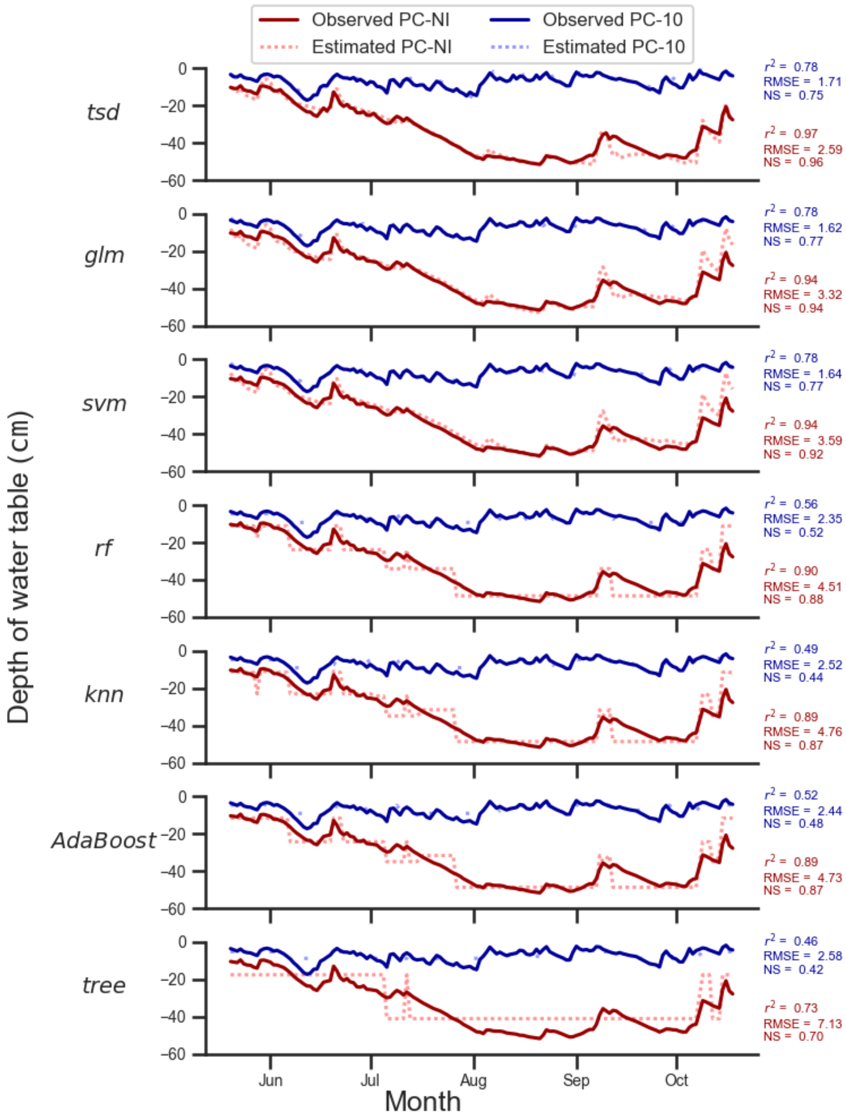

Figure 1.5. Comparison between observed (continuous line) and estimated (dotted line) water table depth for two cases: a well in the middle of the PC-NI basin (red lines), and a well located 1 m from the channel in PC-10 basin (blue lines). Data from 2017.

Impact on the computed daily indicator

To estimate the impact of the error produced by the different methods on cumulative daily indicator computation, Equation 1.12 was used with the observed data and the estimates from each of the seven methods. The Table 1.5 shows the SDW_{15} computed for the six observation wells in each basin. The data show variability within each basin and between basins. Three groups were identified according to multiple non-parametric comparison test of Nemenyi. The first grouping, points where water table depth remained most of the time above or close to -15 cm (a small SDW_{15} value, less than 260 cm-day). This group consists of the wells in basins PC-10 and CC-10. The second group is the basins with a high SDW_{15} value (greater than 1200 cm-day), which means that the water table depth was repeatedly below -15 cm and/or even reached greater depths. This group consists of the wells located at basins PC-NI and PC-20. Finally, the third group consists of the wells in CC-20, which are somewhere in between the two previous groupings.

Table 1.5. Mean SDW_{15} values (cm-days) computed with the water table level observed in the six wells of each basin. Values between parentheses represent the 95% confidence interval.

Basin ID	2016	2017
PC-NI	1729^{b} (1299-2158)	1991^{b} (1552-2430)
CC-20	1065^{ab} (803-1326)	1107^{ab} (644-1573)
CC-10	261^{a} (0-531)	216^{a} (0-467)
PC-20	1495^{b} (1008-1983)	1582^{b} (1142-2021)
PC-10	23^{a} (0-51)	1^{a} (0-3)

Means from observed data followed by different letters indicate differences, according to Nemenyi (Non-parametric test).

Table 1.6 presents performance criteria for the different methods for estimating SDW_{15}. As expected, estimations of water table depth by the *tsd* method to compute the SDW_{15} is the best performing method with the highest R^2 and the lowest RMSE. A RMSE of 131 cm-day is quite low in regard of the range of computed SDW_{15} (Table 1.5).

Table 1.6. Performance criteria for SDW_{15} (cm-day) estimations by the different methods.

Performance criteria	Methods						
	tsd	***glm***	***svm***	***rf***	***knn***	***AdaBoost***	***tree***
R^2	0.98	0.95	0.94	0.95	0.96	0.89	0.95
RMSE (cm-days)	131	200	215	198	182	377	201
NS	0.98	0.95	0.94	0.95	0.96	0.87	0.95

Selection of the reference well

For the evaluation of the different methods, the reference well was chosen as the nearest well (not further than 3.5 m). The selection of the reference well (e.g., based on distance) can have an impact on the estimation performance. To test the impacts (notably on the RMSE estimation) of the selection of the reference well, *tsd* method was chosen with those two cases:

A reference well within the basin: one well was randomly selected per basin as the reference well and, the water table depths for the remaining five wells in the basin were re-estimated. This was done for every basin.

A reference well within another basin: The same reference wells of the previous case were chosen, but in this case the estimation of the daily water table depths is made over the wells of all basins. The procedure is repeated for each reference well and is identified as a run in Table 1.7.

Variations in RMSE were calculated and are presented in Table 1.7, including the case using the nearest well. Changing the nearest well to a random reference well belonging to the same basin, an RMSE increase of 12% (2.48 to 2.77 cm) was observed, and to a random reference well in another basin, the increase was 39% (2.48 to 3.45 cm) on average with five repetitions (runs). The increase made by choosing a random reference well in another basin is expected because those other basins does not have the same water management or hydraulic network type which may influence the daily fluctuation. So, it is preferable that the reference well be chosen from wells belonging to the same basin. Table 1.7 also shows that the basins with higher water table depth fluctuation (PC-NI, CC-20, PC-20), shows larger RMSE.

Table 1.7. Analysis of the RMSE (cm) according to the selection criterion for the reference wells.

Basin ID	Nearest well	Whitin the basin	In another basin				
			Run 1 PC-NI[1]	Run 2 CC-20[1]	Run 3 CC-10[1]	Run 4 PC-20[1]	Run 5 PC-10[1]
PC-NI	3.38	3.29	-	3.89	3.41	2.99	3.47
CC-20	2.71	3.97	3.76	-	2.68	2.92	2.94
CC-10	1.78	2.29	4.47	4.50	-	3.26	1.83
PC-20	2.85	2.36	3.34	3.40	3.01	-	2.98
PC-10	1.10	0.97	4.52	4.45	2.52	3.21	-
Aggregated	**2.48**	**2.77**			**3.45**		

[1]basin of the reference well

Figure 1.6 shows that the error between observed and estimated water table level (h_i - $\hat{h}_i$) is not influenced by the distance to the reference well belonging to the same basin.

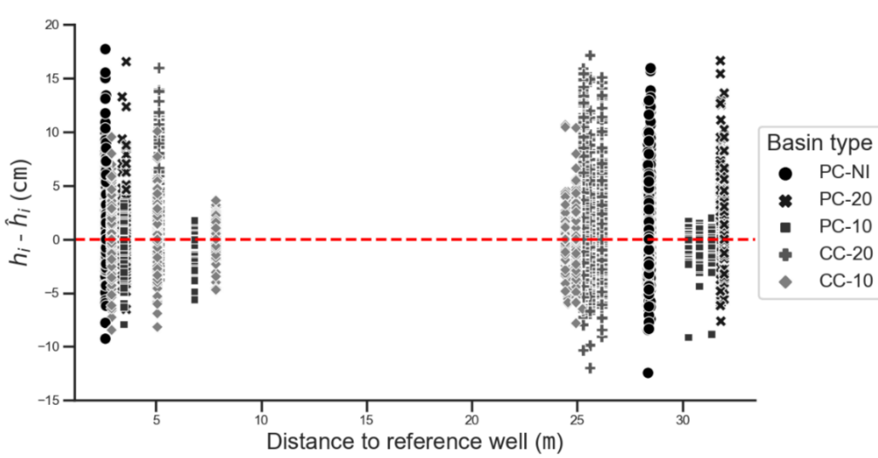

Figure 1.6. Computed values of the error between observed (h_i) and estimated ($\hat{h}_i$) water table depths. The estimated water table depths are based on reference wells belonging to the same basin.

Measurement frequency

The measurement frequency could influence the performance of the estimation methods. After extracting the bimonthly data, the same estimation procedure was also done with the *tsd* method with a weekly and monthly measurement frequency. As show in Table 1.8, the correlation coefficient increases when the measurement frequency is higher. Changing the measurement frequency to weekly measurements decreases the RMSE by 16% (2.08 cm) and to monthly increases the RMSE by 13% (2.80 cm). The *tsd* method can be used with monthly measurements but it leads to higher error.

Table 1.8. Performance criteria for daily estimations of water table depth by the *tsd* method using different measurement frequencies for infrequent data.

Measurement frequency	Performance criteria		
	R^2	RMSE (cm)	NS
Weekly	0.96	2.08	0.96
Bimonthly	0.95	2.48	0.95
Monthly	0.94	2.80	0.93

1.8 Discussion

tsd method performance explanation

According to the criteria performance shown in Table 1.4, *tsd* yielded the lowest RMSE, the lowest AIC and the highest R^2 scores. The RMSE statistics, which is a measure of residual variances between observed and simulated data, was the lowest for *tsd* method. *tsd* predictive accuracy is higher for two reasons:

First, *tsd* uses an appropriate methodological principle. It estimates the daily water table depth as the result of a local component and a regional component, which is observed in real data (Figure 1.1). This type of method considers regional sensitivity (Corzo & Solomatine 2007) and uses a physical concept, which is advisable (Zhao et al. 2020). Moreover, *tsd* method keeps the known data (bimonthly observations) for the estimated well. The other methods generate new data, even for the observed data which is contra-intuitive.

Second, this method considers the time series properties which the other methods do not consider. Time series data show auto-correlation from day-to-day data which the *tsd* method capture by the trend component. The other methods consider daily data as independent. Furthermore, the *tsd* method also captures the local impact of daily phenomena (precipitation, irrigation) through the daily fluctuation from the trend of the reference well without any additional step. Therefore, the estimated water table hydrograph is more realistic than those obtained by the remaining methods (Figure 1.5).

The *tsd* method is also interesting because it does not require any training and it is easy to implement. It can even be used for short observation periods. The testing of this method at other restored ombrotrophic peatlands will be of interest for generalization.

Estimation performance by the range of water table depth variation

When estimations are made regardless of the method, the wells with less variation of the water table level (SD value less than 6 cm, as the example in Figure 1.5, blue lines), show a lower R^2 than the wells with greater variation of the water table level (SD value greater than 8 cm, as the example Figure 1.5, red lines). However, the RMSE is lower for wells with less variation of the water table observations. The range of variation is smaller and for the calculation of R^2 (Equation 1.8), the denominator $[\sum(h_i^2) - (1/N) \cdot \sum(\hat{h}_i^2)]$ becomes smaller. This causes the R^2 to decrease, even though the RMSE is low.

Estimation of daily indicator

According to the computed SDW_{15} values (Table 1.6), *tsd* is the method that estimates values with the least RMSE value. The performance of the method for estimating SDW_{15} follow a similar order of the performance for estimating the daily water table depth, which is not surprising. Because SDW_{15} is a sum, the probable error accumulates according to the square root of the several measurements (Lagacé 2016), in this case, 151 measurements. The probable error of the SDW_{15} based on the estimates can be expressed as Equation 1.13:

$$Error_{SDW15}^2 = (N - n) \cdot RMSE^2 + n \cdot E_h^2 \qquad (1.13)$$

where *N* is the total number of daily estimations, E_h is the error of the water table measurement given by the level logger and the barometric correction and *n* is the number of bimonthly measurements. The probable error can then decrease as more real measurements of the water tables depth are made (in this case bimonthly measurements). For this reason, *tsd* is an interesting estimation method as the coefficient (*N* - *n*) can be reduced. For the other methods (as *svm* and *glm*), *n* is *0* since the bimonthly measurements are used in the training stage and not kept in the generated testing dataset. Since (*N* – *0)* and the RMSE are higher than *tsd* case, this greatly increases the probable error of the sum.

Choice of the reference well

Fluctuations in the water table depth are influenced by water inputs and outputs (precipitation, irrigation and evapotranspiration) and essentially by the configuration and management of the hydraulic network of channels (Price 2001; Price et al. 2003; Holden et al. 2004, 2011). This explains why reference wells belonging to the same basin show lower RMSE than for reference wells belonging to a different basin. The reference well must preferably belong to the same basin's hydraulic network and management. Table 1.7also shows that in some basins (PC-NI, PC-20 and PC-10) that the randomly selected reference well within the basin give a lower RMSE than the original case (the nearest well). This suggest that the nearest well may not be the best choice and other selection strategies may yield better results. This must be further investigated.

1.9 Conclusions

This paper identifies six methods from the literature (*glm*, *svm*, *rf*, *knn*, *AdaBoost* and *tree*) for estimating daily water table depth with bimonthly measurements and daily measurements of some reference wells. It also presents a new method (the time series decomposition, *tsd*), which divides the time series in periods and for each of these periods it determines a trend component and daily fluctuation component. These methods were used to estimate the daily water table depths over two years at a five-*Sphagnum*-cultivation-basin site and, each basin had six observation wells. The *tsd* method was the best-performing method (R^2 = 0.95, RMSE = 2.48 cm, NS = 0.95 and the lowest AIC) following by *glm* (R^2 = 0.92, RMSE = 3.10 cm, NS = 0.92) and *svm* (R^2 = 0.91, RMSE = 3.24 cm, NS = 0.91).

The methods evaluated allows the computation of SDW_{15}, a way of quantifying daily water stress. This indicator varies according to the location of the well and the basin type with computed values between 0 and 2860 cm-days. The *tsd* method is the best method computing SWD_{15} (R^2 = 0.98, RMSE = 131 cm-days, NS = 0.98), which is not surprising.

The *tsd* method was also tested with weekly and monthly measurement frequency. Changing the measurement frequency to weekly measurements decreases the RMSE by 16% (2.08 cm) and to monthly increases the RMSE by 13% (2.80 cm) in comparison to bimonthly measurements (RMSE 2.48 cm).

It is preferable to choose the reference well from within the same hydraulic network and management. The distance from the reference well does not have impact on the RMSE. The selection strategies of the reference well need further investigation. Also, further data collection would be of interest to test the *tsd* method performance on other sites and other fluctuation regimes of water table depth.

Implications for practice

- The new methodology for estimating water table values based on time series decomposition (*tsd*) can be used if there is at least one observation well with daily record per group of basins with the same water regime and preferably weekly logs in all observation wells.

- In case of not being able to have weekly records in all observations wells due to lack of resources or personnel, the same methodology can be used, with the limitation of increasing the estimation error.

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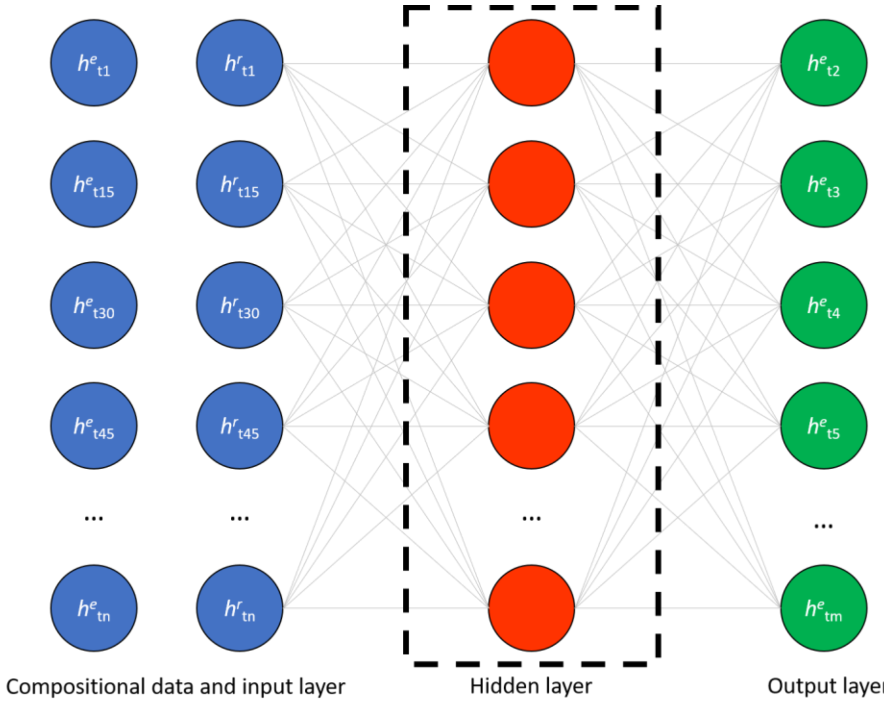
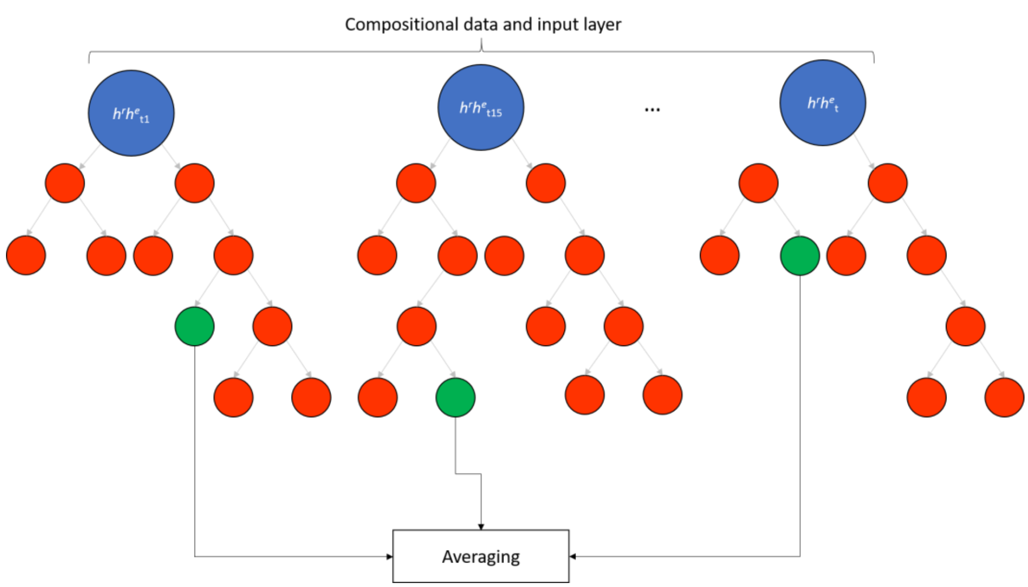
Appendixes

Appendix 1.1. Machine learning architecture for *glm*, *svm*, *knn* and *AdaBoost* method. The input layer is composed of the bimonthly water table levels of the estimated (h^e) and the reference well (h^r). The hidden layer depends on the method, explained in Section 1.2.



Appendix 1.2. Machine learning architecture for *tree* and *rf*. In the case of the *tree* method, only one decision tree is established.



Appendix 1.3. Additional criteria to address bias in estimation methods.

Additional criteria	Methods						
	tsd	***glm***	***svm***	***rf***	***knn***	***AdaBoost***	***tree***
Percentage bias (%)	0.50	-0.05	-0.84	0.31	-0.25	0.82	-0.75
Mean bias error, MBE (cm)	-0.09	0.01	0.16	-0.06	0.05	-0.15	0.13
Mean squared error, MSE (cm^2)	6.15	9.58	10.51	14.77	14.95	17.55	21.92

Chapitre 2 : Seasonal indicators as key descriptors of water stress in Sphagnum farming systems

Sebastian Gutierrez Pacheco, Robert Lagacé, Mélina Guêné-Nanchen, Sandrine Hugron, Stéphane Godbout et Line Rochefort

2.1 Résumé

La paludiculture, sous la forme de la culture de la sphaigne, est un moyen renouvelable et cyclique de produire de la fibre de sphaigne. La durée et la fréquence du stress hydrique dû au niveau de la nappe phréatique dans le profil de la tourbe est un facteur clé du taux d'accumulation de la biomasse dans la culture de la sphaigne. Pour des résultats optimaux, il est nécessaire de définir les seuils de la nappe phréatique au-delà desquels la productivité de la sphaigne diminue. Dans cet article, le nombre de déficits quotidiens en eau (NDW), la somme des déficits quotidiens en eau (SDW) et la moyenne saisonnière de la nappe phréatique (ħ), sont examinés pour quantifier le stress hydrique. La compilation de cinq années de culture expérimentale de sphaigne, à la fois sur des tourbières réaménagées et dans des mésocosmes en serres, a été utilisée pour construire un ensemble de données couvrant une large variation du niveau de la nappe phréatique. Cette étude renforce l'idée que plus le stress hydrique est élevé, plus la productivité des espèces de sphaigne est faible. Parmi les indicateurs de stress hydrique analysés, NDW et SDW ont une corrélation plus forte que celle de ħ avec la productivité des sphaignes. Les seuils de la nappe phréatique correspondent aux niches écologiques préférentielles de la sphaigne pour la profondeur moyenne de la nappe phréatique, et ses valeurs sont comprises entre 7 et 20 cm, ce qui est plus élevé que dans la restauration des tourbières, qui est de 40 cm.

2.2 Abstract

Paludiculture, in the form of *Sphagnum* farming is a renewable and cyclical way to produce *Sphagnum* moss fiber. The duration and frequency of water stress due to the positioning of the water table level in the peat profile is a key driver to biomass accumulation rates in *Sphagnum* farming. For optimal outcomes, it is necessary to define the thresholds depth of water table beyond which the *Sphagnum* productivity decreases. In this article, the Number of daily Deficit of Water (NDW), the Sum of daily Deficit of Water (SDW) and the seasonal average water table (ħ), are examined to quantify water stress. The compilation of data from five years of experimental *Sphagnum* farming, both in managed peatlands and in greenhouse mesocosms, was used to build a dataset covering a wide variation of water table levels. This study strengthens the idea that the higher the water stress, the lower the productivity of the *Sphagnum* species. Among the water stress indicators analyzed, NDW and SDW have stronger correlation with *Sphagnum* productivity than ħ. The thresholds depths of water table

correspond to the *Sphagnum* preferential ecological niche for average water table depth, and its values range from 7 to 20 cm, which is shallower than the 40 cm threshold for successful peatland restoration.

2.3 Introduction

Sphagnum farming is defined as the sustainable production of *Sphagnum* biomass on a renewable and cyclical basis (Pouliot et al. 2015) and often takes place in reclaimed peatlands (Gaudig et al. 2018; Gutierrez Pacheco et al. 2021). Cultivated moss fiber from *Sphagnum* farming could be used as a sustainable alternative to partly diminish the need of extracted peat from peat deposit as a constituent of growing media (Jobin et al. 2014; Aubé et al. 2015). Moreover, *Sphagnum* farming can also be used to provide plant material to restore degraded peatlands, such as those where peat has been extracted for horticultural purposes (Glatzel & Rochefort 2017; Hugron et al. 2020). Paludiculture, in the form of *Sphagnum* farming is proposed as a nature-based solution for climate change mitigation by transforming disturbed peatlands and even agricultural pastures into carbon sinks (Pouliot et al. 2015; Gaudig et al. 2017; Ludwig 2019).

From several experiments done to develop methods to grow *Sphagnum* mosses in farming basins, it has been established that a better control of the hydrological parameters (e.g., soil water tension, water table level) was one of the key drivers to achieve optimal biomass accumulation rates (Price et al. 2002; Pouliot et al. 2015; Brown et al. 2017). The goal of controlling these hydrological parameters is to ensure sufficient water flow to the *Sphagnum* capitula to support its establishment and growth. It is known that growth and most of the photosynthetic activity occur at the *Sphagnum* capitula (Clymo & Hayward 1982). Sufficient water flow to the *Sphagnum* capitula is essentially fulfilled when the water table level is sufficiently high. A water table close to the *Sphagnum* capitula increases the number of water-filled pores, represented by an increase in the hydraulic conductivity of the *Sphagnum* and the peat (Lagacé 2016; Golubev & Whittington 2018).

However, a shallow and stable water table is difficult to maintain uniformly in large-scale field basins, mainly due to two reasons: The first reason is the natural variability of the basin. For example, peat porosity changes both spatially and temporally due to biological processes, such as microbial decomposition (Siegel & Glaser 2006) or the specific botanical composition at different locations forming the peat (Graf & Rochefort 2009), affecting groundwater flow. The second reason is the parabolic profile of the water table created by the irrigation canals. Even if the drainage network is adapted by wooden dams to retain water over summer (Pouliot et al. 2015; Guêné-Nanchen et al. 2017), it was shown that water table level is not uniform because of the hydraulic gradient, which causes the water table level to be higher near the channel than in the center of the basin (Price & Whitehead 2001). The water table level at two different points at the same time of measurement can vary by up to 30 cm in *Sphagnum* farming fields, and such variations affect ground cover and productivity of *Sphagnum* moss (Brown et al. 2017; Kim et al. 2021).

The mean water table level as water deficit indicator

A realistic criterion for determining the soil water availability for plants is the soil matric potential, also called soil water tension (Singh et al. 2014). It has been shown that below -100 mbar (-100 cm) *Sphagnum* growth is gradually reduced (Price & Whitehead 2001). Soil water tension constitutes the force by which water is retained in the soil matrix and is measured by a tensiometer. However, tensiometers do not work well in porous media such as *Sphagnum* moss and peat, which can have a porosity greater than 90% (Boelter 1969; Cornejo et al. 2005). Measuring suction in *Sphagnum* moss with a tensiometer is not recommended because of poor contact with the ceramic tip (Kennedy & Geel 2000). In addition, the tensiometer is not a proper tool for predicting water stress in porous medium such as peat. Besides, the water table level has been shown to strongly control soil water tension and thus the water stress on *Sphagnum* (Moore & Waddington 2015) at least for the first 40 cm, and after that, at a deeper water table the relationship is poor (Price & Whitehead 2001).

In the context of *Sphagnum* farming, the water table level is the usual indicator for water management and water stress assessment. Water table measurements are affordable, easy to implement, and readings can be recorded automatically when no staff is available. In a similar context as the restoration of drained peatlands, many studies have used the mean annual water table level to assess rewetting success (LaRose et al. 1997; Landry & Rochefort 2012) and assist in the interpretation of surface vegetation development (Andersen et al. 2010; González et al. 2014). The evaluation of the water table position relative to the *Sphagnum* capitula or the peat surface is an effective method to estimate the water available for the non-vascular *Sphagnum* mosses that rely primarily on capillary rise (Clymo 1973; Clymo & Hayward 1982). Several researchers have shown that *Sphagnum* growth is at its optimum when the water table is located just below the capitula, regardless of the species preferential ecological niche for average water table depth (Hayward & Clymo 1983; Campbell & Rochefort 2001; Robroek et al. 2009; Kim et al. 2021).

Associating annual *Sphagnum* growth with the average annual water table position does not consider the amplitude of water table variation or the number of times the water table remained at critical depths for *Sphagnum* productivity, which causes water deficit. Brown et al. (2017) are of the opinion that the range of oscillations in seasonal water table level was more important than the average water table position for CO_2 uptake by *Sphagnum* mosses. Repetitive dry conditions resulted in generally lower aboveground net primary production (Weltzin et al. 2000). Mechanistically, Kim et al. (2021) have shown that water table fluctuation inhibited the growth of *Sphagnum* due to fungal infection.

The average value of the water table level over a season or a month does not consider either the duration or the magnitude of the water deficit. Thus, if a single drought event can affect plant productivity, the cumulative effect of prolonged drying events could be far more important (Schouwenaars & Gosen 2007; Taylor et al. 2016).

Figure 2.1 shows two cases with different water management systems where this situation is demonstrated. Both cases were recorded in the third growing season at an experimental *Sphagnum* farming system in Eastern Canada and the *Sphagnum* species considered is *Sphagnum rubellum*. The solid lines represent the daily water table position recorded, and the dotted lines represent the average water table level for each case. There are no significant differences (*p*-value = 0.18) in the average depth of the water table between both cases. For case A, the average water table was 14.4 cm below the surface while for case B it was 16.5 cm below the surface. However, as can be seen in Figure 2.1, there was a greater amplitude of variation for the water table level in the case B where it dropped several times to a depth of 30 cm. A water table depth at 30 cm from the surface has been reported to be detrimental to *Sphagnum* growth (Price 1997; Górecki et al. 2021). As a result, there was a difference in the *Sphagnum* biomass harvested at both cases reaching 366 and 175 g m^{-2} for case A and B, respectively. This example shows that the seasonal average of the water table position does not consider the magnitude and duration of a drought event affecting the growth of *Sphagnum* species, hence the importance of determining complementary information on water deficiency.

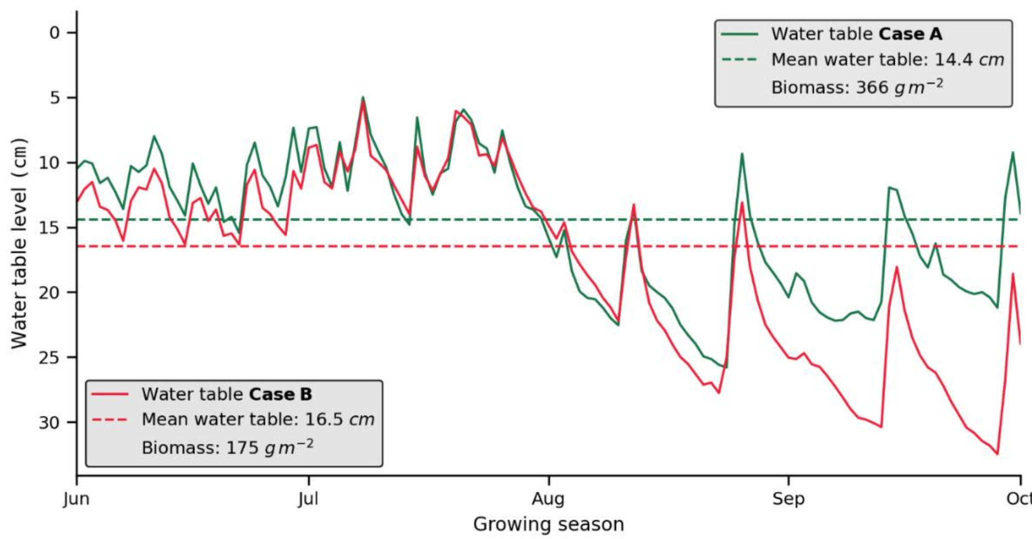


Figure 2.1. Examples of recorded water table levels for two water management systems in a *Sphagnum* farming system in Eastern Canada during the third growing season.

Seasonal water deficit indicators based on daily-water-stress

In the absence of extreme conditions, such as drought or flooding, plants grow in a cumulative staggered manner. However, their growth is strongly influenced by environmental conditions, particularly by the duration and frequency of drought periods. A drought period is represented by high temperatures and/or deep water levels below ground. While the effect of environmental temperature on the growth of *Sphagnum* has been widely studied under the concept of heat accumulation, related to physiological development (Thormann & Bayley 1997; Breeuwer et al. 2008; Flanagan & Syed 2011; Gerdol & Vicentini 2011; Mironov et al. 2019; Campbell & Rydin

2019), little attention has been paid to the duration and frequency of water stress due to deep water table level and its effects on *Sphagnum* growth. The first step to this effect is to define a methodology for the quantification of seasonal water deficit.

The concept of seasonal stress by detrimental water table levels is used in corn production (Kanwar et al. 1988; Haan & Skaggs 2003; Kuang et al. 2012) wheat production (Malik et al. 2001) and soybean production (Evans et al. 1990, 1991). The results on agricultural crops consider that the response to water stress varies according to the species and phenological stage. Phenological stages are not obviously apparent in mosses, so the term growing seasons is used instead of phenological stage in *Sphagnum* farming (Pouliot et al. 2015).

The principal indicator used is the sum of daily exceedances from a 30 cm depth (SEW_{30}, Smedema, 1988). SEW_{30} is a measure of cumulative daily stress caused by excessive soil saturation conditions within the root zone, assumed to be the first 30 cm of the soil profile. The SEW_{30} is calculated during the period of interest, usually the growing season (Hiler 1969; Hardjoamidjojo & Skaggs 1982). This indicator assumes that a water table above 30 cm reduces crop productivity due to lack oxygenation in the root zone. The SEW_{30} indicator is a measure of the stress degree imposed on the crop and reflects both the intensity and duration of excess water stress. Mathematically, the SEW30 value during the entire monitoring period (*n* days) can be calculated as in Equation 2.1:

$$SEW_{30} = \sum_{i=1}^{n}(30 - h_i) \qquad (2.1)$$

where h_i is the daily registered water table below the soil surface. Negative values of summation are neglected.

Based on this concept, other seasonal water stress indicators based on water table depth (*h*) have been developed.

1. Sum of daily Deficits of Water (SDW) calculated as Equation 2.2 (Smedema 1988):

$$SDW_x = \sum_{i=1}^{n}(h_i - h_{DT}) \qquad (2.2)$$

where h_{DT} is the threshold depth of water table from deficit stress begins. As well as h_i, h_{DT} is determined below the surface of the peat. Negative values of summation are neglected.

2. Number of daily Deficits of Water (NDW) calculated as Equation 2.3 (Smedema 1988):

$$NDW = \sum_{i=1}^{n} \begin{matrix} if\ h_i > h_{DT}\ then\ value = 1 \\ if\ h_i \leq h_{DT}\ then\ value = 0 \end{matrix} \tag{2.3}$$

Howie et al. (2020) reported an initial exploration of SDW in the context of peatland vegetation occurrence. In their work, they use the sum of levels deeper than 0 cm (h_{DT} = 0). However, the selection of the threshold at which water deficit stress begins must be consistent with the physiology of the *Sphagnum* moss crop. Thresholds depths of water table correlated with water stress are related to species preferential ecological ranges for water table depth (Campbell and Rochefort, 2001). For example, *Sphagnum* mosses colonizing depressions, mostly species of the subgenus Cuspidata in bogs, are adapted to grow in a very humid environment, sometimes forming floating mats. Further, hummock-typical species, such as *Sphagnum* fuscum or lawn species such as *Sphagnum* rubellum, can tolerate deeper water tables. Campeau and Rochefort (1996) indicated that hummock species such as *Sphagnum fuscum* can tolerate deep water tables better than depression species. Thresholds could also be determined on the response of *Sphagnum* photosynthetic activity in relation to water table (Harley et al. 1989; Murray et al. 1989; Schipperges & Rydin 1998). So far, there is no clear methodology known to determinate the threshold related to seasonal water deficit indicators for *Sphagnum* farming.

The primary objective of this paper was to establish a methodology to quantify water stress due to the positioning of the water table level in the peat profile water table fluctuations, particularly when the water table level drops to depths known to impact *Sphagnum* productivity. Although water table depth is commonly used to assess the hydrological function of *Sphagnum* farming systems, complementary information on water deficit could serve as an additional assessment tool if it is shown to be related to productivity of *Sphagnum* species. A secondary objective of the study was to determine the threshold depth of water table below which the productivity of each *Sphagnum* species begins to decline.

To quantify water stress and compute the water stress indicators, a large amount of data is needed, especially covering a wide variation of the water table level. For this purpose, information from five years of experimental *Sphagnum* cultivation was used. This database concerns three selected systems located in Eastern Canada where the water table level and *Sphagnum* productivity were recorded at different locations.

2.4 Methods

Description of experimental systems

A first experimental site was the *Sphagnum* farming system located in Saint-Modeste (Quebec, 47°49'55" N 69°27'55" W) established in 2012 (Gutierrez Pacheco et al. 2021), hereafter named the Hemiboreal site based on Köppen-Geiger climate classification (Kottek et al. 2006). The average air temperature and cumulative precipitation between May and October were 12.9 °C and 494 mm, respectively (Environment Canada 2021). Six basins (50 m x 10 m) that covered about 3000 m^2 were built within the natural margin of a peat extracted bog on moderately well-decomposed peat (H3–H5 on the von Post scale, mean peat depth of 1.6 m). Of the six basins of the system, four were irrigated basins with two different types of channel configuration (Table 2.1), and the other two basins were not irrigated. The irrigated basins were automatically fed by water collected from the drainage system of the industrial bog (water supply source data: pH = 5.6 ± 0.4, EC = 267 ± 163 $\mu S\ cm^{-1}$). The water table regimes (Table 2.1) were controlled through an automated irrigating installation. The water level in basin channels was monitored by ultrasonic sensors installed at the dams (water outlet of each basin). Thus, when the water level was lower than the targeted level, the pumping system was activated to irrigate the channels. The species cultivated on the Saint-Modeste system were *S. medium* (Hassel et al. 2018), *S. papillosum* and *S. rubellum* and they were manually reintroduced using an area ratio of 1:10. This ratio indicates that moss collected from 1 m^2 of donor site with 10 cm collecting depth was spread over 10 m^2 of restored peatland surface.

A second *Sphagnum* farming system was located in Shippagan (New Brunswick, 47°41'35" N 64°45'47" W) and was established in 2013 in a former block-cut peatland (Brown et al. 2017; Goulet, 2019). This *Sphagnum* farming system is hereafter identified as the Atlantic maritime system because its climate characteristic. The mean air temperature between May and October was 14.0 °C and mean cumulative precipitation between May and October of 511 mm (Dataset from 2000 to 2020, Environment Canada, 2021). From 1940 to 1970, peat was extracted using the manual block-cut method, leaving a topography characterized by alternating baulks and trenches. In 2013, six cultivation basins (50 m x 20 m) were implemented over 6000 m^2. Each basin had a different channel configuration, detailed in Table 2.1. In essence, the basins were grouped into two groups and a different water table level target were assigned to each group, namely 10 and 20 cm below the surface. The six basins were established on slightly-to-moderately-well-decomposed peat (von Post H2–H5, mean peat depth of 1.5 m). The water table regime was also controlled through an automated irrigating installation and each basin was assigned a different water table regime (Table 2.1). Basins were irrigated with water coming from a nearby peatland lake (water supply source data: pH = 4.9 ± 0.5, EC = 104 ± 19 $\mu S\ cm^{-1}$). The excess of water in the channels was evacuated by a check valve actuated by a linear actuator (Goulet 2019). The species introduced for cultivation were *S. flavicomans* and *S. medium* (Hassel et al. 2018), and they were manually reintroduced using an area ratio of 1:10 as explained above.

Finally, an indoor *Sphagnum* culture system was established within the Université Laval greenhouses complex (Quebec, 46°46'32" N 71°16'58" W) using mesocosms (Kim et al. 2021). This *Sphagnum* farming system is hereinafter referred as Mesocosms system. The data used in this paper is from April 2016 to April 2017. The mesocosms consisted of plastic containers measuring 110 cm × 72 cm × 100 cm (length × width × height) which were filled with horticultural peat (von Post H3). The air conditions in the greenhouse were set at 22 °C and 50% of relative humidity during the day, and 18 °C and 85% of relative humidity during the night. Three squared meters for each species were harvested at the Saint-Charles-de-Bellechasse bog (Quebec, 46°45'30" N 70°59'33" W) and only the first 10 cm from the surface was collected. The species introduced for the experiment were *S. rubellum*, *S. medium* (Hassel et al. 2018), and *S. fallax*. *Sphagnum* mosses were spread as fragments of approximately 5 cm long with capitula, on the peat surface in the mesocosms using an area ratio of 1:5. The *Sphagnum* fragments formed a carpet about 1-cm thick covering all the mesocosm surface. The water level in each mesocosm was maintained independently, between 0 to 25 cm below the peat surface, by inverted siphons which controlled the respective water table regimes (Table 2.1). Twice a week, the mesocosms were watered with rainwater until the excess water escaped in the inverted siphons.

For all *Sphagnum* farming systems, the start of each production cycle was established according to an adaptation of Moss Layer Transfer Technique (Quinty & Rochefort 2003; Graf et al. 2012; Pouliot et al. 2015).

Table 2.1. Description for the three experimental systems for *Sphagnum* production.

Experimental system	Mesocosm or basin ID	Drain or channel configuration	Target water table depth (cm)	*Sphagnum* survey
Hemiboreal	PC-20	Peripheral	20	The number of *Sphagnum* samples varies over the five-year experiment. Between 63 and 143 samples of *Sphagnum* biomass and 360 samples of *Sphagnum* carpet thickness were collected along 12 transects systematically disposed.
	PC-10		10	
	PC-NI		Non-irrigated	
	CC-20	Central	20	
	CC-10		10	
	NC-NI	No channel	Non-irrigated	
Atlantic maritime	PC-20	Peripheral	20	The number of *Sphagnum* samples varies over the four-year experiment. About 228 to 239 samples of *Sphagnum* biomass and 600 samples of *Sphagnum* carpet thickness were collected in 25 x 25 cm quadrats along 10 transects that were systematically disposed across the length of basins.
	PC-10		10	
	CD-20	Central drain linked to an irrigation channel on the shorter side of the basin	20	
	CD-10		10	
	LC-20	Four drains linked to an irrigation channel located on the longer side of the basin	20	
	LC-10		10	
Mesocosms	SF	Water table in the mesocosms was controlled by an inverted siphon	Slow fluctuation. Fluctuating water table between 5 and 35 cm over a 30-day period	All the *Sphagnum* biomass in the mesocosms was collected at the end of the 12-month long experiment. The thickness of the *Sphagnum* carpet was measured five times per mesocosm at the end of the experiment. In total there were 20
	FF		Fast fluctuation. Fluctuating water	

Experimental system	Mesocosm or basin ID	Drain or channel configuration	Target water table depth (cm)	*Sphagnum* survey
			table between 5 and 35 cm over a 10-day period	mesocosms (Three experimental units with three different species per mesocosm).
	SWT:0–5		Stable water table between 0 and 5 cm	
	SWT:10–15		Stable water table between 10 and 15 cm	
	SWT:20–25		Stable water table between 20 and 25 cm	

Sphagnum survey

Sphagnum carpet thickness were measured annually using a millimetric ruler. For outdoor experimental systems, the value per sampling point was the average of five measurements, one in each corner of the 25 cm x 25 cm quadrat and one more in the center of quadrat. Sample points for *Sphagnum* carpet thickness were chosen according to a systematic *Sphagnum* survey, which varies among systems (Table 2.1). For the Mesocosms system, there were 20 mesocosms with three experimental units each (all species grown together within a same mesocosm). In total there were 60 experimental units (5 water table treatments x 3 species x 4 blocks). Five measurements were taken per experimental unit. In other words, four times at the experimental unit corners and once in the center. The measurements allow to know the cumulative change of the *Sphagnum* carpet thickness but not the annual *Sphagnum* elongation.

Samples for accumulated *Sphagnum* biomass measurements were collected at the end of each growing season. For the outdoor experimental systems, biomass sampling was done annually, generally between September and October, and for the Mesocosms system sampling was conducted about 13 months after the introduction of the planting material. Biomass samples were collected along transects perpendicular to the length of the basin, and the number of samples per transect varied for each system (Table 2.1). Biomass sampling points were moved from one year to the next to make sure not to sample in areas disturbed in previous years of sampling. A variation in sampling efforts from season to season and between basins was present and was due to labor and basin size constraints. Biomass samples were collected in 25 cm x 25 cm quadrats where all the vegetation newly formed on the residual peat was harvested. Then, different *Sphagnum* species, other mosses, vascular plants, and straw mulch were separated, dried at 70 ˚C and weighted (error of about 1 mg). *Sphagnum* biomass accumulation was calculated as the ratio of dry biomass (g) and the sample area (0.0625 m^2). Since the

Sphagnum biomass sampling points vary annually, the measure is expressed as *Sphagnum* biomass accumulation and not as annual *Sphagnum* productivity.

Water table monitoring and estimation

Observations wells were made of 2-inch diameter PVC. The wells were 1-m long, and they were installed to a depth of approximately 80 cm using an auger. The wells were slotted every 2 cm and they had nylon stockings on the outer surface to prevent the entry of solids in suspension. To record the water table in the wells, there were wells instrumented with pressure transducers and wells that were only monitored manually. For instrumented wells, water table depth was recorded every hour by pressure transducers (U20 HOBO, Onset Computer Corporation, Bourne, MA, USA, accuracy: ± 0.5 cm and Levelogger Edge 3001, Solinst, Georgetown, ON, Canada, accuracy: ± 0.75 cm). The barometric compensation method was used to obtain the corrected hourly readings of the water table and field-installed barometers were used for this purpose (U20-001-04 HOBO, Onset Computer Corporation, Bourne, MA, USA, accuracy: ± 0.3 cm and Barologger Gold—Model 3001, Solinst Canada Ltd., Georgetown, ON, Canada, accuracy: ± 0.75 cm).

The daily value of the water table depth was estimated from hourly measurements as the average between the maximum value ($h_{max,\ i}$) and the minimum value ($h_{min,\ i}$) recorded during each day of the growing season (Equation 2.4).

$$h_i = \frac{h_{max,i} + h_{min,i}}{2} \qquad (2.4)$$

Moreover, infrequent water table measurements (weekly or bimonthly) of the wells at each system were performed manually. Infrequent water table measurements were conducted for all wells, equipped or not with a level logger. Table 2.2 shows the number of instrumented and manually measured wells. The number of wells were different for each experimental system.

The time series decomposition method (*tsd*, Gutierrez Pacheco et al. 2021) was used to estimate the missing daily values of the water table in those wells with infrequent measurements. In summary, this methodology states that the daily water table estimations are a function of the local water table trend, which is detected with infrequent records, and the daily regional fluctuation, detected at the reference well which is the nearest well equipped with a pressure transducer.

Table 2.2. Inventory of observation wells

Experimental System	Year	Wells with pressure transducer*	Wells with manual measurements	Manual measurement frequency	Total number of wells
Mesocosms	1	2	17	Every 2–3 days	19
Atlantic maritime	2	6	44	Weekly	50
	3	2	48		
	4	9	41		
Hemiboreal	1	10	49	Bimonthly	59
	2	11	48		
	3	14	45		
	4	13	46		
	5	15	44		

*Number of instrumented wells varied according to the annual availability of pressure transducers.

Correspondence between biomass samples and well locations

Because the original data collection was not designed to have a water table observation well next to each of the *Sphagnum* sampling point, only the samples located near to an observation well were retained. For the all the systematically distributed locations of biomass and carpet thickness samples, it was necessary to define a correspondence criterion according to the proximity to the observation well.

Field observation shows that the cross-sectional profile of the water table in a *Sphagnum* experimental basin follows a parabolic profile created by the network of irrigation canals. The cross-sectional variation of the water table level is more important than the longitudinal variation. Within 5 m in the longitudinal direction of the basin, the average value of water table level can vary by 4 cm, while the same difference can be found at a shorter distance of about 1.5 m in the cross direction of the basin. For this reason, it is not advisable to make an assignation of the nearest observation well according to a radius of influence (circular zone of influence). So, the nearest well was assigned to each point for samples according to a rectangular zone of influence of each well, which was determined as a rectangle of 3 m x 10 m (Figure 2.2). It means that there is only one observation well per zone of influence. If there is more than one sampling point in the zone of influence, the well information is duplicated by the number of sampling points retained.

The correspondence between samples and well locations was made for the outdoor *Sphagnum* farming systems, since for the Mesocosms system, the water table measurement is representative of the entire mesocosm. Finally, for each sampling location, the information on the *Sphagnum* species cultivated was also retained.

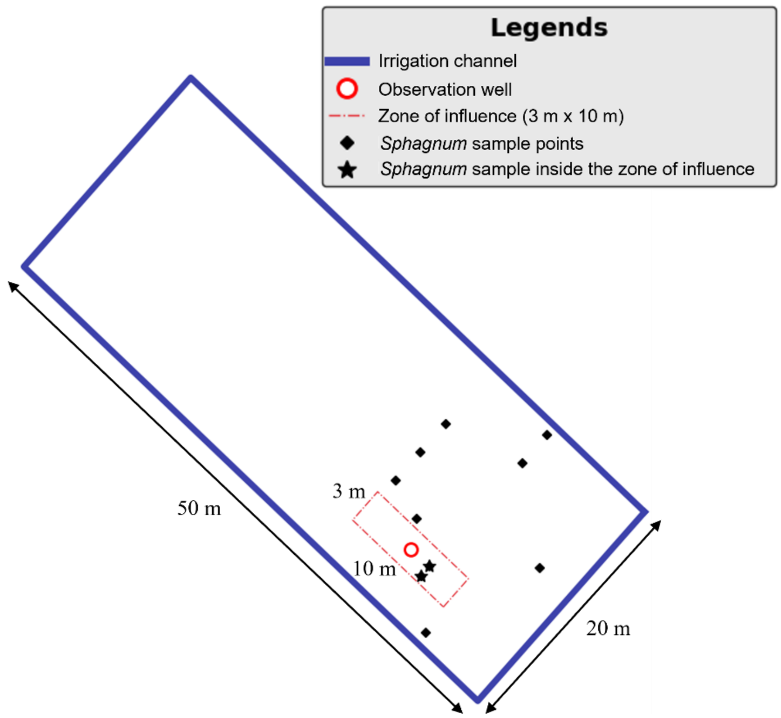


Figure 2.2. Distribution of some *Sphagnum* sample locations and the delimitation of a zone of influence of an observation well.

This adopted correspondence methodology is a very rigorous but pertinent criterion, which results in retaining up to 25% of the collected *Sphagnum* biomass data and up to 27% of the collected *Sphagnum* carpet thickness data. Rejected *Sphagnum* biomass data are generally close to basin edges or do not have an observation well within a 5 m radius. Table 2.3 shows the inventory of biomass and carpet thickness data retained by species and by growth session, after sorting and assigning based on the predefined zone of influence of 3 x 10 m. At Hemiboreal system, the biomass sampling preserved after correspondence methodology varied over the years between 13 and 22%, and between 16 to 18% for the carpet thickness samples. For Atlantic maritime system, the correspondence was more severe and the percentage of retained data varied between 3 and 6%, except for the second growing season which varied between 21 and 25%. The retained data inventory for Mesocosms is not shown in Table 2.3 since one collection was made for each mesocosm.

Table 2.3. Inventory of retained biomass data after assignment with observation wells for outdoor experimental systems.

Growing season	Hemiboreal				Atlantic maritime		
	S. rubellum	*S. medium*	*S. papillosum*	Total harvested samples	*S. flavicomans*	*S. medium*	Total harvested samples
Biomass samples							
1	8	9	10	63	-	-	-
2	28	30	28	138	60	50	239
3	26	19	25	128	9	11	228
4	22	24	18	139	6	13	235
5	29	21	23	143	-	-	-
Carpet thickness samples							
1	-	-	-	-	-	-	-
2	59	66	66	360	161	154	600
3	60	60	62	360	23	32	600
4	59	66	66	360	23	32	598
5	-	-	-	-	-	-	-

Water stress indicators and estimation of thresholds

After the correspondence stage, water stress indicators were computed for the retained biomass data. Three water stress indicators based on daily water table measurements were used, explicitly the sum of daily deficits of water (SDW, Eq. 2.2), the number of daily deficits of water (NDW, Eq. 2.3), and the seasonal average water table ($\hbar$). These indicators serve to quantify water deficit in relation to biomass productivity reduction of the *Sphagnum* species introduced.

For NDW and SDW computation, the values used for threshold depth of water table (h_{DT}, Eq. 2.2 and 2.3) were established between 0 and 40 cm, spaced by 0.5 cm apart. In total, 161 indicators were computed for each *Sphagnum* sampling location, namely 80 SDW indicators, 80 NDW indicators and a single indicator containing the seasonal average water table ($\hbar$). The computation of each water stress indicator for each growth season was made considering the duration of the water table log, which varies among systems as shown in Table 2.4. For the calculation of thresholds depths of water table from the second year for outdoor systems, the total value of the stress indicator since *Sphagnum* cultivation establishment was considered.

Table 2.4. Duration of the water table logs for each *Sphagnum* farming experimental system.

Experimental System	Log start date	Log end date	Log duration (*n*)
Hemiboreal	May 12	October 18	159
Atlantic maritime	May 24	October 3	132
Mesocosms	April 27	April 10 [+1]	348

[+1]Date after one year of cultivation

For each h_{DT} value of the SDW and NDW indicators, and for the seasonal average water table level, a linear regression model is obtained (Figure 2.3). For each case, the Pearson's correlation coefficient (R) for a sample paired data was calculated as Equation 2.5.

$$R = \frac{\sum_{i=1}^{m}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{m}(x_i - \bar{x})^2} \cdot \sqrt{\sum_{i=1}^{m}(y_i - \bar{y})^2}} \qquad (2.5)$$

Where *m* was the number of observations in paired data set after correspondence between water stress indicators and the information of *Sphagnum* survey, x_i was the water stress indicator and y_i was the biological variable, either *Sphagnum* biomass accumulation or *Sphagnum* carpet thickness.

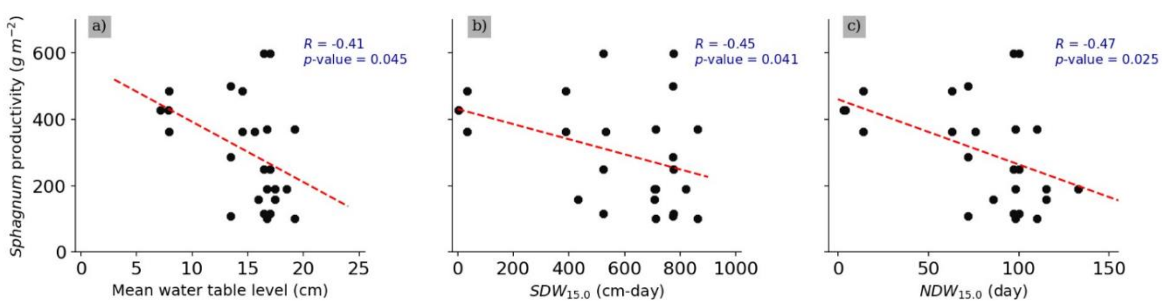


Figure 2.3. Example of the calculation of the threshold depth of water table for each indicator. Linear regression model between *Sphagnum* biomass accumulation and a) seasonal average of water table level, b) SDW15, and c) NDW15.

After finding all the R values for each threshold, the R vs. threshold curves (Figure 2.4) are plotted to find the optimum point. The threshold depth value chosen for SDW and NDW corresponded to the optimum value of the curve. Thus, the water stress threshold value is the value for which the highest Pearson's correlation coefficient was obtained, indicated under the shaded area in the example shown in the Figure 2.4. For the same case, i.e., same species, same system and same growing season, the threshold for SDW and NDW may differ, as in the example shown in the Figure 2.4. Finally, due to the differences between systems, the estimation of the threshold depth of water table was conducted for each system individually.

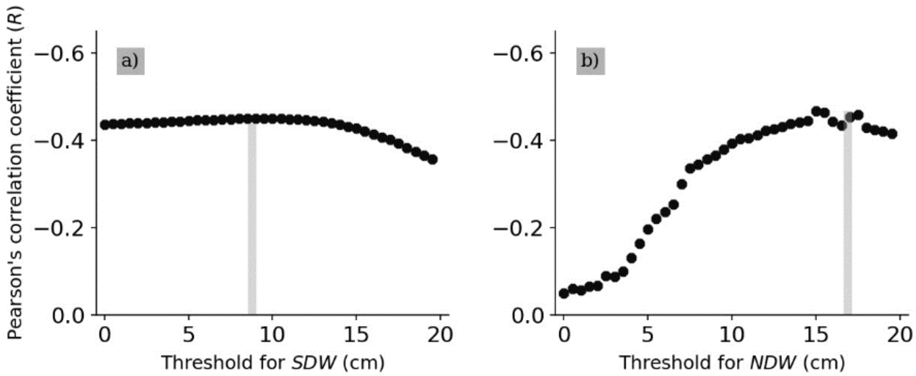


Figure 2.4. Optimum value of the curve between the Pearson's correlation coefficient obtained and the thresholds depth of water table for a) SDW and b) NDW.

To calculate a confidence interval for the threshold depth (h_{DT}), the bootstrapping test was used (Efron 1979). Bootstrap techniques are statistical inference methods using random sampling in the original data base, and in this case, with replacement. In other words, the same observation from the original data set can be randomly retained more than once in the resampling data set. Bootstrapping test was done 100 times over the original data set and the confidence interval was calculated from the 100 optimum threshold values found. The size of the resample set was equal to the size of the original data set. The resampling algorithm was implemented in Python 3 (version 3.7.9, Van Rossum and Drake, 2009) using the utilities of the scikit-learn package (Pedregosa et al. 2011).

Hydrophysical properties of peat

A major advantage of measuring hydrophysical properties of peat in the different systems is to interpret the expected differences in thresholds depths for the same species present in the systems, in this case, *S. medium*. To determine the peat bulk density (ρ_b), three samples for each differentiated peat layer were taken from each experimental system. According to the peat profiles, each of the systems had a different number of identified peat layers: two peat layers in the Mesocosms system (0–40 cm and 40–55 cm), three for Atlantic maritime system (0–30 cm, 30–60 cm, and 60–100 cm), and four for the Hemiboreal system (0–20 cm, 20–40 cm, 40–70 cm, and 70–100 cm).

For all *Sphagnum* farming systems, the auger hole method (Lagacé 2016) was used for *in-situ* measurement of saturated hydraulic conductivity. In summary, a hole is drilled into the peat at the various identified layers. When the water level in the hole reaches equilibrium with the surrounding water table, some of the water is removed from the hole. The water percolates back to the hole under the effect of the hydraulic gradient created, and the rate of ascent observed is directly proportional to the value of the saturated hydraulic conductivity (K_{sat}) and to the geometry of the hole. The circular hole was drilled with a 100 mm diameter auger. The depth of the hole varied according to the different layers identified in the field for each of the systems.

2.5 Results

Performance of water stress indicators

Correlation analysis was used to evaluate the relationship between the *Sphagnum* biological variables and the water stress indicator. For this analysis, the threshold depth values used (h_{DT}) correspond to those in which the greatest Pearson's correlation coefficient found for each indicator, which is calculated for each *Sphagnum* species and each growing season. A detailed breakdown of each h_{DT} value by growing season and by *Sphagnum* species is shown in the appendixes. In general, the water stress indicators show a significant moderate correlation (-0.50 >R> 0.75) for the second and third growing season in the outdoor systems and a very strong correlation (-0.75 >R> 1.0) in the 12-month long experiment at the Mesocosms system (Figure 2.5). There is a trend of decreasing performance of water stress indicators in the order: number of daily deficits of water (NDW) being better than the sum of daily deficits of water (SDW) being better than the seasonal average water table (ħ), especially visible for correlation with the *Sphagnum* biomass (Figure 2.5a).

Closer inspection at the relationship with *Sphagnum* accumulated biomass, the Figure 2.5a shows negligible correlation and positive R values by the more yellowish to red colors. These are the cases where ħ is used for *S. papillosum* and *S. medium* at Hemiboreal system after one growth season, and *S. flavicomans*, at Atlantic maritime experimental system after four growing seasons. This result is somewhat counterintuitive because it considers that the higher the water stress, the lower *Sphagnum* productivity.

Regarding the relationship with *Sphagnum* carpet thickness (Figure 2.5b), as for biomass, the correlation coefficient is high and similar for all the indicators in the Mesocoms system. For outdoor systems, there is only one counterfactual result, which is for *S. flavicomans* at Atlantic maritime system after four growing seasons.

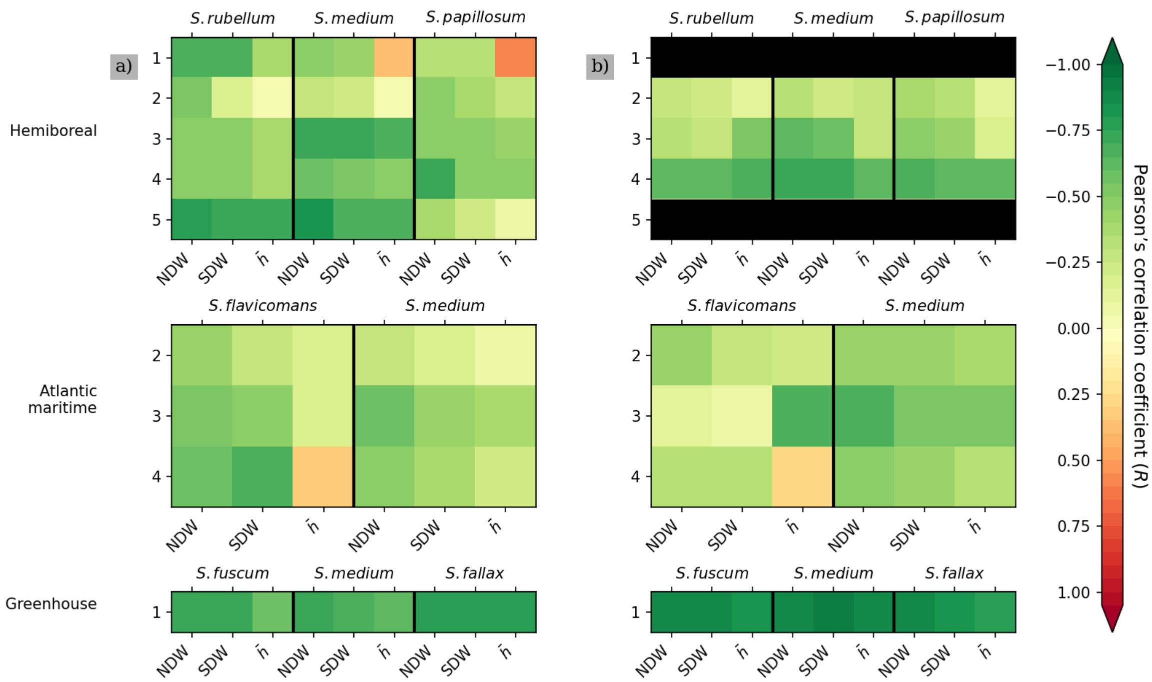


Figure 2.5. Correlation analysis between each water stress indicator with its optimal threshold depth value (h_{DT}) and the *Sphagnum* biological variable a) accumulated biomass and b) carpet thickness. Analysis achieved by experimental system of *Sphagnum* cultivation and discriminated by growing season, organized by rows, and *Sphagnum* species, organized by 3-columns group. Black cells represent missing values of *Sphagnum* carpet thickness.

Strong association for threshold depth calculated in Mesocosms system

As first important result, two of the three indicators used allow to estimate of the threshold depth of water table from deficit stress begins (h_{DT}). The seasonal average water table (ħ) does not allow estimating a fixed h_{DT} value associated with each *Sphagnum* species. This indicator is a measure of central tendency and serves to describe the time series of the water table depth and estimate the probability of the most common value of the water table depth but does not define a water stress zone for which the productivity of the *Sphagnum* is affected. However, the other two indicators, NDW and SDW, satisfy this condition by being measures of variance with respect to the threshold depth of water table (h_{DT}). This value was observed to vary among systems and among *Sphagnum* species analyzed.

Due to the differences between systems, the estimation of the threshold depth of water table based on *Sphagnum* biomass accumulation was conducted for each system individually. In general, the foremost correlation values were found for Mesocosms system. It is for this reason that the results are concentrated mainly on those findings. However, the detailed results for outdoor sites are in the Appendix 2.1, Appendix 2.2, Appendix 2.3 and Appendix 2.4.

When biomass was considered as a biological variable, R absolute values were greater than 0.6 (Table 2.5). The highest thresholds h_{DT} were found for *S. fuscum*, followed by *S. medium* and finally *S. fallax*. Also, in Table 2.5, the threshold depth values for NDW were deeper than for SDW. An analogous result was found when the *Sphagnum* carpet thickness was considered as a biological variable. R absolute values were greater than 0.79 and, in general, thresholds depths are closer to surface than thresholds estimated based on biomass. However, the threshold values (h_{DT}) do not follow the same trend as that observed with the thresholds calculated for biomass. Using NDW, the higher threshold depth is for *S. fallax* (3.8 ± 1.2 cm) meaning thant when the water table level is close to the surface, this species reaches its optimum growth. While *S. medium* is a species that reaches its optimum growth even at values farther from the surface (8.9 ± 0.8 cm). Though, using SDW the values for the three *Sphagnum* species are almost identical (0.2 ± 0.4 cm for *S. fuscum*, 0.1 ± 0.1 cm for *S. medium*, and 0.9 ± 0.9 cm for *S. fallax*). Lastly, the lower performance of the water stress indicators based on *Sphagnum* carpet thickness (R=-0.79 for *S. fallax* using ħ, Table 2.5) is equal to the highest performance based on biomass accumulation (R=-0.79 for *S. fallax* using SDW, Table 2.5). These values of h_{DT} summarized in Table 2.5 can be interpreted considering the value itself and the associated Pearson's correlation coefficient (R). A value of h_{DT} determines, in terms of water table depth, the limit from which water stress begins for each *Sphagnum* species and hence productivity is affected. As far as R is concerned, this refers to the confidence level of the determined h_{DT} , negative value of R means an inversely proportional correlation and a value closer to 1 represents a high confidence level.

Table 2.5. Estimated thresholds depths of number of daily deficits of water (NDW) and sum of daily deficits of water (SDW) indicators and correlation coefficients between water stress indicators and the biological variable for introduced *Sphagnum* species in Mesocosms system.

Biological variable	Water stress Indicator	*S. fuscum*[1]		*S. medium*[1]		*S. fallax*[1]	
		Threshold h_{DT} (cm)	Pearson's coefficient	Threshold h_{DT} (cm)	Pearson's coefficient	Threshold h_{DT} (cm)	Pearson's coefficient
Biomass	NDW	20.1 ± 1.9	-0.71	16.4 ± 1.7	-0.70	6.0 ± 1.6	-0.78
	SDW	13.6 ± 1.8	-0.71	7.2 ± 1.4	-0.69	1.5 ± 1.2	-0.79
	ħ	-	-0.58	-	-0.64	-	-0.76
Carpet thickness	NDW	4.3 ± 0.7	-0.89	8.9 ± 0.8	-0.88	3.8 ± 1.2	-0.85
	SDW	0.2 ± 0.4	-0.86	0.1 ± 0.1	-0.90	0.9 ± 0.9	-0.81
	ħ	-	-0.84	-	-0.89	-	-0.79

[1]The number of paired data is n = 19 for all *Sphagnum* species in Mesocosms system

There is a difference of h_{DT} values determined by *Sphagnum* species when comparing the weighted average of thresholds depth of water table and which is illustrated in Table 2.6. The species from subgenus Acutifolia (*S. flavicomans*, *S. fuscum* and *S. rubellum*) and subgenus Sphagnum (*S. medium* and *S. papillosum*) have deeper thresholds than species of subgenus Cuspidata (*S. fallax*). However, when variation of threshold depth of the water table (h_{DT}) among growing seasons does not show a clear trend for all species analyzed, both for correlation with *Sphagnum* biomass (Appendix 2.1 and Appendix 2.3) or *Sphagnum* carpet thickness (Appendix 2.2 and Appendix 2.4). Considering the different conditions of the peat for each biosystem and the thresholds depth value for *S. medium*, the species present at all systems, the values of the NDW and SDW threshold based on biomass were deeper at Hemiboreal system (20.3 ± 1.0 and 12.6 ± 1.5 cm, respectively) than Atlantic maritime (9.7 ± 1.3 and 11.2 ± 1.6 cm, respectively) and Mesocosms systems (12.6 ± 1.9 and 3.6 ± 1.4 cm, respectively).

Table 2.6. Weighted average of estimated thresholds depth value (h_{DT}) of number of daily deficits of water (NDW) and sum of daily deficits of water (SDW) indicators for all *Sphagnum* species of the systems analyzed.

Subgenus		Acuatifolia			Sphagnum		Cuspidata
Indicator	**Site**	***S. rubellum***	***S. fuscum***	***S. flavicomans***	***S. medium***	***S. papillosum***	***S. fallax***
NDW	Hemiboreal	19.2 ± 1.4			20.3 ± 1.0	18.6 ± 1.0	
	Atlantic maritime			12.5 ± 2.0	9.7 ± 1.3		
	Mesocosms		12.2 ± 2.0		12.6 ± 1.9		4.9 ± 2.0
SDW	Hemiboreal	14.6 ± 1.6			12.6 ± 1.5	11.0 ± 1.5	
	Atlantic maritime			17.4 ± 2.3	11.2 ± 1.6		
	Mesocosms		6.9 ± 1.8		3.6 ± 1.4		1.2 ± 1.5

Differences in the growth conditions between systems

Considering the hydrophysical properties, each system had a different peat profile (Table 2.7). While the depth of the peat profile analyzed in the outdoor systems was 100 cm, the depth of the mesocosms was 50 cm. It is also observed that for the outdoor systems, the last layer was the least permeable (lower value of K_{sat}) and the most decomposed (higher von Post), while for the mesocosm system, the last layer was approximately 10 cm of sand as fill material to ensure drainage. Bulk density (ρ_b) and saturated hydraulic conductivity values (K_{sat}) varied between sites and as a function of depth, finding that the Hemiboreal profile was slightly denser (ρ_b = 0.13 ± 0.05 g cm^{-3}) than the other two systems denser (for Atlantic maritime, ρ_b = 0.11 ± 0.01 g cm^{-3}, and for Mesocosms system, ρ_b = 0.12 ± 0.09 g cm^{-3}).

As for weather conditions, in Atlantic maritime system, the average temperature between May and October was higher (16.3 ± 0.2 ºC) than in Hemiboreal system (15.3 ± 0.4 ºC). Simultaneous, maximum temperatures at Atlantic maritime were slightly higher (21.2 ± 0.3 ºC) than in Hemiboreal system (20.2 ± 0.4 ºC) as shown in Table 2.8. Since the conditions in the Mesocosms system were relatively stable, they are not illustrated. Specifically, the conditions were at 22 °C for air temperature and 50% of relative humidity during the day, and 18 °C and 85% of relative humidity during the night.

Table 2.7. Hydrophysical properties of identified peat layers in *Sphagnum* experimental cultivation systems.

<table>
<tr><th rowspan="2">Depth</th><th colspan="3">Hemiboreal</th><th colspan="3">Atlantic maritime</th><th colspan="3">Mesocosms</th></tr>
<tr><th>VonPost</th><th>Ksat (m day^{-1})</th><th>ρb (g cm^{-3})</th><th>VonPost</th><th>Ksat (m day^{-1})</th><th>ρb (g cm^{-3})</th><th>VonPost</th><th>Ksat (m day^{-1})</th><th>ρb (g cm^{-3})</th></tr>
<tr><td>0</td><td rowspan="4">H3</td><td rowspan="4">1.40 ± 0.43</td><td rowspan="4">0.13 ± 0.05</td><td rowspan="6">H2-H3</td><td rowspan="6">2.01 ± 0.97</td><td rowspan="6">0.11 ± 0.01</td><td rowspan="8">H3</td><td rowspan="8">1.33 ± 0.07</td><td rowspan="8">0.12 ± 0.09</td></tr>
<tr><td>5</td></tr>
<tr><td>10</td></tr>
<tr><td>15</td></tr>
<tr><td>20</td><td rowspan="4">H3-H4</td><td rowspan="4">0.24 ± 0.12</td><td rowspan="4">0.12 ± 0.03</td></tr>
<tr><td>25</td></tr>
<tr><td>30</td><td rowspan="6">H3</td><td rowspan="6">0.72 ± 0.19</td><td rowspan="6">0.11 ± 0.04</td></tr>
<tr><td>35</td></tr>
<tr><td>40</td><td rowspan="6">H4</td><td rowspan="6">0.07 ± 0.02</td><td rowspan="6">0.14 ± 0.04</td><td rowspan="3">Sand</td><td rowspan="3">5.04 ± 4.26</td><td rowspan="3">1.63 ± 0.05</td></tr>
<tr><td>45</td></tr>
<tr><td>50</td></tr>
<tr><td>55</td><td rowspan="10"></td><td rowspan="10"></td><td rowspan="10"></td></tr>
<tr><td>60</td><td rowspan="6">H3-H4</td><td rowspan="9">0.14 ± 0.11</td><td rowspan="9">0.12 ± 0.04</td></tr>
<tr><td>65</td></tr>
<tr><td>70</td><td rowspan="7">H5</td><td rowspan="7">0.0008 ± 0.0002</td><td rowspan="7">0.18 ± 0.03</td></tr>
<tr><td>75</td></tr>
<tr><td>80</td></tr>
<tr><td>85</td></tr>
<tr><td>90</td><td rowspan="3">H5</td></tr>
<tr><td>95</td></tr>
<tr><td>100</td></tr>
</table>

Table 2.8. Temperature conditions for experimental systems for outdoor *Sphagnum* cultivation.

	Hemiboreal					Atlantic maritime			
Years	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**
Growing Degree days, GDD (°C-days)	1899	2058	2008	2073	2057	2156	2153	2113	2110
Mean temperature (°C)	14.5	15.7	15.3	15.7	15.5	16.5	16.2	16.1	16.2
Average of the maximum temperatures (°C)	19.4	20.5	20.1	20.6	20.3	21.3	20.9	20.9	21.6

2.6 Discussion

Relationship of water stress with *Sphagnum* growth

Prior studies have noted the importance of seasonal water deficit indicators for *Sphagnum* farming (Campeau & Rochefort 2002; Brown et al. 2017). Although water table depth is commonly used to assess the hydrological function of *Sphagnum* farming systems (Pouliot el al. 2015; Brown et al. 2017; Gutierrez Pacheco et al. 2021), complementary information on water deficit could serve as an additional assessment tool due to its demonstrated relationship to productivity of *Sphagnum* species.

The results of this study indicate a negative correlation between *Sphagnum* productivity in terms of biomass accumulation and carpet thickness and the water stress indicators, namely the Number of daily Deficit of Water (NDW), the Sum of daily Deficit of Water (SDW) and the seasonal average water table (ħ). Using the three water stress indicators, correlation coefficients up to -0.82 for *Sphagnum* biomass accumulation and up to -0.90 for *Sphagnum* carpet thickness were observed. These negative correlation between *Sphagnum* productivity and the water stress indicators is consistent with previous studies in *Sphagnum* farming and also in *Sphagnum* peatland restoration (Price 1996; Price et al. 2003; Ketcheson & Price 2014; McCarter & Price 2014; Pouliot et al. 2015; Guêné-Nanchen et al. 2018) which report that the higher the water stress, the lower the productivity of the *Sphagnum* species in terms of biomass accumulation and carpet thickness, but without using any means of seasonal water stress quantification and without defining a threshold depth of water table.

This inverse relationship may be explained by the increase in peat water tension that *Sphagnum* species must overcome to maintain flows to its capitula. In parallel, vertical hydraulic conductivity decreases rapidly as peat moisture content decreases, so fewer saturated pores are available for water transport (Lagacé 2016; Golubev & Whittington 2018). As a result, insufficient water flux to the *Sphagnum* capitula reduce photosynthesis and growth (Rydin 1993; Gerdol et al. 1996; Sagot & Rochefort 1996).

The results indicate that NDW and SDW could be used to quantify water stress related to *Sphagnum* productivity. Among the *Sphagnum* systems analyzed, NDW and SDW show stronger correlation with productivity than ħ. The ħ has a regular performance (0.6 >R >-0.76), and even positive R values which are not consistent from a biological point of view. Although ħ is a usual indicator for water management and water stress assessment, the average value of the water table level does not consider either the duration or the magnitude of the water deficit. Another advantage of the use of seasonal water deficit indicators as NDW and SDW is that they allow the calculation of threshold depth of water table from deficit stress begins.

The thresholds depth values found, either using SDW or NDW, generally fluctuate between 7 and 20 cm. Those thresholds values correspond to more shallow water tables compared with 40 cm threshold established by Price et al. (2003) and Ketcheson and Price (2011). A comparison of water table depth ranges and their effect on species abundance, as described by Gignac et al. (1991), shows that the results found in the present study are closer to the surface. For *Sphagnum fuscum*, a hummock-typical specie, they found that the ecological range according to the water table varied between 30 to 60 cm, while for *Sphagnum papillosum*, a lawn specie, it ranged from 10 to 40 cm. This discrepancy can be explained by the fact that for *Sphagnum* farming, the choice is to maintain a high rate of photosynthesis to increase productivity (Rydin 1993; Sagot & Rochefort 1996; Schipperges & Rydin 1998), consequently the threshold of water table depth is shallower, while a threshold ranging from 30 to 50 cm may be adequate for *Sphagnum* recolonization in ecological restoration of ombrotrophic bogs.

There are still many unanswered questions about the differences in water stress values inter species, inter and intra systems and inter growing seasons. Part of these differences can be explained by the variation in residual peat and local climatic conditions, which are discussed in the next section. Variation of threshold depth of the water table (h_{DT}) among growing seasons does not show a clear trend for all species analyzed. Further research should be undertaken to investigate the threshold depth differences when the mosses are multiplying to cover the ground surface and biomass accumulation stage (when growth is mostly upward in the formed carpet). Biomass accumulation stage is defined as the moment at which the *Sphagnum* coverage reaches 90% (Gaudig et al. 2017; Gutierrez Pacheco et al. 2019). This future work should be carried out with more controlled water table conditions and a better association between biological variables and water stress based on daily water table values.

Factors related to threshold depths of water table

For this study it was found that the species from subgenus Acutifolia (*S. flavicomans*, *S. fuscum* and *S. rubellum*) and subgenus Sphagnum (*S. medium* and *S. papillosum*) have deeper thresholds than species of subgenus Cuspidata (*S. fallax*) (Table 2.6). On average, the threshold depth of water table (h_{DT}) for the species from subgenus Acutifolia was 13.8 ± 1.9 cm, from subgenus Sphagnum 12.5 ± 1.4 and from subgenus Cuspidata 3.1 ± 1.8 cm. The threshold depth of water table differs in response to the morphology of each species (Goetz & Price 2015; Taylor & Price 2015; Golubev & Whittington 2018; Elliott & Price 2020), and consequently could have a significant impact in *Sphagnum* productivity when changes in the water and climate regime are greater. This behavior of the threshold depth value according to the *Sphagnum* subgenera corresponds to the preferential ecological for water table depth (Lindholm & Vasander 1990; Gignac et al. 1991; Campbell & Rochefort 2001) and to the ability of hummock-lawn species to resist water loss more effectively (Rydin & McDonald 1985; Campeau & Rochefort 1996; Sagot & Rochefort 1996; Grosvernier et al. 1997).

For the Mesocosms species, where conditions were more controlled, this behavior is clearer (Table 2.5). Also, for the Mesocosms system, a stronger correlation was found between *Sphagnum* productivity, in terms of biomass accumulation and carpet thickness, and water stress indicators. Based on biomass accumulation, the threshold depth value to NDW and SDW follows the preferential ecological range *S. fuscum* > *S. medium* > *S. fallax*. This outcome is complementary to that of Kim et al. (2021) who report that the response to these three *Sphagnum* species at the Mesocosms system is a function of the different water table regimes.

Considering the different conditions of peat in each biological system and the threshold depth value for S. medium, a species present in all systems, the biomass-based threshold was deeper in the Hemiboreal system than in the Atlantic maritime and Mesocosms system. A possible explanation for this might be extracted from hydrophysical properties of the first peat layers (Table 2.7). Peat in Hemiboreal system is slightly denser, having a lower K_{sat} than peat in Atlantic maritime and Mesocosms. These values indicate that the pore size is smaller, so the peat has more Readily Available Water defined as the soil moisture held between water content at field capacity (θ_{CC}) and water content at refill point (θ_{RP}) (Price et al. 2003; Caron et al. 2015), which results in a deeper water table drop without stressing the *Sphagnum* species. In other words, it results in a higher h_{DT} value, which is the case for this study. Peat structure of Hemiboreal system may have a higher water reserve for the *Sphagnum*, so the value of the threshold depth could be deeper. This is consistent with data from Verry et al. (2011), who compare two peat profiles with similar characteristics to those of Hemiboreal and Atlantic maritime system. They compared two profiles, one with a density of 0.14 g cm^{-3} and the other 0.12 g cm^{-3}. For the first, they determined a water content of 0.60 cm^3 cm^{-3} at -100 mbar, while the water content for the second was 0.45 cm^3 cm^{-3}.

Another factor to consider is the weather conditions recorded shown in Table 2.8. In Atlantic maritime system, the average temperature between May and October was higher (16.3 ± 0.2 ºC) than in Hemiboreal system (15.3 ± 0.4 ºC). Simultaneous, maximum temperatures at Atlantic maritime were slightly higher (21.2 ± 0.3 ºC) than in Hemiboreal system (20.2 ± 0.4 ºC). Higher temperature results in a higher demand in terms of evaporation by the *Sphagnum* (Goetz & Price 2015; Moore & Waddington 2015), and consequently the threshold depth closer to the surface. However, the differences in these studies were significantly higher in terms of temperature (on the order of 5 ºC) and precipitation (on the order of 400 mm). While temperature and precipitation regime can affect the h_{DT} value, it is attributed that the differences found are largely due to the stratified peat profile. For *S. medium*, the *Sphagnum* species common to all systems, h_{DT} value was determined closer to the surface for Atlantic maritime system than for Hemiboreal system. Thresholds depths were 20.3 ± 1.0 cm using NDW and 12.6 ± 1.5 using SDW in the Hemiboreal system, while in the Atlantic maritime system, the thresholds depths were 9.7 ± 1.3 cm using NDW and 11.2 ± 1.6 cm using SDW.

Importance of site-specific conditions

Despite of the use of a water management system in the analyzed outdoor experimental systems, the variation of the water table position was present. The application of the site-specific water stress indicator allowed us to identify a part of the productivity variation in *Sphagnum* farming. However, in the case of outdoor systems, the method of association between *Sphagnum* samples and well locations is not entirely direct, i.e., biomass and moss carpet thickness sampling was not designed to be done in the vicinity of a water table measurement. This study was limited by the methodology for retaining *Sphagnum* biomass data corresponding a nearby observation well. Further studies could use a site-specific approach.

Another part of *Sphagnum* productivity variation is due to the intrinsic variability of the biosystem and intra-seasonal variation (Chirino et al. 2006). Factors such as microclimatic and microtopography conditions, peat layer thickness, field preparation, and interaction with companion plants (Rochefort et al. 2003; Pouliot et al. 2015; Guêné-Nanchen et al. 2017; Grobe et al. 2021; Moore et al. 2021) play a role in the accumulation of *Sphagnum* biomass. These factors influence the correlation coefficients obtained, especially for outdoor sites, where most of these factors are difficult to control. Therefore, certain points within the same basin do not generate the expected productivity, despite establishing an optimal water table for *Sphagnum* growth. A site-specific approach can thus be used to identify basin clusters that share similar water stress condition and comparable hydrophysical and chemical properties.

Considerations for a future reliable predictive model

For the correct calculation of water deficit indicators, knowledge of the specific threshold depth of water table for the *Sphagnum* species is required. Currently, no clear methodology for the estimation of these thresholds depths is reported and this study shows the procedure and results using the correspondence with the highest Pearson's correlation value for a given growing season.

The water stress indicators for outdoor systems have a weak to acceptable correlation (Appendix 2.1, Appendix 2.2, Appendix 2.3 and Appendix 2.4). In outdoor systems, the threshold depth value is influenced by climate conditions and the hydrophysical conditions of the peat. Thus, this value is highly dependent on the context of each system. To predict *Sphagnum* productivity based on water stress due to water table fluctuations, it might be possible to use stress-day-index models (Hiler 1969; Evans et al. 1990, 1991). These models allow to determine the productivity related to a water stress level, quantified by a water stress indicator, and a crop sensitivity factor. For the moment, this study identified the indicators to quantify water stress and the possible values for the water table depth threshold. The next step will be to identify the crop sensitivity factor, which may also be a function of *Sphagnum* cultivation age and *Sphagnum* species. It is recommended that these tests be carried out under controlled conditions, for example using lysimeters such as those used by Evans, Skaggs and Snee (1990).

2.7 Conclusions

The aim of the present paper was to establish a methodology to quantify water stress due to the drop of water table level damaging to *Sphagnum* productivity. This study used three indicators, namely the Number of daily Deficit of Water (NDW), the Sum of daily Deficit of Water (SDW) and the seasonal average water table ($\bar{h}$), the latter commonly used. Among the indicators used, NDW and SDW have stronger correlation with productivity than ħ. Overall, this study strengthens the idea that the higher the water stress, the lower the productivity of the Sphagnum species, hence the negative correlation found between Sphagnum productivity in terms of biomass accumulation and carpet thickness and the water stress indicators tested.

A secondary objective of the study was to determine the threshold depth of water table below which the productivity of each *Sphagnum* species begins to decline. The optimum value of the curve between the correlation coefficient values and the threshold depth for NDW and SDW were used. In general, the species from subgenus Acutifolia (*S. flavicomans*, *S. fuscum* and *S. rubellum*) and Sphagnum (*S. medium and S. papillosum*) have deeper threshold depth than species of subgenus Cuspidata (*S. fallax*). The threshold depth of water table determined for each of the subgenres as follows from subgenus Acutifolia 13.8 ± 1.9 cm, from subgenus Sphagnum 12.5 ± 1.4 and from subgenus Cuspidata 3.1 ± 1.8 cm. Moreover, when considering the same *Sphagnum* species established at different sites, the changes in threshold depth value at different sites may be explained by factors such as the system climatic conditions and the hydrophysical peat properties. For the analyzed *Sphagnum* farming experimental systems, the estimated thresholds depth value fluctuates between 7 and 20 cm. These values correspond to water table closer to the surface than the reported in the literature for *Sphagnum* peatland recolonization, which is 40 cm, and this is because in *Sphagnum* cultivation the aim is to maximize productivity.

Implications for practice

- The use of NDW and SDW requires daily values of the water table depth, which can be estimated by estimation methodologies such as the one developed in Chapter 2.

- The methodology used for determination of water table depth threshold should be revised to have a better association between seasonal water stress indicator and *Sphagnum* productivity measurements.

- Water management thresholds in *Sphagnum* farming should correspond to the water table depth thresholds of each species, which range from 7 to 20 cm. On average, the threshold depth of water table determined for each of the subgenres as follows from subgenus Acutifolia 13.8 ± 1.9 cm, from subgenus Sphagnum 12.5 ± 1.4 and from subgenus Cuspidata 3.1 ± 1.8 cm. The variation of the threshold values from one species to another corresponds to the ecological preference in terms of water table depth.

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Appendixes

Appendix 2.1. Estimated thresholds depths of number of daily deficits of water (NDW) and sum of daily deficits of water (SDW) indicators and correlation coefficients between the water stress indicators and the *Sphagnum* biomass accumulation for introduced species in Hemiboreal system.

Growing season	*S. rubellum*		*S. medium*		*S. papillosum*	
	Threshold[1] (cm)	Pearson's coefficient	Threshold[1] (cm)	Pearson's coefficient	Threshold[1] (cm)	Pearson's coefficient
NDW						
1	20.2 ± 2.5 b	-0.69	21.5 ± 3.0 ab	-0.49	10.2 ± 7.3 b	-0.31
2	6.2 ± 0.7 c	-0.51	20.7 ± 2.1 b	-0.28	20.4 ± 1.4 a	-0.46
3	19.3 ± 1.1 b	-0.47	21.8 ± 1.0 ab	-0.74	16.9 ± 1.2 ab	-0.49
4	18.5 ± 2.2 b	-0.49	24.3 ± 1.7 a	-0.56	15.4 ± 0.6 b	-0.72
5	24.6 ± 0.8 a	-0.76	16.2 ± 0.4 c	-0.82	14.5 ± 3.0 b	-0.38
Weighted average	18.5 ± 0.9	-	20.5 ± 0.8	-	15.9 ± 0.9	-
SDW						
1	21.8 ± 1.5 a	-0.65	31.0 ± 1.2 a	-0.44	19.8 ± 0.3 a	-0.33
2	14.0 ± 2.1 b	-0.15	22.6 ± 2.0 b	-0.21	19.3 ± 1.1 a	-0.39
3	13.7 ± 1.4 b	-0.45	12.3 ± 0.8 d	-0.71	8.8 ± 1.6 b	-0.45
4	19.0 ± 2.9 a	-0.46	19.4 ± 2.5 c	-0.51	1.2 ± 0.5 c	-0.45
5	9.6 ± 1.0 c	-0.74	2.9 ± 0.9 e	-0.68	13.4 ± 3.1 b	-0.20
Weighted average	15.6 ± 0.9	-	15.3 ± 1.1	-	11.7 ± 1.1	-
ħ						
1	-	-0.37	-	0.39	-	0.60
2	-	-0.02	-	-0.03	-	-0.27
3	-	-0.37	-	-0.66	-	-0.41
4	-	-0.39	-	-0.49	-	-0.46
5	-	-0.71	-	-0.68	-	-0.09

[1]Values in the same column and same indicator, followed by different letters indicate differences according to Tukey-Kramer test (α = 0.05). The number of paired data is specified in Table 2.3

Negligible association (R ≥ -0.25)	Weak association (-0.25 >R ≥ -0.50)	Moderate association (-0.50 >R ≥ -0.75)	Very strong association (-0.75 >R ≥ -1.0)

Appendix 2.2. Estimated thresholds depths of number of daily deficits of water (NDW) and sum of daily deficits of water (SDW) indicators and correlation coefficients between the water stress indicators and the *Sphagnum* carpet thickness for introduced species in Hemiboreal system.

Growing season	*S. rubellum*		*S. medium*		*S. papillosum*	
	Threshold[1] (cm)	Pearson's coefficient	Threshold[1] (cm)	Pearson's coefficient	Threshold[1] (cm)	Pearson's coefficient
NDW						
1	-	-	-	-	-	-
2	22.1 ± 1.7 b	-0.29	20.1 ± 1.5 ab	-0.32	19.9 ± 0.7 b	-0.38
3	28.6 ± 1.1 a	-0.31	18.9 ± 1.1 b	-0.60	26.9 ± 0.7 a	-0.48
4	14.6 ± 1.2 c	-0.63	21.2 ± 0.6 a	-0.71	18.1 ± 0.6 c	-0.68
5	-	-	-	-	-	-
Weighted average	19.9 ± 1.0	-	20.2 ± 0.6	-	21.3 ± 0.6	-
SDW						
1	-	-	-	-	-	-
2	25.8 ± 1.9 a	-0.22	20.1 ± 2.4 a	-0.24	17.1 ± 1.1 a	-0.33
3	24.9 ± 1.3 a	-0.29	10.8 ± 0.8 b	-0.58	18.2 ± 1.0 a	-0.43
4	3.7 ± 0.8 b	-0.60	5.7 ± 1.1 c	-0.71	0.9 ± 0.4 b	-0.61
5	-	-	-	-	-	-
Weighted average	13.6 ± 1.4	-	9.9 ± 1.1	-	10.3 ± 1.0	-
ħ						
1	-	-	-		-	
2	-	-0.11	-	-0.26	-	-0.10
3	-	-0.54	-	-0.29	-	-0.17
4	-	-0.69	-	-0.60	-	-0.60
5	-		-		-	

Missing values of *Sphagnum* carpet thickness for the first and fifth seasons.

[1]Values in the same column and same indicator, followed by different letters indicate differences according to Tukey-Kramer test (α = 0.05). The number of paired data is specified in Table 2.3

Negligible association (R ≥ -0.25)	Weak association (-0.25 >R ≥ -0.50)	Moderate association (-0.50 >R ≥ -0.75)	Very strong association (-0.75 >R ≥ -1.0)

Appendix 2.3. Estimated thresholds depths of number of daily deficits of water (NDW) and sum of daily deficits of water (SDW) indicators and correlation coefficients between water stress indicators and *Sphagnum* biomass accumulation for introduced species in Atlantic maritime system.

Growing season	*S. flavicomans*		*S. medium*	
	Threshold[1] (cm)	Pearson's coefficient	Threshold[1] (cm)	Pearson's coefficient
NDW				
2	6.7 ± 2.1 c	-0.40	9.4 ± 1.6 a	-0.25
3	19.4 ± 2.0 b	-0.52	7.0 ± 1.6 a	-0.58
4	27.4 ± 1.6 a	-0.57	7.4 ± 1.1 a	-0.48
Weighted average	19.0 ± 1.5	-	7.6 ± 0.9	-
SDW				
2	21.6 ± 3.0 b	-0.25	19.8 ± 1.5 a	-0.15
3	21.4 ± 2.1 b	-0.45	7.1 ± 1.7 b	-0.40
4	30.4 ± 1.8 a	-0.65	7.8 ± 2.9 b	-0.35
Weighted average	25.8 ± 1.5	-	9.5 ± 1.3	-
ħ				
2	-	-0.15	-	-0.09
3	-	-0.17	-	-0.37
4	-	0.31	-	-0.21

[1]Values in the same column and same indicator, followed by different letters indicate differences according to Tukey-Kramer test (α = 0.05). The number of paired data is specified in Table 2.3

Negligible association	Weak association	Moderate association	Very strong association
(R ≥ -0.25)	(-0.25 >R ≥ -0.50)	(-0.50 >R ≥ -0.75)	(-0.75 >R ≥ -1.0)

Appendix 2.4. Estimated thresholds depths of number of daily deficits of water (NDW) and sum of daily deficits of water (SDW) indicators and correlation coefficients between water stress indicators and Sphagnum carpet thickness for introduced species in Atlantic maritime system.

Growing season	*S. flavicomans*		*S. medium*	
	Threshold[1] (cm)	Pearson's coefficient	Threshold[1] (cm)	Pearson's coefficient
NDW				
2	2.4 ± 0.2 c	-0.41	19.7 ± 1.0 a	-0.42
3	16.2 ± 2.8 a	-0.11	4.8 ± 0.8 c	-0.66
4	7.3 ± 1.8 b	-0.33	14.5 ± 1.6 b	-0.47
Weighted average	6.1 ± 1.3	-	11.8 ± 1.0	-
SDW				
2	2.8 ± 0.9 c	-0.25	16.7 ± 1.0 a	-0.41
3	31.0 ± 0.1 a	-0.08	7.0 ± 0.5 b	-0.51
4	8.5 ± 2.5 b	-0.31	16.6 ± 2.4 a	-0.40
Weighted average	9.1 ± 1.7	-	12.9 ± 1.0	-
ħ				
2	-	-0.24	-	-0.36
3	-	0.66	-	-0.53
4	-	-0.30	-	-0.34

[1]Values in the same column and same indicator, followed by different letters indicate differences according to Tukey-Kramer test (α = 0.05). The number of paired data is specified in Table 2.3

Negligible association (R ≥ -0.25)	Weak association (-0.25 >R ≥ -0.50)	Moderate association (-0.50 >R ≥ -0.75)	Very strong association (-0.75 >R ≥ -1.0)

Chapitre 3 : Adaptation and validation of the Boussinesq model to stratified peat profiles for modeling water table evolution in rewetted bogs

Sebastian Gutierrez Pacheco, Robert Lagacé, Mélina Guêné-Nanchen, Sandrine Hugron, Stéphane Godbout et Line Rochefort

3.1 Résumé

La culture de la fibre de sphaigne en tant que type de paludiculture sur des tourbières réhumidifiées, nécessite un niveau de nappe phréatique relativement élevée et stable comme principal vecteur pour favoriser la croissance de la sphaigne. À cette fin, un réseau hydraulique de gestion de l'eau est construit pour contrôler le niveau de la nappe phréatique. Cependant, la prédiction de la position de la nappe phréatique en fonction de la gestion du réseau hydraulique est un défi, en partie à cause de l'hétérogénéité du profil de la tourbe. Cette étude propose une adaptation de l'équation de Boussinesq, normalement utilisée pour décrire l'hydraulique des écoulements souterrains. Dans le cadre de cette étude, cette équation a permis de représenter le comportement hydrophysique des substrats identifiés dans un système de culture de sphaigne avec un petit nombre de paramètres, dont la conductivité hydraulique saturée de chaque couche identifiée, la porosité effective et la densité apparente. La performance du modèle développé a été évaluée en considérant des données réelles provenant d'un système expérimental de culture de sphaigne dans l'est du Canada. Pour ce site expérimental, trois horizons ont été identifiés, à savoir : l'horizon 0-30 cm (von Post H2-H3), l'horizon 30-60 cm légèrement plus décomposé (von Post H3) ; et l'horizon 60-100 cm modérément décomposé (von Post H5). L'évolution de la nappe phréatique a été testé sur le même basin de 1000 m^2 avec deux configurations hydrauliques différentes à des moments différents (canaux périphériques et micro-canaux d'irrigation).

Le modèle développé explique 91 % de la variation observée du niveau de la nappe phréatique, même lors du changement de configuration du réseau hydraulique de gestion des eaux du même bassin. L'erreur principale du modèle est causée par la profondeur pour laquelle il n'y a pas d'information sur la conductivité hydraulique saturée.

3.2 Abstract

Sphagnum fiber farming as a form of paludiculture on rewetted bogs, requires a relatively high and stable water table as the main driver to improve *Sphagnum* growth. For this purpose, a hydraulic water management network

is constructed to control the level of the water table. However, predicting the water table depth as a function of the hydraulic network management is a challenge, in part, due to the heterogeneity of the peat profile. This study proposes an adaptation to the Boussinesq equation, normally used to describe the hydraulic groundwater. In this study, this equation was used to represent the hydrophysical behavior of each identified substrate in a *Sphagnum* culture system with a small number of parameters, including saturated hydraulic conductivity of each identified layer, effective porosity, and bulk density. The performance of the developed model was evaluated against real data from an experimental *Sphagnum* farming system in eastern Canada. For this experimental site, three-peat layers were identified, namely: 0-30 cm layer (von Post H2-H3), 30-60 cm layer slightly more decomposed (von Post H3); and 60-100 cm layer moderately decomposed (von Post H5). The evolution of the water table was tested in a single basin of 1000 m^2 with two different hydraulic configurations at different times (peripheral channels and micro irrigation channels).

The model developed explains 91% of the observed variation of the water table level, even when changing the configuration of the hydraulic water management network of the basin. The principal error of the model is given for the depth for which there is no information on the saturated hydraulic conductivity.

3.3 Introduction

Sphagnum cultivation is the production of biomass on rewetted bogs, and for optimal production, it is necessary to control the water table level as close to the surface and as stable as possible. After removing the acrotelm and part of the catotelm, peat extraction is carried out down to the usable substrate (the layer having a von Post of H1-H3 for growing substrates and the layer having a von Post of H4-H7 to make potting soil when mixed with mineral soil; Parent, 2001). Thus, the remaining non-extracted peat layers are generally quite decomposed and compacted (Clymo et al. 1998). In this remnant horizon: pores are smaller than in the upper peat-extracted horizons, saturated hydraulic conductivity is lower (Van Seters & Price 2001), water retention capacity is higher (Schlotzhauer & Price 1999), and pore density may increase after drainage, which reduces interstitial spaces (Price 1997). These are conditions that are not favorable for *Sphagnum* moss growth, precisely because the flow of water to the *Sphagnum* capitula is limited to compensate evaporation, causing water stress in *Sphagnum* mosses.

The use of irrigation channels has been reported to maintain near-surface water levels and to reduce water stress (Pouliot et al. 2015; Guêné-Nanchen et al. 2017; Gaudig et al. 2018). In *Sphagnum* moss cultivation systems, it is common to find irrigation channel networks that border the cultivation basins (peripheral channel), or a cross the basins (central channel), as shown in Figure 3.1. These irrigation channels are fed by an irrigation system that takes water from the drainage system of nearby extraction sites or nearby water bodies (e.g., lakes or ponds). The maximum water level in the channels is controlled by the height of a wooden sluice gate.

Generally, the gate is located downstream of the channels. These channels must be filled to a higher water level than the water table level expected in the cultivation basins. In this way, a favorable hydraulic gradient is established for groundwater to flow within the peat for rewetting.

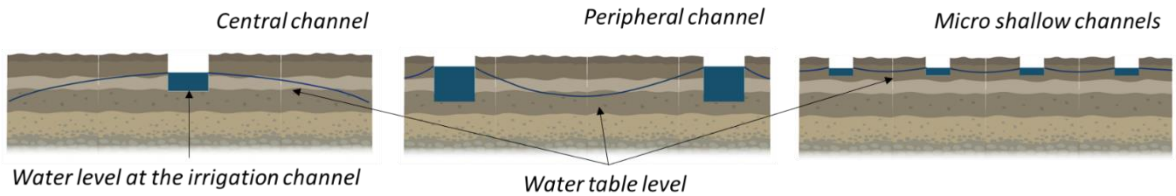

Figure 3.1. Conceptual representation of the main types of a hydraulic network of irrigation channels used under irrigation mode in *Sphagnum* cultivation. Irrigation mode occurs when the hydraulic gradient is high enough to drive water flow from the channels to the basin.

A new concept for improving the hydraulic network has been explored by the authors (Gutierrez Pacheco et al. 2021) and consist of modifying the existing irrigation channel network by constructing micro shallow channels (Figure 3.1). The main idea of the micro surface channel is to reduce the distance between irrigation channels by constructing channels closer to each other, which contributes to the uniformity of the observed water table. Such channels can be implemented in an established basin by connecting perpendicularly the established main channels, either peripheral or central channels, to each of the new micro channels. Likewise, the concept is to modify an established channel network, either peripheral channel or central channel. Implementation of micro shallow channels make use of the shallowest layer and does not to alter the deeper layers. It is assumed that the shallower layer, being less decomposed, has a higher saturated hydraulic conductivity, which allows a more rapid horizontal flow of groundwater.

The irrigation channel network design depends largely on the hydrophysical characteristics of the residual catotelm, which is the bottom layer of peat, more decomposed and normally saturated by the water table. The spacing of irrigation devices (drains and/or channels) should consider site conditions, e.g., 5 m is recommended in areas of strongly humified peat (Gaudig et al. 2017) and 10 – 20 m in lightly humified areas (Gaudig et al. 2013; Brown et al. 2017). These recommendations were made based on observations, but no technical criteria have been reported in the *Sphagnum* biomass production literature. Another aspect to consider is the differentiated layers of peat profile, which has been observed either in restored peatlands (Kennedy & Price 2004; McCarter & Price 2014) and several experimental sites of *Sphagnum* production (Taylor & Price 2015). Likewise, it has not been considered in the irrigation channel network design.

Furthermore, the conception of the irrigation hydraulic network must consider two water flows present in this type of peatland: precipitation and evapotranspiration. Precipitation is described as the most important water inflow of *Sphagnum* bogs (Price 1997; Brust et al. 2018); and although for sphagnum mosses, the transpiration component is negligible, the evapotranspiration in hydrological models is considered a combination of the evaporation from the sphagnum and the evapotranspiration from the companion vascular plants (Nichols & Brown 1980).

Numerical models of groundwater flow can be used to predict the water table depth in restored peatlands and *Sphagnum* cultivation basins. These numerical simulations often use the Darcy equation (1856), as well as the Richards (1931) and Boussinesq (1877) models, assuming that the flow in the saturated zone is proportional to the saturated hydraulic conductivity and the hydraulic gradient. However, representing water movement in post-extracted peatlands (Ballard et al. 2011; Susilo et al. 2012) and in a *Sphagnum* culture (Taylor & Price 2015; Brust et al. 2018) has been reported as a scientific challenge. Dimitrov et al. (2010) emphasize the importance of differentiating the horizons typically present (fibric, mesic, and humic) due to their significant differences that imply significant effects on hydrologic response. Also, numerical models rely heavily on measurements of hydraulic conductivity of peat, which on many occasions is not stated for the different layers of peat profile. This is necessary because the hydraulic conductivity of peat can vary by several orders of magnitude over just a few meters, vertically or horizontally (Holden & Burt 2003; Taylor & Price 2015).

Most of the reported research on groundwater modeling in organic soils and peat are based on the Richard's equation (Richards 1931) which requires the entire definition of the relationships between pressure head, soil moisture, and hydraulic conductivity. This involves the construction of the water retention curve and the hydraulic conductivity curves for all the differentiated layers of the peat profile (McCarter & Price 2014; Elliott & Price 2020). A downside from the use of Richard's equation, that considers the unsaturated zone, consist in requiring further characterization of the peat, usually based on laboratory tests, which does not allow to describe field-scale observations (Schwärzel, et al. 2006a; 2006b). A simple way to represent the fluctuation of the water table is through the Boussinesq equation for unconfined horizontal aquifers, which does not require the water retention curves or the hydraulic conductivity curves. This equation simplifies the description of water flow through unconfined aquifers because it considers that groundwater flows horizontally in an unconfined aquifer where the media is homogeneous and isotropic, and that the groundwater discharge is proportional to the saturated peat thickness (Dupuit, 1863, and Forchheimer, 1930, assumptions). Boussinesq equation has shown interesting results for mineral soils, when the Dirichlet boundary conditions (time-variant or specific values at a fixed position) are known (Kacimov et al. 2016; Kong et al. 2016).

The main objective of this paper is to develop a numerical model able to predict the evolution of the water table level within a *Sphagnum* cultivation system considering the hydrophysical characteristics of the stratified peat profile. Following the development of the model, this paper shows its validation for two types of hydraulic channel network configurations.

3.4 Model description

The modeling approach used in this study consisted of a horizontal flow between the water in the irrigation channel and the water table in the cultivation basins. For versatility and simplicity of the model, minor processes have been neglected such as deep groundwater fluxes, and development has focused primarily on a restored bog peatlands in eastern Canada where water table is controlled by the irrigation system. This site was also chosen because it has a stratified peat profile, which is shown in detail in the methodology section.

Conceptual model

Regardless of the type of irrigation channel network (Figure 3.1), when channels are used in irrigation mode, the channels must be filled to a higher water level than the water table level expected in the cultivation basins. In this way, a favorable hydraulic gradient is established for groundwater flow within the basin. Analogously, when channels are used in drainage mode, the channel level should be lower than the water level in the basin. The hydrological parameters of the simplified conceptualization of the groundwater are presented in Figure 3.2 and the mathematical model are introduced in the following sections. The groundwater flow is considered mostly horizontal, and the total horizontal flow is equal to the sum of horizontal flows of each peat layer below the water table level. The following assumption were also made: No vertical or horizontal flow in the lower part of the last identified peat layer because the last layer had small value of saturated hydraulic conductivity of peat, k_i (less than one tenth of k_i of first layer); also, the outside of the basin bordering the irrigation channel is of infinite extension.

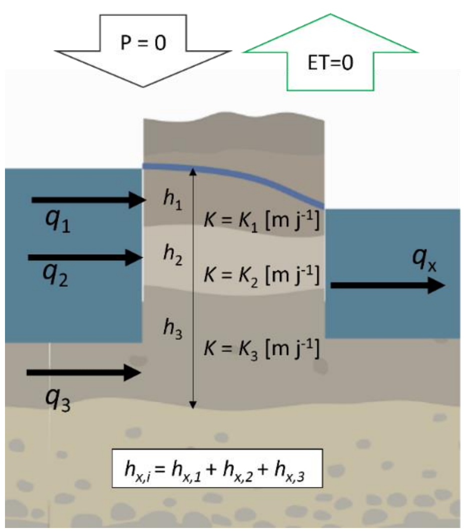

Figure 3.2. Conceptual description of groundwater flow in a stratified medium (example of 3 identified layers).

Mathematical model

The water table movement can be represented by the Boussinesq equation (Eq. 3.1), and it is assumed that a) water flows horizontally in a basin of a *Sphagnum* cultivation system and, b) the water discharge is described by the Darcy equation for stratified peat.

$$\mu \frac{dh}{dt} = \frac{d}{dx} Q_x + P - ET \qquad (3.1)$$

Where h is the water table elevation above the reference level, Q_x is the horizontal flow, μ is the effective porosity, P refers to precipitation and ET is the evapotranspiration of the *Sphagnum* plant community. It is necessary to clarify that in a *Sphagnum* culture there are also vascular plants, and that is why the term transpiration is considered. Likewise, for the simplicity of the model, it was considered that the unsaturated zone representation has only vertical water fluxes to the water table, caused by precipitation, and from the water table, by the evapotranspiration, which directly affect the water table elevation (Figure 3.2).

The horizontal flow Q_x is estimated using the Darcy equation considering the stratified medium and considering the Dupuit-Forchheimer assumptions. The total flow in a stratified medium is the sum of the flows in each layer up to the water table and can be expressed by Equation 3.2:

$$Q_x = \sum_{i=1}^{m} (\zeta_i - \zeta_{i-1})\, k_i \, \frac{dh}{dx} \quad , \qquad \zeta_m \leq h \qquad (3.2)$$

Where m is the number of identified peat layers bellow the water table, h represents the water table elevation, ζ_i is the elevation of i-th strata, and k_i is the saturated hydraulic conductivity of the i-th strata.

3.5 Methods

Study site

Sphagnum cultivation site was located in the Acadian peninsula, New Brunswick (47°41’35"N 64°45’47"W), and the experimental farm established in 2013 in a former block-cut peatland (Brown et al. 2017; Goulet 2019). During the study period (2018-2019). The mean air temperature between May and October was 15.5 °C, and mean cumulative precipitation between May and October of 279 mm (Dataset from 2000 to 2020, Environment Canada, 2021). Whitin the experimental site, a 20 m x 50 m basin was chosen for the present study. The basin had a 70 cm x 100 cm (depth x width) peripheral channel between 2013 and 2018. The peripheral channel bordered the perimeter of the basin and hereinafter this configuration is referred as PC configuration. In 2019, the hydraulic network of the basin was modified by the addition of four 20 cm x 20 cm, 20 m long micro shallow channels, perpendicular to the length of the basin and spaced every 10 meters apart and connected to the peripheral channel for their water supply. The latter is henceforth assigned as micro channels (MC) configuration. The vertical walls of micro shallow channels were cut with a chainsaw and peat removal was done by hand.

Basins were irrigated with water coming from a nearby peatland lake (pH = 4.9 ± 0.5, EC = 104 ± 19 µS cm^{-1}). The water table level in the main channel was controlled through an automated irrigation installation. Water from the lake entered from only one point in the basin, upstream of the peripheral channel. Then, water level in basin channel was monitored by ultrasonic sensors installed at the dams, which was a wooden structure located downstream, at the water outlet of the basin. When the water level was lower than the targeted level, the pumping system was activated to irrigate the channels. Finally, in periods of excess water, such as snow melt, the maximum water level in the channels was controlled by an adjustable drainage device (Goulet 2019), which consisted of a one-way valve connected to the lower part of the dam. The device had an extruded polystyrene float that actuated the opening of the valve according to the water level upstream of the dam.

Field methods

Water table elevation data were required for model validation. The model was tested in the same *Sphagnum* cultivation basin, except that the channel network was modified from PC to MC between 2018 and 2019. Water table elevation (h) was recorded at one observation well located at mid-distance between the main channels when the basin was configurated with PC and at one observation well located midway between micro shallow channels after their construction (MC). In other words, in the case of PC, observation well was 10 m from the channel, and 5 m from the micro shallow channels in the case of MC. The observation wells were made of 2-in diameter PVC pipe and were installed at a depth of approximately 70 cm using a 125 cm ling hand auger, which had wide blades in the first 20 cm. The wells were 1-m long, slotted every 2 cm and covered by nylon stockings on the outer surface to prevent the entry of solids in suspension.

The water table elevation (h) was measured indirectly by recording the water pressure in observation well every hour by a pressure logger (HOBO U20, Onset Computer Corporation, Bourne, MA, USA, accuracy: ± 0.5 cm). Water table elevation (h) was obtained by correcting the water pressure measurements from pressure loggers with the barometric pressure measurements from a Barometric pressure logger (HOBO U20-001-04, Onset Computer Corporation, Bourne, MA, USA, accuracy: ± 0.5 cm) and considering the offset between the peat surface and pressure sensor position. Finally, water table elevation (h) is calculated using the HOBOware Pro software.

Peat bulk density (ρ_b), decomposition degree of peat, saturated hydraulic conductivity (k_i) and effective porosity (μ) were the considered hydrophysical properties measured. Three locations were randomly chosen within the basin to measure the hydrophysical properties, and they were sampled once in 2018. The values determined are shown in Table 3.1. For the determination of ρ_b, three samples were taken for each differentiated peat layer. Based on peat profile, the differentiated peat layers were established as 0–30 cm, 30–60 cm, and 60–100 cm. The degree of decomposition based on the von Post scale (von Post 1922; von Post & Granlund 1926) was assessed manually in the field, three samples for the same sampling points and depths at which ρ_b was sampled. The auger hole method in stratified media (van Beers 1983; Lagacé 2016) was used for *in-situ* measurement of saturated hydraulic conductivity (k_i) for each peat layer of the same sampling points. In summary, the auger method consists of drilling a hole into the peat and the bottom of the hole must coincide with the bottom of the identified layer. The same hole was used for the three layers identified, digging each time up to the following layer, starting from the shallowest to the deepest layer. When the water level in the hole reaches equilibrium with the surrounding water table in each case, 75% of the water is removed from the hole. The water percolates back to the hole under the effect of the hydraulic gradient created, and the rising rate of the water level in the hole is directly proportional to the value of k_i and to the geometry of the hole. This methodology allows estimating k_i for the layers below the water table, which during the sampling was 10 cm. For depth 0-10 cm, the same properties as 10-30 cm were assumed. Finally, for the estimation of the effective porosity (μ), the water table fluctuation method was used (Bourgault et al. 2017). All hydrophysical properties were considered time invariant.

Table 3.1. Hydrophysical properties

Depth (cm)	von Post	ρ_b	k_i (m day^{-1})	μ
0 – 30	H2 – H3	0.11 ± 0.01	2.01 ± 0.97	0.04
30 – 60	H3	0.11 ± 0.04	0.72 ± 0.19	0.03
60 – 100	H3-H5	0.12 ± 0.04	0.14 ± 0.11	0.02

A weather station at the site recorded precipitation (TE525-L tipping-bucket rain gauge, Texas Electronics, Dallas, TX, USA), global solar radiation (CS301 pyranometer, Apogee Instruments, Logan, UT, USA), energy balance (NR-LITE2 rugged net radiometer, Kipp & Zonen OTT HydroMet Corp USA, Sterling, VA, USA), air temperature and relative humidity (HygroVUE5 sensor, Campbell Scientific, Edmonton, AB, Canada), and wind speed (05305-L wind monitor, R. M. Young, Traverse City, MI, USA) every 15 minutes and averaged hourly.

For this study, the evapotranspiration value (ET_i) of the *Sphagnum* cultivation was assumed to be the potential evapotranspiration ($ET_{p,i}$) and its value was determined according to the equation of Rochette and Dubé (1989) (Equation 3.3) based on temperature measurements and extraterrestrial radiation estimation. The equation of Rochette and Dubé was calibrated to the Penman method (Penman et al. 1967).

$$ET_i = ET_{p,i} = -2.40 + 0.065\, T_{max,i} + 0.083\left(T_{max,i} - T_{min,i}\right) + 0.00414\, R_i \qquad (3.3)$$

Evapotranspiration is expressed in mm day^{-1}, $T_{max,i}$ and $T_{min,i}$ are the maximum and minimum daily temperatures, both in ° C respectively, and R_i the extraterrestrial radiation in cal cm^{-2} day^{-1}.

Evapotranspiration from *Sphagnum* changes depending on the time of day (Nichols & Brown 1980; Petrone et al. 2001; Kettridge & Waddington 2014; Kettridge et al. 2017). To better approximation of the variation of evapotranspiration during the day, the day was divided into four periods for which the estimation of the ET_i was computed using the equation of Rochette and Dubé for each period. Then, the ET_i values between the periods were estimated with a linear interpolation.

Initial and boundary conditions

As mentioned above, the study was carried out in a single basin which had a peripheral channel in 2018 (PC), and then in 2019, its hydraulic network was modified adding four micro shallow channels (MC). Therefore, although the peat profile of the basin is assumed to be time invariant, the initial and boundary conditions were different.

To ensure an initial condition as close to steady state as possible, and to establish a quasi-homogeneous initial water table elevation along the basin cross section, the observation periods were chosen where a) no rain for at least five preceding days, b) a significant rise in the water level in the irrigation channel is recorded, shortly after the beginning of the observation period, c) there were similar climatic conditions. These considerations drove to only consider the periods from June 20th to July 1st, 2018, for PC configuration (12 days) and from June 19th to 27th, 2019 for MC configuration (9 days). Since the water table level was recorded every hour, this resulted in 288 observations of the water table for PC and 216 for MC. The initial values of water table elevation (h_0) at midway between channels were -37 and -27 cm for PC and MC, respectively. Because the response of each hydraulic network configuration was different, the final value of the water table in the midway between channels (h_f in Table 3.2) differs for each case.

During the observation period for each case, the water level at the peripheral channel ($H_{channel}$), the precipitation (P) and the evapotranspiration (ET) were not constant. Then, time-dependent boundary conditions were established for $H_{channel}$, P and estimated ET. While estimated ET and measured P were determined from the data of the weather station, the $H_{channel}$ were hourly recorded by the irrigation system. The initial and final value of $H_{channel}$ for each case are shown in the Table 3.2.

Table 3.2. Initial and boundary conditions for water table simulations.

Case	Number of simulated days	Time step (h)	Midway between channels		Irrigation channel	
			h_0 (cm)	h_f (cm)	$H_{channel,0}$ (cm)	$H_{channel,f}$ (cm)
PC	12	1	-37	-15	-24	2
MC	9	1	-27	-6	-14	3

Numerical model and mesh

In the present work, the Open-source Field Operation and Manipulation (Open FOAM) C++ libraries were used (Weller et al. 1998; Orgogozo 2015; Greenshields 2017). The simulation model uses the Boussinesq and Darcy equation (Eq. 3.1 and 3.2) as governing equations to compute the water table level for stratified media. The porous media (peat layers) were represented as a 1D mesh (Figure 3.3). To refine the mesh in places where there are important changes in the water table level, i.e., near the channels, the cell expansion ratio of the simpleGrading definition was used. The cell expansion ratios were defined as 10 to the right and 0.1 to the left. The ratio is that of the width of the end cell along one edge of a block to the width of the start cell along that edge. Figure 3.3 represents the mesh used for the PC configuration. For the MC configuration, the mesh was similar, except that the midway was at 5 m from the irrigation channel. Also, the initial time step is 5 min, and the maximum time step is 1 h. Finally, the RichardFOAM is the base solver, but was modified to work in one dimension and the Boussinesq and Darcy equation for stratified media were implemented.

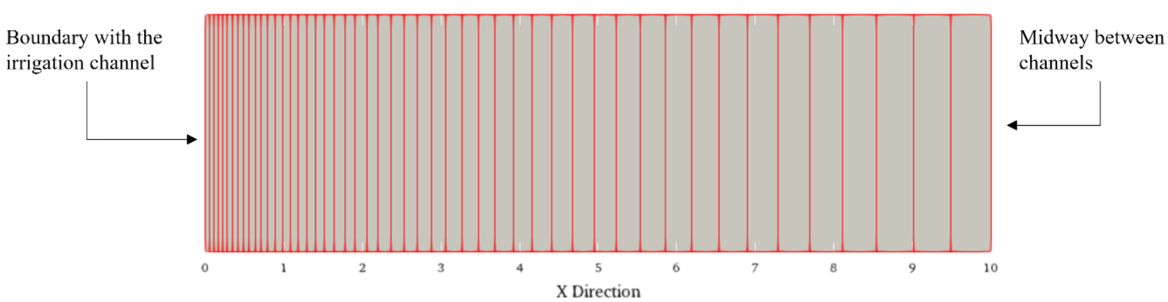

Figure 3.3. Computational domain for PC and 1D mesh refined at boundary.

Model validation and performance

Three statistics were used to evaluate the performance of the model: Coefficient of determination (R^2), the root-mean-square error (RMSE), and the Index of agreement (IoA). These statistics were calculated according to equations 4.4 to 4.6:

$$R^2 = 1 - \left[\frac{\sum(h_i^2 - \hat{h}_i^2)}{\sum h_i^2 - \frac{1}{N}\sum \hat{h}_i^2}\right] \qquad (3.4)$$

$$RMSE = \sqrt{\frac{\sum(h_i^2 - \hat{h}_i^2)}{N}} \qquad (3.5)$$

$$IoA = 1 - \left[\frac{\sum(h_i - \hat{h}_i)^2}{\sum\left(|\hat{h}_i - \bar{\bar{h}}| + |h_i - \bar{\bar{h}}|\right)^2}\right] \qquad (3.6)$$

where h_i are the observed water table elevations, $\hat{h}_i$ are the estimated water table elevations, $\bar{\bar{h}}_i$ is the mean of observed water table elevation and *N* the number of observations. The best fit between simulated and observed data shows the RMSE close to zero, the R^2 and IoA close to one.

3.6 Results

Simulation of the water table rise

The developed model reflected the hydrological regime observed in the scenarios analyzed, i.e., PC or MC configurations, as shown by Figure 3.4. For PC, the evolution of the water table elevation in the basin (2.02 cm day^{-1}) is 7% slower than the increases in the channel water level (2.14 cm day^{-1}). In the case of MC, the purple lines and the blue points of the Figure 3.4 are closer together, indicating that the evolution of the water table in the basin (1.75 cm day^{-1}) is similar to the increase of water level in the irrigation channel (1.85 cm day^{-1}). The field data used for this simulation show the influence of the water level in the channel ($H_{channel}$) on the water table elevation in the middle of the basin (h_i). There is a high correlation (R=0.72) between $H_{channel}$ and h_i, which is even stronger than the correlation P and h_i (R=0.24) or ET and h_i (R=0.10).

The observed data as well as the estimates of developed model show that the water level (h_i) at the channel ($H_{channel}$), seems to have a strong correlation with the water table elevation (Pearson's coefficient of 0.72). Precipitation show negligeable influence on h_i (Pearson's coefficient of 0.24) and this may be because the rainfall recorded in this period was not effective rainfall, i.e., it was less than 2 mm (Chirino et al. 2006; Radu & Duval 2017, Kang et al. 2018).

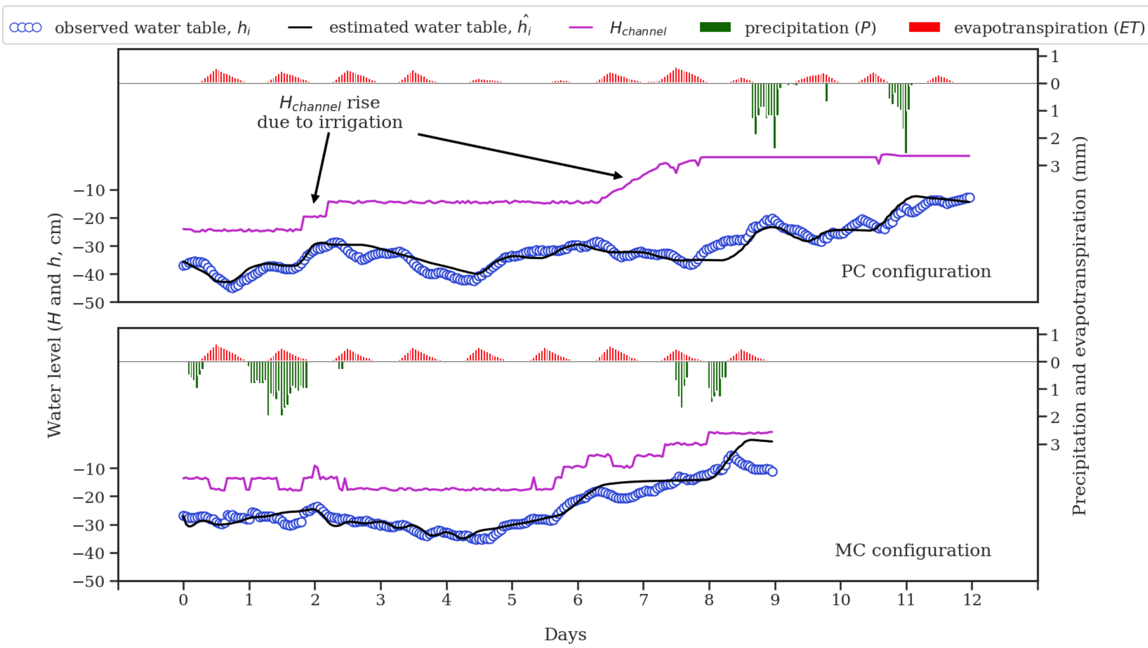

Figure 3.4. Recorded precipitation (*P*, in mm), estimated evapotranspiration (*ET*, in mm), water level at the channel $H_{channel}$ (cm), simulated ($\hat{h}_i$) and observed (h_i) water table levels at the mid-distance between the channels (in cm).

Model validation

Using the hydrophysical properties of peat detailed in Table 3.1, the initial conditions detailed in the Table 3.2, the recorded precipitation values (*P*) and estimated evapotranspiration values (*ET*) according to the Rochette and Dubé (1989) model, the performance of the Boussinesq model adapted to stratified media was evaluated by comparing simulated and observed water table levels (Figure 3.4). The simulated and observed water table fits at $R^2 = 0.91$ (Figure 3.5) indicating that the model and the input parameters describe 91% of the water table variation observed during the experiment. For both cases, the same coefficient of determination (R^2) is obtained, suggesting that the model can estimate the water table evolution in the two different configurations.

There was no difference in model accuracy in terms of R^2, between the two cases PC and MC (Figure 3.5). However, the fit between the observed and estimated water table level shows that when the water table is between 0 and -10 cm, the model error increases. This error may be due to the conditions under which the saturated hydraulic conductivity and the porosity were measured. At the time of the measurement, the water table was 10 cm deep, which did not allow the correct *in-situ* measurement of the hydraulic conductivity and porosity between 0 and 10 cm.

Although this analysis focused on the metrics around the variance of the error, the result (Appendix 3.1) shows that the model tends to underestimate water table elevation values with a mean bias error of 0.44 cm.

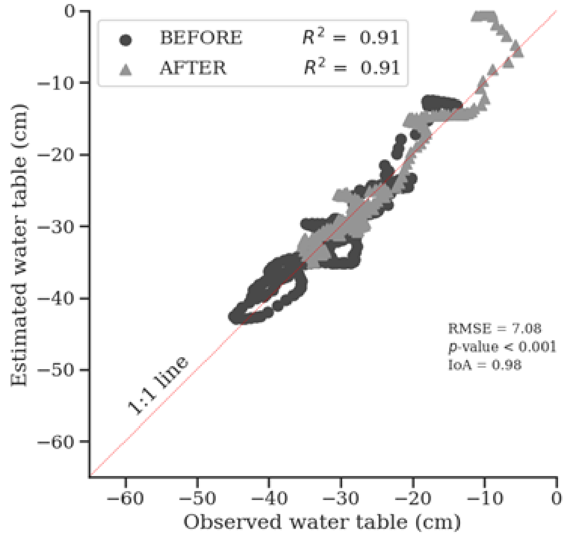

Figure 3.5. Observed and simulated water table level at mid-distance between the channels.

Use of micro shallow channels

The use of micro channels is promising since there is a faster rise in water table level in *Sphagnum* culture systems. When comparing mean observed values of the ninth day at the observation well located at mid-distance between the channels, under the peripheral channel configuration (PC) the water table rises from -37.0 to -31.7 cm (Δh_{9days} = 5.3 cm), while under the 10-m-spaced micro shallow channels (MC) the water table rises from -27.0 to -12.1 cm (Δh_{9days} = 14.9 cm).

From the numerical simulation, it was estimated that horizontal flow per unit area between the channel and the center of the basin, q_x, varied with configuration. In average, q_x was estimated at 1.4 ± 0.04 cm day^{-1} for MC configuration, which is estimated to be 1.5 times the estimated average for q_x for the PC configuration which was 0.9 ± 0.04 cm day^{-1}. Part of this difference is since the hydraulic gradient for the MC configuration (0.026 m m^{-1}) was greater than that calculated for PC configuration (0.021 m m^{-1}). A higher gradient is obtained by the reduction of the distance between channels, which is inversely proportional to the hydraulic gradient.

Also, as the water table rises faster, the horizontal flux q_x increases once the water table saturates the most permeable layer, which is the one between 0 – 30 cm depth. This condition is quickly met with the use of micro shallow channels. After 7.5 days, this layer is half saturated under the MC configuration, while this condition is not met during the entire period analyzed for PC configuration.

3.7 Discussion

Performance of Boussinesq model adapted for stratified medium

The developed model adapted for stratified media offers reliable predictions of water table levels for the two evaluated hydraulic network, PC and MC configurations during 12-day and 9-day simulation period, respectively. It is worth pointing out that these hydraulic network configurations were implemented for the same basin in two different years. For both cases, the model explains 91% of the observed variation of the water table level. The model is a combination of:

- The unidimensional model based on Boussinesq equation, which assumes groundwater flow is mostly horizontal, and flow is proportional to the saturated hydraulic conductivity of each saturated horizon. These assumptions have been corroborated by Allaire et al. (1994),
- The representation of peat profile stratification,
- The field measurement of saturated hydraulic conductivity with a representative sample (30 to 50 cm diameter sample, van Beers, 1983), with the auger hole method,
- The field measurement of precipitation,
- And the estimation of evapotranspiration by the of Rochette and Dubé equation (1989), which is calibrated by the Penman energy balance methodology.

In addition to the demonstrated performance, which is based on all the above points, this simple model offers a simple and easy to implement mathematical framework. It only requires a few hydrophysical properties of peat and little calculation time (about 30 seconds to analyze 12 days of simulation). Another interesting finding is that the channel configuration does not change the performance of the simulation model. However, with a small data set size, caution must be applied, as the findings might not be satisfactory if other types of *Sphagnum* farm conditions are considered.

Regarding the model discrepancies based on the limited data set, higher prediction errors by the model were observed when the water table level was between 0 and -10 cm. For this depth, saturated hydraulic conductivity was not measured, and this represent a limitation of the developed model. Homogeneity was assumed within the 0-30 cm layer, which has also been used by researchers in peatland hydrology studies (Bradley & Van Den Berg 2009; Elliott & Price 2020). However, the fact that this study implements three layers with different hydrophysical properties reflects some of the inherent variability observed in organic peat media. Another possible explanation for this error is the peat swelling in response to increased water content (Kennedy & Price 2005), which was not considered in this study.

For an optimal representation of the porous media, it is recommended to characterize the layers observed directly in the field, e.g., by measuring the saturated hydraulic conductivity *in-situ*. The auger hole technique for saturated hydraulic conductivity in stratified media allows a larger undisturbed peat sample (30 to 50 cm diameter sample, van Beers, 1983), which is not possible with laboratory methods (McCarter et al. 2017). However, the major limitation of this *in-situ* methodology is that only the layers below the water table are considered. In the case of this study, the water table was at a depth of 10 cm during the measurement of saturated hydraulic conductivity (k) and it was only possible to quantify the value of k for the depth between 10 and 100 cm. Possibly for the upper layers, another measurement technique can be used or even choose a time when the water table is as close as possible to the surface.

Implementation of micro shallow irrigation channels

When the water table rise was analyzed in both cases, it was shown that the modification of the peripheral channel with micro shallow channels (MC) has a faster response to increase the water table given a favorable water level condition of the irrigation channel. As demonstrated in the previous section, the unit water flow rate was 1.5 times higher for the MC configuration compared to the PC configuration. These results are likely to be related to the reduction of the distance that separates the channels, which were 20 m for PC and 10 m between micro shallow channels (MC). This is in complete agreement with Gaudig et al. (2013), Brown et al. (2017) and Gaudig et al. (2017) who suggest a network of irrigation channels spaced 10 m in lightly humified peatlands.

In addition, the selection of a shallow channel of 20 cm deep has a justification based on field observation. Since the saturated hydraulic conductivity (k_i) of the deepest identified layer is relatively low (fourteen times smaller than the first layer, Table 3.1), it is not necessary to dig deep channels. These findings cannot be extrapolated to all *Sphagnum* cultivation systems. In this case, this decision was made considering that the first layer up to 30 cm deep are more permeable, which benefits rewetting.

Finally, it is important to highlight that *Sphagnum* farming requires not only irrigation, but also the hydraulic network of channels must be managed to control the discharge of excess water and thus prevent long periods of flooding, which would also reduce *Sphagnum* growth (Rochefort et al. 2002; Van Gaalen et al. 2007; Granath et al. 2009).

3.8 Conclusion

The aim of the present study was to predict the water table level within a *Sphagnum* cultivation system considering the hydrophysical characteristics of the observed peat profile and implementing a numerical model based on the Boussinesq equation. The model performance predicting water table levels was R^2 = 0.91, RMSE = 7.08 cm and IoA = 0.98. The developed model has simulated the evolution of the water table in a *Sphagnum* cultivation basin under two types of irrigation networks, namely peripheral channel, and micro shallow channels, each implemented in different years. The performance of model includes the spacing between channels, the field representation of peat profile stratification, field measurement of saturated hydraulic conductivity with a more representative sample, field measurement of precipitation and estimation of evapotranspiration by the Rochette and Dubé model, calibrated by the Penman energy balance methodology.

Prior to this study, it was difficult to make predictions about how the hydraulic network of irrigation channels must be designed for a *Sphagnum* cultivation system. The model presented provides the possibility to simulate the fluctuation of the water table level in the *Sphagnum* cultivation basin depending on the characteristics of the peat profile, the characterization of the hydraulic network of irrigation channels (channel spacing), and water flows due to precipitation and evapotranspiration. The micro shallow irrigation channels, as an alternative to reducing channel spacing, provide a faster response to rewetting and then its practical use need to be explored in depth.

Implications for practice

- The use of the developed model will allow a better design of new *Sphagnum* cultivation systems and the hydraulic evaluation of already established hydraulic networks.

- There are still many unanswered questions about saturated hydraulic conductivity (k_i) measurement. The use of the auger hole methodology is recommended for the determination of k_i for each layer identified in the peat profile. This methodology allows the use of a larger undisturbed sample, between 30 and 50 cm in diameter, which is not possible with laboratory methodologies.

- The implementation of micro shallow channels in a basin where there is already an established peripheral channel allows to increase the water table raising into the basin after an increase in the water level of the channel.

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Appendixes

Appendix 3.1. Additional metrics that target the bias of the developed numerical model

Additional criteria	
Percentage bias (%)	1.60
Mean bias error, MBE (cm)	-0.44
Mean squared error, MSE (cm^2)	7.08

Conclusions générales

Comme d'autres auteurs (Pouliot et coll. 2015; Ludwig 2019; Grobe et coll. 2021), les résultats de cette thèse correspondent au fait que la culture de la sphaigne nécessite davantage de recherches pour atteindre soit le statut de culture commerciale ou soit le rôle de site donneur, dans le cas de l'utilisation de la biomasse comme matériel végétal pour d'autres sites de restauration. Pour y arriver, il est nécessaire d'analyser les facteurs clés pour optimiser la croissance de la sphaigne. L'hydrologie et les relations écohydrologiques ont été démontrés comme facteurs clés d'optimisation dans la culture de sphaigne (Moore et Waddington 2015; Gaudig et coll. 2018; Kim et coll. 2021). Afin de contribuer à l'étude plus approfondie de ces deux facteurs, cette thèse visait à l'analyse du continuum sphaigne – tourbe – flux d'eau – climat afin d'optimiser la conception et l'opération du système de gestion de l'eau des systèmes de culture de sphaigne.

Les piliers de cette thèse sont l'utilisation du concept de stress hydrique saisonnier en culture de sphaigne et l'identification des indicateurs de stress hydrique associés à la croissance des sphaignes. Les indicateurs identifiés pour quantifier le stress hydrique étaient la somme des nappes journalières sous la profondeur de la nappe seuil identifiée (SEW) et nombre de jours où la nappe phréatique est sous la profondeur de la nappe seuil (NDW). La SEW considère l'amplitude de la variation de la nappe phréatique et le NDW contemple la fréquence à laquelle la nappe phréatique se trouvait à des profondeurs critiques pour la productivité des sphaignes. Chacun de ces indicateurs nécessite des relevés quotidiens de la profondeur de la nappe phréatique, d'où l'importance d'estimer les profondeurs de la nappe phréatique pour les cas où un relevé hebdomadaire ou bimensuel de la nappe phréatique est tenu pour tous les puits répartis sur le site de culture de sphaigne, ainsi que les relevés quotidiens dans certains puits de référence.

Cette thèse considère l'analyse de trois systèmes expérimentaux de culture de sphaigne et plus de six ans de mesure en hydrologie dans ces systèmes. De plus, à notre connaissance, c'est la première étude à introduire le concept de stress hydrique saisonnier en culture de sphaigne. Cette approche ouvre la porte à l'utilisation d'une zone de confort hydrique, qui est définie par des seuils hydro-écologiques correspondant à la niche préférentielle de l'espèce de sphaigne par rapport à la microtopographie et à la position de la nappe phréatique, également appelée gradient butte-dépression (Campbell et Rochefort 2001). À même temps, cette thèse ouvre la porte au travail conjoint de diverses disciplines pour faire face à la réorientation et la revitalisation des tourbières post-production de tourbe, soit une forme de paludiculture qui conserve les stocks de carbone résiduels.

Pour l'optimisation de la gestion de l'eau en vue d'optimiser la croissance dans la culture de sphaigne, trois défis ont été identifiés et sont détaillés dans l'introduction de cette thèse. Ces défis identifiés étaient :

- Saisir l'hétérogénéité spatiale et temporelle du comportement hydrologique dans les tourbières remouillées.

- Quantifier le stress hydrique saisonnier subi par les espèces de sphaigne en culture et définir une métrique utile pour l'évaluation de la gestion de l'eau en culture de sphaigne. Parallèlement, Il est nécessaire de vérifier que le stress hydrique saisonnier est lié à la productivité des espèces de sphaigne.

- Établir un modèle pour la conception et l'évaluation du réseau d'approvisionnement en eau pour les systèmes de culture de sphaigne.

Chacun de ces défis a été décrit dans trois chapitres différents de cette thèse. Toutefois, ils doivent être considérés comme des actions conjointes plutôt que des solutions individuelles, visant à améliorer la gestion de l'eau dans des systèmes de culture de sphaignes et ainsi augmenter la productivité du système.

Une mention importante est que les chapitres présentés dans cette thèse présentent une fusion entre eux. Le chapitre 1 est utile au chapitre 2 et le chapitre 2 rend pertinente l'existence du chapitre 3.

Défis 1 : hétérogénéité spatiale et temporelle du niveau de la nappe phréatique

Étant donné que le suivi hydrologique en culture de la sphaigne consiste en une observation peu fréquente des puits d'observation sur le site, complétée par un suivi quotidien de certains puits de référence (Shaffer et coll. 2000; Pouliot et coll. 2015; Brown et coll. 2017; Guêné-Nanchen et coll. 2017), le chapitre 1 identifie six méthodes d'apprentissage automatique couramment utilisées dans la littérature (glm, svm, rf, knn, AdaBoost et tree) pour estimer la profondeur quotidienne de la nappe phréatique à partir de mesures peu fréquentes, e.g., bimensuelles, et de mesures quotidiennes de certains puits de référence. Ce chapitre présente également une nouvelle méthode (la décomposition des séries temporelles, tsd), qui divise la série temporelle des profondeurs de la nappe phréatique en périodes et pour chacune de ces périodes, la méthode détermine la tendance et la composante de fluctuation quotidienne associées à la composante locale et à la composante régionale de la nappe phréatique, respectivement.

Il a été identifié que certaines méthodes d'apprentissage automatique donnent des résultats fiables (R^2 entre 0,82 et 0,92, RMSE entre 3,10 et 4,68 cm). Toutefois, la décomposition des séries temporelles utilise un principe méthodologique plus approprié et obtient de meilleurs résultats (R^2 de 0,95 et RMSE de 2,48 cm). Cette méthode estime la profondeur quotidienne de la nappe phréatique comme le résultat d'une composante locale et d'une composante régionale, ce qui est observé dans les données réelles. Ce type de méthode prend en compte la sensibilité régionale (Corzo et Solomatine 2007) et définit le comportement de la nappe phréatique comme le résultat d'une composante locale (principalement le drainage et l'irrigation) et d'une composante régionale (principalement les précipitations et l'évapotranspiration). De plus, la méthode tsd conserve les données connues (observations bimensuelles) pour le puits estimé. Les autres méthodes génèrent de nouvelles données, même pour les données observées, ce qui est contre-intuitif. De plus, la méthode de décomposition des séries temporelles capture également l'impact local des phénomènes quotidiens (précipitations, irrigation) à partir de l'information du puits de référence sans aucune étape supplémentaire. Par conséquent, l'hydrogramme estimé de la nappe phréatique est plus réaliste que ceux obtenus par les autres méthodes.

Ensuite, ce chapitre aborde la sélection du puits de référence et l'effet de la fréquence des mesures de la profondeur de la nappe phréatique dans les puits estimés sur l'estimation globale de la profondeur quotidienne de la nappe phréatique. Pour la méthode tsd, le changement de la fréquence de mesure à des mesures hebdomadaires diminue la RMSE de 16 % (2,08 cm) et à des mesures mensuelles augmente la RMSE de 13 % (2,80 cm) par rapport aux mesures bimensuelles (RMSE 2,48 cm).

À la fin de ce chapitre, il est recommandé d'utiliser la méthode tsd puisqu'elle ne nécessite aucun entrainement ce qui la rend facile à mettre en œuvre. Aussi, il est recommandé de choisir le puits de référence dans le même réseau hydraulique (ou avec le même type de gestion) et un relevé bimensuel ou hebdomadaire sur les puits estimés. Cela étant dit, il n'est pas possible de recommander une distance par rapport au puits de référence, mais il faut tenir compte de la similitude du site et s'assurer que le puits de référence appartient au même réseau hydraulique ou au même régime hydraulique.

Le chapitre 1 aborde aussi la question du nombre d'enregistreurs du niveau de la nappe phréatique, souvent posée par ceux qui s'intéressent au contrôle de la nappe phréatique dans la culture des sphaignes. La réponse est d'en placer autant que possible pour couvrir la plus grande proportion du site. Cependant, cela n'est pas possible en raison de contraintes budgétaires ou logistiques. Grâce à ce travail, il a été possible de trouver une méthodologie qui n'utilise qu'un seul enregistreur de niveau de nappe phréatique par ensemble de bassins ayant le même régime, en plus des enregistrements peu fréquents (hebdomadaires ou bimensuels) effectués par le personnel de terrain.

Pour l'avenir, cette méthodologie pourrait être utilisée non seulement dans la culture des sphaignes mais aussi dans les projets de réhumidification des tourbières. Notamment, dans des projets en restauration des milieux humides où la mesure de la nappe phréatique est nécessaire et souvent, seuls certains puits instrumentés peuvent être installés, en complément aux enregistrements manuels peu fréquents de la nappe phréatique (Rocco Russo et Strack 2019; Guérin et coll. 2020; Isabel et coll. 2020).

Défis 2 : stress hydrique saisonnier et profondeur seuil de la nappe phréatique

Le chapitre 2 aborde la relation entre la croissance de la sphaigne et le stress hydrique saisonnier. Pour ce faire, il est indispensable de disposer de valeurs quotidiennes de la profondeur de la nappe phréatique, ce qui a été assuré par le travail effectué au chapitre 1. Le stress hydrique saisonnier fait référence à la fréquence et à l'intensité avec lesquelles la nappe phréatique dépasse le seuil de stress hydrique. Cette étude est la première à faire intervenir un concept de stress hydrique cumulatif dans les systèmes de culture de sphaigne. Les indicateurs identifiés pour quantifier le stress hydrique étaient la somme des nappes journalières sous la profondeur de la nappe seuil identifiée (SEW) et nombre de jours où la nappe phréatique est sous la profondeur de la nappe seuil (NDW). La SEW considère l'amplitude de la variation de la nappe phréatique et le NDW fait référence à la fréquence à laquelle la nappe phréatique se trouvait sous des profondeurs critiques pour la productivité des sphaignes. En outre, cette étude est basée sur le principe que les différents types d'architectures de communautés de sphaignes déjà étudiés (Rydin 1985; Schipperges et Rydin 1998; McCarter et Price 2014) exercent une influence sur la valeur de la profondeur seuil de la nappe phréatique.

Avant cette étude, aucune méthodologie claire n'a été rapportée pour l'estimation de ces nappe seuils de stress hydrique et cette étude montre la procédure et les résultats en utilisant la correspondance avec l'accumulation de biomasse et la croissance des mousses en termes d'épaisseur du tapis muscinal. En effet, en plus d'être le premier travail à prendre en compte le stress hydrique chez les espèces utilisées en culture de sphaigne, cette thèse démontre que les profondeurs seuils correspondent à la niche écologique préférentielle de chaque espèce de sphaigne par rapport à la profondeur de la nappe phréatique. En général, les espèces du sous-genre Acutifolia (*S. flavicomans*, *S. fuscum* et *S. rubellum*) et du sous-genre Sphagnum (*S. medium* et *S. papillosum*) ont des nappe seuils plus près de la surface que les espèces du sous-genre Cuspidata (*S. fallax*). En moyenne, le profondeur seuil de la nappe phréatique (h_{DT}) pour les espèces du sous-genre Acutifolia était de 13,8 ± 1,9 cm, du sous-genre Sphagnum de 12,5 ± 1,4 et du sous-genre Cuspidata de 3,1 ± 1,8 cm. Ces valeurs correspondent à des nappes plus élevées que celle rapportée dans la littérature pour la recolonisation des tourbières de sphaigne lors de projets de restauration, qui est de 40 cm, et ceci parce que dans la culture de sphaigne l'objectif est de maximiser la productivité, et pas seulement la survie des mousses à travers le temps.

Par ce chapitre, il est possible de quantifier le stress hydrique causé par la fluctuation de la nappe phréatique sous la profondeur seuil. Des coefficients de corrélation entre le stress hydrique et la productivité de la sphaigne allant jusqu'à 0,90 sont trouvés, surtout pour les espèces cultivées en serre où il y a un plus grand contrôle sur les conditions spécifiques au site. La corrélation avec la croissance de la sphaigne est faible à acceptable pour les systèmes de culture à l'extérieur, et en partie en raison d'autres facteurs de variabilité non contrôlés, tels que les précipitations et la température, qui jouent un rôle dans la croissance des sphaignes (Moore 1989; Breeuwer et coll. 2008; Küttim et coll. 2019; Bengtsson et coll. 2021).

En référence à ces facteurs non-contrôlés, ce chapitre mentionne brièvement que les profondeurs seuils de la nappe phréatique sont influencées par les conditions climatiques et les conditions hydrophysiques de la tourbe. Il a été constaté que les températures extérieures plus élevées entraînent un seuil de nappe phréatique plus proche de la surface. Une température plus élevée emmène une demande plus importante en termes d'évaporation par les sphaignes (Goetz et Price 2015 ; Moore et Waddington 2015), et par conséquent le débit sortant plus élevé dû à l'évapotranspiration doit être compensé par un débit plus élevé vers le capitule de la sphaigne. En termes de débit d'eau en milieu saturé, cela représente donc que le seuil de stress en termes de nappe phréatique est plus élevé.

Concernant l'effet des conditions hydrophysiques de la tourbe sur la profondeur seuil de la nappe phréatique, lorsque l'horizon de tourbe en contact avec la sphaigne est plus dense (dans notre cas, il y a un léger changement de 0.13 ± 0.05 à 0.11 ± 0.01 g cm^{-3}) et ayant une valeur de conductivité hydraulique plus faible (dans notre cas, il y a un changement de 2,01 ± 0,97 à 1,40 ± 0,43 m $jour^{-1}$), les valeurs des profondeurs seuils de la nappe phréatique sont plus profondes. Par exemple, dans le cas de *Sphagnum medium*, l'espèce commune à tous les systèmes analysés, la profondeur cible varie de 9,7 à 20,3 cm en utilisant NDW comme indicateur. En fait, une densité apparente plus élevée et une conductivité hydraulique saturée indiquent que la taille des pores est plus petite, et donc la tourbe peut retenir une plus grande quantité d'eau (Price et coll. 2003 ; Caron et coll. 2015), ce qui signifie que la nappe phréatique peut être plus profonde sans entrainer de stress hydrique aux sphaignes. Toutefois, ces observations sont encore préliminaires et devront être vérifiées par un contrôle plus poussé des conditions hydrophysiques de l'horizon en contact avec la sphaigne.

L'utilisation du concept de stress hydrique saisonnier ouvre la porte à l'utilisation d'une zone de confort hydrique, définie par la profondeur seuil de la nappe phréatique et correspondant à la niche préférentielle par rapport à la microtopographie et à la position de la nappe phréatique. Par conséquent, cet indicateur de stress hydrique pourrait non seulement être appliqué à la culture des sphaignes, où il existe un certain contrôle de la nappe phréatique, mais sera encore plus important dans d'autres applications telles que la restauration écologique des fens (Ketcheson et coll. 2017; Lemmer et coll. 2020), restauration de tourbières affectées par la construction d'une route (Guérin et coll. 2020; Isabel et coll. 2020; Pouliot et coll. 2021), restauration de l'hydrologie par blocage des fossés (Van Seters et Price 2001; Peacock et coll. 2013; González et Rochefort 2014), le rétablissement de la végétation des tourbières après un incendie (Howie et coll. 2020; Guêné-Nanchen et coll. 2021), entre autres.

Défis 3 : estimer les fluctuations des niveaux de la nappe phréatique par modélisation

Étant donné qu'une zone de confort a été définie avec le stress hydrique saisonnier quantifié au chapitre 2, il est important d'estimer la fluctuation de la nappe phréatique dans un système de culture de sphaigne en fonction du système de gestion de l'eau. Le chapitre 3 part du fait que dans la culture de sphaigne, il ne suffit pas de bloquer le réseau de drainage (Price et coll. 2003; Quinty et Rochefort 2003) créé lors de l'extraction de la tourbe, comme c'est le cas dans la restauration. Un système d'irrigation est nécessaire pour répondre aux besoins en eau, notamment en période estivale. Ce chapitre est une introduction à l'analyse hydrologique du réseau d'approvisionnement en eau utilisé en culture de sphaigne. Comme expliqué dans l'introduction de cette thèse, le but n'est pas de restaurer réellement le régime hydrologique de la tourbière ombrotrophe; au lieu de cela, nous nous concentrons sur la réorientation de la tourbière ombrotrophe après l'extraction de tourbe pour la paludiculture sous la forme de système de culture de sphaigne.

Un modèle simple a été développé et implémenté, basé sur l'équation de Boussinesq (1877) décrivant la fluctuation de la nappe phréatique en fonction de l'écoulement souterrain, et l'équation de Darcy (1856) décrivant l'écoulement de l'eau dans un milieu saturé. Ce modèle a décrit 91 % de la variation observée du niveau de la nappe phréatique pour deux types de configuration de canaux sur le même site. Toutefois, l'une des limites de l'étude était le temps d'observation. En raison des limitations techniques du système d'irrigation, seuls 21 jours d'observation ont été utilisés. L'une des suggestions est donc d'explorer l'application de ce modèle pour une saison de croissance complète, ce qui équivaut plus ou moins à 4 mois.

La performance du modèle est également un résultat d'une bonne estimation de paramètres d'entrée du modèle. La combinaison de la mesure continue du niveau d'eau dans les canaux d'irrigation, les mesures sur place des précipitations, l'approximation de l'évapotranspiration par un modèle utilisant des mesures de la température sur le site et de la radiation extraterrestre, ainsi que les mesures *in-situ* de la conductivité hydraulique saturée ont fourni des informations précises pour représenter l'écoulement souterrain et la fluctuation du niveau de la nappe phréatique dans le bassin de culture de sphaigne étudié sous deux configurations de canaux d'irrigation (canal périphérique et micro-canaux).

En particulier, pour la mesure de la conductivité hydraulique saturée, la méthodologie du trou à la tarière (Lagacé, 2016) est suggérée car elle utilise un échantillon de tourbe plus représentatif et non altéré, et aussi parce qu'elle permet d'estimer la valeur de la conductivité hydraulique saturée pour chaque horizon du profil de tourbe identifié sous la nappe phréatique.

Un résultat important de ce chapitre est l'exploration de micro-canaux d'irrigation afin d'améliorer l'hydrologie des bassins de culture de sphaigne, ainsi que l'amélioration du réseau hydraulique des canaux d'irrigation en réduisant l'espacement entre les canaux. Sur la base des résultats du chapitre 3, il est suggéré d'aller de l'avant avec les micro-canaux d'irrigation (canaux de 20 cm x 20 cm, espacés de 10 m) et la réduction de l'espacement entre les canaux d'irrigation (réduction de 20 m à 10 m) car ils permettent à la nappe phréatique de monter plus rapidement et ils permettent une profondeur de la nappe phréatique plus uniforme.

Recommandations pour l'avenir

Enfin, des travaux futurs sont suggérés pour optimiser l'hydrologie dans les systèmes de culture de sphaigne et les projets de ré-humidification de tourbières. Ces suggestions sont classées sous forme de points pour chaque défi abordé.

Défis 1 : saisir l'hétérogénéité spatiale et temporelle du niveau de la nappe phréatique

- Il est suggéré que la méthode de décomposition des séries temporelles (tsd) pour l'estimation des valeurs quotidiennes de la profondeur de la nappe phréatique soit utilisée dans d'autres projets de restauration écologique, y compris dans les tourbières minérotrophes et aussi une utilisation en culture de sphaigne avec une plus grande base de données. L'utilisation dans les tourbières minérotrophes peut être intéressante car, contrairement aux tourbières ombrotrophes, leur alimentation en eau ne dépend pas seulement de l'eau de pluie et du fait qu'elles sont connectées à la nappe phréatique régionale (Rochefort et Lode 2006; Rydin et Jeglum 2013). Le succès de cette méthode dépend de la sélection du puits de référence, qui doit encore être étudiée. Pour l'instant, il est certain que le choix doit considérer la similitude du site et s'assurer que le puits de référence appartient au même réseau hydraulique ou a le même régime hydraulique. De plus, un autre facteur de réussite sont les mesures manuelles dont il est conseillé qu'elles soient bimensuelles ou hebdomadaires.

- Les stratégies de sélection du puits de référence doivent être étudiées plus en détail. De plus, il serait intéressant de collecter d'autres données pour tester les performances de la méthode tsd sur d'autres sites et d'autres régimes de fluctuation de la profondeur de la nappe phréatique.

Défis 2 : stress hydrique saisonnier et profondeurs seuils de la nappe phréatique associés

- Pour prédire la productivité des sphaignes en fonction du stress hydrique dû aux fluctuations de la nappe phréatique, il est possible d'utiliser des modèles de type stress-jour-index (Hiler 1969 ; Evans et al. 1990, 1991). Ces modèles permettent de déterminer la productivité liée à un niveau de stress hydrique, quantifié par un indicateur de stress hydrique, et un facteur de sensibilité de la culture. Pour l'instant, cette étude a identifié les indicateurs permettant de quantifier le stress hydrique et les valeurs possibles pour les profondeurs seuils de la nappe phréatique. La prochaine étape consistera à identifier le facteur de sensibilité des cultures, qui peut également être fonction de l'âge de la culture de la sphaigne. Il est recommandé de réaliser ces tests dans des conditions contrôlées, par exemple à l'aide de lysimètres tels que ceux utilisés par Evans, Skaggs et Snee (1990).

Défis 3 : conception et de l'évaluation du réseau d'approvisionnement en eau

- Il est attendu que le modèle hydrologique développé puisse servir de base à de projets de culture de sphaignes et, bien sûr, gérer des zones beaucoup plus vastes. Tout nouveau projet doit prendre en compte la stratification du milieu tourbeux et les propriétés physiques de la tourbière afin de choisir la configuration adéquate du réseau hydraulique. Enfin, ce projet vise à expliquer l'importance du flux horizontal faisant varier la nappe phréatique qui alimente le flux vertical nécessaire pour la croissance de la sphaigne.

- Si la mise en œuvre des micro-canaux est approfondie, il sera également nécessaire d'analyser l'adaptation des équipements déjà disponibles, voire la conception de nouveaux équipements pour la construction et l'entretien des micro-canaux d'irrigation.

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